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From Demand Deficit to Development Strategy: Navigating Mini-Grid Viability in a Fragile Context [*]

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Abstract

Four in five people without access to electricity live in Sub-Saharan Africa, where mini-grids are seen as a key solution to closing the energy access gap. Yet investment in mini-grids remains constrained by low and unpredictable demand, especially in fragile and conflict-affected settings. We study electricity demand in North Kivu, Democratic Republic of Congo – a region marked by conflict and institutional fragility. Drawing on census data from five localities, we track connection rates and electricity consumption over a six-year period. In addition, a detailed pre-connection survey allows us to link household and firm characteristics to actual connection uptake and electricity consumption. We find that demand is highly heterogeneous, and only weakly associated with pre-grid data. This makes planning and sizing of mini-grids particularly difficult and risky. We then examine how the local mini-grid operator, Virunga Energies, has addressed this challenge through an integrated development strategy that includes supporting industrial clients, providing micro-credit, promoting electric cooking, and leveraging temporary anchor loads. The case highlights how mini-grid viability in fragile settings may depend less on improved demand forecasting and more on the capacity to build and coordinate demand alongside infrastructure. This has implications for electrification policy, investment design, and the role of public and donor support in overcoming coordination failures.

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In 2022, an estimated 685 million people worldwide lacked access to electricity, with the vast majority – 571 million – residing in Sub-Saharan Africa. Strikingly, 382 million of these individuals lived in countries that appeared on the World Bank's Fragile and Conflict-Affected Situations list (IEA 2024). In these fragile and conflict-affected countries, only 40% of the population has access to electricity, compared to 62% in other Sub-Saharan African countries.[1] Moreover, it is in these fragile contexts that the pace of electrification barely keeps up with population growth (IEA 2024). Without targeted strategies, these regions will continue to fall behind.

Mini-grids are often presented as a scalable solution for rural electrification in Africa.[2] Compared to lower-cost off-grid alternatives like solar home systems, they offer higher-capacity electricity (Grimm et al. 2017), which is essential for driving business development and industrialization (Chakravorty, Pelli, and Ural Marchand 2014; Dinkelman 2011; Kassem 2024; Rud 2012; Ratledge et al. 2022), as well as for supporting critical services like education and health care (Lewis 2018; Lipscomb, Mobarak, and Barham 2013). As such, access to mini-grid electricity is considered a precondition for achieving many SDG targets (Fuso Nerini et al. 2018). However, their long-term viability depends on sufficient and sustained electricity demand (Ankel-Peters et al. 2025; Blodgett et al. 2017; Blimpo, Postepska, and Xu 2020). A key difficulty lies in sizing mini-grids to match this demand: poorly sized systems either waste resources or fail to meet user needs

[1] Own calculation based on the 2025 World Bank list of Fragile and Conflict-Affected Situations and the electrification dataset of the International Energy Agency (https://trackingsdg7.esmap.org/downloads; accessed on May 16, 2025).

[2] A mini-grid is a localized electricity network that operates independently of the main grid, using sources like solar, wind, or diesel to generate and distribute power to a specific area. The World Bank estimates that 380 million people in SSA will need to be connected via mini-grids by 2030 – at a cost of $127 billion (ESMAP 2022). In 2022, an estimated 48 million people were connected to 21,500 mini grids, ranging from small systems serving a handful of customers in remote settlements to larger networks supporting hundreds of thousands in towns. These are mostly powered by solar energy (50%) and hydro energy (35%) (ESMAP 2022).

(Scott and Coley 2021; Gelchu, Ehnberg, and Ahlgren 2023). This is particularly challenging in fragile settings where poverty, market frictions, and institutional weakness may undermine stable demand in the first place (Ahlborg et al. 2015).

This paper investigates this challenge in North Kivu, Democratic Republic of Congo (DRC), one of the most conflict-affected regions in the world. Nationally, electricity access is just 21%, and in North Kivu it drops to a mere 8%, despite abundant hydropower potential (IEA 2024; World Bank 2021). We study the case of Virunga Energies (VE), a private mini-grid operator that has installed three run-of-river hydropower plants with a combined capacity of 30 MW. Drawing on administrative billing records, georeferenced census data, household and business surveys, and key informant interviews conducted over several episodes of fieldwork, we explore patterns of electricity demand and evaluate strategies – such as coordinated planning, institutional integration, and blended finance – that could help boost and stabilize demand, thereby supporting mini-grid sustainability in fragile contexts.

To that end, we study four rural and one urban locality served by Virunga Energies. Prior to the grid rollout, we collected census data on 27,555 parcels and detailed survey data from 911 households and 291 small businesses, capturing information on housing quality, appliance ownership, non-grid energy use, and socioeconomic characteristics. We then link this data to VE's administrative billing. This allows us to track connection rates and electricity consumption at the locality-level over a six-year period, and link pre-grid characteristics of households and businesses to actual connection uptake and electricity consumption.

We find strong heterogeneity in connection rates and electricity consumption both across and within localities, with pockets of low uptake. Furthermore, while certain pre-electrification characteristics – such as housing quality, parcel ownership and prior energy use – are correlated with uptake and usage, electricity demand proves difficult to predict with precision (as in e.g. Allee et al. 2021; Blodgett et al. 2017; Hartvigsson and Ahlgren 2018). These findings highlight the limitations of demand forecasting in mini-grid planning and underscore that electricity demand is highly context-dependent, even in seemingly similar settings. Qualitative interviews with VE key informants suggest that differences in uptake between localities were partly explained by demonstration effects, where early adopters influenced others to connect (see also Bos, Chaplin, and Mamun 2018), and location-specific difficulties in securing formal land titles – a prerequisite for obtaining a connection. While land tenure has been widely recognized as a constraint to infrastructure investment (see e.g. Galiani and Schargrodsky 2010), its role as a direct obstacle to household-level electricity access has, to our knowledge, not been highlighted in existing studies.

In a second step – guided by the same key informants and drawing on several episodes of fieldwork and firsthand observations conducted over a seven-year period in the region – we examine how VE has responded to low and uncertain demand through an integrated development model that stimulates electricity use among both commercial and residential clients. Their strategy combines multiple reinforcing interventions, including promoting the rise of industrial clients, offering microcredit to Small and Medium-sized Enterprises (SMEs), subsidizing electric cooking appliances, and temporarily absorbing excess supply through large anchor loads. Together, these interventions have improved system utilization and financial sustainability in one of the most fragile regions in the world. This integrated approach is made possible by blended finance, and VE's embeddedness in the Virunga Alliance, a Public-Private partnership that seeks to set up transformative projects for sustainable development in communities near Virunga National Park.[3] The key take-away is that effective coordination between electrification and sustainable development is crucial for achieving a mutually beneficial outcome; without such alignment neither activity may be viable.

This paper contributes to the growing literature on rural electrification in low-income settings in three ways. First, it provides rare empirical evidence from a fragile and conflict-affected context, where data on electricity demand and mini-grid performance remain scarce (Kraft and Luh 2022; VanderWilde, Fitch, and Mueller 2018). In the DRC, this lack of demand data constrains private investment planning needed to harness the country's vast hydropower potential (World Bank 2020). Second, it highlights the limits of demand forecasting approaches, even when based, as in our case, on fine-grained census and survey data collected *prior* to grid installation. This aligns with findings from others who relied on energy use surveys, smaller samples, or post-connection data (Louw et al. 2008; Blodgett et al. 2017; Hartvigsson and Ahlgren 2018; Wassie and Ahlgren 2023; Ruhinduka et al. 2024). Third, it adds to recent work on the institutional and strategic dimensions of mini-grid viability by documenting how an integrated model can help overcome coordination failures and improve financial performance (Hartvigsson et al. 2021; Kyriakarakos, Balafoutis, and Bochtis 2020; Mbazima and Lemaire 2025). By focusing on one of the most challenging environments for electrification, our findings speak to ongoing debates about how to design sustainable mini-grid systems where the development stakes – and risks – are highest (Ahlborg et al. 2015; Dagnachew, Choi, and Falchetta 2023).

[3] For more information, see https://virunga.org/alliance/

This latter contribution also relates to broader debates in development economics around coordination failures (Murphy, Shleifer, and Vishny 1989), and market formation in environments where first movers generate significant knowledge spillovers (Hausmann and Rodrik 2003). Electrification is often framed as a technical or infrastructure challenge, yet it is deeply shaped by market and institutional frictions, certainly in fragile settings. The VE case study shows that weak and unpredictable demand reflects not just affordability constraints but also missing or underdeveloped markets for complementary goods and services – such as appliances, credit, or input supply chains. In such environments, early investors in mini-grids face significant risks but generate positive externalities: they reveal information for future investors, help stimulate complementary markets, and shift the system toward a higher-demand equilibrium (Foster and Rosenzweig 2010). Yet if these first-mover firms collapse under financial strain, no one follows, and the market remains stuck in a low-equilibrium trap. Blended finance – where part of the investment is supported by donors or governments – plays a critical role in de-risking these pioneering efforts and correcting the market failure (Juhász, Lane, and Rodrik 2024). These insights speak to a wider class of development challenges where infrastructure, demand, and institutional capacity must be jointly addressed to unlock growth.

I. Background

North Kivu province (see Panel A of Figure 1) spans almost 60,000 km² and counts around 7 million people, with an estimated 1.9 million living in the provincial capital Goma. Largely dependent on subsistence farming, half of the population lives in extreme poverty and nearly a third faces acute food insecurity (UNOCHA 2024; World Bank 2021). Over the past three decades, North-Kivu has experienced some of the most violent and persistent conflicts in the DRC

(Autesserre 2010; Stearns 2021), with social and economic instability further exacerbated by volcanic eruptions and disease outbreaks, including Ebola and Covid-19 (Stoop et al. 2021; Maombi et al. 2025). Despite these challenges, North-Kivu is among DRC's provinces with the highest potential for economic growth, being rich in agricultural and mineral resources, and the possibility to develop regional and international trade through its borders with Uganda and Rwanda (World Bank 2021). The relative dynamism of North-Kivu is reflected in the energy sector, as the province hosts some of the country's few private investments in electrification.

- Figure 1 about here -

Until the liberalization of the sector in 2014, electricity supply in the DRC was the monopoly of the national electricity company SNEL (Société Nationale d'Electricité). The 2014 electricity law created the Electricity Regulatory Authority as an independent regulator, and aimed to attract private investments through public-private partnerships (Mubenga et al. 2023). These investments mostly materialized in North-Kivu, where four private sector players operate grids powered by small or mid-sized hydro power or solar plants: Virunga Energies, SOCODEE, ENK, and Nuru. In 2021, their combined grids offered a capacity of 32 Megawatt (MW), thereby largely surpassing the 7 MW capacity of SNEL in the province (World Bank 2021).[4] Yet, North-Kivu's electrification rate remains extremely low, estimated around 8%.

[4] Virunga Energies had a generation capacity of 30 MW; SOCODEE operated a 5MW transmission line and distribution grid in Goma but bought power from Virunga Energies; Nuru operated a 1.3 MW solar / battery plant; ENK operated a 1.8 MW solar-powered system. Other companies, including Altech, BBOXX and Weast Energy, distributed solar home systems in North-Kivu (World Bank 2021).

Our case study focuses on Virunga Energies (VE), the largest electricity provider in North-Kivu. It is part of the public-private partnership Virunga Alliance, which also encompasses Virunga Foundation (an NGO) and the Congolese Institute for Nature Conservation. Together, they aim to protect the natural resources of Virunga National Park, while also bringing about economic development and security. The Park covers about 7,900 km^2 of North-Kivu (Figure 1) and is the oldest and most biodiverse national park in Africa. However, in 2024 an estimated 15% of the Park's surface area was degraded due to cropland expansion for subsistence agriculture and the heavy reliance of North-Kivu's population on firewood and charcoal for cooking (Merode, d'Huart, and Henrard 2025). The Alliance seeks to stimulate more sustainable livelihood options, with grid electrification potentially playing a vital role in driving economic diversification, fueling the transition to clean cooking, and reducing conflict (Rud 2012; Kassem 2024; Stoop and Verpoorten 2024; Desbureaux et al. 2025; Maombi Ndatabaye, Stoop, and Verpoorten 2025).

It is in this context that VE embarked on a project aiming to roll out several mini-grids with a combined capacity of 100 MW. About 30 MW is already generated by three run-of-river hydropower plants: Mutwanga (1.4 MW), servicing the locality of Mutwanga in Beni territory; Matebe (13.2 MW), providing electricity to about 15 localities in Rutshuru territory and to the city of Goma; and Luviro (14.6 MW) servicing three localities in Lubero territory. Panel B of Figure 1 shows the location of the powerplants. To distribute their electricity from the plants to these localities, VE has constructed networks with high, medium and low voltage lines. The grid became operational in March 2019 in Mutwanga and in November 2021 in Lubero. The Matebe powerplant became operational in 2017, and localities on the road to

Goma were gradually connected to the grid, before the city itself was connected in June 2019. [5]

For households and SMEs, VE charges a mono-phase connection fee of $123-$173, while more powerful three-phase connections are available for $226. For large businesses, connection charges are negotiated on a case-by-case basis depending on the location of the business, the material needed for the connection, and the quantity of electricity required. Once connected, clients can purchase pre-paid electricity from VE liaison officers at $0.250 per kilowatt-hour (kWh) for household connections and a slightly lower rate of $0.235 per kWh for SME connections. Industrial clients are not required to pre-pay electricity and benefit from a lower usage rate of $0.149 per kWh. VE further pursues a social mission by providing free public lighting in the city of Goma and the 20 villages connected to its grid, and free electricity to 78 health centers and 49 public buildings and schools. They further provide electricity at a preferential rate to three water pumping stations in Goma, providing access to clean water for 700,000 people (Merode, d'Huart, and Henrard 2025).

In the following sections, we examine patterns of electricity uptake and consumption in the city of Goma and four rural localities connected to VE's grid. Before presenting our findings and discussing VE's strategies for navigating challenges and opportunities in this fragile and conflict-affected context, we first describe our data and outline the methodology used.

[5] A first small powerplant, Mutwanga I (0.35 MW), was already installed in 2013 but covered only a limited area of the locality. In March 2019, Mutwanga II (1.4 MW) was installed, and the grid was strongly expanded. An additional hydropower plant with an expected capacity of 26 MW is currently under construction in Rwanguba, close to Matebe, and will soon become operational.

II. Data and Methods

A. Data

We draw on four data sources to analyze the demand for grid electricity.

Census data.— We conducted a parcel-level census in five localities, part of three broad regions (see Panel B of Figure 1). These localities were selected because they offered the opportunity to collect data prior to their connection to the grid: in 2019 in Mutwanga and Goma, and in 2021 in Lubero territory. For each parcel, we collected GPS coordinates and indicated whether it consisted of a household, an SME, or an institution (e.g., church, school, hospital). Enumerators further rated the construction quality of the main building on a scale from 1 (very poor quality) to 4 (very high quality), providing us with a wealth proxy.[6] Figure 2 provides a graphical example of the census data collected for Mutwanga.

- Figure 2 about here -

In total, we registered 27,555 parcels, including 25,584 households, 1,682 SMEs and 289 institutions. The majority (61%) of parcels are located in Goma, with the remainder distributed across Mutwanga (21%) and the three localities in Lubero territory (17%).

Survey data.— Relying on the census data as a sampling frame, we drew a random sample of households and SMEs in each of the five localities. Our sample includes 911 households and 291 SMEs. Appendix A provides detailed information on the

[6] In SSA, it is commonly observed that the construction quality, particularly with respect to the materials used for roofs and walls, is strongly correlated with measures of wealth (Iddi et al. 2022; Tusting et al. 2019). To ensure that enumerators rated construction quality in a similar way, we organized a specific training and simulation exercise.

sampling process and shows the distribution across localities. The survey included detailed questions on sociodemographic characteristics, energy use, and wealth. Two years after the baseline, we conducted a follow-up survey to identify which households and SMEs had connected to the VE grid, and to record their electricity meter numbers to link them with VE electricity consumption data.

Electricity data.— From VE, we obtained client data for the geographical areas covered by our census. For each client, we have information on the date they got connected to the grid and their electricity purchase transactions between January 2019 and December 2024. In total, we have information on 13,479 clients and 1,945,076 electricity purchase transactions. Most of these clients – 12,863 or 95% – are households, while the remaining 616 are SMEs.[7] VE holds exclusive rights to electricity distribution in the zones allocated to them, enabling us to capture all electricity purchases made by the clients in our database.

Qualitative interviews.— Finally, we conducted open-ended interviews with five purposely selected VE staff members who are actively involved in the decision making and implementation of the company's electricity provision strategy. These interviews shed light on the quantitative findings by providing locality-specific context. Combined with our firsthand observations in the region, they provide a deeper understanding of VE's strategies for mitigating risk in an environment where electricity demand is uncertain.

[7] Our database only includes information on households and SMEs connected to the VE grid within the geographical area covered by our census. At the end of 2024, approximately 37,000 households, 1,800 SMEs, and 17 industrial companies were connected to VE's grid in North-Kivu. The clients that are not included in our database are mostly located in Rutshuru territory, between the Matebe powerplant and the city of Goma, and in other city blocks of Goma that were electrified by VE at a later stage, after we had already conducted our census. Section III.C provides a broad overview of VE's electrification strategy and client portfolio.

B. Methods

Evolution of grid connections and electricity consumption.— We rely on VE's electricity data to create a monthly panel of electricity consumption for the 13,479 clients in our five localities.[8] The database covers the period from January 2019 to December 2024; 72 months. Given the different dates at which the grid became operational, the database contains information on electricity consumption for a period of 70 months for Mutwanga, 67 months for Goma, and 38 months for Lubero. In total, we have information on electricity purchases for 570,690 client-month observations. Relying on clients' connection date and the parcel count from our census, we describe the evolution of electricity uptake and connection rates over time and across our three research areas.[9] We further describe the evolution of monthly electricity purchases by households and SMEs, drawing on insights from the open-ended interviews to contextualize the differences both across and within research areas.

Electricity demand in our sample.— To study the determinants of electricity demand, we link our survey data with pre-grid characteristics of households and SMEs to their actual electricity uptake and consumption. We estimate two econometric models. First, we estimate the following linear probability model[10]:

$$C_{ia} = \beta_0 + \beta_1 \mathrm{X}_{ia} + \beta_2 \mathrm{Z}_{ia} + \beta_3 \mathrm{W}_{ia} + \varepsilon_{ia} \tag{1}$$

[8] The VE database records purchases of pre-paid electricity. VE clients have no incentive to save kWh on their meters, and they typically make three to four electricity purchase transactions per month. Hence, monthly electricity purchases serve as a reliable proxy for actual monthly electricity consumption.

[9] Connection rates are calculated by dividing the number of VE clients located within the geographical area covered by our 2019 census by the number of parcels we recorded in the census. While the number of parcels in these zones has remained relatively stable over time, the number of businesses has fluctuated significantly. As a result, our data only allow us to provide a general overview of connection rates and do not allow for differentiation between households and SMEs.

[10] Our findings are robust to using Logit or Probit estimations instead (see Appendix D).

where i represents a household or small business in research area a. The outcome variable, C_{ia}, indicates whether the household or small business is connected to the grid at the time of the follow-up survey. X_{ia}, Z_{ia}, and W_{ia} are, respectively, vectors of baseline variables capturing socio-demographic characteristics, energy use related variables, and variables capturing wealth; ε_{ia} represents the error term. Equation (1) is estimated separately for households and small businesses.

Second, for households and small businesses that connected to the grid, we estimate the determinants of electricity consumption through the following linear model:

$$kWh_{ia} = \beta_0' + \beta_1' X_{ia} + \beta_2' Z_{ia} + \beta_3' W_{ia} + \varepsilon_{ia}' \tag{2}$$

which is identical to equation (1), except that the outcome variable is now the natural logarithm of the average monthly kWh consumed by the household or small business. This is calculated for the period from the time of connection up to the follow-up survey and is denoted by kWh_{ia}. In both models, we control for differences across research areas and enumerators by including both research area and enumerator fixed effects. To account for heteroskedasticity, we estimate robust standard errors. All models account for sampling weights (see Appendix A for details).

III. Results & Discussion

A. Evolution of grid connections and electricity consumption

Panel A of Figure 3 highlights the differences in connection rates across the three research areas. Two years after the grid installation, both Goma and Mutwanga had a connection rate of about 35% in the areas covered by the census. It is important to note, however, that Mutwanga had a head start as 15% of parcels were already connected to the grid in January 2019 through a smaller hydro powerplant (0.35 MW). The installation of a new, more powerful, hydro powerplant (1.4 MW), hence increased the connection rate by about 20 percentage points in two years. In Lubero, on the other hand, much fewer people connected to the grid, with a connection rate of 11.7% after two years.

Looking further down the line, connection rates continued to increase in all research areas, albeit at a slower rate in Mutwanga: in December 2024, the last month in our database, 13,479 clients were connected in the areas covered by the census. At that time, the grid had been operational for 70 months in Mutwanga, 67 months in Goma and 38 months in Lubero. The city of Goma accounted for most of these clients (11,006 or 81.7%), while the rural areas of Mutwanga and Lubero accounted for 1,685 and 788 clients each – implying overall connection rates of 72.6%, 43.4%, and 25.7%, respectively, within the zones covered by our census.

- Figure 3 about here -

Panels B and C of Figure 3 show how the number of clients evolved over time, focusing respectively on households and SMEs. In Mutwanga, we observe that the expansion of the grid almost immediately led to approximately a doubling of the number of household and SME client connections, followed by a more gradual pace of connections over time. In the city of Goma, we observe a steady increase over time in both types of connections. In Lubero, an interesting pattern unfolds as we observe generally low overall connection rates but a comparatively high number of SME connections. For instance, when comparing research areas in December 2024, Lubero accounts for only 5% of household connections (660 clients), while it accounts for 21% of SME connections (128 clients). At this point, SMEs constituted 16% of clients in Lubero, while this share was much lower in both Mutwanga (7%) and Goma (3%).[11]

The interviews shed further light on these findings. Virunga staff members noted that the lower connection rates among households in Mutwanga and Lubero are primarily due to their rural context. In these areas, households struggle more to afford a grid connection due to economic constraints. In addition to the connection fee of about $150, households face an investment of up to $120 for costs of in-house electric wiring. This resonates with the findings of Ruhinduka et al. (2024), who show that in-house wiring costs remain an important barrier to electricity uptake in rural Tanzania, where connection fees are strongly subsidized by the government.

In addition to economic constraints, legal requirements and trust also play a role in explaining electricity take-up. A legal requirement mandates that individuals present land deeds to be able to connect to the grid. However, obtaining a land deed in the DRC is often a long, complex and costly process, particularly so in rural areas with limited state infrastructure. To overcome this hurdle, VE offered to assist prospective clients with obtaining land titles. However, this proved challenging. Due to the high prevalence of land conflicts in the region, land titling is a sensitive matter, and households were often reluctant to present the necessary documents to

[11] Appendix C shows the distribution of clients by type and research area.

Virunga, e.g. sales deeds demonstrating their land ownership. This was particularly the case in Lubero, where VE had not yet been able to build a reputation as a fully trustworthy actor. In Mutwanga, such trust issues had already been overcome, as the population was familiar with VE through the smaller powerplant that it established in 2013. When the electricity grid in Mutwanga was expanded in 2019, 15% of parcels was already connected, allowing others to observe the benefits of electricity access. As found in other contexts (e.g., Bos, Chaplin, and Mamun 2018), this 'demonstration effect' likely boosted electricity uptake in Mutwanga compared to Lubero.

- Figure 4 about here -

Figure 4 displays the evolution of average monthly electricity purchases (in kWh) among household and SME clients. In Goma and Lubero, average purchases rose sharply during the first six months following grid installation. After this initial increase, electricity purchases remained relatively stable over time, albeit with some fluctuations. In Mutwanga, average electricity purchases remained relatively stable from the start of the grid expansion. This suggests that while initial need may drive short-term increases in usage, long-term adoption patterns depend on broader economic and social factors. These patterns align with findings from a recent study on South-African households, showing that the median time to adopt appliances like stoves, refrigerators, and televisions ranges from 4 to 14 years after gaining grid access (Dinkelman et al. 2024).

Over the study period, household clients on average consumed 14 kWh per month in Mutwanga, 40 kWh in Goma and 34 kWh in Lubero (see Appendix B for descriptive statistics). Average electricity consumption was hence low in all research areas, with 14 kWh allowing to provide basic lighting, phone charging, and powering small electrical devices such as a radio, while 40 kWh allows to power some additional appliances such as a television, electric iron, or a water heater.[12] As expected, SME clients purchased significantly more electricity, while the averages were still relatively low at 67 kWh per month in Mutwanga, 358 kWh in Goma and 170 kWh in Lubero. These numbers are comparable to monthly electricity consumption reported for households (30 kWh) and SMEs (137 kWh) connected to a mini-grid in rural Ethiopia (Wassie and Ahlgren 2023). The figures highlight several disparities across research areas. Among household clients, what stands out is the relatively high monthly electricity purchases in Lubero compared to Mutwanga. This is linked to the previously mentioned low household connection rates in Lubero: those who did connect, are likely to be higher-consuming users. In the case of SMEs, Goma stands out with much higher average electricity purchases – an expected pattern given that it is the provincial capital and economically more vibrant than the rural areas of Lubero and Mutwanga.

These averages further hide large heterogeneity within research areas. Figure 5 shows boxplots for average monthly electricity purchases, calculated for each client over their entire connection period. Among households, the median is just 9 kWh in Mutwanga and Lubero, compared to 27 kWh in Goma (Panel A). However, the top 5% of consumers use significantly more, averaging over 39 kWh per month in Mutwanga, 80 kWh in Lubero, and 107 kWh in Goma. Some outliers consume as much as 400 kWh per month in Mutwanga, 500 kWh in Lubero, and 1,500 kWh in Goma and (panel B).[13] Among SME clients, median values are again lowest in Mutwanga (34 kWh), higher for Lubero (84 kWh), and significantly higher for Goma (169 kWh) (Panel C). The top 5% of SME consumers on average use more

[12] Our follow-up survey, conducted about two years after grid installation, shows that households who connected to the grid significantly increased their ownership of electric appliances, most notably by purchasing televisions, electric irons, water heaters, and freezers.

[13] Note that some clients who are registered as households with VE may also have an economic activity, explaining their higher electricity consumption. Additionally, in Goma, some households unofficially share their VE connection with other households, contributing to increased usage.

than 319 kWh per month in Mutwanga, 391 kWh in Lubero, and 1,207 kWh in Goma (panel D).

- Figure 5 about here -

- Figure 6 about here –

Finally, Figure 6 displays total monthly electricity consumption for our three research areas. Both for household and SME clients, total monthly purchases continue to increase over time, as additional clients connect to the grid. With its large client base, the city of Goma consumes by far most electricity, accounting for 89% of electricity purchased across our three research areas in December 2024. The rural areas of Mutwanga and Lubero account for 6% and 5%, respectively. It is further interesting to note that while SME connections only represented 4.6% of the client base in December 2024, they accounted for 19% of total electricity purchased. In Lubero, where relatively few households connected, SMEs even account for 56% of electricity purchased.

As previously noted, the data presented in this section are restricted to the geographical areas covered by our census and therefore reflect only a subset of VE's overall client base. Before expanding on VE's broader electrification strategy and client portfolio (in Section III.C), we turn to analyzing the determinants of electricity demand.

B. Determinants of electricity demand

We analyze the determinants of electricity demand by linking pre-grid characteristics of households and SMEs to their connection decisions and electricity consumption over the two years following grid installation. Table 1 provides baseline descriptive statistics for the 911 households and 291 SMEs in our sample.

- Table 1 about here -

The average household head is 46 years old and male (78%), with 31% having completed secondary education. Households on average count 6.8 members, with a dependency ratio of 47%, indicating that about half of the members are not in the active age group (15 to 60 years). Prior to the grid installation, more than half of households (63%) owned a solar panel, which they used to power an average of 3.8 electrical devices. The most common type of devices were mobile phones (owned by 89%), radios (64%), and televisions (31%), with some households (8%) owning a computer. On average, households spent about $13 per month on energy expenditures, mostly on charcoal and wood for cooking. Most households (83%) own their parcel, but only 27% live in a house with high or very high construction quality.

About half of the SMEs in our sample (47%) are small shops or traders, primarily selling food, beverages, or clothing. Around 38% provide services such as hairdressing, tailoring, phone charging, milling, woodworking or repairs. The remaining 15% consist of small restaurants and bars. These businesses are mostly owned by men (76%), with the average owner being 37 years old, and about half (49%) having completed secondary education. The average business counts 2.7 employees, including the owner. About half of businesses (48%) owned a solar panel prior to grid installation, while 20% owned a generator. On average, businesses owned 1.8 electrical devices. The most common ones were radios (35%), televisions (19%), and computers (12%), while some businesses also had a fridge, freezer, razor, sewing machine, or wood working tools. Energy expenditures averaged $30 per month, with approximately $5 allocated to charcoal and the remainder spent on electricity, mostly on fuel to power a generator. Monthly sales averaged $697; 27% of businesses owned their parcel, and just over half (55%) were located in buildings of (very) high construction quality.

At the time of the follow-up survey, about two years after grid roll-out, 38% of households and 40% of SMEs had connected to Virunga Energies' electric grid. The distribution of connection rates across research areas aligns with the patterns observed in the previous section.[14] For both households and SMEs, connection rates were highest in Goma (62% and 52%), followed by Mutwanga (42% and 45%) and Lubero (10% and 31%). Overall, connected households consumed on average 26 kWh per month, whereas SMEs had a substantially higher average consumption of 94 kWh. As observed in the previous section, electricity usage varied considerably within both groups. One source of heterogeneity is the research area. For households, consumption is highest in Goma (37 kWh), followed by Lubero (28 kWh) and Mutwanga (11 kWh). A similar pattern is observed for SMEs, with consumption being highest in Goma (129 kWh), followed by Mutwanga and Lubero (70 kWh and 64 kWh).

[14] While it is valuable to compare overall trends, directly comparing connection rates from survey respondents with those reported in the previous section presents challenges. First, the previous section calculates connection rates by dividing the number of VE clients by the total number of parcels recorded in the census. Due to a lack of parcel-level connection data, we cannot disaggregate these connection rates by households or businesses. Second, the follow-up survey experienced an overall attrition rate of 16% due to out-migration of households and businesses closures (see Appendix A for details). Although we know these respondents were not connected to VE's grid at the time of the follow-up survey, we lack information on households or businesses that may have replaced them.

- Table 2 about here -

Table 2 analyses the determinants of electricity uptake and consumption among households. First, we observe that household socio-demographic characteristics – which include the gender, age, and education of the household head, as well as the household size and dependency ratio – are not significantly related to electricity uptake (column 1). Instead, baseline characteristics related to energy usage and household wealth do play an important role, with wealthier households and those with higher initial energy consumption being more likely to connect once the grid becomes available. For instance, households that owned a solar panel had connection rates that are 10.1 percentage points higher, while each electrical device owned is associated with a 2.7 percentage point increase. Connection rates further significantly increase with initial energy expenditures and monthly income. Households owning their parcel are 31 percentage points more likely to connect to the grid, while living in a house of (very) high construction quality increases connection rates by 15 percentage points. Column 2 examines the relationship between these characteristics and electricity consumption among connected households. We find that construction quality is the only factor with a significant association, with households residing in higher quality homes consuming more electricity.

- Table 3 about here -

In contrast to households, relatively few pre-grid characteristics are significantly associated with electricity uptake for SMEs (Table 3, column 1). We do find that businesses who owned a solar panel at baseline are 20 percentage points more likely to connect to the grid. Additionally, parcel ownership also matters for businesses, as it is associated with a 12.5 percentage point higher likelihood of electricity take-up. In column 2, we turn to electricity consumption among connected businesses.

The findings suggest that consumption is generally higher in larger businesses, owned by older or male proprietors. We further find that electricity consumption is significantly lower in Mutwanga and Lubero compared to Goma.

Overall, while pre-grid characteristics related to energy use and wealth provide useful insights into electricity uptake and consumption patterns, the results in TablesTable ***2*** andTable ***3*** highlight the importance of unobserved factors. The R-squared values indicate that the models only explain a modest share of the variation in household electricity uptake (42%) and consumption (45%), with even lower explanatory power for SMEs (20% and 39%). Moreover, a substantial portion of the explained variation is driven by area fixed effects (see Appendix D), highlighting the influence of local contextual differences – even across relatively similar settings – which limits the reliability of pre-grid characteristics for accurately predicting electricity uptake and usage.

- Table 4 about here -

During the follow-up survey, we asked unconnected households and businesses about future connection plans. The large majority, 81% of households and 77% of SMEs indicated they still planned on getting connected to the grid in the future (Table 4). We followed up with an open question asking about the reason why they were not yet connected, or why they did not want to connect at all. The answers can be summarized in two main reasons. Most importantly, financial constraints play a role for 86% of households and 61% of SMEs. Representative answers include “a lack of financial means to connect”, “the connection fee is too high”, and “the connection costs are high and we cannot afford them now”. Second, 6.5% of households and 22% of business owners mentioned they were not (yet) connected, because they do not own the parcel they live or operate in – making it impossible to connect if the house owner is not willing or able to provide the necessary documents. Representative answers include “the house owner refused to provide the necessary documents to connect”, “we are waiting for the decision of the house owner, we would like to connect, but we are still renting”, and “I am still renting, when I own my proper house, I will connect”.

C. Enhancing the financial sustainability of mini-grids

Our analysis reveals that electricity uptake and consumption is linked to household wealth and energy use profiles. Yet, due to large heterogeneity both between and within research areas, predicting uptake and consumption remains challenging, and, overall, electricity consumption remains low. This mirrors a consistent finding in low-income settings (Blodgett et al. 2017; Allee et al. 2021; Hartvigsson et al. 2021). Some authors have therefore concluded that mini-grids are too risky and should not be considered viable, advocating instead for cheaper off-grid solutions such as solar home systems, despite their inability to support productive uses of electricity (Sievert and Steinbuks 2020; Ankel-Peters et al. 2025). Others have argued that such low-tier equilibrium represents a coordination failure, in which neither productive users nor electricity investments materialize because each relies on the presence of the other (Kyriakarakos, Balafoutis, and Bochtis 2020; Scott and Coley 2021; Kraft and Luh 2022; Dagnachew, Choi, and Falchetta 2023). They have proposed several measures, including targeting productive users as anchor customers, promoting agricultural transformation, and vertically integrating energy provision with enterprise development.

While overcoming the coordination failure may be the first-best outcome, its success depends on several conditions, including the identification of reliable anchor clients, the presence of market access and input supply chains to make agricultural transformation viable, strong local institutions or actors capable of vertical integration, and 'patient capital' or blended finance to absorb early-stage risk (Peters, Sievert, and Toman 2019; Puig et al. 2021). At first sight, North Kivu seems an unlikely candidate for meeting these enabling conditions. Poor road networks limit market access and constrain economic activity, while widespread corruption, weak institutions and the constant threat of violence undermine investment and long-term planning. On the other hand, the region's fertile land and significant hydropower potential present economic opportunities. Crucially, on the institutional front, VE operates within the framework of the Virunga Alliance – a public-private partnership that brings together government authorities, the NGO Virunga Foundation, other civil society actors, and the private sector around a shared vision of sustainable development. This embeddedness in a broad and locally anchored coalition places VE in a strong position to break out of the low-demand trap (Merode, d'Huart, and Henrard 2025).

One key pillar of this strategy is the promotion of industrial activity through the creation of five industrial zones located on the outskirts of the Virunga National Park. Each industrial zone provides reliable access to electricity and water, shared security services, and legal assistance.[15] Several industrial clients have already been established in these zones with support from the Virunga Alliance. A prominent example is the soap factory Sicovir, which transform palm oil into 800 tons of soap each month, with plans to expand into edible oil production in 2025. Additional processing units include flour mills, a biscuit factory, coffee processing and

[15] In 2023, the Musienene zone was granted Special Economic Zone status by the Congolese government, exempting entrepreneurs from import and profit taxes for five years, further enhancing its attractiveness to investors.

roasting stations, cocoa fermentation centers, and a chocolate factory; all part of vertically integrated value chains for local agricultural products.[16]

To reduce dependence on external investors – who are often reluctant to invest in the Kivu's unstable context – five companies have been set up with the Virunga Foundation as capital shareholder: Sicovir (soap and oil), Virunga Enzymes (papaya-based enzymes), Virunga Development (industrial park and SME investment), Virunga Chocolate, and Virunga Origins, which manages the international marketing and distribution of the "Made in Virunga" product line.

In parallel, the Alliance has implemented an innovative entrepreneurship and microcredit program aimed at enabling local business growth. This system, developed in partnership with Equity BCDC bank, provides credit to entrepreneurs who are already connected to the VE grid. The loan repayment mechanism is uniquely designed by incorporating repayments into electricity purchases through a markup on the kWh price. For example, a typical repayment markup might be 20%, which still keeps purchasing kWh more cost-effective than fueling a generator. By 2024, the loan portfolio had grown to nearly 5 million USD, and almost 500 entrepreneurs had received training and business plan support between 2019 and 2024. A new partnership with the Grameen Trust is currently being developed to further professionalize credit management.

Perhaps the boldest and most original initiative of VE has been its turn to Bitcoin mining. Initially introduced as a technical substitute for load banks during the commissioning phase of the 14.6 MW Luviro hydropower plant in 2020, mining

[16] The local agricultural transformation component is central to the Alliance's approach. Recognizing both the ecological risks of unregulated agricultural expansion and the economic potential of value-added processing, the Alliance works with 32 cooperatives and producer groups totaling 12,000 members.

computers have since offered a stable, high-load energy demand. By 2024, they consumed 7 MW – an essential solution given that initial electricity demand in the area was far below the plant's capacity, necessitating a reliable anchor load to ensure efficient plant operation. This solution not only allows early loan repayments – thanks to the revenues generated by mining with zero-carbon energy – but also produces excess heat that can be repurposed, for example, to accelerate cocoa drying. The bitcoin mining will be phased out when local demand gradually absorbs all capacity of the local hydro plant.

Another innovative activity that contributes to boosting electricity demand is VE's promotion of electric cooking. In partnership with researchers, the company conducted a randomized experiment involving 1,600 households in Goma, distributing energy-efficient electric pressure cookers (EPCs) free of charge (Desbureaux et al. 2025). The initiative was met with strong interest – 92% of invited households attended the EPC distribution session – and led to a notable increase in electricity use, averaging 11 kWh per household per month. Increased electricity sales from EPC use generate an estimated $2.31 in additional monthly revenue per household, amounting to $116 over the EPC's five-year lifespan – more than covering the intervention's cost. In addition, the reduction in CO_2 emissions opens opportunities for monetization through carbon credits, further enhancing the financial sustainability of this vertically integrated 'tool-and-fuel' approach to clean cooking and electrification.

Together, these diverse but interconnected activities generate relatively stable electricity demand, contributing to the VE's financial viability. It is important to note that this strategy has been made possible through a blended financing model, with substantial donor support from both public and philanthropic sources. Over time, the share of loan financing has increased. In fact, VE was the first company in eastern DRC to receive a loan from a foreign investment bank – British

International Investment (BII) – marking a milestone in the organization's financial maturity.[17] While grants remain essential, especially in such a high-risk environment, the use of loans reflects a growing confidence in the financial sustainability of Virunga's model.

V. Conclusion

This study set out to examine the challenges and opportunities of mini-grid electrification in fragile and conflict-affected settings by analyzing electricity demand and system viability in North Kivu, DR Congo. Leveraging rich, panel data from census records, household and SME surveys, as well as administrative billing data and qualitative interviews, we assessed patterns of electricity uptake and consumption across five localities connected to the Virunga Energies mini-grid.

Our findings reveal three core insights. First, electricity uptake is closely tied to wealth, prior energy use, and land tenure, with financial constraints and the absence of formal property rights posing key barriers. Second, despite these statistical associations, their explanatory power is limited: electricity demand proves highly heterogeneous and difficult to anticipate, even when drawing on detailed pre-grid data. This underscores the challenges of accurately sizing mini-grids in such contexts. Third, and most importantly, the case of Virunga Energies illustrates that mini-grid viability in fragile settings depends not only on infrastructure provision but also on the proactive cultivation of demand through coordinated development strategies. These include the promotion of industrial anchor clients, targeted

[17] https://www.bii.co.uk/en/our-impact/direct-header/virunga/

microcredit schemes, electric cooking subsidies, and innovative uses of temporary anchor loads such as Bitcoin mining.

These findings carry several policy implications. First, mini-grid investment strategies in fragile contexts should move beyond static demand estimation and embrace dynamic, integrated approaches that address underlying market and institutional failures. Second, blended finance models are crucial for de-risking early investments and enabling complementary investments that stimulate productive uses of electricity. Third, regulatory frameworks must be flexible enough to accommodate vertically integrated initiatives that combine electrification with enterprise development and non-traditional business models – like VE's tool-and-fuel approach to clean cooking – that align commercial viability with social and environmental impact.

Achieving universal electricity access in Sub-Saharan Africa will require bold, adaptive strategies that recognize the deep interlinkages between energy, institutions, and development. The experience from North Kivu suggests that, even in the most fragile environments, progress is possible when electrification efforts are embedded in a broader vision of inclusive and sustainable growth.

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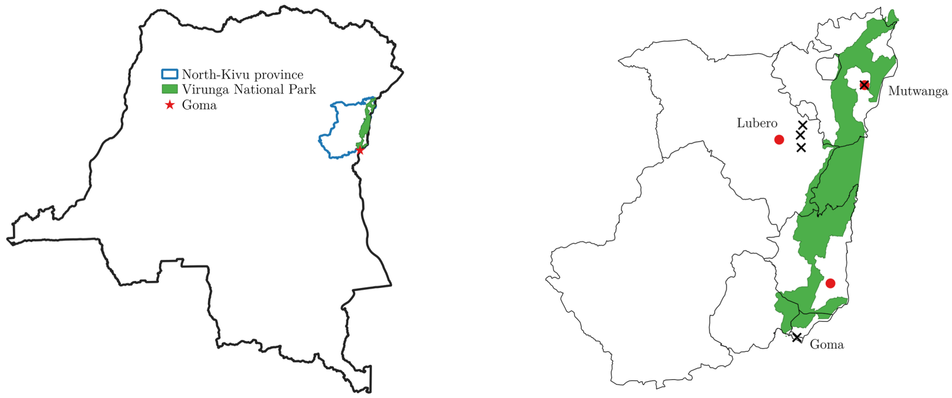
Figures

Figure 1. Study area

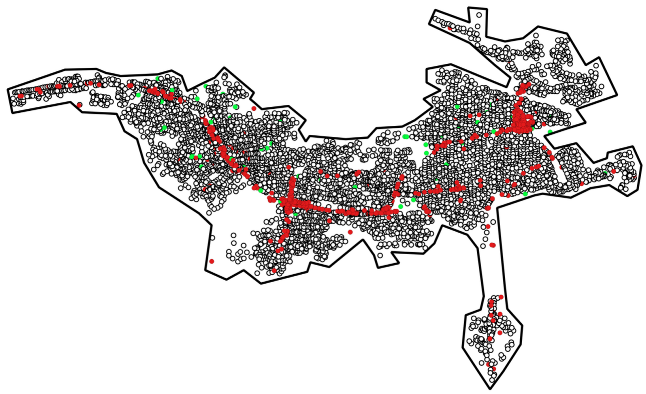
Panel A: North-Kivu in DRC

Panel B: Localities in North-Kivu



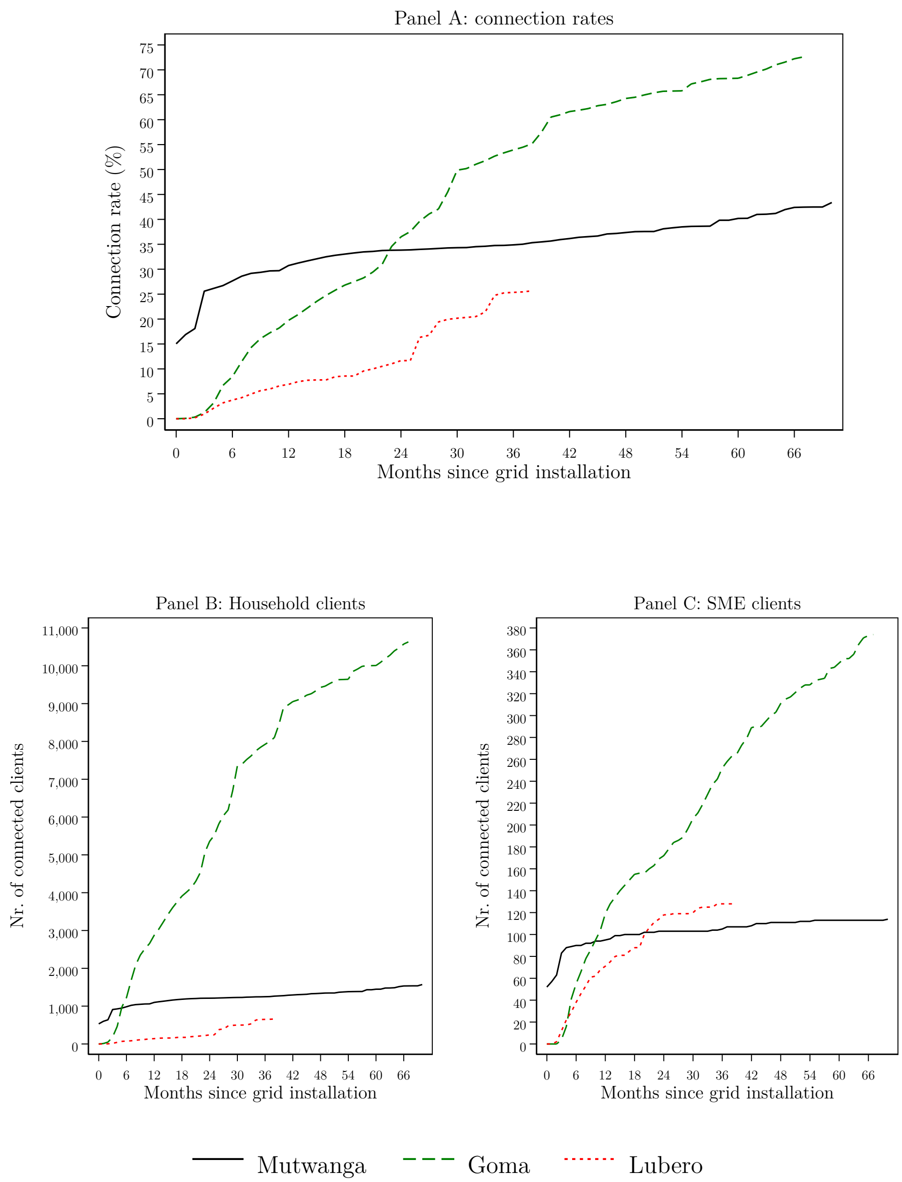
Notes: Panel A locates the province of North-Kivu within the DRC, highlighting Virunga National Park and the provincial capital Goma. Panel B zooms in on North-Kivu and shows the location of the three hydro-power plants (red dots) and the five localities (black crosses) included in our study: Mutwanga in Beni territory; Lubero, Kimbulu and Musienene in Lubero territory; and Katoyi, a city block of Goma. In our analyses, we group the three localities in Lubero territory and hence focus on three research areas.

Figure 2. Census data



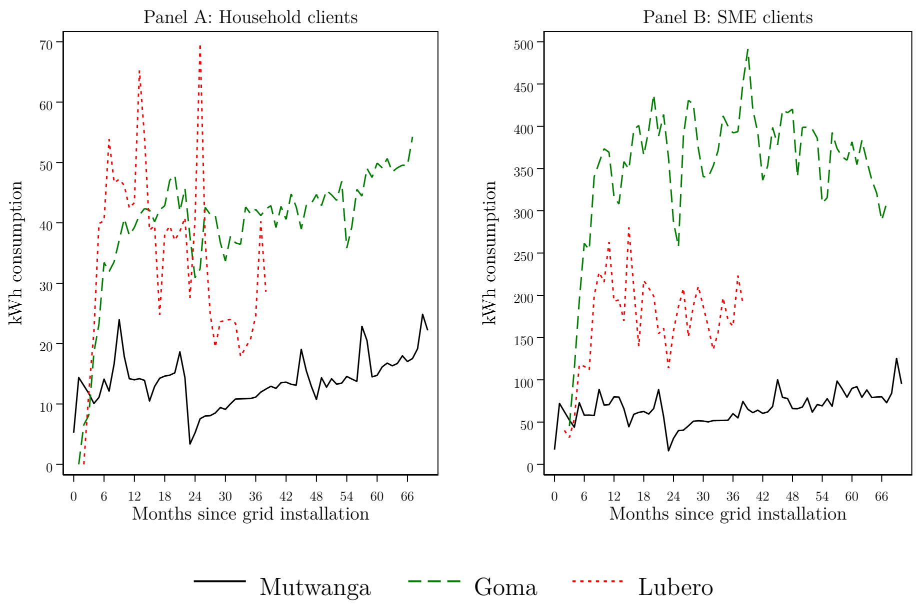
Notes: This map shows census data for Mutwanga, indicating the outline of the village, the location of households (transparent circles), small businesses (red circles) and institutions (green circles).

Figure 3. Evolution of connection rates and clients



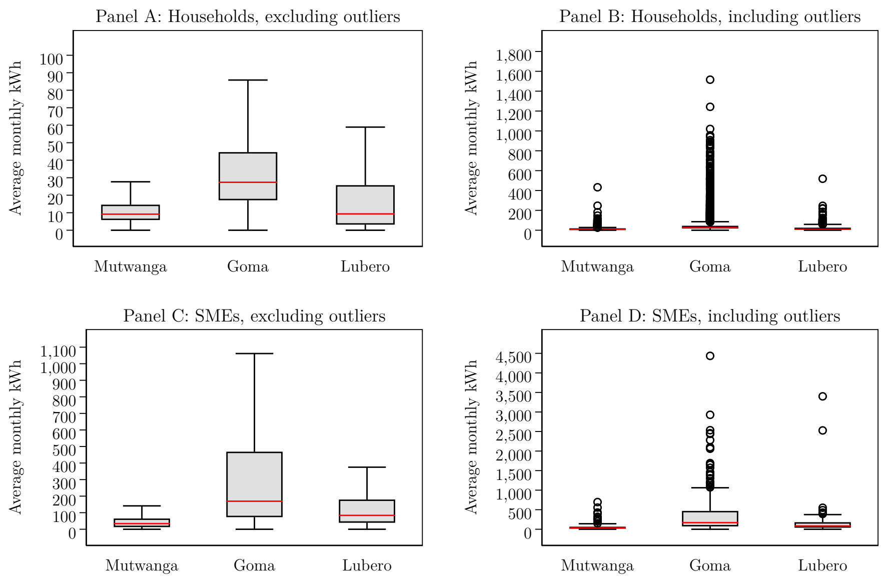
Notes: Panel A shows the evolution of connection rates, based on VE data and the number of parcels recorded during our census. Panels B and C display the evolution of connected clients based on VE data, separating households and SMEs. In Mutwanga, 584 clients (15% of parcels) were already connected to the grid in 2019 through a smaller hydropower plant.

Figure 4. Average monthly electricity consumption



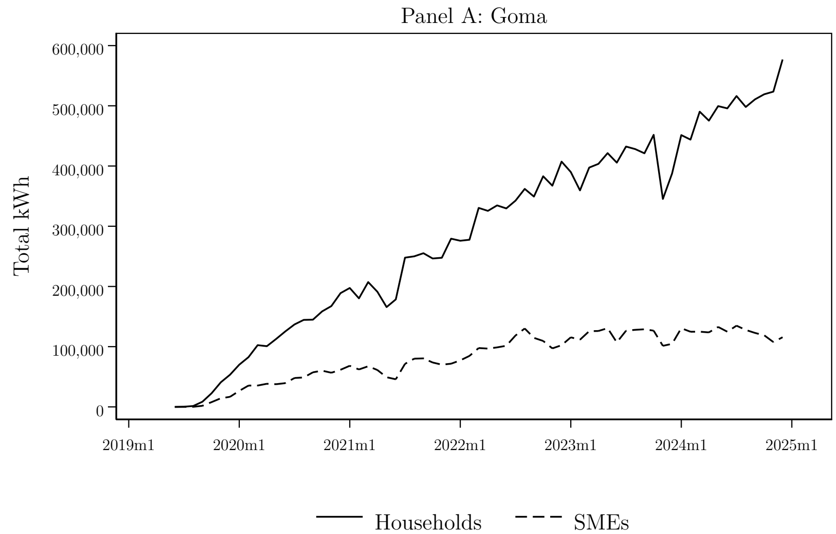
Notes: This Figure relies on VE data to show the evolution of average kWh consumption by connected households (Panel A) and SMEs (Panel B) for the three research areas. Panels B and C of Figure 3 show how the number of connected clients evolved over time.

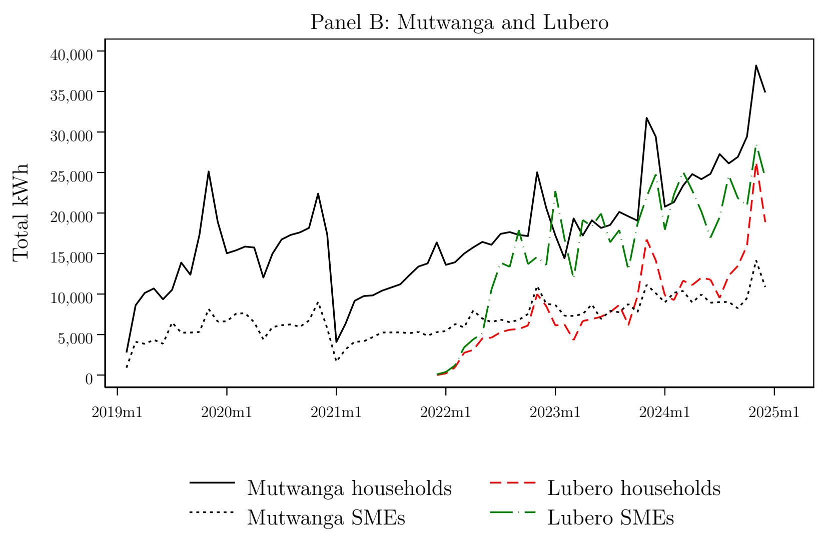
Figure 5. Heterogeneity in monthly electricity consumption



Notes: This Figure shows boxplots for average monthly electricity consumption (in kWh) calculated for each client over their connection period. For Mutwanga this is based on 1,571 households and 114 SMEs; for Goma 10,632 households and 374 SMEs; and for Lubero 660 households and 128 SMEs. Panels A and C exclude outliers, while these are plotted in Panels B and D.

Figure 6. Total monthly electricity consumption





Notes: This Figure shows total monthly electricity consumption for household and SME clients across the three research areas. In December 2024, the last month in our database, Mutwanga counted 1,571 household and 114 SME clients; Goma 10,632 households and 374 SMEs; and Lubero 660 households and 128 SMEs.

Tables

Table 1. Describing the sample

	Obs	Mean	Std. Dev.	Min	Max
	Panel A: Households				
Socio-demographics					
male household head	911	0.78	0.41	0	1
age household head	911	46	13	19	79
secondary education or higher	911	0.31	0.46	0	1
household size	911	6.8	2.88	1	18
dependency ratio	911	0.47	0.21	0	1
Energy profile					
owns solar panel	911	0.63	0.48	0	1
nr. of electrical devices	911	3.84	2.99	0	24
monthly energy expenditure ($)	911	13.36	11.69	0	98
Wealth					
monthly household income ($)	911	123	235	0	2,665
owns parcel	911	0.83	0.38	0	1
(very) high construction quality	911	0.27	0.44	0	1
Electricity uptake and consumption					
connected to VE grid	911	0.38	0.49	0	1
average monthly consumption (kWh)	395	26.34	47.88	0.00	524.21
	Panel B: Small businesses				
	Obs	Mean	Std. Dev.	Min	Max
Socio-demographics					
male owner	291	0.76	0.43	0	1
age owner	291	37	12	19	75
secondary education or higher	291	0.49	0.5	0	1
nr. employees (incl. owner)	291	2.73	1.75	1	10
Energy profile					
owns solar panel	291	0.48	0.50	0	1
owns generator	291	0.20	0.40	0	1
nr. of electrical devices	291	1.83	4.05	0	56
monthly energy expenditure ($)	291	30.46	86.13	0	800
Wealth					
monthly sales ($)	291	697	1,353	18	7,900
owns parcel	291	0.27	0.44	0	1
(very) high construction quality	291	0.55	0.50	0	1
Electricity uptake and consumption					
connected to VE grid	291	0.40	0.49	0	1
average monthly consumption (kWh)	117	93.53	159.76	5.13	1099.55

***Notes**:* Descriptive statistics for key household and small business characteristics prior to the grid roll-out. The household dependency ratio is calculated as the number of members younger than 15 or older than 64, divided by household size. Sampling weights are applied.

Table 2. Household electricity uptake and consumption

	(1) Electricity uptake	(2) Electricity consumption
Socio-demographics		
male household head	-0.006	0.062
	(0.036)	(0.156)
age household head	0.000	-0.000
	(0.001)	(0.004)
secondary education or higher	-0.041	0.050
	(0.035)	(0.100)
household size	0.001	-0.020
	(0.006)	(0.016)
dependency ratio	-0.062	-0.130
	(0.073)	(0.184)
Energy profile		
owns solar panel	0.101***	-0.001
	(0.030)	(0.097)
nr. of electrical appliances	0.027***	0.025
	(0.006)	(0.016)
log monthly energy expenditure	0.044***	-0.001
	(0.016)	(0.048)
Wealth		
log monthly income	0.023**	0.024
	(0.009)	(0.021)
owns parcel	0.312***	-0.086
	(0.039)	(0.213)
(very) high construction quality	0.152***	0.183**
	(0.028)	(0.074)
Research area (ref. = Goma)		
Lubero	-0.450***	-0.098
	(0.040)	(0.151)
Mutwanga	-0.150***	-1.041***
	(0.044)	(0.111)
Enumerator fixed effects	Yes	Yes
Observations	911	395
R^2	0.417	0.445

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. Column 1 shows estimated coefficients from a linear probability model, with household electricity uptake as the outcome variable. Column 2 is based on the subsample of connected households and shows estimated coefficients from a linear regression with log average monthly electricity consumption (in kWh) as the outcome variable. Sampling weights are applied, and robust standard errors are shown between brackets.

Table 3. Small business electricity uptake and consumption

	(1) Electricity uptake	(2) Electricity consumption
Socio-demographics		
male owner	0.100	0.527***
	(0.073)	(0.195)
age owner	-0.004	0.016**
	(0.003)	(0.007)
secondary education or higher	0.040	-0.099
	(0.059)	(0.153)
nr. employees (incl. owner)	0.016	0.109*
	(0.017)	(0.062)
Energy profile		
owns solar panel	0.199***	-0.082
	(0.064)	(0.173)
owns generator	0.044	-0.314
	(0.103)	(0.325)
nr. of electrical appliances	0.004	-0.014
	(0.009)	(0.042)
log monthly energy expenditure	0.019	0.078
	(0.022)	(0.060)
Wealth		
log monthly sales	0.000	0.024
	(0.026)	(0.081)
owns parcel	0.125*	-0.288
	(0.070)	(0.178)
(very) high construction quality	-0.071	0.057
	(0.063)	(0.231)
Research area (ref. = Goma)		
Lubero	-0.125*	-0.333*
	(0.076)	(0.190)
Mutwanga	0.053	-1.013***
	(0.091)	(0.302)
Sector (ref. = Small shops & traders)		
services	-0.005	0.242
	(0.078)	(0.240)
bars & restaurants	0.038	-0.040
	(0.094)	(0.224)
Enumerator fixed effects	YES	YES
Observations	291	117
R^2	0.200	0.394

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. Column 1 shows estimated coefficients from a linear probability model, with small business electricity uptake as the outcome variable. Column 2 is based on the subsample of connected businesses and shows estimated coefficients from a linear regression with log average monthly electricity consumption (in kWh) as the outcome variable. Sampling weights are applied, and robust standard errors are shown between brackets.

Table 4. Why not (yet) connected?

	not connected at follow-up	wants to connect in future	reason not (yet) connected	
			lack of money	does not own parcel
Households	354	81.07%	85.88%	6.50%
Small businesses	93	77.42%	61.29%	21.51%

Notes: During the follow-up survey, we asked unconnected households and businesses whether they planned on getting connected in the future. We followed up with an open question about the reason for not (yet) connecting. This table presents summary statistics based on a categorization of the answers. Appendix B presents information on attrition in the follow-up survey.

Appendix to

From Demand Deficit to Development Strategy: Navigating Mini-Grid Viability in a Fragile Context

By ELIE LUNANGA, NIK STOOP, MARIJKE VERPOORTEN, AND SÉBASTIEN DESBUREAUX

A. Sampling

We conducted a parcel-level census in five localities set to be connected to Virunga Energies' electricity grid (see Panel B of Figure 1 in the main manuscript). In Mutwanga and Goma, data collection happened in 2019, while data in the three localities of Lubero territory was collected in 2021. For each parcel, we collected GPS coordinates and indicated whether it consisted of a household, a small business, or an institution (e.g., church, school, hospital). Enumerators further rated the construction quality of the main building on a scale from 1 (very poor quality) to 4 (very high quality), providing us with a wealth proxy. Figure 2 in the main manuscript provides a graphical example of the census data collected for Mutwanga. In total, we registered 27,555 parcels, including 25,584 households, 1,682 small businesses and 289 institutions. Relying on the census data as a sampling frame, we drew a random sample of households and small businesses in each of the five localities. Our sample includes 911 households and 291 small businesses. Table A1 shows how they are distributed across the census and the sample in the three research areas.

Table A1. Households and businesses by area

	Households		**Small businesses**	
	Census	*Sample*	*Census*	*Sample*
Mutwanga	5,513	312	317	43
Goma	15,911	299	829	98
Lubero	4,160	300	536	150
Total	25,584	911	1,682	291

Notes: This Table shows the distribution of households and small businesses in the census and the sample, across the three research areas.

Besides enabling an analysis of the demand for electricity, the survey data was also collected to assess the socio-economic impact of grid electrification. At the time when we were planning our fieldwork in Mutwanga and Goma in 2019, research had highlighted that the demand for electricity in rural Kenya was low (Lee et al., 2019). We therefore oversampled relatively wealthier households and businesses, assuming they were more likely to connect to the grid. In Lubero territory, where the fieldwork took place two years later, we drew a simple random sample of households and businesses from the census, stratified by construction quality.[1] As a result of this sampling strategy, our sample overrepresents relatively wealthier households and businesses. To account for potential sampling biases, all analyses include sampling weights that were calculated as the inverse probability of being selected from the census data. The distribution of construction quality presented in Table A2 shows that our weighted sample closely approximates the census, both for households and businesses.

Table A2. Sample weights

	Households			**Small businesses**		
	census	*unweighted sample*	*weighted sample*	*census*	*unweighted sample*	*weighted sample*
very bad	28.19%	16.86%	24.63%	14.51%	9.62%	13.48%
rather bad	47.97%	40.40%	48.53%	32.64%	36.08%	31.47%
rather good	19.03%	33.37%	21.06%	29.37%	30.93%	30.40%
very good	4.78%	9.55%	5.78%	23.48%	23.37%	24.64%

Notes: This Table shows the distribution of construction quality for households and small businesses in the census, the unweighted sample, and the sample that corrects for sampling weights.

[1] In Lubero three localities were being connected to the grid, here our sample was drawn proportional to population size in each locality.

B. Survey attrition

At baseline, we surveyed 911 households and 291 businesses. However, for 16% of households and 24% of businesses we were not able to conduct a follow-up survey two years later. Short phone surveys and information from neighbors and relatives indicate that household attrition was mainly due to people relocating away from the research area, while most business attrition was due to the activities being shut down by the time of the follow-up survey. Table A3 presents an overview of respondent numbers and attrition rates by research area.

Table A3. Survey attrition

	Total	**Mutwanga**	**Goma**	**Lubero**
households baseline	911	312	299	300
households follow-up	768	234	270	264
households attrition	15.70%	25.00%	9.70%	12.00%
small businesses baseline	291	43	98	150
small businesses follow-up	222	34	61	127
small businesses attrition	23.71%	20.93%	37.76%	15.33%

Notes: This Table displays the number of households and small businesses surveyed at baseline and follow-up in each research area, along with the attrition rate.

We know that households and businesses who dropped out of the sample were not connected to VE's grid at the time of the follow-up survey. Hence, we still include these households and businesses when studying the determinants of electricity uptake, coding them as not having connected. As the following Tables show, we obtain qualitatively similar findings when dropping them from the sample.

Table A4. Electricity uptake among households

	(1) Including attritors	(2) Dropping attritors
Socio-demographics		
male household head	-0.006	-0.015
	(0.036)	(0.042)
age household head	0.000	-0.001
	(0.001)	(0.001)
secondary education or higher	-0.041	-0.055
	(0.035)	(0.039)
household size	0.001	-0.003
	(0.006)	(0.006)
dependency ratio	-0.062	-0.006
	(0.073)	(0.084)
Energy profile		
owns solar panel	0.101***	0.103***
	(0.030)	(0.035)
nr. of electrical devices	0.027***	0.024***
	(0.006)	(0.006)
log monthly energy expenditure	0.044***	0.048***
	(0.016)	(0.018)
Wealth		
log monthly income	0.023**	0.025***
	(0.009)	(0.010)
owns parcel	0.312***	0.308***
	(0.039)	(0.053)
(very) high construction quality	0.152***	0.157***
	(0.028)	(0.029)
Research area (ref. = Goma)		
Lubero	-0.450***	-0.515***
	(0.040)	(0.048)
Mutwanga	-0.150***	-0.076
	(0.044)	(0.051)
Enumerator fixed effects	Yes	Yes
Observations	911	768
R^2	0.417	0.452

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. This Table shows estimated coefficients from a linear probability model, with household electricity uptake as the outcome variable. Column 1 includes attrited households, coding them as not having connected to VEs grid. Column 2 drops these households from the sample. Sampling weights are applied, and robust standard errors are shown between brackets.

Table A5. Electricity uptake among SMEs

	(1) Including attritors	(2) Dropping attritors
Socio-demographics		
male owner	0.100	0.046
	(0.073)	(0.087)
age owner	-0.004	-0.004
	(0.003)	(0.003)
secondary education or higher	0.040	0.016
	(0.059)	(0.064)
nr. employees (incl. owner)	0.016	-0.002
	(0.017)	(0.018)
Energy profile		
owns solar panel	0.199^{***}	0.167^{**}
	(0.064)	(0.072)
owns generator	0.044	0.148
	(0.103)	(0.100)
nr. of electrical appliances	0.004	0.024^{**}
	(0.009)	(0.012)
log monthly energy expenditure	0.019	0.008
	(0.022)	(0.022)
Wealth		
log monthly sales	0.000	0.003
	(0.026)	(0.031)
owns parcel	0.125^{*}	0.227^{***}
	(0.070)	(0.075)
(very) high construction quality	-0.071	-0.017
	(0.063)	(0.071)
Research area (ref. = Goma)		
Lubero	-0.125^{*}	-0.357^{***}
	(0.076)	(0.078)
Mutwanga	0.053	-0.136
	(0.091)	(0.102)
Sector (ref. = Small shops & traders)		
services	-0.005	-0.095
	(0.078)	(0.090)
bars & restaurants	0.038	0.020
	(0.094)	(0.100)
Enumerator fixed effects	YES	YES
Observations	291	222
R^2	0.200	0.345

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. This Table shows estimated coefficients from a linear probability model, with SME electricity uptake as the outcome variable. Column 1 includes attrited SMEs, coding them as not having connected to VEs grid. Column 2 drops these SMEs from the sample. Sampling weights are applied, and robust standard errors are shown between brackets.

C. Electricity data

Table A6 provides a tabular overview of the number of household and SME clients connected to the VE grid in each research area. The data only cover clients that are located within the geographical area covered by our census and present the situation in December 2024 – the last month in our dataset. Table A7 provides a tabular overview of average monthly electricity consumption for household and SME clients in each research area, covering the period from January 2019 to December 2024.

Table A6. VE clients by research area

	Households		**SMEs**		**Total**	
	Number	*%*	*Number*	*%*	*Number*	*% SMEs*
Mutwanga	1,571	12%	114	19%	1,685	7%
Goma	10,632	83%	374	61%	11,006	3%
Lubero	660	5%	128	21%	788	16%
Total	12,863	100%	616	100%	13,479	5%

Notes: This Table shows the distribution of VE household and SME clients across the three research areas for December 2024, the last month in our database.

Table A7. Average monthly electricity consumption

	Household clients				
	Obs	Mean	Std. Dev.	Min	Max
Mutwanga	70	13.87	4.05	3.37	24.86
Goma	67	39.82	9.79	0.00	54.26
Lubero	37	34.46	14.40	0.00	69.74
	SME clients				
	Obs	Mean	Std. Dev.	Min	Max
Mutwanga	70	66.60	18.54	16.03	125.33
Goma	65	357.96	71.66	45.15	491.20
Lubero	37	170.47	54.53	31.70	280.16

Notes: This table shows descriptive statistics for average monthly electricity purchases (in kWh) of household and SME clients. For each month, average consumption is calculated for the clients connected at that time. This includes 70 months for Mutwanga, 67 months for Goma and 37 months for Lubero.

D. Alternative specifications

Tables A8-A11 replicate the findings from Tables 2 and 3 in the main manuscript, while also showing specifications that do not include area fixed effects. In the main manuscript we model electricity uptake using a linear probability model. Tables Table **A8** and Table **A9** show that our findings are robust to using Logit or Probit estimations instead.

Table A8. Electricity uptake among households

	LPM		Logit	Probit
	Without area FE	With area FE		
	(1)	(2)	(3)	(4)
Socio-demographics				
male household head	0.017	-0.006	0.001	-0.005
	(0.037)	(0.036)	(0.035)	(0.034)
age household head	-0.002	0.000	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
secondary education or higher	0.022	-0.041	-0.032	-0.028
	(0.036)	(0.035)	(0.032)	(0.031)
household size	0.008	0.001	-0.001	-0.002
	(0.006)	(0.006)	(0.005)	(0.005)
dependency ratio	-0.179**	-0.062	-0.078	-0.097
	(0.074)	(0.073)	(0.073)	(0.072)
Energy profile				
owns solar panel	0.102***	0.101***	0.096***	0.095***
	(0.032)	(0.030)	(0.027)	(0.028)
nr. of electrical devices	0.042***	0.027***	0.022***	0.022***
	(0.006)	(0.006)	(0.006)	(0.006)
log monthly energy expenditure	0.077***	0.044***	0.038**	0.036**
	(0.016)	(0.016)	(0.015)	(0.015)
Wealth				
log monthly income	0.007	0.023**	0.024***	0.023***
	(0.009)	(0.009)	(0.008)	(0.008)
owns parcel	0.305***	0.312***	0.332***	0.337***
	(0.035)	(0.039)	(0.053)	(0.048)
(very) high construction quality	0.049	0.152***	0.170***	0.166***
	(0.032)	(0.028)	(0.029)	(0.027)
Research area (ref. = Goma)				
Lubero		-0.450***	-0.479***	-0.474***
		(0.040)	(0.046)	(0.044)
Mutwanga		-0.150***	-0.154***	-0.156***
		(0.044)	(0.051)	(0.048)
Enumerator fixed effects	Yes	Yes	Yes	Yes
Observations	911	911	911	911
R^2	0.323	0.417		
Pseudo R^2			0.410	0.407

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. Columns 1 and 2 report estimated coefficients from a linear probability model, while Columns 2 and 3 present marginal effects derived from Logit and Probit estimations, respectively. Sampling weights are applied, and robust standard errors are shown between brackets.

Table A9. Electricity uptake among SMEs

	LPM		Logit	Probit
	Without area FE	With area FE		
	(1)	(2)	(3)	(4)
Socio-demographics				
male owner	0.086	0.100	0.101	0.101
	(0.072)	(0.073)	(0.072)	(0.069)
age owner	-0.004	-0.004	-0.004	-0.004
	(0.003)	(0.003)	(0.003)	(0.002)
secondary education or higher	0.044	0.040	0.040	0.040
	(0.059)	(0.059)	(0.055)	(0.054)
nr. employees (incl. owner)	0.011	0.016	0.015	0.015
	(0.017)	(0.017)	(0.016)	(0.016)
Energy profile				
owns solar panel	0.202***	0.199***	0.192***	0.193***
	(0.063)	(0.064)	(0.057)	(0.056)
owns generator	0.047	0.044	0.047	0.053
	(0.103)	(0.103)	(0.094)	(0.092)
nr. of electrical devices	0.004	0.004	0.004	0.004
	(0.009)	(0.009)	(0.008)	(0.007)
log monthly energy expenditure	0.022	0.019	0.018	0.018
	(0.022)	(0.022)	(0.020)	(0.020)
Wealth				
log monthly sales	0.024	0.000	0.001	0.001
	(0.023)	(0.026)	(0.025)	(0.024)
owns parcel	0.149**	0.125*	0.117*	0.121*
	(0.069)	(0.070)	(0.063)	(0.062)
(very) high construction quality	-0.113*	-0.071	-0.070	-0.069
	(0.063)	(0.063)	(0.059)	(0.059)
Research area (ref. = Goma)				
Lubero		-0.125*	-0.116	-0.114
		(0.076)	(0.071)	(0.069)
Mutwanga		0.053	0.059	0.065
		(0.091)	(0.088)	(0.088)
Sector (ref. = Small shops & traders)				
services	-0.002	-0.005	-0.006	-0.008
	(0.079)	(0.078)	(0.075)	(0.074)
bars & restaurants	0.030	0.038	0.038	0.035
	(0.094)	(0.094)	(0.086)	(0.086)
Enumerator fixed effects	Yes	Yes	Yes	Yes
Observations	291	291	291	291
R^2	0.185	0.200		
Pseudo R^2			0.162	0.162

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. Columns 1 and 2 report estimated coefficients from a linear probability model, while Columns 2 and 3 present marginal effects derived from Logit and Probit estimations, respectively. Sampling weights are applied, and robust standard errors are shown between brackets.

Table A10. Electricity consumption among connected households

	Without area FE (1)	With area FE (2)
Socio-demographics		
male household head	-0.058	0.062
	(0.163)	(0.156)
age household head	0.003	-0.000
	(0.004)	(0.004)
secondary education or higher	0.259**	0.050
	(0.116)	(0.100)
household size	-0.015	-0.020
	(0.018)	(0.016)
dependency ratio	-0.091	-0.130
	(0.227)	(0.184)
Energy profile		
owns solar panel	0.089	-0.001
	(0.111)	(0.097)
nr. of electrical devices	0.045***	0.025
	(0.017)	(0.016)
log monthly energy expenditure	0.215***	-0.001
	(0.048)	(0.048)
Wealth		
log monthly income	0.001	0.024
	(0.024)	(0.021)
owns parcel	-0.003	-0.086
	(0.392)	(0.213)
(very) high construction quality	0.104	0.183**
	(0.092)	(0.074)
Research area (ref. = Goma)		
Lubero		-0.098
		(0.151)
Mutwanga		-1.041***
		(0.111)
Enumerator fixed effects	Yes	Yes
Observations	395	395
R^2	0.245	0.445

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. This table shows estimated coefficients from a linear regression with log average monthly electricity consumption (in kWh) as the outcome variable. Sampling weights are applied, and robust standard errors are shown between brackets.

Table A11. Electricity consumption among connected SMEs

	Without area FE (1)	With area FE (2)
Socio-demographics		
male owner	0.534**	0.527***
	(0.209)	(0.195)
age owner	0.017**	0.016**
	(0.008)	(0.007)
secondary education or higher	-0.021	-0.099
	(0.170)	(0.153)
nr. employees (incl. owner)	0.108	0.109*
	(0.068)	(0.062)
Energy profile		
owns solar panel	0.038	-0.082
	(0.189)	(0.173)
owns generator	-0.135	-0.314
	(0.353)	(0.325)
nr. of electrical devices	0.007	-0.014
	(0.042)	(0.042)
log monthly energy expenditure	0.062	0.078
	(0.064)	(0.060)
Wealth		
log monthly sales	0.008	0.024
	(0.083)	(0.081)
owns parcel	-0.382*	-0.288
	(0.202)	(0.178)
(very) high construction quality	0.041	0.057
	(0.224)	(0.231)
Research area (ref. = Goma)		
Lubero		-0.333*
		(0.190)
Mutwanga		-1.013***
		(0.302)
Sector (ref. = Small shops & traders)		
services	0.197	0.242
	(0.243)	(0.240)
bars & restaurants	-0.013	-0.040
	(0.219)	(0.224)
Enumerator fixed effects	Yes	Yes
Observations	117	117
R^2	0.280	0.394

Notes: *p < 0.1, ** p < 0.05, *** p < 0.01. This table shows estimated coefficients from a linear regression with log average monthly electricity consumption (in kWh) as the outcome variable. Sampling weights are applied, and robust standard errors are shown between brackets.

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