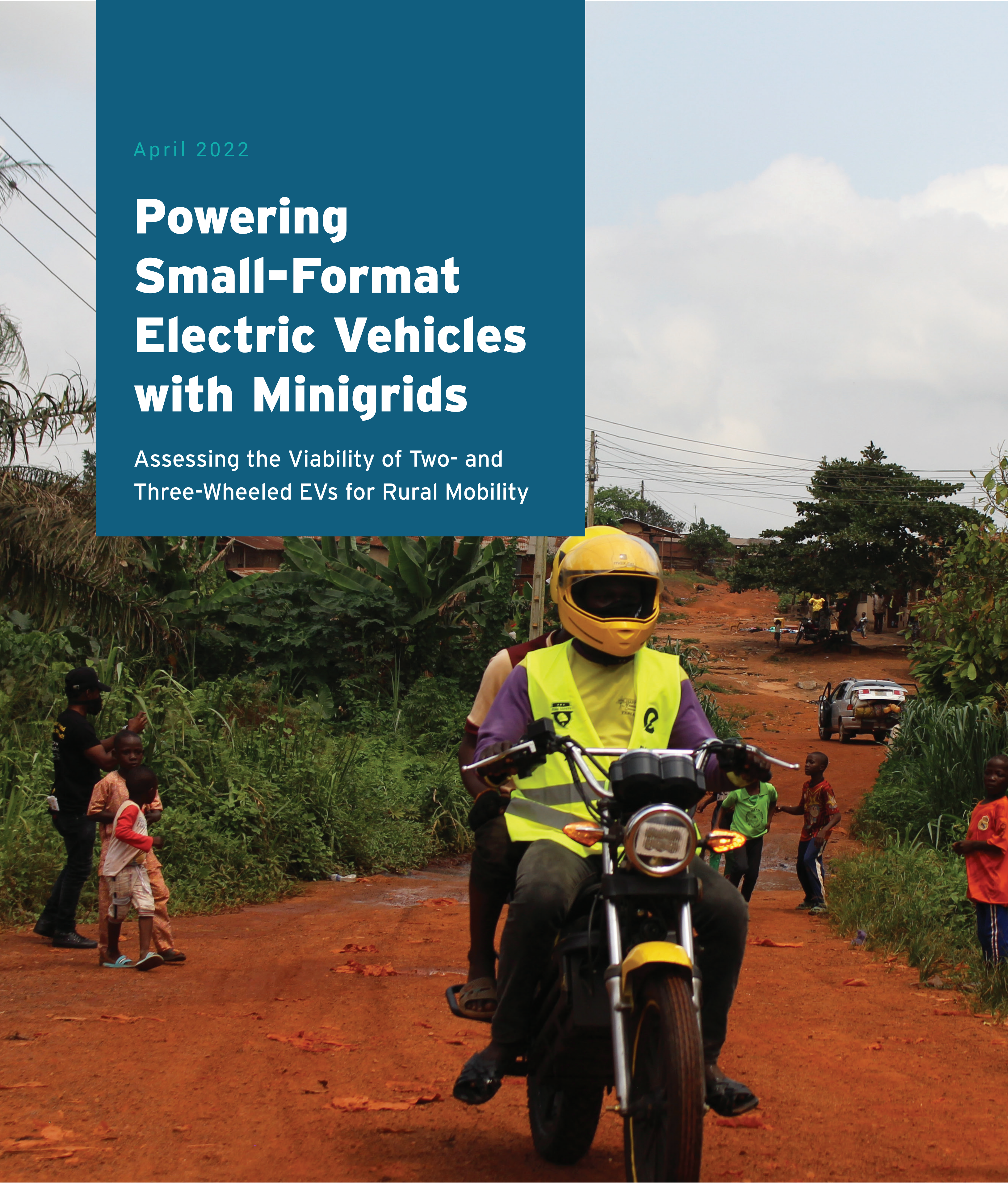
April 2022

Powering Small-Format Electric Vehicles with Minigrids

Assessing the Viability of Two- and Three-Wheeled EVs for Rural Mobility



Shell Foundation

FACTOR[e] VENTURES

Authors and Acknowledgments

Authors

Andrew Allee, John Schroeder, James Sherwood

Authors listed alphabetically. All authors from RMI unless otherwise noted.

Contributors

Amanda DelCore
Factor[e]

Emily Goldfield
RMI

Deepak Goel
Nicholas Jones
Emma Miller
Shell Foundation

Contacts

Andrew Allee, **aallee@rmi.org**
James Sherwood, **jsherwood@rmi.org**

Copyrights and Citation

Andrew Allee, James Sherwood, John Schroeder, *Powering Small-Format Electric Vehicles with Minigrids*, RMI, 2022, **http://www.rmi.org/insight/minigrid-ev**

RMI values collaboration and aims to accelerate the energy transition through sharing knowledge and insights. We therefore allow interested parties to reference, share, and cite our work through the Creative Commons CC BY-SA 4.0 license. **https://creativecommons.org/licenses/by-sa/4.0/**.

Acknowledgments

The authors gratefully acknowledge the contributions of pilot project participants in India (SMV Green Solutions, Grassroots Energy) and Nigeria (MAX, Rubitec Solar).

This work also builds upon contributions by Kendall Ernst and Pranav Lakhina (RMI).

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

Disclaimer

RMI researched, wrote, and produced this report independently. The findings reflect RMI's analysis free of influence from commissioning and other entities.

Cover photo: In Nigeria, a local MAX-certified electric vehicle driver takes a customer from Gbamu Gbamu community to a junction with a regional highway. **Photo credit:** MAX

Partners

This report was commissioned by Factor[e] Ventures in collaboration with and funded by the Shell Foundation.

About Shell Foundation

Shell Foundation is a UK-registered charity, founded by Shell in 2000, that creates and scales business solutions to enhance access to energy and affordable transport. We exist to serve the low-income communities most affected by these issues.

About Factor[e]

Factor[e] Ventures is a team of impact investors and venture builders dedicated to supporting the people and ideas that turn challenges in energy, agriculture, mobility, and waste into decarbonized solutions for emerging and frontier markets.

Table of Contents

Executive Summary

Minigrids can power two- and three-wheeled electric vehicles at cost parity with fossil-fueled alternatives. Two pilot projects show that business models must align electric vehicle and minigrid operator incentives while tailoring mobility offerings to the needs of rural customers.

People living in rural areas throughout the world are held back by limited access to both affordable transportation and electricity. For those living in communities where renewably powered minigrids are a better option than extending the grid, integrating electric vehicles may stack the benefits of clean, affordable transport on top of those from reliable electricity access. In turn, the energy revenues from fueling the EVs can go to the local electricity supplier instead of trickling up the fossil fuel supply chain. These electricity sales to EVs can bolster the minigrid's financial sustainability and allow the operator to recoup system costs at a lower electricity price for all customers.

This report describes two pilot studies that tested this concept in practice at rural minigrids in Nigeria and India:

- **In Nigeria, mobility company MAX leased electric two-wheelers to certified local drivers.** These drivers used the vehicles to transport people and goods to hubs within a 20-km radius, covering an average of 17 km and consuming about one kilowatt-hour (kWh) of minigrid electricity per daily rental. MAX considers the pilot program a success and is expanding rural operations as well as establishing a major business vertical in domestic EV production.

- **In India, social enterprise SMV Green Solutions leased lithium-ion batteries to local drivers who already owned and operated electric three-wheelers.** These customers were initially skeptical about the value proposition of the monthly battery subscription model. Although participating local drivers reported better range and lower costs over the lead-acid batteries they were using previously, many ultimately sidestepped the minigrid charging process by topping up their leased lithium-ion batteries at grid connections near the local market where demand for ride-hailing was highest. These factors combined with the high cost of maintaining rural operations led SMV to discontinue the pilot.

Drawing from EV Global Positioning System (GPS) data, smart meter readings, and participant interviews, along with supplementary technoeconomic modeling of vehicle costs at a range of energy prices and of minigrid economic performance for several EV-minigrid scenarios, this study concludes that:

- **Small-format electric vehicles such as the two- and three-wheelers studied here can be cost competitive with petrol alternatives** at a wide range of energy prices (Exhibit 5, page 20).

- At the costs, rental revenues, and vehicle utilization observed in the Nigeria pilot, investments in leased electric two-wheelers are expected to pay back within the vehicle life.

- EV owners and operators appreciate the low fuel costs that come with the energy efficiency of lightweight EVs such as two- and three-wheelers. However, this efficiency also translates to small minigrid electricity sales for the handful of small-format EVs deployed in the pilots. **In a technoeconomic model based on the Nigeria pilot, the 3 kWh per day used by the EV fleet only reduces the tariff by 1% in an optimized minigrid design** (Exhibit 6, page 23).

- EVs are more cost competitive with fossil-fueled vehicles, and more beneficial to minigrids, the more they are used. The results of these pilots suggest that the priority of EV-minigrid business model innovation and subsequent pilots should be to **increase vehicle utilization**.

- Vehicle utilization depends fundamentally on the needs and preferences of local drivers and mobility customers, which were not systematically assessed by the pilot projects discussed in this study.

- **Customer research can help EV operators adapt their mobility business models to local needs and achieve higher vehicle utilization.** Some customer preferences may be solved with new EV models (e.g., offering EVs with more powerful electric motors or higher capacity batteries at a higher rental fee). Others may require business model innovation that provides paths to asset ownership or offers competitive fee structures.

- **Future pilots should prioritize business model innovation to increase vehicle utilization, informed by customer engagement and by data describing the use patterns and costs of both EVs and incumbent vehicles.**

The pilot projects and supplementary analysis presented in this study offer compelling evidence that minigrid-powered EVs can simultaneously support access to clean transportation and electricity. By tailoring business models to customer needs and boosting vehicle utilization, further pilots can pave the way to a future where electric mobility is the option of first resort for moving people and goods, all while strengthening local electricity demand and lowering tariffs for all.

Introduction

Billions of people are living without adequate access to energy and transportation. More than 70% of rural Africans are unable to reach jobs, education, and health care due to inadequate transport.[1] Concurrently, nearly 800 million people lack access to electricity, and billions more have unreliable connections.[2] Responding to both mobility (Sustainable Development Goal 11.2) and energy (Sustainable Development Goal 7) challenges requires more equitable provision of services subject to environmental (e.g., greenhouse gas emissions) and infrastructure (e.g., roads, energy supply) constraints.

Pairing renewably powered minigrids with affordable EVs in rural areas could contribute to both goals. Minigrids are a least-cost solution for supplying 24-7 electricity to many communities without adequate grid service, and they often integrate solar power or other low-carbon energy sources.[3] However, the financial viability of most minigrids requires strategies to increase electricity sales from customers whose loads may start small and grow slowly.[4]

Small-format electric vehicles such as two-wheelers (E2Ws) and three-wheelers (E3Ws) are becoming increasingly cost competitive with internal combustion engine (ICE) vehicles, and global sales are growing by about 14% per year.[5] If EVs can deliver mobility services that outcompete incumbent fossil-powered mobility in minigrid-powered communities, then introducing these vehicles could boost minigrid electricity sales and reduce the overall price of electricity required for the utility to meet its financial obligations.

In 2019, Shell Foundation initiated a pilot to test this concept under real-world operating conditions at rural minigrid sites. Through the project, partners deployed small-format EVs and charging infrastructure to test two business models in two geographies: (1) a daily E2W leasing model at a solar-hybrid minigrid in Ogun State, Nigeria; and (2) a battery leasing model for E3Ws at a biogas-powered minigrid in Bihar, India.

The business models tested here have four core roles: electricity provider, EV owner/operator, EV driver, and mobility customer. These roles can be played by separate actors as depicted in Exhibit 1 (next page), but the exact arrangement of these roles and which entities perform them can vary widely. For example, in the India pilot, local E3W drivers owned their e-rickshaws and only leased lithium-ion batteries. Box 1 (page 10) and Box 2 (page 17) explain the business models tested in the pilots in detail. Both pilots offered new batteries or vehicles to established local drivers, and both used a battery swapping model that allowed drivers to top up their EVs without long waits at a charger.

The following sections use pilot data, participant interviews, and technoeconomic modeling to address these questions:

1. How are electric vehicles used in minigrid-powered communities?

2. How cost competitive are electric vehicles versus fossil-fueled alternatives in these rural contexts?

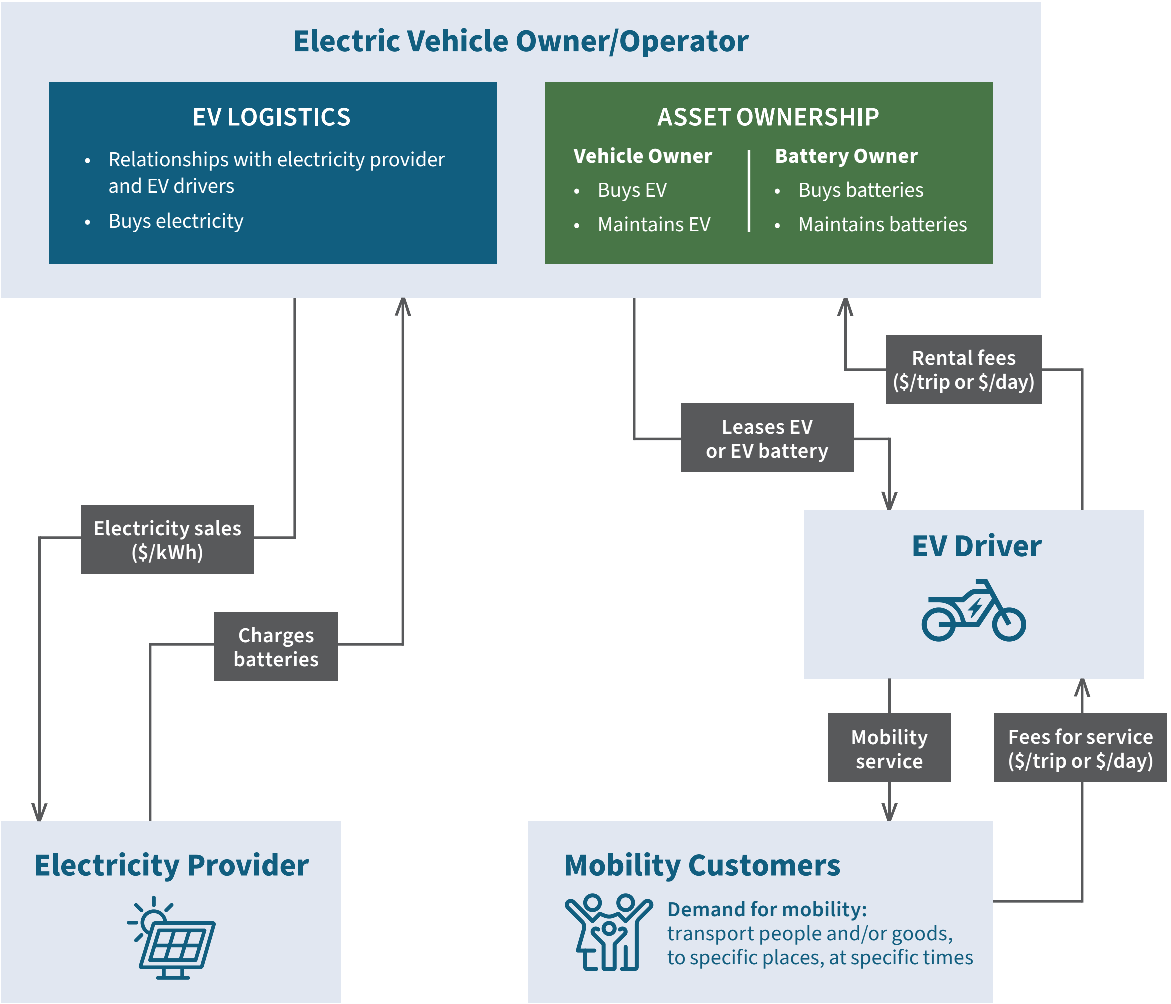
3. Moving forward, what key considerations will determine the success of minigrid-powered mobility?

The results suggest that small-format electric vehicles can compete with fossil-fueled alternatives on total cost of ownership basis at a broad range of electricity and fuel prices. If implemented through a business model that meets the needs of EV drivers (and, where applicable, the drivers' customers), the addition of EV charging loads improves minigrid economics and lowers the electricity price required to recoup the minigrid system investment. However, in a minigrid scenario reflecting the Nigeria pilot's level of EV use, the additional loads from EV charging only reduced the tariff for an optimally sized minigrid by 1%. EV and minigrid operators both stand to benefit from business models that raise demand for electric mobility services, thereby increasing EV fleet utilization along with electricity sales.

This report analyzes these small, targeted pilots to give early insights on the viability of powering small EVs with rural minigrids, but it does not exhaustively answer the above questions, and it raises many new ones. The concluding section describes how further piloting the EV-minigrid concept can improve business models and specifies which data should be collected to do so.

Exhibit 1

EV-Minigrid Business Model Components



Nigeria Pilot: Leasing Two-Wheeled EVs at a Solar-Hybrid Minigrid

Nigeria Pilot Context

In 2020, Shell Foundation supported a project that introduced electric two-wheelers to Gbamu Gbamu community in rural southwest Nigeria in partnership with MAX, a mobility company, and Rubitec Solar, a renewable energy developer.

Nigeria is home to Africa's largest economy and more than 200 million people, 40% of whom live on less than $1.90 per day, and 45% of whom lack reliable electricity access.[6] An estimated 22 million small gasoline generators fill the gap left by a lack of reliable electricity connections, collectively totaling about 42 gigawatts of capacity (roughly eight times larger than the national grid's current peak capacity).[7] The operation of these generators demonstrates an ability to pay for power that is supporting the development of a commercial market for minigrids and other distributed energy resources.[8]

One in two Nigerians live in rural areas, where transportation services are limited by road quality and access to affordable and safe transport modes.[9] In a 2013 survey, fewer than 35% of surveyed rural households owned a motorized vehicle.[10] In a baseline survey of two-wheeled taxis in Gbamu Gbamu, customers paid between $1.30/trip (500 naira) and $2.60/trip (1,000 naira) for local routes.[i] This is significantly higher than the national average of $0.75/trip (280 naira) for comparable routes in May 2021.[11]

These challenges suggest an opportunity for distributed energy resources to cost-effectively serve electricity customers, and for minigrid-powered electric vehicles to serve as a reliable electricity customer that addresses local transportation needs. Through the pilot, MAX introduced its own custom-built E2W models to drivers in Gbamu Gbamu community, a minigrid-connected town in rural Ogun State, Nigeria. MAX offered daily E2W leases to trained local drivers according to the business model described in Box 1 (next page). The pilot offered charging via a battery swap model, and the fleet's battery-to-vehicle ratio was 1.5. MAX staff members based in Gbamu Gbamu were on call if drivers experienced issues, and routine maintenance was performed on-site.

All vehicle charging was conducted at a centralized charging depot powered by Rubitec's solar-hybrid minigrid,[12] which has provided reliable electricity to roughly 2,500 residents of Gbamu Gbamu since 2018. Rubitec created a special $0.34/kWh (130 naira/kWh) tariff for EV charging, which is a discount over the tariff of $0.46/kWh (175 naira/kWh) offered to most other minigrid customers.

The minigrid is powered by an 84 kilowatt-peak (kWp) solar array, a lead-acid battery bank, and a backup diesel generator to serve over 550 small residential households and 150 larger customers and businesses including barber shops, restaurants, hotels, welders, and more. The minigrid's electricity tariffs are cost competitive with previously incumbent diesel generation, and the nearest grid access point is a

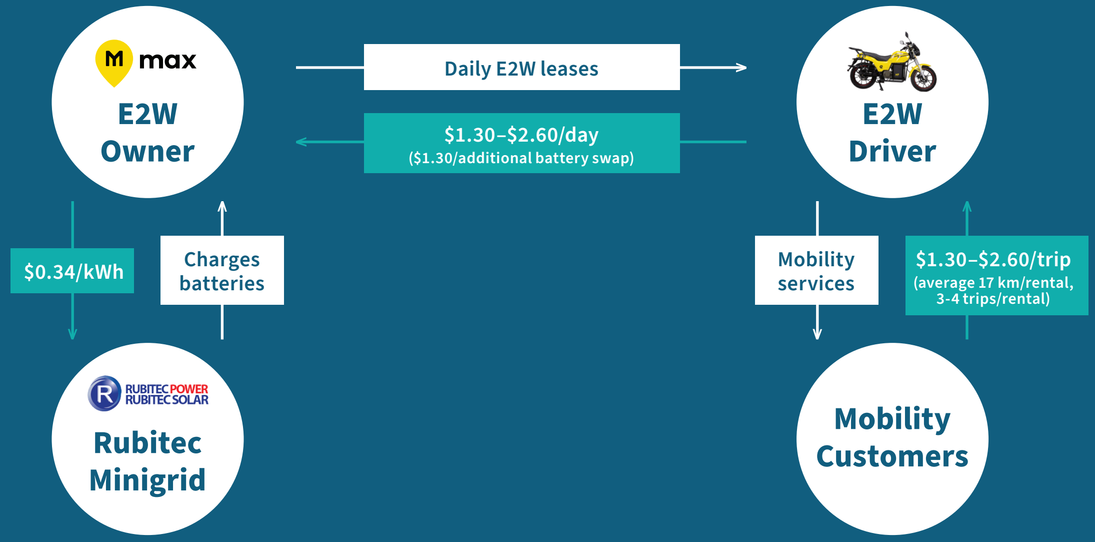
---

[i] Using an exchange rate of approximately 379 naira per US dollar. In practice, the exchange rate varied between the baseline survey (conducted in 2019) and the data analysis period (early 2021). Naira values converted into dollars are rounded for readability.

40-minute drive in good road conditions. The pilot operated from September 2020 and was ongoing as of November 2021. This report analyzes data collected over five months, from January through April 2021, for which hourly EV charger and in-motion telematics data was available, and during which time the pilot had established a steady state of vehicle deployment and use. Exhibit 2 (next page) presents additional summary statistics for the pilot.

Box 1

Business Model: Renting E2Ws to Certified Local Drivers



Driver Training

In the Nigeria pilot, E2Ws owned and maintained by MAX were rented to local drivers who had completed the company's driver certification. EV training was provided to interested drivers, and there was no randomized control or other experimental design employed in driver selection. The certification process included an on-site driving test and training on the electric vehicles themselves (e.g., the battery swap process, how to interpret the charge gauge). To prolong battery pack life, the training also advised drivers to return for a swap before the battery state of charge dipped below 35%. Pilot data on battery state of charge was not available to clarify drivers' compliance with this policy. MAX policy also restricted operating hours to no later than 9 p.m. for safety reasons, though 75% of trips were completed by 7 p.m.

E2W Rentals

Most drivers checked out an E2W in the morning, paying $1.30 (500 naira) per day to rent a base model, or $2.60 (1,000 naira) per day to rent a model with an upgraded 1.5 kW motor. In a baseline survey conducted by MAX, petrol bike drivers expected to spend $1.30–$5.20 per day on fuel alone (500–2,000 naira). This fuel expenditure is based on a reported black market fuel cost of $0.56 per liter (L) (roughly 200 naira/L), which was 40% more expensive than the price at the pump but still significantly offset by Nigeria's fossil fuel subsidies of $0.09–$0.11/L (35–40 naira/L), which make Nigeria's petrol prices among the cheapest in Africa.

At the efficiency observed in the pilot, the E2Ws had roughly 70 km of maximum range. Yet, the average E2W rental drove 17 km, consuming an estimated 0.9 kWh of energy costing $0.35 (130 naira) to replenish at the minigrid. Interviews with drivers indicate that a typical day included three or four trips at fares ranging from $1.30–$2.60 (500–1,000 naira), depending on distance. Given these rates, the drivers expected to pay off their rental fee after two or three customers.

Battery Swap Charging Model

The vehicles were parked and charged at a centralized EV depot operated by MAX that utilized a battery swap model. Each time an E2W departed the charging station, a freshly charged battery was moved from the charger to the vehicle and the discharged battery from the vehicle was placed onto the charger (Exhibit 4, page 14). If a customer ran low on capacity from the first battery, it could be swapped for a fully charged battery at the depot for an additional $1.30 (500 naira), although MAX staff members report that most renters did not require a swap before returning the E2Ws at the end of the day. To ensure adequate swapping capacity, MAX maintained 1.5 batteries for every E2W. The battery charging was powered entirely by the Rubitec minigrid, which also rented the charging depot building and charging infrastructure to MAX for $40.00 (15,000 naira) per month.

Nigeria Pilot Results

During the 114-day study period, a group of over 20 MAX-certified local drivers chose the electric two-wheelers for at least some of their trips, covering 5,400 km, paying an estimated $570 (216,000 naira) in rental fees, and consuming 340 kWh of electricity worth $109 (41,000 naira). Compared with incumbent drivers interviewed in a baseline survey, the E2W drivers reported charging customers similar fares (500–1,000 naira per trip), driving a similar number of trips per day of work (three or four), and operating during similar hours (early morning through early evening).

Drivers used the electric vehicles for both personal trips and to provide fee-for-service transport for people and goods, mostly between Gbamu Gbamu and regional hubs within a 20 km radius. Exhibit 3 (next page) presents the travel patterns exhibited in the GPS tracker data collected for each E2W, showing that most trips were to surrounding communities. The most common route was from the charging depot to the junction with the paved A121 highway, 16 km away. The junction serves as a commercial center and transport hub for communities along the road, and drivers often rented E2Ws for this single route, either by themselves or with paying mobility customers. The EVs often spent extended amounts of time at the junction while waiting for customers for the return trip or parked while the driver caught a bus or taxi to another town. The E2Ws were also used to transport goods such as cocoa beans and bananas to markets in surrounding communities.[13]

Exhibit 2

Nigeria Pilot Summary Statistics	
Pilot data period	January 7–April 30, 2021 (114 days)
EV electricity tariff	$0.34/kWh
Fleet size	4–5 MAXe Series M1 E2Ws
Fleet mean distance traveled	48 km traveled/day
Charging station load	3.0 kWh/day across 5 chargers
Typical minigrid customer load	0.5 kWh/day
Fleet estimated efficiency	53 watt-hours (Wh)/km[14]

To provide these services, Gbamu Gbamu's two-wheeler drivers required vehicles fit for transporting goods and passengers along the area's rutted dirt roads, some of which become impassable after heavy rain. The MAX team used the pilot site to iteratively improve its E2W design to better suit driver preferences. The first model tested, the MAXe Series M1, was the company's first electric vehicle offering. The M1 is a lower-cost design with a 1 kW motor, 3.6 kWh battery, and reinforced suspension, frame, and tires ready for rugged roads. At first, some drivers would overload and "burn out" the smaller-capacity motor in the M1 when transporting heavier loads. The MAX team responded by upgrading some E2Ws with a 1.5 kW motor. Once this more powerful alternative was introduced, many drivers preferred it.

Exhibit 3 Serving Mobility Customers' Needs with E2Ws

Traveling to the Highway Junction:

A MAX-certified driver takes a customer from the community center to the A121 highway junction. This junction is the confluence of rural roads to many communities in the area, and it is a major hub. MAX's drivers' customers came here to catch buses to other cities, conduct business, and purchase goods that aren't available in town.

Photo credit: MAX

Transporting Plantains to a Neighboring Community Market:

A MAX-certified driver transports a medium-sized bunch of plantains from Gbamu Gbamu to a neighboring community market, where the seller can negotiate a higher price. These bunches can weigh as much as 20 kilograms. Cocoa beans, and cocoa-derived products, were also popular items transported on the E2Ws.

Photo credit: Nneka Chile

MAX E2W TRIPS

Example trip to highway junction

Average trip statistics:
Distance: *16 km*
Duration: *38 min*
Speed: *26 kmph*

Trips to nearby villages

Example trip to community market:
Distance: *7 km*
Duration: *27 min*
Speed: *16 kmph*

All trips

Average trip statistics:
Distance: *3 km*
Duration: *16 min*
Speed: *12 kmph*

Darker lines correspond to more frequently traveled routes.

Vehicle development continued throughout the pilot, causing the number of vehicles deployed on-site to fluctuate from 5 to 11 vehicles, although 4 to 5 vehicles were active during the data period analyzed in this report (January–April 2021). MAX ultimately produced and tested two subsequent E2W models during the pilot, and the company has made electric two-wheelers a business vertical.[15] The MAXe Series M3, which features a larger battery and motor delivering up to 160 km of range and an 85 km per hour (kmph) top speed, is now in pilot testing on-site with sales expected in 2022.

EV charging and operation data show how MAX's battery swap and check-out process created a daytime charging load for the minigrid to serve (Exhibit 4, next page). Each morning, drivers checked out E2Ws from the charging depot for a day of driving. Before the E2W left the depot, a MAX attendant swapped the discharged battery from the EV with a freshly charged battery from a charger. On average, the spent battery was recharged over the next five hours, drawing 1.6 kWh of power. This charging load occurs exclusively during daytime hours, naturally tracking minigrid solar production, and complementary to the early morning trough in demand from other minigrid loads.

Such a consistent load profile also means that the charger bank was drawing zero power about 67% of the time. The E2Ws were active during the day, usually not driving enough to require a return to the charging station for a midday battery swap. The drivers returned the vehicles in the early evening hours, just as the minigrid load begins its evening peak phase as customers turn on their lights, televisions, fans, and other household appliances.

> **“On an average day, approximately half of the deployed E2Ws were rented, covering nearly 50 km across the fleet and drawing 3 kWh of electricity from the vehicle chargers.”**

During the analysis period, all of the E2W chargers collectively accounted for 1% of total minigrid electricity sales. The total electricity consumption of the EV fleet was about six times that of the average minigrid customer, and roughly comparable to the consumption of a typical small business customer. The minigrid load did not grow appreciably during the study period, and the EV charging loads were also steady over time.

On an average day, approximately half of the deployed E2Ws were rented, covering nearly 50 km across the fleet and drawing 3 kWh of electricity from the vehicle chargers. This translates to an average of 2.5 vehicles operated in the fleet each day, each covering nearly 20 km per vehicle per day, and consuming 1.2 kWh of energy per vehicle per day. A maximum of four E2Ws were checked out in a 24-hour period. Assuming that E2Ws could operate from 6 a.m. to 6 p.m., Monday through Sunday (84 hours/week), the vehicles spent 35% of this time in operation (8% moving, and 27% stopped away from the charging depot). As Exhibit 4 (next page) shows, driving occurred mostly in the daytime. The fleet performed at an average efficiency of 53 Wh/km, assuming 15% charging losses from meter to battery.[16] This energy efficiency is roughly triple that of a Tesla Model 3,[17] and on par with the claimed efficiency of the Harley-Davidson LiveWire.[18]

Based on the pilot data, the unit economics for an E2W rental fleet are feasible for the EV operator under the business model tested here. A $1,300 E2W with an upgraded motor, used in a fleet with a 1.5 battery-to-vehicle ratio, rented an average of 3.5 times per week at $2.60 per rental, will pay back in roughly nine years considering the total cost of vehicle ownership. The payback period could be reduced to four years if the daily vehicle utilization rate increased from the 50% observed in the pilot to the 80% rate used in the High

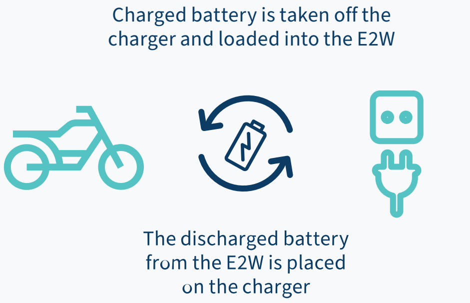
Exhibit 4

How the Nigeria Pilot Battery Swap Model Created Daytime Charging Loads

1 **Drivers check out E2Ws from the charging depot starting at 8 a.m., on average, and drive during daylight hours**

Photo credit: MAX

2 **Before leaving the depot, MAX staff swap out the E2Ws' discharged batteries. The EV chargers draw power to replenish them**

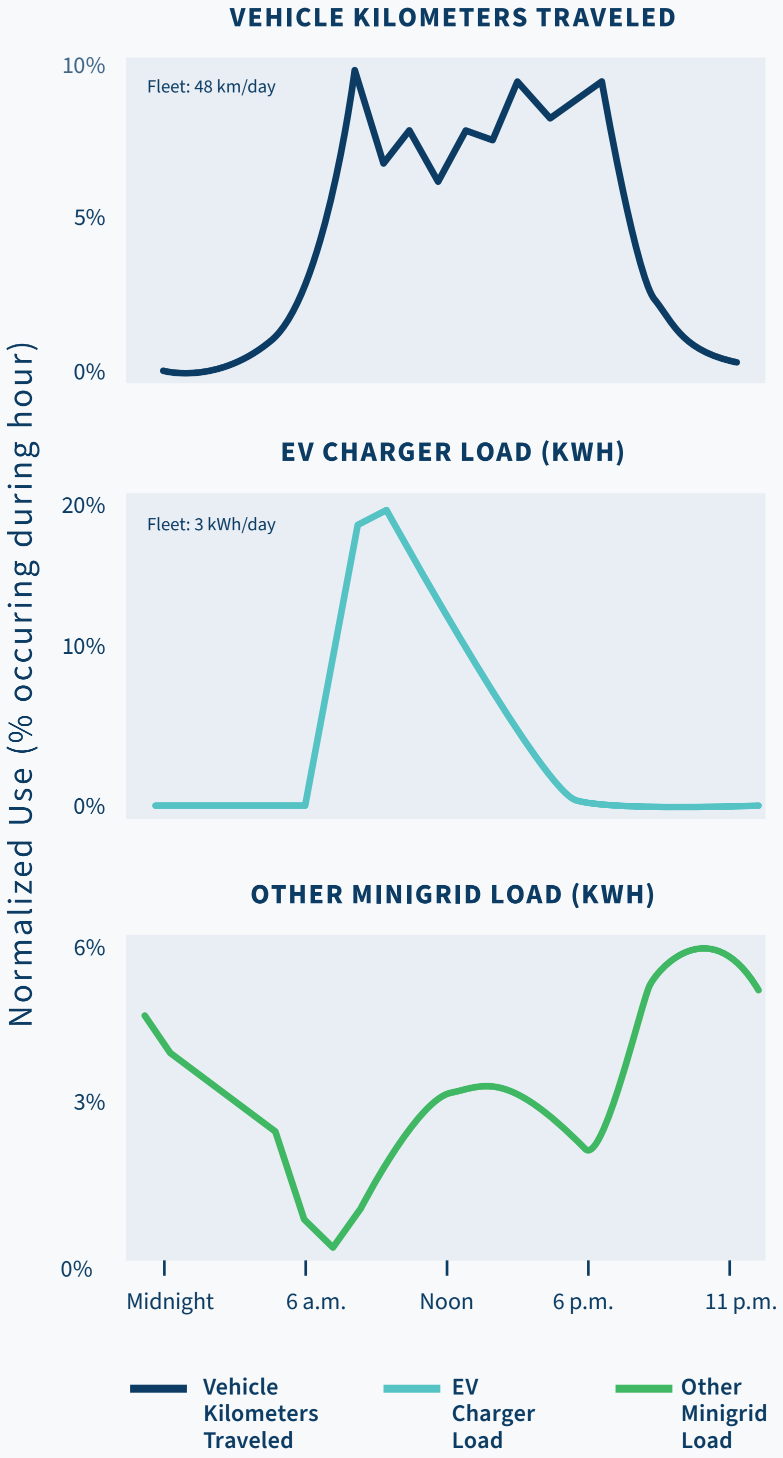


Charged battery is taken off the charger and loaded into the E2W

The discharged battery from the E2W is placed on the charger

3 **Drivers return the E2Ws during early evening hours, just as the minigrid load reaches its evening peak**

Average Time of Use for EV Drivers, EV Chargers, and other Minigrid Loads



VEHICLE KILOMETERS TRAVELED

EV CHARGER LOAD (KWH)

OTHER MINIGRID LOAD (KWH)

Curves represent the fraction of kilometers traveled or kilowatt-hours consumed during a particular hour of an average day. Areas under the curves equal 100%.

E2W Load scenario described below, which is commensurate with rates observed in other rental fleets.[19] These calculations do not consider operational overhead, which was relatively low for this Nigeria pilot. Future pilots may consider how partnering with the minigrid can keep charging infrastructure costs low, and how local labor can contribute to EV maintenance and charging depot management.

In summary, the Nigeria pilot used a vehicle rental business model to successfully introduce electric two-wheelers to a rural community served by a solar-hybrid minigrid. Throughout the pilot, the EV operator upgraded its vehicle offerings to suit customer needs and meet the demands of the rural context. The EVs competed with petrol-powered alternatives in the area, and the pilot data suggests a strong likelihood that the vehicle rental model can be deployed profitably at minigrid electricity prices. However, the current EV models offered only ~70 km in range given a 3.6 kWh battery capacity and an observed efficiency of 53 Wh/km. In addition, MAX's driver training encouraged drivers to take shorter trips to minimize battery depth of discharge. In a baseline survey of 19 incumbent petrol motorcycle drivers working in Gbamu Gbamu, respondents reported covering an average of 100 km per day, although empirical data was not collected to verify the petrol drivers' use patterns.

This data suggests that range limitations could leave a large proportion of mobility customer demand to continue to be served by incumbent ICE vehicles that could make longer trips. MAX's discussions with drivers also indicate that petrol two-wheelers are sometimes preferred for heavier loads, and that some drivers prefer to own their vehicle (in which case, only petrol options are available for purchase). Future E2W models may reach these customer segments by incorporating larger battery packs, more battery swapping options, more hauling capacity, or a business model that accommodates drivers who own their vehicles.

At the 53 Wh/km efficiency observed in the pilot and a $232/kWh battery cost, each additional kilometer of range requires another $12 in up-front battery costs. Introducing new, possibly more expensive, EVs would raise questions about the per-day rental fee required to pay back these models and drivers' willingness to pay more to use them. On the other hand, longer-range vehicles may increase the fleet utilization as local drivers choose to forgo petrol two-wheelers for even their longer trips. MAX intends to continue exploring these questions, and others, through continued investment in rural e-mobility testing.

India Pilot: Leasing Lithium-Ion Batteries to Three-Wheeled EVs at a Biogas Minigrid

India Pilot Context

In 2019, Shell Foundation initiated a pilot that introduced a lithium-ion battery leasing service for E3Ws at a minigrid near rural Munger, Bihar. Over four months of operation, SMV Green Solutions, a social enterprise focused on mobility, offered improved batteries to five local E3W owners via a subscription model. Grassroots Energy, a local biogas minigrid, powered the battery charging.

India is populous and rapidly urbanizing, and it has made strides in electrification since the early 2000s, having achieved almost 100% electrification at a household level through the Saubhagya Scheme.[20] Yet 65% of the population lives in a rural area where many still lack a quality grid connection and receive power only intermittently. One in two homes and businesses face a power outage of at least eight hours per day despite being connected to the grid, according to a survey of 12,000 rural customers.[21]

Renewably powered minigrids have been serving Indian customers reliable electricity for decades: nearly 150 minigrids provide an estimated four megawatts of capacity in Bihar alone.[22] However, though rural Indian minigrid customers are often willing to pay a premium for more reliable power, they tend to consume only small amounts to meet basic lighting and other low-power needs.[23]

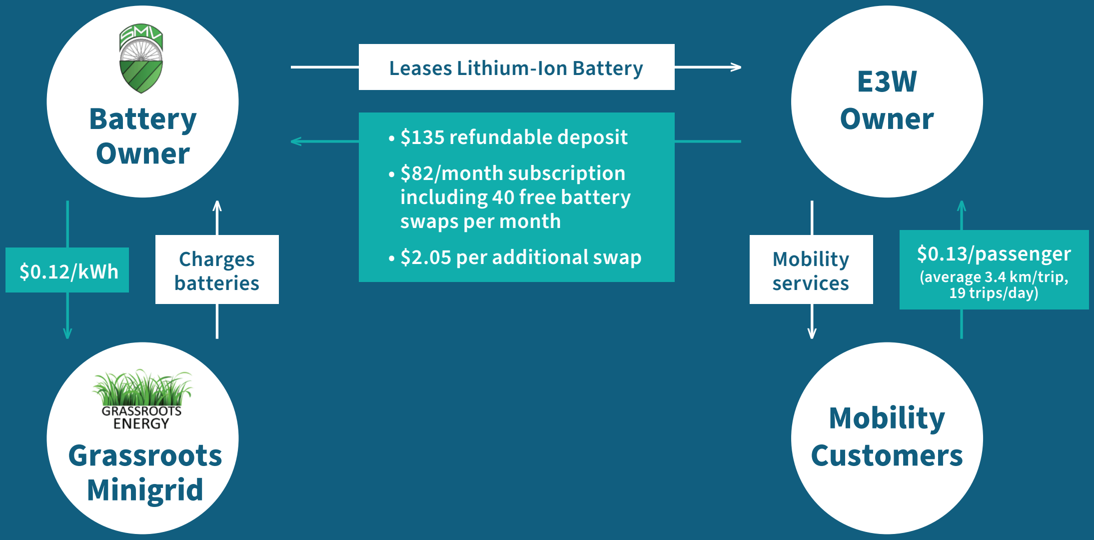
India is already a world leader in electrifying mobility and is aiming for even higher EV sales penetration across vehicle segments in the coming years, especially for small-format vehicles.[24] This growth is underpinned by government support such as the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme, and the fact that India's private vehicles tend to be smaller models that are most cost-effective to electrify (e.g., two-wheelers make up more than 70% of registered vehicles).[25] India is also the largest E3W market in the world by far: about half of all rickshaws in the country are now electric.[26]

Most of these E2Ws and E3Ws today use lead-acid batteries, although alternative chemistries such as lithium-ion are increasing in popularity as costs fall. Battery swap services offered by companies such as SMV Green Solutions, an Indian social enterprise focusing on last-mile transportation, allow drivers to lease lithium-ion batteries for use in their own vehicles, extending their range and eliminating drivers' responsibility for battery charging and maintenance.[27]

The India pilot analyzed here tested the viability of minigrid-powered E3W charging offered under the SMV battery swap model described in Box 2 (next page). The fleet's battery-to-vehicle ratio was 1.5. The charging station was established at a 30 kW biogas minigrid operated by Grassroots Energy.[28] The minigrid is fueled by local agricultural wastes and serves customers in the surrounding areas, where the utility-scale grid service is intermittent and at a voltage insufficient for EV charging. The minigrid is about 15 km from the nearest market, which is a major demand center for mobility services.

Box 2

Business Model: Lithium-Ion Battery Leasing to Local E3W Owners



During the pilot, SMV leased lithium-ion batteries to local E3W owners who provided mobility services to customers. Interested drivers were recruited for participation without employing a randomized control or other experimental design for driver selection. The local drivers owned the vehicles and paid to access fully charged batteries, rather than managing charging and battery maintenance themselves. To ensure adequate swapping capacity, SMV purchased 1.5 batteries for every vehicle participating in the pilot. This model allowed drivers to maintain vehicle ownership, which they strongly preferred, without taking on the up-front cost of upgrading to higher quality batteries. SMV noted that drivers have demonstrated much less interest in an offer to lease entire E3Ws.

The battery lease fee structure consisted of a refundable $135 (10,000 rupee) deposit, an $82 (6,000 rupee) monthly subscription fee including 40 free battery swaps per month, and a $2.05 (150 rupee) fee for additional swaps. A total of $217 (16,000 rupees) was due on the first day of enrollment in the program, to cover both the deposit and first month of subscription fees. The additional per-swap fee was always the same, regardless of the state of charge upon return. SMV paid the minigrid a fixed rate of $0.12 (8.5 rupees) per kilowatt-hour of electricity used by the battery chargers. The battery lease prices were set with the aim of making this model a comparable price to driving a lead-acid battery electric rickshaw, as SMV estimates that lead-acid batteries must be replaced every six months at a cost of $275 (20,000 rupees).

Through the pilot, SMV retrofitted five lead-acid-powered E3Ws owned by local drivers to run on SMV's swappable lithium-ion battery packs, which were charged at the minigrid. Prior to the pilot, these drivers typically charged their lead-acid batteries on the utility-scale grid, where suitable service was available. SMV's business model aimed to provide the drivers with higher-capacity batteries, charged close to home, on a subscription basis. The subscription offered 40 free swaps per month before charging $2.05 per swap. The battery swap model also offered decreased charging times compared with EVs with fixed lead-acid batteries that must stop to recharge. SMV noted that considerable engagement was required to convey the benefits of the lithium-ion battery and the swap subscription model to local drivers who drove E3Ws powered by lead-acid batteries.

India Pilot Results

Although drivers reported savings from the battery leasing subscription, SMV incurred high costs associated with operating in a rural area, and drivers did not ultimately follow the procedures of the minigrid charging model. During the project, five participating drivers covered 13,400 km over approximately four months and drove roughly the same distances as their peers using lead-acid batteries (50 km/day, on average). In a survey, both pilot participants and other local drivers reported averaging approximately 20 trips per day. The estimated daily incomes and costs were also similar between the two groups under the SMV fee structure, with driver profits estimated at $0.05–$0.09 (4–7 rupees) per kilometer driven.[ii]

However, several aspects of the rural pilot operations did not go according to plan, raising operating costs to the point where it did not make sense for SMV to continue operations after conclusion of the pilot. One problem was that subsidized grid service was available in the main operating zone near the market, allowing the drivers to sidestep the battery swap business model by charging the batteries themselves with grid power. It appears that it was simply cheaper and more convenient to charge on the main grid near the market than to drive 15 km back to the battery swap station, and that the grid reliability in this area was good enough to meet the need. This could be one reason that most drivers did not perform more than one swap per day, on average. SMV attempted to close the loop by delivering minigrid-charged battery packs to the market to recoup the per-swap charge that was sidestepped by this charging defection, but this raised SMV's costs further.

> **“One problem was that subsidized grid service was available in the main operating zone near the market, allowing the drivers to sidestep the battery swap business model by charging the batteries themselves with grid power.”**

This charging behavior also refuted a key hypothesis of the battery swap model: that drivers would favor quick battery swaps that minimize the downtime required for charging during business hours and maximize their time on the road. Although the pilot did not collect definitive data explaining why drivers did not frequently utilize this benefit of a swapping service, one reason could be that drivers were not driving enough kilometers per day to deplete their 5.8 kWh batteries. This battery size would allow 62 km of range based on the 94 Wh/km efficiency

---

[ii] Using an exchange rate of 73 rupees per US dollar.

assumed in the total cost of ownership modeling presented below (drivers reported an average daily distance of only 50 km/day). Pilot participants hypothesize that using a smaller battery—which costs the battery owner less up front and can be sustained at lower per-swap driver fees—might strike a balance between the battery owner's costs and the drivers' interest in utilizing quick battery swaps throughout the day.

The charging defection is just one example of how rural operations posed new challenges to Varanasi-based SMV, which mostly operates in urban areas. Managing day-to-day activities in a remote area took significant time and resources outside of the day-to-day activities of urban-based staff. For example, the rural battery swap outpost required its own maintenance strategy, anticipating potential delays in receiving spare parts and avoiding involuntary driver downtime. Rural drivers were also more cost sensitive and unwilling to pay more than $2.05 (150 rupees) per swap (though SMV estimates that it would have required twice as much per swap to break even on the project). SMV reported that the pilot's rural area was more sparsely populated, shrinking the customer base for the drivers. This may be one reason the pilot drivers covered about half as many kilometers per day as urban drivers.[29]

Grassroots Energy, the minigrid operator, enjoyed the additional electricity sales from the battery chargers and was disappointed that the pilot project did not continue. The negotiated tariff of $0.12 (8.5 rupees) per kWh was higher than the minigrid's estimated operating cost of $0.08 (6 rupees) per kWh. The minigrid operator, which runs its 15 kilovolt-ampere generator four to six hours per day on an as-needed basis, was hopeful that the EV charging would allow the generator to run at higher capacity to increase efficiency. Grassroots reported that charging loads from the five battery swap participants were too small and inconsistent to make a meaningful difference in generator capacity utilization, although load data was not available for further analysis.

In summary, the India pilot deployed a lithium-ion battery lease model with five rural drivers who exclusively operated electric three-wheelers before, during, and after the intervention. However, despite electric vehicles being a suitable tool for this context, the accompanying business model did not provide cost-competitive, minigrid-powered lithium-ion battery swapping services because of high operational costs incurred by the EV operator and charging defection by the drivers. Since there are already many electric rickshaws operating in the area, a simpler business model in which the minigrid provides charging as a service may be a first step to building relationships with drivers and better understanding their needs.

Cost Comparison of Two- and Three-Wheeled EVs with Petrol-Powered Alternatives

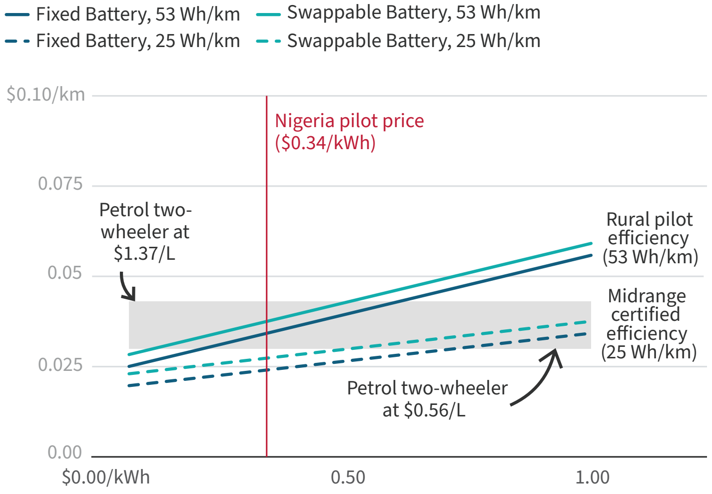
Additional technoeconomic analysis of scenarios that build on pilot data shows that lithium-ion E2Ws and E3Ws are cost competitive with petrol-powered alternatives on a total cost of ownership (TCO) basis at a wide range of energy prices (Exhibit 5). Whether a fossil-fueled or electric option is cheapest depends on a combination of underlying vehicle characteristics (e.g., up-front cost, maintenance, efficiency) and energy prices (e.g., cost of a liter of fuel or kilowatt-hour of electricity).

Exhibit 5

Total Cost of Ownership of Small-Format Electric Vehicles at Varying Electricity Prices

Two-Wheeler Total Cost of Ownership

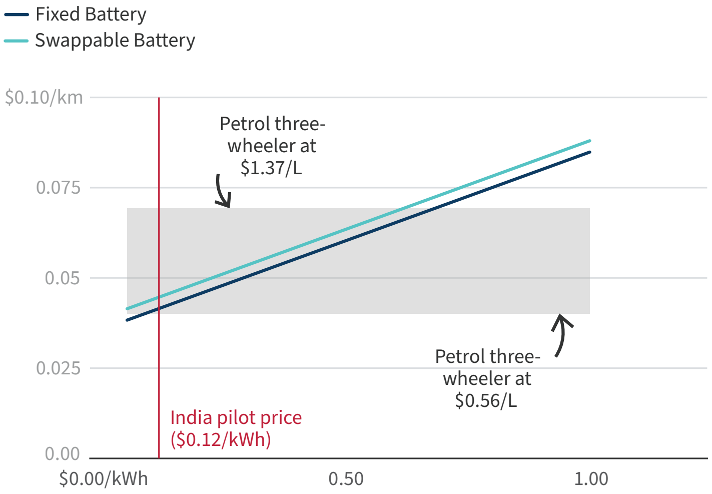
Cost per kilometer at a range of energy prices



Total cost of ownership for vehicles traveling 25 km/day. Vehicle efficiencies are based on the Nigeria pilot vehicle performance (53 Wh/km) and the middle range of certified efficiencies reported in Weiss, Cloos and Helmers (2020) (25 Wh/km). Petrol price ranges are indicative of 2021 prices observed in New Delhi ($1.37/L) and at the Nigeria pilot site ($0.56/L).

Three-Wheeler Total Cost of Ownership

Cost per kilometer at a range of energy prices



Total cost of ownership for vehicles traveling 100 km/day at 94 Wh/km efficiency. Petrol price ranges are indicative of 2021 prices observed in New Delhi ($1.37/L) and at the Nigeria pilot site ($0.56/L).

The two-wheeler modeling presented here is representative of a two-wheeled electric vehicle driven 25 km/day in a rural commercial fleet and is analogous to the vehicle used in the Nigeria pilot described above. The three-wheeler modeling is based on a commercial fleet e-rickshaw driving 100 km/day and is analogous to the vehicles used in the India pilot.

Exhibit A.1 (page 30) presents the vehicle prices, efficiencies, and financing costs used in the total cost of ownership modeling. Taxes and fees were based on the Indian regulatory environment, *excluding* FAME II subsidies for small-format electric vehicles, which provide incentives per kWh of EV battery capacity.[iii] Adding in FAME II subsidies further reduces TCO for E2Ws and E3Ws by 4%–10% (the effect varies based on the price of electricity). These TCO results are not perfectly reflective of the EV pilots, which provided only early, limited data on EV use for a few vehicles at two sites.

Changes to TCO model inputs can shift the cost advantage between electric and ICE options, and the model was especially sensitive to changes in up-front vehicle cost, vehicle efficiency, and average daily mileage. For example, the pilot E2Ws operated on rugged roads at low speeds, requiring about 53 Wh of energy for every kilometer traveled (Exhibit 5, leftmost figure, solid lines). Roughly doubling E2W efficiency to 25 Wh/km, a reasonable value for small E2Ws driving on smooth roads,[30] shows the E2W beating a petrol alternative at significantly higher electricity prices (Exhibit 5, leftmost figure, dashed lines). Combining this higher efficiency with the up-front FAME II subsidy for E2Ws makes the electric option cheaper than a petrol two-wheeler up to an electricity cost of $0.90/kWh when petrol is as cheap as $0.56/L.

As modeled, fleets utilizing a swappable battery arrangement required a 38% and 15% increase in up-front investment for E2Ws and E3Ws, respectively, to fund the extra battery capacity required to support the 1.5 battery-to-EV ratio used in both pilot projects. This extra capital investment increased TCO per kilometer by 10% and 6% for E2Ws and E3Ws, respectively, at the Nigeria pilot tariff of $0.34/kWh. However, if a swappable model can allow the EV operator to obtain a lower electricity tariff or spend more time driving customers (i.e., instead of waiting for a fixed battery to charge), the savings or extra revenue could justify the extra up-front cost. For example, a swappable battery E2W operator paying $0.24/kWh has the same total cost of ownership as a fixed battery E2W operator paying $0.34/kWh.

For minigrids seeking to maximize utilization of daytime solar power, a time-of-use discount could incentivize EV users to pursue an operating model that charges batteries during the day. If a swappable battery arrangement is required for the EV operator to achieve daytime charging, the modeling above shows that the extra up-front cost can be justified with a plausible electricity price discount.

Although petrol is a common fossil fuel source for E3Ws, it is not always the cheapest on a total cost of ownership basis. At a representative petrol price of $1.07/L, compressed natural gas (CNG) price of $0.68/L, and diesel price of $1.04/L, CNG- and diesel-powered three-wheelers reduced TCO by roughly 30% and 10% compared with the petrol three-wheeler, respectively. Although unsubsidized E3Ws are still the lowest-cost option if electricity is as cheap as $0.06/kWh, CNG and diesel models may be the lowest-cost alternative to petrol models in some cases. Further analysis of the comparative economics for these fuels will be most useful if it is tailored to the specific prices and fuel availability observed in the target market.

[iii] The subsidies include 10,000 rupees (roughly $135) per kWh for three- and four-wheeled EVs, and 15,000 rupees (roughly $205) per kWh for two-wheelers, up to 40% of purchase cost. More details can be found at **https://fame2.heavyindustry.gov.in**.

Impact of EV Charging on Minigrid Economics

Supporting analysis shows that adding EV charging increases electricity sales, but minigrid economic benefits depend on the size and timing of charging loads.

Introducing the Nigeria pilot EV loads from five electric two-wheelers to a representative Nigerian minigrid generated 3 kWh in additional daily electricity demand, a 2% increase over the baseline load. Additional technoeconomic analysis shows that adding these EV loads reduces the tariff required to recoup investment in an optimally sized minigrid by about 1% (Exhibit 6, next page). Raising the EV adoption to 10 vehicles and increasing the percentage of the fleet rented each day from 50% to 80% raised the daily charging load to 9.6 kWh/day and reduced the minigrid tariff by 6%. These results show that adding EV charging loads at the level observed in the pilots can indeed benefit minigrid operators, but not significantly more than adding a typical minigrid commercial customer.

Summary of Minigrid Modeling Results

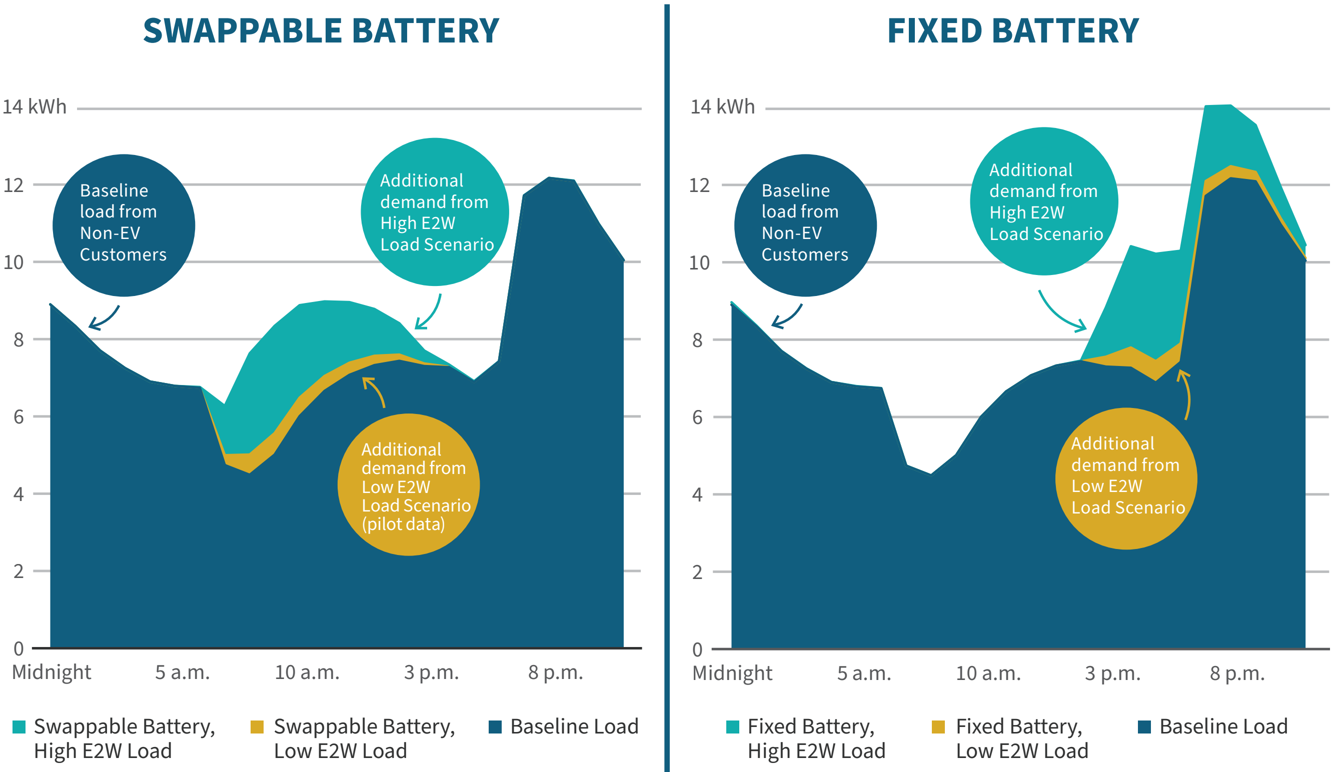
To better understand the effect of introducing EV charging on minigrid economics, additional technoeconomic modeling considered several scenarios with differing charging modalities, levels of EV adoption, and minigrid sizing accuracy:

Charging modality	A **Swappable Battery** scenario following the pattern observed in the Nigeria pilot, where charging begins around 8 a.m. and occurs during daylight hours, and a **Fixed Battery** scenario where vehicles are charged in the evening when the E2Ws are returned (4 p.m., on average).
EV adoption	A **Low E2W Load** scenario representing the Nigeria pilot fleet of five E2Ws where 50% of fleet vehicles are rented each day, on average, and a **High E2W Load** scenario increasing the number of E2Ws to 10 and raising the fleet capacity utilization to 80%.
Minigrid sizing accuracy	An **Optimally Sized** scenario where the minigrid solar, battery, and generator capacity are closely matched to load in-line with theoretical best practice, and an **Oversized** scenario where the loads anticipated by minigrid designers are 50% larger than the actual electricity demand of non-EV customers. The Oversized scenario is reflective of many existing minigrids.

Exhibit 6 shows the economic impact of adding EV loads to an optimally sized minigrid.[iv] The underlying technoeconomic models were based on data representative of actual Nigerian minigrid customers but do not directly model the Gbamu Gbamu minigrid where the pilot took place. This section briefly summarizes these results while Appendix B (page 31) provides further methodological detail and discussion. Exhibits B.1 (page 34) and B.2 (page 35) present detailed results for the Optimally Sized and Oversized scenarios, respectively, including minigrid tariffs, capital expense, and generator fuel cost as well as EV fleet size, annualized cost of ownership and E2W payback period at both discounted and cost-reflective electricity tariffs. Exhibit B.3 (page 38) lists minigrid modeling assumptions and inputs.

Exhibit 6

Effect of Adding E2W Loads to an Optimally Sized Rural Nigerian Minigrid



	Low E2W Load	High E2W Load	Low E2W Load	High E2W Load
Minigrid Tariff Decrease vs. Baseline[a]	1%	**6%**	0%	4%
E2W Payback Period (yrs)[b]	9.1	4.0	5.7	**2.7**

[a] The Baseline scenario required a $0.53/kWh tariff to recover costs and earn a 15% EIRR over the minigrid project life.

[b] Calculated based on total cost of ownership at Nigeria pilot conditions, including the Nigeria pilot minigrid tariff ($0.34/kWh). Estimated rental revenues were also based on the Nigeria pilot: each daily rental earned the operator $2.60, and daily fleet utilization rates were 50% and 80% for the Low and High E2W Load scenarios, respectively.

[iv] A minigrid with assets sized to serve customers' current electricity demand at lowest cost.

For an optimally sized minigrid, the economic benefit of adding EVs depended first on the size of the charging loads, and secondarily on the time of day when they occurred.

In the Low E2W Load scenario, a fleet of five swappable battery E2Ws increased electricity sales by 3 kWh/day and decreased the tariff required to achieve a 15% internal rate of return on equity (EIRR) by 1%. This scenario is representative of the Nigeria pilot fleet's activity, where 50% of the vehicles were rented each day, averaging 48 km per day across the fleet. Increasing the number of E2Ws to 10 and raising the fleet capacity utilization to 80%, as in the High E2W Load scenario, increased the charging load to 9.6 kWh/day and reduced the tariff by 6% for a fleet of E2Ws using swappable batteries.

Charging EVs in the daytime was slightly more favorable for the minigrid than charging EVs at night. Following the pattern observed in the Nigeria pilot, the Swappable Battery scenarios began charging around 8 a.m., and most charging occurred during daylight hours. The total cost of serving this daytime load was 1%–2% lower than the cost of charging the vehicles in the evening when the E2Ws were returned, as assumed in the Fixed Battery scenarios. The cost savings of daytime charging were driven by higher utilization of daytime solar and lower diesel fuel consumption compared with nighttime charging. The higher solar utilization also decreased average emissions: a minigrid serving the High E2W Load during the day emitted 8% less carbon per kilowatt-hour across all customers compared with a minigrid charging these E2Ws at night.

Appendix B (page 31) also describes the effect of adding these EV loads to a minigrid that is oversized relative to current customer loads. Adding EVs to an underutilized system is beneficial regardless of charging time, reducing the tariff by 1.4% and 8% relative to the baseline tariff of $0.65/kWh for Low and High E2W Loads, respectively.

> **“The higher solar utilization also decreased average emissions: a minigrid serving the High E2W Load during the day emitted 8% less carbon per kilowatt-hour across all customers compared with a minigrid charging these E2Ws at night.”**

It is possible to recoup E2W investments with a daily E2W leasing business model at minigrid electricity prices. Improved vehicle utilization is key to reducing payback periods to less than five years.

Exhibit 6 (page 23) also shows the estimated payback period for EVs in each minigrid scenario considering the economic conditions of the Nigeria pilot. At the gross profit margins realized in the Nigeria pilot business model, leasing E2Ws will pay back the initial E2W investment within the vehicle's 10-year life span, at all electricity prices and daily utilization rates considered in the above scenarios. The estimated payback period for an E2W with a swappable battery at the Nigeria pilot's electricity tariff and fleet utilization is approximately nine years. Holding the electricity price constant, this payback can be cut to about three years by using an E2W with a fixed battery (lowering upfront costs), and by increasing fleet utilization from pilot levels, where 50% of the fleet capacity is rented per day, to the High E2W Load scenario utilization of 80%. However, if the fixed battery E2W must charge in the evening at a higher cost per kWh, then there could be a tradeoff between upfront and operational costs. These tradeoffs must be considered given the specifics of each prospective project.

E2Ws can beat petrol two-wheelers on cost at some minigrid electricity prices but they may need a discount to compete if EV utilization is low.

Exhibit B.1 (page 34) shows detailed EV fleet economics, including the annualized cost of ownership for the vehicles in each minigrid scenario. Exhibit B.2 (page 35) shows corresponding results for the Oversized minigrid scenario.

In the Low E2W Load scenario, a petrol two-wheeler traveling 12 km per day costs $250 per year on a total cost of ownership basis.[v] To cover the same distance, a fixed battery E2W costs about $275 per year at a cost-reflective minigrid tariff of $0.53/kWh, which is the rate required to achieve a 15% EIRR for the Fixed Battery/Low E2W Load scenario. However, reducing the electricity price to the $0.34/kWh offered in the Nigeria pilot brings E2W costs even with a petrol alternative.

In the High E2W Load scenario, EVs traveling 19 km per vehicle per day are cost competitive with petrol two-wheelers even at higher cost-reflective minigrid tariffs. For example, at the $0.50/kWh tariff required to achieve a 15% EIRR for the Fixed Battery/High E2W Load scenario, the fixed battery E2W beats the petrol two-wheeler costs by $5 per vehicle per year.

---

[v] Using a fuel cost of $0.56/L reported by drivers in Gbamu Gbamu, and an operating fuel efficiency of 19 km/L. The operating efficiency recorded for E2Ws during the Nigeria pilot was approximately half of the expected efficiency for small E2Ws driving on smooth roads per Weiss, Cloos, and Helmers, 2020. Applying a similar low-speed, rough road penalty to the petrol two-wheeler efficiency yields the 19 km/L value used for this comparison.

Conclusion

Scaling electric mobility to accompany a growing minigrid industry is potentially profitable for both minigrid and EV operators. For rural families and businesses with ability to pay for motorized transport, this growing availability of small-format EVs can provide a direct path to economical and clean transportation. Today's small-format electric vehicles can compete on cost with fossil-fueled alternatives at minigrid electricity prices, but EV-minigrid business models must increase vehicle utilization to fully realize these benefits. Future interventions should prioritize business model innovation and data collection that can be used to tailor EV offerings to the needs of each minigrid community.

Minigrid-EV business models must align electric vehicle and minigrid operator incentives while prioritizing the specific needs of rural mobility customers.

As EV and battery technology improve and costs decline, small-format EVs are expected to meet an increasing share of transportation demand. Lighter vehicles such as two- and three-wheelers enjoy high energy efficiency compared with heftier four-wheeled models: each 50% reduction in EV mass increases efficiency by 40%.[31] This efficiency advantage for small-format vehicles and falling battery costs have stimulated an estimated 14% annual growth in global E2W and E3W sales in recent years.[32] These facts make it very likely that rural minigrid operators and EV operators will be confronting when and how to implement minigrid-powered e-mobility in the coming years. To seize this opportunity, minigrid and electric vehicle operators need business models that align their economic incentives while prioritizing the specific needs of rural mobility customers.

The pilot results and modeling presented here show that small-format electric vehicles available today can be profitably deployed at rural minigrid sites. At a minigrid in rural Ogun State, Nigeria, electric two-wheelers were rented to local drivers who provided mobility services to minigrid community members at cost parity with petrol-powered two-wheeler taxis. At the relatively low daily mileage (12 km/day for each E2W, on average) observed in the Nigeria pilot, the EVs would cost about as much as fossil-powered two-wheelers covering the same distance per year, on a total cost of ownership basis. Across several EV-minigrid cost and vehicle utilization scenarios, investments in E2Ws operating at a Nigerian minigrid would pay back within the vehicle's expected operating life. MAX, the Nigerian mobility company operating the pilot E2Ws, is continuing operations at the minigrid and has plans to expand electric mobility offerings in rural areas.

In contrast, a pilot of a battery leasing business model in Bihar, India, experienced significant challenges leasing minigrid-charged lithium-ion batteries to local E3W owners. Pilot participants, who already owned and operated E3Ws powered by lead-acid batteries, were able to extend their range and cut costs by upgrading to the lithium-ion batteries offered in the pilot. But these E3W drivers were skeptical of the value proposition of the new batteries, and they ultimately sidestepped the minigrid charging process by charging their leased batteries at grid connections near the local market where demand for ride-hailing was highest. These factors, combined with the high cost of maintaining rural operations for SMV, the Indian mobility firm offering the battery leases, led the company to discontinue the pilot.

While adding EV charging increased electricity sales—the 3 kWh/day used by the Nigeria pilot fleet was about 10 times the median minigrid customer's daily load—additional technoeconomic modeling shows this amount of additional daytime load only reduces the tariff by 1% in an optimized minigrid design (Exhibit 6, page 23). Even tripling EV electricity demand only decreases the tariff by 6%.

In contrast, a separate analysis of a similarly sized Nigerian minigrid community found that introducing agricultural processing loads including cassava grating, maize milling, and rice milling added enough daytime load to decrease the minigrid tariff by nearly 20% relative to a baseline scenario.[33] **It would take eight E2Ws operating at the Nigeria pilot level of utilization to match the 1.7 megawatt-hours required for a single mill to process 90 tons of rice per year.** In this frame, EV charging at the adoption levels studied here should mostly be considered a beneficial productive use customer, and potentially a minigrid's largest load, but not an anchor load in the traditional sense.

These experiences suggest that minigrid-powered electric vehicles can offer mobility services that local customers want, at prices that drivers and customers are willing to pay, and at costs that the EV operator can profitably sustain, provided that:

1. The EVs on offer have the range, capacity, and ruggedness required to serve local customers' needs.
2. The minigrid can offer an electricity tariff at which electric vehicles are competitive with fossil-fueled incumbents (see Exhibit 5, page 20).
3. Cheaper charging is not available or convenient within the natural EV operating area.

Optimizing the business model: raising vehicle utilization through better customer value propositions

In an EV or EV battery leasing business model, high vehicle utilization is the key to strong revenues and to realizing EVs' operating cost advantage over ICE vehicles. Further, high EV utilization raises electricity consumption, which can motivate minigrid operators to negotiate with EV operators on price. **Therefore, the priority of EV-minigrid business model innovation in subsequent pilots should be to increase vehicle utilization.**

Vehicle utilization depends fundamentally on customer preferences and needs, which were not systematically assessed by the pilot projects discussed here. Both business models relied on directly substituting EVs or improved batteries into local drivers' "taxi service" business models. **A key weakness limiting EV utilization was misalignment between what local drivers and customers needed, and what the EV operation could provide.** E3W drivers in the India pilot were skeptical of SMV's value proposition: a better battery charged at a local minigrid. Perhaps as a result, **E3W drivers sidestepped the minigrid charging** despite having 40 free battery swaps per month through their subscription. Data from the Nigeria pilot shows existing demand for transportation within a rural area, with frequent travel between central hubs such as town centers and road junctions (Exhibit 3). **However, despite this demand, roughly**

half of the E2Ws on site sat idle each day. Interviews with MAX hinted that range anxiety and EV hauling capacity may have been one reason that five E2Ws were not fully utilized by MAX's cohort of 20 trained drivers. Local Nigerian drivers seemed to prefer a new E2W model with a higher-powered motor when it was introduced, but no specific data on these drivers' vehicle preferences (or the needs of their taxi customers) was collected.

Customer research, for both local drivers and the people who hire them, can help EV operators adapt their mobility offerings to local needs and achieve higher vehicle utilization. Some customer preferences may be solved with new EV models (e.g., offering a more powerful E2W or higher capacity battery for a higher rental fee). Other needs may prompt new approaches to the e-mobility business model including, for example:

- Lease-to-own programs that allow local drivers to pay a surcharge on their daily rental to earn credit toward EV ownership
- Direct EV or battery sales to minigrid community members, who may charge at home
- Fee-for-service businesses enabled by special-purpose vehicles such as milk chilling and transport, high-capacity E3Ws with cargo beds, last-mile delivery, etc.
- Minigrid-owned EV charging as a service, or minigrid-owned EVs for lease

Future pilots should prioritize customer research and collect detailed vehicle use data

Given the promise shown by minigrid-powered EVs, a next iteration of demonstration pilots should prioritize customer market research that can help tailor business models to increase vehicle capacity utilization. They should also collect detailed data on how vehicles are used—for fossil-fueled incumbents and EVs alike. Conversely, at this stage of market development, pilots that test complicated technological interventions (e.g., using EV batteries for minigrid services) are not likely to solve the Achilles heel of low vehicle utilization.

Specifically, future projects should start with customer research to learn:

- Customers' needs for mobility services, including **who** different customer types are, **what** they want to transport, **where** it needs to go, and **when** it needs to arrive. This could include preliminary **tracking of incumbent vehicles** to observe driving patterns and distances, which would inform selection of EV models and battery capacity for the site, in addition to **ensuring that the EV operating territory does not include grid-connected areas where charging defection may occur.**
- The baseline operations and cash flow for incumbent mobility service providers, including a log of costs, revenues, fuel expenditure, trip distances, and vehicle performance prior to the introduction of EVs. **It may be advisable to pay these incumbent drivers for their support in collecting this valuable data.**

During the pilot, data collection should include:

- **For EVs:** telematics data describing vehicle movement as well as time series data on charger electricity consumption and battery state of charge. This data will give more granular detail on EV costs of operation, efficiency (i.e., energy used during each specific trip), and customer experience (e.g., batteries consistently returned at a very low state of charge may indicate that customers are facing range limitations).

- **For ICE vehicles still in operation:** continued monitoring of the baseline data mentioned above, to enable a like-for-like comparison between ICE and EV drivers' vehicle use and cash flow.

Building—and publishing—this broader dataset will allow the private sector, investors, and policymakers to make informed decisions that can help further establish and scale the e-mobility sector in sub-Saharan Africa, India, and other regions with underserved rural communities. In doing so, these partners can pave the way to a future where electric mobility is the first option for moving people and goods as communities grow, all while strengthening local electricity demand and lowering tariffs for all.

Appendix A

Vehicle Total Cost of Ownership Inputs

Exhibit A.1 **Key Inputs for Modeling Vehicle Total Cost of Ownership**

Model Parameter	Two-Wheeler		Three-Wheeler			
	Petrol	Electric	CNG	Petrol	Diesel	Electric
Vehicle specifications						
Vehicle up-front price (Ex-showroom, including battery, post general sales tax)	$908	$1,300	$3,630	$3,315	$3,808	$5,342
Average life (years)	10	10	6	6	6	6
Battery size (kWh)	-	3.6	-	-	-	5.8
Average distance traveled in a day (km)	25	25	100	100	100	100
Battery life cycles*	-	1,000	-	-	-	1,000
Battery-to-vehicle ratio	-	1.5	-	-	-	1.5
Vehicle efficiency (km/L for petrol and diesel, km/kg for CNG, Wh/km for electric)	38	53	28.4	20	25.4	94
Fuel economy/vehicle efficiency improvement (% YoY)	0.25%	-1%	0.25%	0.25%	0.25%	-1%
Maintenance costs ($/100 km)	0.70	0.35	1.21	1.21	1.21	0.60
Base year battery price ($/kWh)	-	232	-	-	-	232
General sales tax on battery prices (%)	-	18%	-	-	-	18%
Taxes, insurance						
Road tax (% of ex-showroom price)	8%	8%	-	-	-	-
Insurance premium (% of vehicle up-front cost)	3%	3%	3%	3%	3%	3%

* Battery replacement cost is incurred during the year in which the battery life cycles are exceeded, using the $/kWh rates for that year according to an RMI cost schedule (e.g., $90/kWh in 2030).

The above vehicle cost of ownership input values were sourced from the World Resources Institute's total cost of ownership calculators,[34] RMI market research, and from the pilots via direct data collection or participant interviews.

Appendix B

Detailed Minigrid Modeling Methods and Results

Minigrid Model and EV Scenario Description

This appendix describes the technoeconomic minigrid modeling in depth, including detailed results for a set of EV-minigrid scenarios that add charging loads to an optimally sized minigrid (Exhibit B.1, page 34) and an oversized minigrid (Exhibit B.2, page 35). These minigrid models are based on data representative of actual Nigerian minigrid customers but do not directly model the Gbamu Gbamu minigrid. A performance-based grant of $350 per connection was assumed for every minigrid design, which is a subsidy currently available from the Nigerian Electrification Project.[35] A scenario-based modeling approach was used to examine the effect of varying EV electricity demand and EV charging times on the economics of both optimally sized and oversized minigrid systems. Exhibit B.3 (page 38) presents key assumptions and inputs used across minigrid models.

Charging Modality Scenarios: Swappable Battery versus Fixed Battery

Here, the charging modality affects the timing of EV charging loads served by the minigrid. The charging hours in the Swappable Battery scenarios follow the patterns observed in the Nigeria pilot, where discharged batteries were removed from the E2Ws and placed on the chargers in the morning (as in Exhibit 4, page 14). Swappable battery charging starts around 8 a.m. and occurs mostly during the morning hours. In the Fixed Battery scenarios, we assume that charging must occur while the EV is stationary, and that charging begins at the average rental return time (4 p.m. in the Nigeria pilot).

In practice, the electric vehicle charging time is not solely determined by whether the battery is swappable or fixed. For instance, in the Nigeria pilot, traders commonly used the E2Ws to commute between local communities with differing market days. If EV charging were available at these markets, an onboard battery could be charged while the driver stops to conduct business during the day. In contrast, a highly utilized fleet of vehicles using a battery swap model may need to charge outside of daytime hours if demand for battery swaps is sufficiently high during the daytime. The scenarios modeled here are examples. Practitioners should consider how their business model and conditions on the ground may change the timing of EV charging.

EV Adoption and Use Scenarios: Low versus High E2W Loads

In these scenarios, the level of EV adoption (i.e., number of E2Ws) and use (i.e., kilometers traveled per day by the fleet) affects the size of EV charging loads served by the minigrid. The Low E2W Load scenario directly uses data from the five-vehicle fleet operating during the Nigeria pilot: on an average day 50% of vehicles were rented to customers and the fleet traveled 48 km. The High E2W Load scenario models a fleet of 10 E2Ws, which was the fleet size MAX originally intended for the site. In addition to deploying a larger number of vehicles, the High E2W Load scenario rents 80% of the fleet vehicles each day, which corresponds to the lower end of daily utilization reported in other fleets,[36] and averages 190 km traveled per day across the fleet.

Minigrid System Sizing: Optimal versus Oversized

HOMER Pro was utilized to optimize minigrid system components to serve the minigrid load in each scenario.[37] In a typical minigrid design process, the developer selects a site, estimates or measures the loads expected from prospective customers, and then sizes solar, battery, and generator capacity to serve this anticipated load at lowest cost. However, in the absence of preexisting customer data, minigrid designers' estimates for rural customers' loads rely on "bottom-up" forecasts based on customer surveys.[38] These are often inaccurate, typically overpredicting electricity demand.[39] RMI has observed more than a fivefold difference between expected and actualized customer loads at some Nigerian minigrid sites. This error ripples through the minigrid design and operation process, as oversized assets cost more up front and then operate at low capacity utilization. Once an oversized minigrid has been built, its operators often seek to raise asset utilization through demand stimulation programs or recruitment of new commercial loads.

This study tested two approaches to minigrid asset sizing:

1. **An "optimally sized" approach** where the load profile used for asset sizing is exactly the same as the customer load profile that the minigrid actually serves (including both EV and "baseline" customer loads). This assumes perfect knowledge of customer demand prior to system construction, and the HOMER Pro asset sizing algorithm employs this perfectly accurate load profile in its least-cost optimization. This created a minigrid design utilizing 65 kWp of solar capacity, 260 kWh of lead-acid battery capacity, and a 23 kW generator, with a total up-front system cost of approximately $360,000 to serve the Low E2W Load/Swappable Battery scenario. Exhibit B.1 (page 34) presents the results of this approach.

2. **An "oversized minigrid" approach** where the load profile used for asset sizing is a customer baseline load that is 1.5 times larger than the non-EV loads that the minigrid actually serves. This models a scenario where a minigrid developer overestimates customer loads by 50% (i.e., a "50% oversize"), and the HOMER Pro asset sizing algorithm employed this oversized load profile in its least-cost optimization. This created a minigrid design utilizing 95 kWp of solar capacity, 390 kWh of lead-acid battery capacity, and a 34 kW generator, with an up-front system cost of approximately $435,000. Each subsequent model used these assets to serve the baseline load plus any added EV charging load per the scenarios described above. The only difference in capital expenses across scenarios comes from the additional metering required for the EVs in each scenario. Exhibit B.2 (page 35) presents the results of this approach.

The oversizing factor used here (50% relative to the baseline load) is based on a conservative expectation of load prediction accuracy. A recent study co-authored by RMI shows that combining customer survey and smart meter data from preexisting minigrid customers can lower absolute load prediction error to about 40% across a portfolio of sites.[40] This accuracy was achieved using an industry-leading dataset with standardized data across over 1,400 customers. For other minigrid developers, a 50% load prediction error is a reasonable assumption.

Detailed Minigrid Modeling Results

Optimally Sized Minigrid

Introducing electric vehicle charging to an optimally sized minigrid increased electricity sales and reduced the tariff required to achieve a 15% EIRR. The Swappable Battery, High E2W Load scenario decreased the tariff by 6% relative to a baseline of $0.53/kWh. Under the battery swap scenarios, the charging load occurred in the morning in synchrony with solar production. In the High E2W Load case, this higher solar utilization decreased the minigrid's overall CO_2 emissions by 8% on a per-kWh basis compared with a baseline scenario with no EV loads.

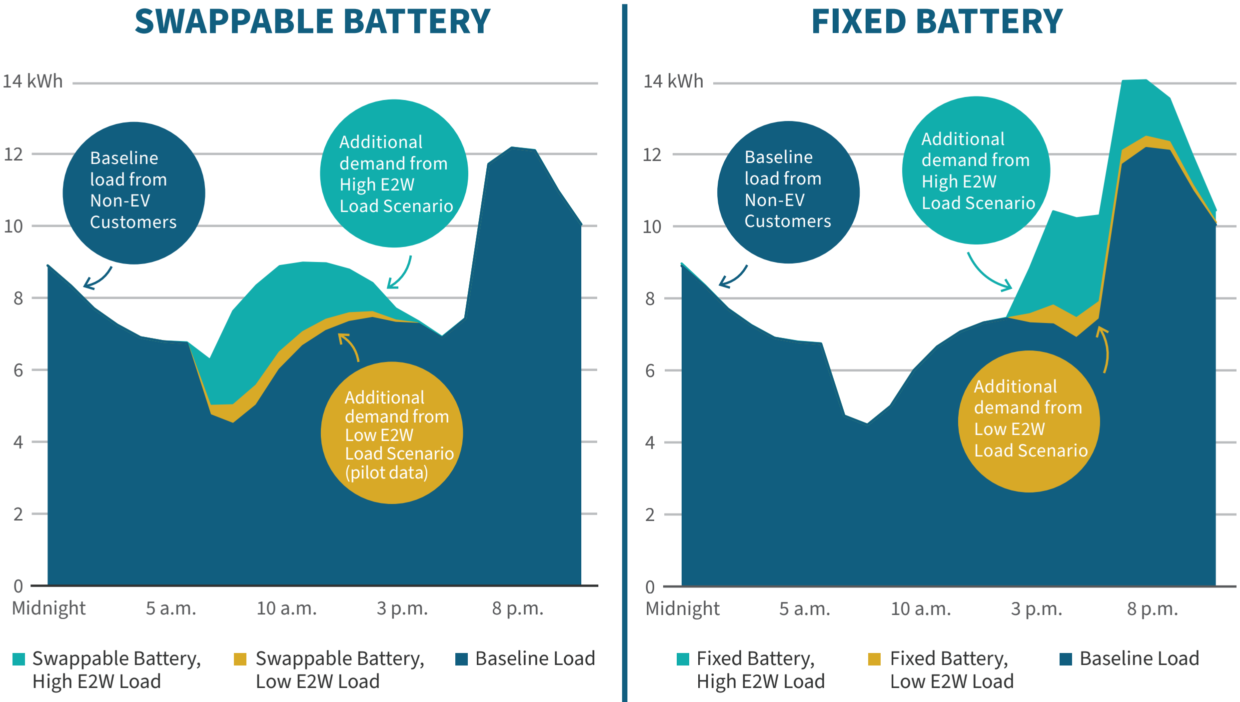
The economic benefit to the minigrid depended primarily on the size of the charging loads, and secondarily on the time of day when they occurred. As Exhibit B.1 (next page) shows, the minigrid tariff was lowest ($0.50/kWh) for the scenario with High E2W Load adoption, with charging occurring during the daytime hours. The scenario with High E2W Load but nighttime charging had the next-lowest tariff ($0.51/kWh), followed by the Low E2W Load scenario utilizing daytime charging ($0.525/kWh). In the Low E2W Load, Fixed Battery scenario, the minigrid economics were negligibly changed relative to the baseline.

Oversized Minigrid

Electric vehicle charging has a slightly different impact on the economics of preexisting minigrids with generation and storage assets that are oversized relative to the loads they serve. Exhibit B.2 (page 35) presents results for the same electric vehicle adoption scenarios, but for solar-hybrid minigrids that have been designed to serve 50% more load than is realized in the baseline. In general, the oversized minigrids serve the minigrid community load at much higher cost than right-sized designs: the baseline minigrid tariff is $0.65/kWh for the oversized system, which is 22% higher than the baseline tariff for the corresponding optimally sized system. For oversized scenarios, where there is significant excess solar production available at zero marginal cost and battery banks are overbuilt, the diesel generator is not needed as often. As a result, the generator fuel costs for the oversized system were an order of magnitude lower than for the right-sized system. This further reduced the influence of EV charging timing on minigrid economics. Adding Low E2W Load scenario charging to the oversized minigrid reduces the tariff by 1.4% compared with the baseline regardless of the timing of the charging. Similarly, introducing High E2W Load scenario electricity sales reduces the tariff by 8% for both charging modalities.

In summary, adding EV charging loads to an oversized minigrid has a stronger relative effect on system economics than for an optimally sized system. These benefits depend almost entirely on the magnitude of the charging loads (and not the timing) at the EV adoption and use explored here (i.e., 3–10 kWh of charging load per day on a 95 kWp solar-hybrid system). However, oversized systems are overpriced by definition and so they always have poorer economics than comparable minigrids whose assets are closely tailored to customer electricity demand.

Exhibit B.1 Effect of Adding E2W Loads to an Optimally Sized Rural Nigerian Minigrid



	Baseline	Low E2W Load	High E2W Load	Low E2W Load	High E2W Load
MINIGRID ECONOMICS					
Tariff to achieve 15% EIRR ($/kWh)	0.53	0.53	0.50	0.53	0.51
Capital Expense ($)	360,216	363,357	371,832	366,633	374,225
Generator Fuel Cost (avg. $/yr)	3,382	3,418	3,288	3,374	3,492
ELECTRIC VEHICLE FLEET ECONOMICS					
Number of E2Ws Deployed		5	10	5	10
Daily distance (km/vehicle/day)		12	19	12	19
E2W Capital Expense ($/vehicle)		1,800	1,800	1,300	1,300
Annualized Cost of Ownership ($/vehicle/yr)[a]					
At 15% EIRR tariff		303	348	274	321
At discounted pricing of $0.34/kWh[b]		276	312	246	282
E2W Payback Period (yr)[c]					
At 15% EIRR tariff		10.5	4.4	6.5	3.0
At discounted pricing of $0.34/kWh [b]		9.1	4.0	5.7	2.7

[a] Using Nigeria pilot average EV efficiency of 53 Wh/km, 10-year vehicle life.

[b] Nigeria pilot minigrid tariff.

[c] Revenue based on daily rental rates of $2.60, and daily utilization rates of 50% and 80% for the Low and High Load scenarios, respectively.

Exhibit B.2

Effect of Adding E2W Loads to a 50%-Oversized Rural Nigerian Minigrid

		SWAPPABLE BATTERY		FIXED BATTERY	
	Baseline	Low E2W Load	High E2W Load	Low E2W Load	High E2W Load
MINIGRID ECONOMICS					
Tariff to achieve 15% EIRR ($/kWh)	0.65	0.64	0.60	0.64	0.60
Capital Expense ($)	434,021	435,736	437,451	435,737	437,453
Generator Fuel Cost (avg. $/yr)	753	809	923	822	983
ELECTRIC VEHICLE FLEET ECONOMICS					
Number of E2Ws Deployed		5	10	5	10
Daily distance (km/vehicle/day)		12	19	12	19
E2W Capital Expense ($/vehicle)		1,800	1,800	1,300	1,300
Annualized Cost of Ownership ($/vehicle/yr)[a]					
At 15% EIRR tariff		319	370	289	340
At discounted pricing of $0.34/kWh[b]		276	312	246	282
E2W Payback Period (yr)[c]					
At 15% EIRR tariff		11.6	4.6	7.0	3.1
At discounted pricing of $0.34/kWh [b]		9.1	4.0	5.7	2.7

[a] Using Nigeria pilot average EV efficiency of 53 Wh/km, 10-year vehicle life.

[b] Nigeria pilot minigrid tariff.

[c] Revenue based on daily rental rates of $2.60, and daily utilization rates of 50% and 80% for the low and high adoption scenarios, respectively.

Limitations of Minigrid Modeling Results

The minigrid designs produced by HOMER Pro's least-cost optimization algorithm, and the economic performance of those designs, are largely intuitive for solar-hybrid minigrid systems. As expected, adding larger charging loads lowered tariffs more than adding smaller charging loads. Likewise, adding EV charging loads in the daytime increased solar capacity utilization and was more favorable to solar-hybrid minigrid economics than nighttime charging.

The amount of generator fuel consumed by the Low E2W Load, Swappable Battery scenario was slightly higher than the baseline design's fuel consumption, indicating that in some least-cost designs, even daytime loads can occasionally induce generator use. For example, if a cloudy day causes a smaller solar array to be unable to serve loads while maintaining the battery bank state of charge, the generator will run. As expected, however, the increase in generator fuel use in an optimally sized minigrid was highest for the High E2W Load, Fixed Battery scenario, which introduced the largest EV charging loads on top of evening peak demand by other customers.

However, readers should note that the small differences in electricity load between scenarios (a 2%–5% increase over baseline electricity demand) may test the precision of the HOMER Pro optimization algorithm. When the input load profiles differ by this small amount, slight differences in how the algorithm works (e.g., stochastic variability added to calculate system peak loads and the effect of weather on insolation) can more easily influence modeling outcomes. In practice, the addition of productive use loads representing just 2% of overall electricity sales is likely to be "within the margin of error" when minigrid developers are pitching a new project or evaluating the performance of an operating system.

The results presented in this report indicate that small loads from low-level EV charging move minigrid system economics in the right direction, and that daytime loads are slightly preferred to nighttime loads. Minigrid developers can maximize these benefits with larger, better-utilized fleets, and are encouraged to conduct their own scenario modeling to assess the sensitivity of their system economics to the amount of EV load that materializes in their customer portfolio.

EV Cost Competitiveness at Minigrid Tariffs

Exhibits B.1 and B.2 (pages 34 and 35) also show the annual total cost of ownership and estimated payback period for EVs in each minigrid scenario considering the economic conditions of the Nigeria pilot. This section discusses EV cost competitiveness based on cost-reflective tariffs calculated for the optimally sized minigrid scenarios.

In the low-mileage Low E2W Load scenario, the EVs need a discounted minigrid tariff to beat petrol two-wheelers on cost.

A petrol two-wheeler traveling 12 km per day (as in the Low E2W Load scenarios), with an operating fuel efficiency of 19 km/L,[vi] and fuel cost of $0.56/L, costs $250 per year on an annualized TCO basis.

At a discounted tariff of $0.34/kWh, an E2W with a fixed battery costs about the same amount to cover the same annual distance. At the $0.53/kWh tariff required to achieve a 15% EIRR for the Fixed Battery, Low E2W Load scenario, charging EVs at the cost-reflective tariff makes the electric option about $25 per vehicle per year more expensive than the petrol option.

In the high-mileage High E2W Load scenario, EVs are nearly cost equivalent with petrol alternatives even at higher, cost-reflective minigrid tariffs.

Increasing the daily distance per vehicle to 19 km (as in the High E2W Load scenarios), brings annual costs for a petrol two-wheeler to $305. At the discounted minigrid tariff of $0.34/kWh, the fixed battery E2W costs just $282 to cover the same distance, easily beating the petrol option. The swappable battery E2W nears cost parity with the petrol option at $312 annual cost per vehicle. At the $0.51/kWh tariff required to achieve a 15% EIRR for the Fixed Battery/High E2W Load scenario, the fixed battery E2W costs $321 per vehicle per year, which is $15 higher than the petrol option.

[vi] The operating efficiency recorded for E2Ws during the Nigeria pilot was approximately half the expected efficiency for small E2Ws driving on smooth roads per per Weiss, Cloos, and Helmers, "Energy Efficiency Trade-Offs," 2020. Applying a similar low-speed, rough road penalty to the petrol two-wheeler yields a 19 km/L fuel efficiency, which is the value used for this comparison.

These results reflect the fact that electric vehicles, which tend to cost more up front than ICE alternatives but have an operating cost advantage, are increasingly attractive in high-mileage applications (e.g., ride-hailing).[41]

Electric vehicles using a swappable battery charging modality must purchase more than one battery per vehicle across a fleet (e.g., 1.5 batteries per vehicle in these pilots), making them more expensive up front than EVs requiring just one fixed battery per vehicle (e.g., $240 extra for a swappable battery E2W modeled here). Holding electricity prices constant, this makes fixed battery EVs cheaper on a total cost of ownership basis. However, if swappable battery configurations can allow EV operators to take advantage of time of use discounts for daytime charging, this cost advantage could be reversed.

For example, in the High E2W Load scenario, a swappable battery EV receiving a discounted time of use tariff of $0.34/kWh costs $312/year to own and operate, which is lower than the $321/year paid for a fixed battery EV at the default service rate of $0.51/kWh. In addition, swappable batteries may reduce the opportunity cost associated with fixed battery charging, which requires drivers to pause their service while waiting to refuel. Practitioners should weigh the cost savings of the fixed battery option against the flexibility of the swappable battery option given their specific circumstances and customer preferences.

Finally, simple payback periods calculated for each scenario show that the gross profit margins of operating electric vehicles will pay back the initial E2W expense within the vehicle’s 10-year life span, at all the electricity prices and daily utilization rates considered here. These payback periods are most sensitive to the vehicle utilization (i.e., the number of days the E2W is in use and earning revenue). The cost of driving the E2W on these operating days is the second most important factor and depends on both initial vehicle cost and the electricity price on offer.

Exhibit B.3 Key Inputs for Modeling Minigrid Loads and Economic Performance

Model Parameter	Description	Source or Explanation
Minigrid Load Scenarios	**Minigrid asset sizing was determined by HOMER Pro optimizations using 24-hour average load profiles constructed according to the assumptions below**	
Baseline minigrid customer load (excluding EV charging)	500 minigrid customers utilizing an average of 0.37 kWh/customer/day	The baseline minigrid customer load profile is based on hourly smart meter data from Nigerian minigrid customers. This data was sourced from multiple developers and does not describe the load of any one site.
Swappable battery charging hours	Average charging event started at 8 a.m. and lasted five hours.	Directly used E2W charging data from the smart meters deployed in the Nigeria pilot.
Fixed battery charging behavior	Average charging event started at 4 p.m. and lasted five hours	Assumed fixed battery began charging upon return of the rented EV, which was 4 p.m. on average, according to pilot telematics data.
Low E2W Load scenario	Five E2Ws averaging 3.0 kWh/day of charging across the fleet, at 50% average daily vehicle utilization rate	Directly used E2W charging data from the smart meters and telematics data trackers deployed in the Nigeria pilot. Daily utilization rate describes the total E2W check-outs divided by total vehicle-days in analysis period.
High E2W Load scenario	Fleet of 10 E2Ws averaging 9.6 kWh/day of charging across the fleet, achieving an 80% daily vehicle utilization rate	Assumed doubling of fleet size compared with pilot fleet, which is the number of EVs MAX originally intended to maintain on-site. Assumed that fleet daily vehicle utilization could be brought closer to the US rental car standard, which ranged from 80%–100% in a survey of regional rental car managers.[42] We assumed that driver behavior (e.g., typical distance traveled per trip) held constant between the Low and High scenarios and scaled charging event loads given this increased fleet size and utilization.
Annual load growth	1%	Assumed load growth for a rural Nigerian minigrid. Minigrid assets are optimized to serve the customer load expected in year one of operation but are sufficient to serve load at the end of project life.
Minigrid Financing		
Grant support	$350 grant per connection	Capital expense grants, performance-based financing, or other concessional finance tools are often used to support minigrid deployment in hard-to-electrify regions. This study assumes a $350 per connection subsidy, which is the performance-based grant available to developers in 2021 through the Nigeria Electrification Project.
Debt interest rate	7%	RMI Nigeria market research, suitable for US dollar-denominated debt.
Equity interest rate	10%	RMI Nigeria market research.
Debt-to-equity ratio	0.6	RMI Nigeria market research.
Project life	20 years	

Endnotes

1. Sustainable Mobility for All, *Global Mobility Report 2017: Tracking Sector Performance*, 2017, **http://hdl.handle.net/10986/28542**.

2. International Energy Agency, et al., *Tracking SDG 7: The Energy Progress Report*, World Bank, 2021, **https://trackingsdg7.esmap.org/**.

3. Josh Agenbroad et al., *Minigrids in the Money: Six Ways to Reduce Minigrid Cost by 60% for Rural Electrification*, Rocky Mountain Institute, 2018, **https://rmi.org/insight/minigrids-money/**.

4. Africa Minigrid Developers Association, *Benchmarking Africa's Minigrids*, Africa Minigrid Developers Association, 2020, **http://africa-energy-portal.org/sites/default/files/2020-08/AMDA%20Benchmarking%202020.pdf**.

5. Patrick Hertzke et al., "Global Emergence of Electrified Small-Format Mobility," *McKinsey & Company* (blog), October 6, 2020, **www.mckinsey.com/industries/automotive-and-assembly/our-insights/global-emergence-of-electrified-small-format-mobility**.

6. World Bank, "World Bank Open Data," 2021, **https://data.worldbank.org/**.

7. Access to Energy Institute, *Putting an End to Nigeria's Generator Crisis: The Path Forward*, June 2019, **https://a2ei.org/resources/uploads/2019/06/A2EI_Dalberg_Putting_an_End_to_Nigeria%E2%80%99s _Generator-Crisis_The_Path_Forward.pdf**.

8. Abdulmumini Yakubu et al., *Minigrid Investment Report: Scaling the Nigerian Market*, Nigerian Economic Summit Group; RMI, August 2018, **https://info.rmi.org/nigeria_minigrid_investment_report_2018**.

9. Sustainable Mobility for All, *Global Roadmap of Action Towards Sustainable Mobility: Universal Rural Access*, 2019, **https://thedocs.worldbank.org/en/doc/662991571411009206-0090022019/original/UniversalRuralAccessGlobalRoadmapofAction.pdf**.

10. Africa Community Access Partnership, *The Failure of Rural Transport Planning and Policy to Support Women's Entrepreneurship*, Africa Community Access Partnership, March 2014, **https://assets.publishing.service.gov.uk/media/57a089f140f0b64974000336/Entrepreneurship-AFCAPgen127-v140416.pdf**.

11. National Bureau of Statistics, "Transport Fare Watch (May 2021)," Nigerian National Bureau of Statistics, June 2021, **https://nigerianstat.gov.ng/elibrary/read/1241040**.

12. Rubitec Solar Ltd., 2021, **www.rubitecsolar.com**.

13. Nneka Chile, "Nigerian Firm Bets on E-Bikes amid Petrol Rises," *Reuters*, December 7, 2020, video, 1:42, **https://reut.rs/37I9AR1**.

14 Considering 15% charging losses per Elpiniki Apostolaki-Iosifidou, Paul Codani, and Willett Kempton, “Measurement of Power Loss during Electric Vehicle Charging and Discharging,” *Energy* 127 (May 15, 2017): 730–42, **https://doi.org/10.1016/j.energy.2017.03.015**.

15 MAX, “Pioneering Electric Vehicle Mobility in Africa for a Greener Earth,” 2021, **www.max.africa/electric-vehicles**.

16 Apostolaki-Iosifidou, Codani, and Kempton, “Measurement of Power Loss,” 2017.

17 U.S. Department of Energy, “Find a Car,” 2021, **www.fueleconomy.gov**.

18 Harley-Davidson Motorcycles, “Electric: LiveWire,” 2021, **www.harley-davidson.com/us/en/motorcycles/livewire.html**.

19 David Franklin, “Rental Car Fleets in Line with Solid Demand,” Blueshift Research, February 5, 2014, **https://blueshiftideas.com/reports/021401RentalCarFleetsinLinewithSolidDemand.pdf**.

20 World Bank, “World Bank Open Data,” 2021.

21 Smart Power India, *Rural Electrification in India: Customer Behaviour and Demand*, February 2019, **www.rockefellerfoundation.org/wp-content/uploads/Rural-Electrification-in-India-Customer-Behaviour-and-Demand.pdf.**

22 Sustainable Energy for All, *State of the Global Mini-Grids Market Report 2020*, Sustainable Energy for All, July 2020, **www.seforall.org/system/files/2020-06/MGP-2020-SEforALL.pdf**.

23 Anjali Sharma, Shalu Agrawal, and Johannes Urpelainen, “The Adoption and Use of Solar Mini-Grids in Grid-Electrified Indian Villages,” *Energy for Sustainable Development 55* (April 2020): 139–50, **https://doi.org/10.1016/j.esd.2020.01.005**.

24 NITI Aayog and RMI, *India’s Electric Mobility Transformation: Progress to Date and Future Opportunities*, April 2019, **https://rmi.org/insight/indias-electric-mobility-transformation/**.

25 Madhav Pai et al., *Motorized Two-Wheelers in Indian Cities: A Case Study of the City of Pune*, EMBARQ India; World Resources Institute, March 2014.

26 Hertzke et al., “Global Emergence,” 2020.

27 Providing Safe, Reliable & Affordable Mobility Solutions in the Last Mile Transportation,” 2021. **www.smvgreen.com**.

28 Grassroots Energy Inc., 2021, **www.grassrootsenergy.co**.

29 Parveen Kumar and Subrata Chakrabarty, “Total Cost of Ownership Analysis of the Impact of Vehicle Usage on the Economic Viability of Electric Vehicles in India,” *Transportation Research Record* 2674, no. 11 (November 1, 2020): 563–72, **https://doi.org/10.1177/0361198120947089**.

30 Martin Weiss, Kira Christina Cloos, and Eckard Helmers, “Energy Efficiency Trade-Offs in Small to Large Electric Vehicles,” *Environmental Sciences Europe* 32, no. 1 (March 18, 2020): 46, **https://doi.org/10.1186/s12302-020-00307-8**.

31 Weiss, Cloos, and Helmers, “Energy Efficiency Trade-Offs,” 2020.

32 Hertzke et al., “Global Emergence,” 2020.

33 Scarlett Santana et al., *Agricultural Productive Use Stimulation in Nigeria: Value Chain & Mini-Grid Feasibility Study*, Power Africa Nigeria Power Sector Program, Rocky Mountain Institute and Deloitte Consulting, July 2020, **https://pdf.usaid.gov/pdf_docs/PA00WQX4.pdf**.

34 See **www.wricitiesindia.org/content/tco-evaluator** and Kumar and Chakrabarty, “Total Cost of Ownership Analysis,” 2020.

35 Rural Electrification Agency, “The Nigeria Electrification Project (NEP),” *Rural Electrification Agency* (blog), July 17, 2018, **https://nep.rea.gov.ng/minimum-subsidy-tender-for-solar-hybrid-mini-grid/**.

36 Franklin, “Rental Car Fleets,” 2014.

37 Homer Energy, “HOMER Pro,” 2021, **www.homerenergy.com/products/pro/index.html**.

38 Stefano Mandelli, Marco Merlo, and Emanuela Colombo, “Novel Procedure to Formulate Load Profiles for Off-Grid Rural Areas,” *Energy for Sustainable Development* 31 (April 2016): 130–42, **https://doi.org/10.1016/j.esd.2016.01.005**.

39 Courtney Blodgett et al., “Accuracy of Energy-Use Surveys in Predicting Rural Mini-Grid User Consumption,” *Energy for Sustainable Development* 41 (December 2017): 88–105, **https://doi.org/10.1016/j.esd.2017.08.002**; Elias Hartvigsson and Erik O. Ahlgren, “Comparison of Load Profiles in a Mini-Grid: Assessment of Performance Metrics Using Measured and Interview-Based Data,” *Energy for Sustainable Development* 43 (April 2018): 186–95, **https://doi.org/10.1016/j.esd.2018.01.009**.

40 Andrew Allee et al., “Predicting Initial Electricity Demand in Off-Grid Tanzanian Communities Using Customer Survey Data and Machine Learning Models,” *Energy for Sustainable Development* 62 (June 1, 2021): 56–66, **https://doi.org/10.1016/j.esd.2021.03.008**.

41 Ross McLane et al., *Racing to Accelerate Electric Vehicle Adoption: Decarbonizing Transportation with Ridehailing*, RMI, January 2021, **https://rmi.org/wp-content/uploads/dlm_uploads/2021/01/RMI_Insight_Brief_Accelerating _EV_Transition-1.pdf**.

42 Franklin, “Rental Car Fleets,” 2014.