

Article

Designing PAYGO Business Models for Affordable Electric Mobility: A Techno-Economic Case Study of E-Bicycles in Windhoek, Namibia

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Abstract

Low-income households in cities like Windhoek spend over 20% of their income on public transport. Electric bicycles (e-bikes) offer a cleaner, more affordable alternative, but adoption remains low due to high upfront costs, driven largely by the lithium-ion battery, which can account for around 40% of total bike cost. This study proposes and evaluates a Pay-As-You-Go (PAYGO) business model that separates e-bike and battery ownership, using a portable, IoT-enabled smart battery management system to embed financing, monitoring, and lease enforcement directly into the battery, analogous to PAYGO solar home systems. The Business Model Innovation (4I) framework and Business Model Triangle structure the proposal, and a MATLAB-based techno-economic model compares its 10-year total cost of ownership (TCO) against conventional transport. PAYGO Battery-as-a-Service battery (PAYGO BAAS) reduces per-trip operating costs by 43% relative to taxis, but this excludes battery-access payments, however BAAS carries the second-highest 10-year TCO of all options evaluated. The electric bike lease-to-own model offers the better balance of low upfront cost and long-run affordability, with PAYGO's smart enforcement serving as a risk-reduction mechanism for transitional leasing rather than a substitute for eventual ownership.

Keywords: PAYGO e-mobility, battery management system, e-bike, IoT, sustainable transport

1. Introduction

1.1 Background of Study

According to Gololo et al (2022), a transport affordability benchmark established in 1996 in South Africa considers transport unaffordable when households spend more than 10% of their income on it. Individuals from low- and middle-income backgrounds disproportionately allocate a higher share of their income to transportation costs when accessing essential services such as education and healthcare (Gololo et al., 2022; Etin-Osa, 2023). According to Namibia's Sustainable Urban Transport Master Plan (SUTMP) (2013), nearly 87% of Windhoek's population are low-income earners and struggle to pay for transport, with many spending around 24% of their income just on mobility. This financial strain is rooted in colonial-era urban planning that forced low-income populations to live far from employment hubs. Taxis account for 46.2% of all trips, followed by walking at 26%, while only 1.7% of residents use municipal buses. According to the plan, without intervention, average car commute times are projected to increase from 9 minutes in 2012 to 54 minutes by 2032. The current trends reflect similar challenges seen in larger cities across the world, including reduced accessibility that leads to social isolation and exclusion of the urban poor, increasing traffic congestion, high costs associated with roads and parking infrastructure, unacceptably high traffic accident rates, elevated transport expenses for consumers, growing energy dependence, and rising levels of pollution.



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Affordable electric bikes offer a potential solution to Namibia's traffic congestion and affordability problems in transport. Studies have shown that the cost of commuting via electric bikes is significantly lower than that of public transport. De Vries (2006) stated that for the price of one 30-seater bus, 130-150 e-bikes could be purchased and operated more cheaply. Beyond the economic benefits, e-bikes offer environmental benefits. Given that road cars alone account for over 74.5% of transport-related emissions, the transportation industry remains a major contributor to global greenhouse gas emissions, contributing around 12% of yearly emissions (Dankers, 2024). According to De Vries (2006), electric bikes offer a 95% reduction in CO₂ emissions per 100 km travelled compared to a small motor car, resulting in massive reductions in the impact of greenhouse gases on the environment and the people who live in these congested areas. As the continent's electric mobility landscape evolves, the adoption of e-bikes could play a pivotal role in addressing pressing urban challenges and advancing a greener future in the Global South.

Despite the many advantages of electric bicycles, their widespread adoption in Namibia and across Africa remains limited due to several persistent challenges. Electric bikes can be expensive upfront, particularly due to battery costs. Many potential users worry about their range on a single charge, especially for longer trips. The limited public charging stations make regular use more challenging, and with few electric bikes on the road, there's still a lack of real-world performance data and experience. Together, these factors slow the large-scale deployment of electric bicycles despite their potential benefits (Dukulis et al., 2013; Kulkarni et al., 2024).

1.1 Problem Statement

The rapid advancement of electric mobility solutions has sparked growing interest in cost-effective, sustainable transportation financing models. However, there is currently a lack of research into the implementation of smart PAYGO systems in the electric mobility space and their potential to reduce upfront costs and increase electric vehicle adoption in low- and middle-income communities in Africa. This study tackles a real problem: electric bicycles are too expensive for people in low-income areas to afford upfront. We examine whether a Pay-As-You-Go (PAYGO) battery system for e-bikes could be economically viable by spreading costs over time rather than requiring a large initial payment. To determine whether this model makes financial sense for users, we compare the total net present cost of ownership of a PAYGO financed e-bike with other ways people get around—owning a car, taking taxis, or riding public buses. The goal is to determine whether PAYGO delivers affordable, sustainable transportation. Our results add to what we know about smart mobility solutions and new business models for electric bikes.

1.2 Objective of the Study

The primary objective of this study is to develop the concept of and evaluate the savings potential of the PAYGO e-bike model for the low- and middle-income communities in Namibia. To achieve these objectives, the following research questions:

·How would a PAYGO Battery-as-a-Service (BAAS) operate, add value and generate revenue?

- Is the PAYGO electric mobility model more cost-efficient for the user than traditional lease-to-own schemes, when evaluated using net present cost (NPC) per kilometre?
- Which variables most significantly influence the cost efficiency of a PAYGO-based e-bike system for the user?
- How competitive is the PAYGO electric mobility model compared to conventional urban transport options, including public buses and taxis, particularly for low- to middle-income users?

1.3 Significance of the Study

Researchers have studied PAYGO financing technology in solar home systems, prepaid electricity meters, and LPG systems, but surprisingly little research has examined its use for e-mobility—particularly e-bikes in Namibia. We don't yet have studies examining whether a PAYGO-financed e-bike system would be technically and economically feasible in the Namibian context.

Understanding how PAYGO e-bikes could work in Namibia would help us design transportation solutions that fit the country's specific socio-economic realities and environmental needs. Getting this right could mean better access to sustainable transport, lower carbon emissions, and new economic opportunities for Namibians.

2. Literature Review

Owning an automobile remains out of reach for most individuals in Africa, with a continent-wide motorisation rate of 44 per 1,000, compared to a global average of 180. There is an even more pronounced gap in the SADC region, with more than half of the population walking long distances or relying on unreliable public transport to access vital medical services, education, opportunities, or to deliver services to earn an income (Cloete, 2020). The number of electric vehicles (EVs) registered in a country is a direct measure of the adoption of electric mobility. As of now, the adoption of EVs in Namibia is slow, with only five light vehicle charging stations available in the country as of 2024, despite a target of 10,000 EVs by 2030, while South Africa had 1119 EVs in 2019 (Sovacool et al., 2022). According to Khan et al. (2022), Africa continues to import approximately 1.5 million used vehicles each year, reinforcing its dependence on inefficient, highly polluting transport technologies. Over the past decade, fossil fuel demand in the transport sector increased by nearly 50%, highlighting the growing environmental burden of current mobility patterns. Under existing policy trajectories, vehicle-related well-to-wheel CO₂ emissions are projected to more than double by 2050, reaching nearly 2.3 times their 2020 levels. In contrast, an accelerated shift toward electric and other zero-emission vehicles could reverse this trend, reducing transport-related CO₂ emissions to more than 50% below 2020 levels by mid-century. These projections highlight why shifting to electric mobility is so important—it's essential for cutting emissions, strengthening energy security, and putting Africa's transport sector on a more sustainable path.

E-bikes, or electric bikes, are considered an eco-friendly option for urban mobility. They can particularly benefit low-income communities by reducing transport costs, emissions, and private car use. Nevertheless, high levels of poverty in many African cities limit household purchasing power. This puts a significant damper on poorer urban communities' capacity to adopt new mobility options, such as electric transport, and to maintain them. As a result, in many developing regions, particularly sub-Saharan Africa, e-bikes are financially out of reach of the average consumer. Consequently, it continues to exclude the very populations that would benefit most from its long-term cost savings (Sovacool et al., 2022). PAYGO technology allows consumers to pay for products in instalments, often via a mobile money platform, thereby mitigating the need for a sizeable upfront cash payment (Baker, 2023; Lighting Global et al., 2022).

The unit costs of electric bicycles vary widely throughout the literature, depending on the electric bicycle system design, component selection, and the extent of the methodology. As per Keseev (2020), the total price of a self-assembled electric bicycle has reached N\$20655 (US\$1, 215) in Bulgaria, whereas Etin-Osa (2023) records a significantly lower conversion price of N 2050.71 (US 120.63) in Nigeria. Yan et al. (2018) also offer one of the most extensive market-based studies, surveying suppliers of electric bicycles, with an average response price of N\$7454.67 (US\$438.51). It is quite lower than the landed price of about N\$16150 (US\$950) that Giki et al. (2024) cite on electric bicycles in Tanzania.

The exceptionally low price advertised by Etin-Osa (2023) is an outlier that can be explained by the fact that the battery capacity of the system is low. There was a limited range of 8.3 km using the 36 V, 3.4 Ah battery, which is low in contrast to 30-40 km ranges published by Giki et al. (2024). Cost differentials are also attributed to battery chemistry. Yan et al. (2018) primarily discussed lead-acid battery systems, whereas Keseev (2020) and Giki et al. (2024) investigated lithium-ion batteries. According to Yan et al. (2018), the mean cost of lead-acid batteries was N\$1445 (US\$88), by far less than the landed cost of lithium-ion batteries of N\$4590 (US\$ 270) found by Giki et al. (2024). However, this cost advantage comes with a shorter battery life than lithium-ion batteries. The average battery life of lithium-ion batteries is about three years, or 800 charge cycles, compared to about two years for lead acid batteries (Yan et al, 2018). Rahman et al. (2017) found that lithium-ion battery prices have declined substantially over the past decade, falling by approximately 65% since 2010 to around US\$350 per kWh in recent years. Continued technological progress and economies of scale are expected to drive costs further down, with projections indicating prices below US\$120 per kWh by 2030.

However, battery degradation and lifetime performance influence long-term system costs of the battery to the user. Keseev (2020) reports that a 1 kWh lithium-ion battery achieved a range of 50–70 km with an expected lifetime of 700 charge cycles at 70% depth of discharge (DoD). However, there were major degradation rates in seven years of operation and 350 charge cycles. This deterioration presumably results from the combined effects of cycling and calendar ageing. Vasylyev (2025) establishes that the average state of charge (SOC), depth of discharge, operating temperature, C-rate and total number of cycles are highly important in determining the battery degradation. These considerations are especially applicable in the modelling of the cost of battery deployment in systems where the cost is monetised because of the finite energy throughput over their end-of-life. To maximise the lifetime of the battery, it was proposed that the battery have an average SOC of 50%, cycling between 20% and 80% SOC. The calendar ageing of the battery is maximised, reducing the duration of time it idles at 100% (Vasylyev, 2025).

Van Waes et al. (2018) state that the widespread adoption of sustainable energy and transport technologies requires radically innovative business models. Within this broader challenge, the integration of Pay-As-You-Go (PAYGO) financing models into e-bike systems may be a promising, yet underexplored, solution. PAYGO technologies have demonstrated success in improving affordability and access to energy services—most notably in solar home systems and LPG markets across East Africa (Shupler et al., 2020; Mergulhao et al., 2023).

The business model innovation literature, however, is engaged only lightly here, despite the study's own framing as a business model contribution. Work on resource-constrained innovation in emerging markets shows that business models built around cost, "good-enough," and frugal innovation capabilities are organized differently from those in resource-rich settings, with value creation typically achieved by reducing operational costs and re-engineering existing platforms rather than developing new products (Sharmelly & Ray, 2021). The PAYGO BAAS model is best understood as a cost-innovation business model response to capital constraints, not simply a cheaper product. Separately, the servitization and product-service-systems literature speaks directly to the ownership-versus-access trade-off this study investigates. In the closest available analogue, Zhou et al. (2025) show that Battery-as-a-Service outperforms Battery-as-a-Product specifically when battery cost or degradation rates are high, since the provider can retain and redeploy used batteries and adjust service quality — the same mechanism this study identifies in the PAYGO BAAS configuration. A recent structured review of the wider Battery-as-a-Service literature further finds that existing work remains fragmented across engineering, economic, and policy domains, with adoption driven by battery cost, infrastructure, and regulatory support (Haldar et al., 2026), underscoring the absence of a resource-constrained African case in this literature.

Finally, the PAYGO solar literature — the closest existing analogue to the proposal here — treats PAYG not as a financing mechanic but as a business model innovation, one whose central design challenge is matching repayment schedules to the irregular income patterns of low-income households (Yadav et al., 2019). This is the risk this study's enforcement mechanism is designed to manage, and it is the literature this paper's contribution should be read against.

There is currently limited research on the implementation of PAYGO financing technologies in electric bicycles. Most existing studies assume outright ownership of electric bikes or focus on adoption mechanisms such as purchase subsidies, rebates, or fiscal incentives. In addition, most of the electric bicycle research is concentrated in developed economies or in mature markets such as China, where large-scale adoption has already occurred. There is a clear absence of studies examining PAYGO-enabled electric bicycles as an adoption pathway within Namibian and broader African contexts. The significance of this study lies in its contribution toward addressing this gap by exploring how smart, PAYGO-based technologies can improve access to affordable, sustainable, and inclusive transport solutions in low- and middle-income markets.

3. Methodology

3.1 Business Model Design

In this study, the Business Innovation 4I framework (Figure 1) and Magic Triangle (Figure 2) were applied to develop and propose a PAYGO electric bicycle business model centred on a smart, PAYGO-enabled battery management system (BMS). The 4I Business Model Innovation Framework is a structured approach used to analyse and develop business model innovations. The framework consists of 4 stages: the initiation, ideation, integration, and implementation stages. The framework is supported by the Business Model Magic Triangle, which is a conceptual framework used to describe and evaluate the core logic of a business model through three interdependent dimensions: Value Proposition, Value Chain and Revenue Model.

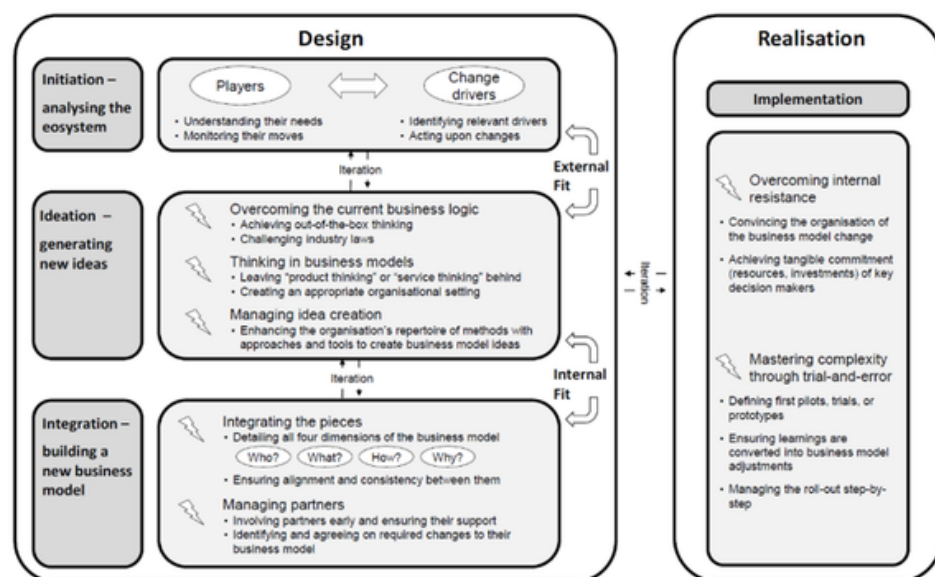


Figure 1: 4I Framework (Fluchter, 2014)



Figure 2: Business Model Magic Triangle (Fluchter, 2014)

3.1.1 Initiation Stage

During the initiation phase of the 4I framework, an understanding of the current players and change drivers of the electric bike market in Namibia was developed. The incumbent business model described in Figure 3 was informed by consultations with two local electric bike providers operating in Windhoek, conducted between October and December 2025 through semi-structured interviews during site visits. Providers were identified via a search for affordable electric bike suppliers in Namibia. Companies returned by this search were subjected to a preliminary screening, retaining only those offering bikes priced below N\$35,000 and providing rental options; this threshold was set with reference to the willingness-to-pay values reported by Giki et al. (2024). Informal semi-structured interviews were then conducted with the managers of the shortlisted companies to identify current product offerings and pricing.

Out of the 14 companies that came out of the search. EBIKES4AFRICA and the PAY (Physical Active Youth) After-School Centres were the only players in Windhoek that were found to offer affordable electric bike offerings to low-to-middle income individuals. EBIKES4AFRICA offers a range of electric bicycles priced between N\$15000 and N\$49000 through direct sales and a short-term rentals model shown in Figure 3, while PAY operates a rental-only model targeting students and young professionals. The EBIKES4AFRICA business model is a very simple sales model; the e-bikes are bought from an international supplier or locally manufactured and then sold directly to the customer or rented out to clients at a monthly rate. Electric bicycles are typically rented out at approximately 10% of their retail value per month, enabling a 10-month payback period for each bicycle. Users receive full access to the battery, along with a battery key and charger, without any remote monitoring or control mechanisms to enforce delinquent payments. Prospective lessors are commonly required to provide proof of income, proof of residence, recent bank statements, a refundable deposit and valid identification. These measures are intended to protect the operator from potential losses associated with misuse or non-payment. However, the cost of recovery remains high because the bikes have no tracking mechanism or means of preventing continued use of the bike in the case of default.

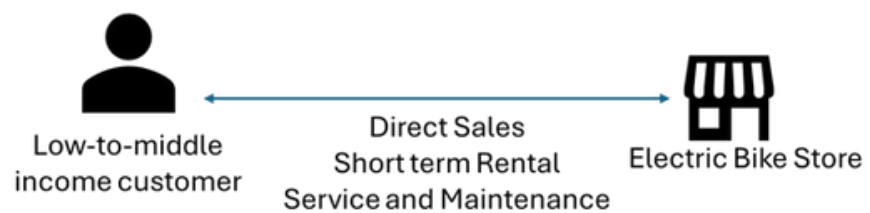


Figure 3: Current Electric Bike Business Model in Namibia

3.1.2 Ideation Stage

Some existing pay-as-you-go (PAYGO) systems were examined, which are currently deployed in Namibia. These included prepaid electricity meters, mobile airtime voucher systems, and PAYGO solar home systems. The identified systems incorporate mechanisms that address affordability challenges through consumption-based payment structures. Similar to PAYGO solar systems, users pay only for the energy they consume or make incremental payments toward system ownership through a lease-to-own arrangement. These approaches have been shown to increase the adoption of sustainable energy technologies by reducing upfront costs and aligning payments with users' cash flow. Likewise, prepaid electricity systems allow consumers to pay as they consume, eliminating large end-of-month bills while reducing the need for active monitoring and debt collection by utilities.

Our study explored how smart, IoT-enabled PAYGO Battery Management System (BMS) could be used to embed financing, battery monitoring, and lease enforcement directly into the battery in a similar manner to prepaid electricity meters and some solar PAYGO systems in homes.

3.1.3 Integration

During the integration stage, a PAYGO ecosystem diagram was developed to illustrate the interactions among system actors and the operational flow of the proposed solution. The Business Model Triangle, presented in Figure 2, was then constructed to define the model's value proposition, value creation and delivery architecture, and revenue mechanisms.

3.2 Techno-Economic Analysis

3.2.1 Total Cost of Ownership for PAYGO BAAS and PAYGO Lease

EBIKES4AFRICA's African BushBike and battery pricing as a benchmark. Table 1 presents the key technical and economic parameters of the African BushBike used in this study. To calculate the Net Present Cost (NPC) for this scenario, a 10% deposit was applied to the total bike cost, with the remaining balance amortised over one year to ensure full capital recovery by the end of the lease period. These cash flows were modelled in MATLAB using the `pvfix` and `pvar` functions to convert annualised figures into present values. The mathematical logic shows equations. (1) through (7).

$$C_{deposit-s1} = r_{deposit} \cdot C_{B+b} \quad (1)$$

$$C_{annual-lease-s1} = \frac{C_{B+b} - C_{deposit-s1}}{t_{lease}} \quad (2)$$

$$C_{maint-s1} = 0.1 \cdot C_B \quad (3)$$

$$C_{charging-s1} = E_{why} * C_{elec} \quad (4)$$

$$C_t = C_{annual-lease-s1} + C_{maint-s1} + C_{charging-s1} + C_{replacement} \quad (5)$$

$$NPC_{S1} = C_{deposit-s1} + \sum_{t=0}^T \frac{C_t}{(1+r)^t} \quad (6)$$

$$TCO_{per-km} = \frac{NPC_{S1}}{D_t} \quad (7)$$

Table 1: African BushBike Parameters

Parameter	Value
Price of African BushBike (20-inch tyre, No Battery)	N\$ 19000(US\$ 1118)
Motor Power	500W
Motor Torque	180 Nm
Battery (20Ah 48V; 960Wh; 13S8P) – 800 Charge Cycles)	N\$10000(US\$ 589)
Lease Period	1 Year
Interest Rate (Prime Rate Namibia) (BON, 2025)	10%
Deposit rate	10% of CAPEX
Annual Maintenance Cost	10% of Frame CAPEX
Electricity Cost in Namibia	N\$ 2.6/kWh

The model incorporates several key variables: $C_{deposit}$ represents the deposit cost on the bike frame and battery, $r_{deposit}$ is the deposit rate, C_{B+b} is the total cost of the bike, including the PAYGO battery, and t_{lease} is the lease period offered by the company to recoup the initial investment. The total annual energy required for the battery to complete all trips is denoted by E_{why} , while C_{elec} represents the unit electricity cost from the grid. $C_{replacement}$ It is calculated as the cost of a new battery after the remaining capacity in the battery is unable to cover the energy demand of the round-trip commute.

The Net Present Cost (NPC) of the scenario is represented by NPC_{S1} , and is the total distance travelled throughout the study period. D_t is calculated by multiplying the distance per round trip by the number of trips in a year and the study period. This study assumes a 10-year project lifetime (T). According to Yan (2018), this is the expected duration before a user in China typically scraps the bike. Consequently, we assume there is no salvage or scrap value at the end of these 10 years. This horizon is adopted in the absence of comparable scrappage data for Namibia or the wider SADC region, and e-bike replacement behaviour there may differ from urban Chinese markets given differences in climate, road conditions, and second-hand market structures. The 10-year figure should therefore be treated as an illustrative rather than a locally validated assumption. TCO_{per-km} is the total cost of ownership over 10 years.

The second configuration conceptualised PAYGO as a battery-as-a-service model, analogous to prepaid electricity systems. Under this approach, ownership of the battery is retained by the provider, while the bicycle frame is leased to the user under a conventional lease-to-own agreement, which can still be enforced through the PAYGO BMS. Battery access is subscription-based, with users paying a subscription fee to access the network of batteries but continuously paying for charging credits for home charging capabilities. The charging credits are equivalent to the electricity units bought for prepaid electricity meters, but in this case, the energy entering the battery is measured and gradually deducted from the units that were purchased. Once the charging units available on the battery are exhausted, the battery shuts off charging until sufficient units are uploaded on the battery. By embedding the monetisation strategy within the hardware-software link between the battery and the mobile application, the system can support both home charging and a battery-swapping network from eqn. (8) to eqn. (14), the model for this scenario is outlined, considering only home charging.

$$C_{deposit-S2} = r_{deposit} \cdot C_B \quad (8)$$

$$C_{annual-lease-S2} = \frac{C_B - C_{deposit-S2}}{t_{lease}} \quad (9)$$

$$C_{maint-S2} = 0.1 \cdot C_B \quad (10)$$

$$C_{charging-S2} = E_{why} \cdot C_{elec} + C_{wh} \cdot E_{why} \quad (11)$$

$$C_t = C_{annual-lease-S2} + C_{maint-S2} + C_{charging-S2} \quad (12)$$

$$NPC_{S2} = C_{deposit-S2} + \sum_{t=0}^T \frac{C_t}{(1+r)^t} \quad (13)$$

$$TCO_{per-km} = \frac{NPC_{S2}}{D_t} \quad (14)$$

The model uses several variables: $C_{deposit}$ represents the deposit cost on the bike frame, excluding the battery, $r_{deposit}$ is the deposit rate of the company, C_b is the total cost of the bike excluding the PAYGO battery, t_{lease} and is the lease period offered by the company to recoup the initial investment. The total annual energy required for the battery to complete all trips is denoted by E_{why} , while E_{elec} represents the unit electricity cost from the grid. C_{wh} is the degradation cost per kWh of charging units under the PAYGO model. In the BAAS model, there is no replacement cost for the user. The Net Present Cost (NPC) of the scenario is represented by NPC_{S2} , and D_t is the total distance travelled throughout the study period. D_t is calculated by multiplying the distance per round trip by the number of trips in a year and then multiplying by the total number of years in the study period. This study assumes a 10-year project lifetime. We assume there is no salvage or scrap value at the end of these 10 years. TCO_{per-km} is the total cost of ownership over 10 years.

3.2.2 Total Cost of Ownership for Alternative Mobility Options

All the abovementioned models were benchmarked against alternative mobility options, including outright electric bicycle purchase, taxi usage, bus transport, and private car ownership. To find the total cost of ownership of these models, the following data inputs were used for these net present cost calculations. These parameters have been summarised in the following table.

Table 2: Cost Parameters for ICE Transport Mode Option

Car/Motorcycle Cost (Second hand)	N\$ 30000 (US\$1764)
Petrol Cost	N\$20/l(US\$ 1.17)
Petrol Consumption Rate	0.08 l/km (De Vries, 2006)
Taxi Fare (Round Trip)	N\$ 26 (US\$1.53);
Bus Fare (Round Trip)	N\$ 17 (US\$ 1)

For the ICE car scenario, the capital cost of the car was assumed to be a second-hand car obtained from car dealerships in Namibia, and half of the values of the cheapest cars were used for this scenario. The taxi and bus fares were found from recent reports in the Namibian about the topics. The net present cost was calculated using the eqn. (15) – (28).

$$C_{\text{maint-car}} = 0.1 \cdot C_{\text{car}} \quad (15)$$

$$C_{\text{petrol-y}} = N_{\text{trips}} \cdot C_{\text{petrol}} \cdot r_{\text{petrol}} \cdot d_{\text{trip}} \quad (16)$$

$$C_t = C_{\text{maint-car}} + C_{\text{petrol-y}} \quad (17)$$

$$NPC_{\text{car}} = C_{\text{car}} + \sum_{t=0}^T \frac{C_t}{(1+r)^t} \quad (18)$$

$$TCO_{\text{per-km}} = \frac{NPC_{\text{car}}}{D_t} \quad (19)$$

Where $C_{\text{maint-car}}$ is the annual maintenance cost. The 10% annual maintenance assumption is applied uniformly across e-bikes and cars for comparability across options, given the absence of Namibia-specific maintenance cost data disaggregated by vehicle type. In practice, e-bikes typically incur lower maintenance costs than cars due to fewer moving parts and lower running speeds, so this assumption is likely conservative for the e-bike scenarios and should be revisited as local maintenance cost data becomes available. $C_{\text{petrol-y}}$ is the annual cost of petrol N_{trips} with being the number of round-trips in a year, C_{petrol} is the per-litre cost of petrol, r_{petrol} is the petrol consumption rate of the vehicle and d_{trip} is the distance covered per round trip.

The annual cost for the model was modelled in MATLAB using eqn. (20) to (2). is the number of round-trips in a year. and are the unit costs of the round-trip using a taxi and a bus, respectively

$$C_{Taxi} = N_{trips} \cdot C_{taxi} \quad 10 \text{ year}(20)$$

$$C_{Bus} = N_{trips} \cdot C_{Bus} \quad (21)$$

Finally, a single-parameter sensitivity analysis was conducted on both PAYGO configurations to identify the variables exerting the greatest influence on economic outcomes. The analysis evaluated seven key parameters: bike and battery capital expenditure (CAPEX), single round-trip distance, annual trip frequency, battery cycle life (energy throughput), annual maintenance costs, and motor power rating. Each parameter was adjusted by $\pm 20\%$ from the base case. The results were visualised using a tornado diagram to identify the sensitivity of the TCO to different commute parameters. The $\pm 20\%$ range applied here approximates plausible variation in technical and cost parameters, but understates the range some behavioural and policy-driven variables could realistically take: trip frequency may fall well below or rise well above this band with changes in employment or route conditions, and electricity tariffs in Namibia are subject to policy revision that could exceed $\pm 20\%$ within the study horizon. The single-parameter approach also does not capture compounding effects where several variables shift simultaneously. A scenario-based or ranged sensitivity analysis would better characterise these risks and is identified as a direction for future work.

3.2.3 Battery Degradation Model

To best evaluate pay-as-you-go (PAYGO) ownership costs, battery degradation and worst-case use case were modelled to identify the highest cost per kWh through use patterns that worst-effectively impact battery life. This is done to find the highest cost of battery degradation due to customer usage, given the Namibian context.

The cycling degradation model developed by Sayfutdinov et al. (2020) was selected for this study. Given that, Sayfutdinov et al. (2020) is about grid-scale battery siting/sizing, not e-bike degradation specifically, we adapted their cycling degradation formulation and recalibrated its constants against the manufacturer's rated 800-cycle lifetime for electric bike batteries.

$$SOC_{avg} = \frac{\sum SOC \Delta t}{\Delta t} \quad (22)$$

$$\Delta C_{idling} = 1.977 \cdot 10^{-11} \cdot e^{0.07511 \cdot T} \cdot 1.639 \cdot e^{0.007388 \cdot SOC_{avg}} \cdot t^{0.8} \quad (23)$$

Where ΔC_{idling} is the capacity fade due to idling calendar ageing, T is the temperature in Kelvin, SOC_{avg} is the storage state of charge, and t is time in months.

$$\Delta C_{fade} = (a_{DOD} \cdot DOD^2 + b_{DOD} \cdot DoD) \cdot \eta_{cycles}$$

Where ΔC_{fade} is the capacity fade due to cycle ageing, and DoD is the depth of discharge of each cycle. $a_{DOD} = 4.83 \cdot 10^{-3}$, $b_{DOD} = 2.83 \cdot 10^{-5}$ η_{cycle} is the number of cycles.

$$C_0 = C_0(1 - \Delta C_{idling}) \quad (26)$$

Where C_0 is the initial capacity, $E_{nominal}$ is the rated nominal capacity of the battery.

$$EOL = 0.8 \cdot C_0 \quad (27)$$

Where EoL is the battery capacity at the end of life of the battery, determined as 80% of the typical battery capacity. The MATLAB model simulates each battery cycle, reducing it by the capacity cycle fade, repeating this until EoL. The total energy throughput is determined at the end of the model.

$$C_i = C_{i-1}(1 - \Delta C_{fade}) \quad (28)$$

$$E_{EOL} = \sum_{i=1}^{N_{EOL}} E_i = \sum_{i=1}^{N_{EOL}} DOD * C_{i-1} \quad (29)$$

$$C_{Wh} = \frac{C_B}{E_{EOL}} \quad (30)$$

Where C_{Wh} is the battery degradation cost. C_B is the capital expenditure cost of the PAYGO battery, including the profit margin and PAYGO module. E_{EOL} is the total energy throughput at the end of life of the battery. The cycling degradation models were applied to estimate the cost per kilowatt-hour over the battery's operational lifetime. After determining the cost per kilowatt-hour under the PAYGO model and the energy consumption for the base-case trip scenario, the models were simulated in MATLAB and the results compiled into a tabular format for analysis.

3.2.4 Energy Consumption Model

The motion of the electric bicycle is modelled as a one-dimensional longitudinal system subjected to resistive forces and a power-limited drive force. Given the goal of the study, the commute from Omungwindi, Katutura (low-income location), to the main city centre of Windhoek was used as the trip route for the model. The relief between the two points was used to determine slope steepness for the model (). There are at least 20 total necessary stops, and these were used to implement acceleration stop and start cycles in the model. This trip was modelled to find the energy consumption per trip and per km.

According to Eq. (31), the total resistive force acting on the bicycle is given by the sum of rolling resistance, gravitational force due to road gradient, and aerodynamic drag. The driving force is constrained by both the maximum allowable force. Applying Newton's second law, the longitudinal acceleration is expressed in Eq. (33). The velocity () and position () are updated using a forward Euler discretisation with time step Δt . The cumulative electrical energy consumption in watt-hours is computed using Eq. (38). The battery power demand () accounts for motor-controller efficiency . The cumulative electrical energy consumption in watt-hours is computed as from the beginning of the trip till the end of the round trip, where d = the total distance of the round trip.

Table 3: Base Case User Scenario

User Base Case Scenario	Value
Mass (Bike + Rider) (m)	115kg (75 kg + 40kg)
Road angle slope ()	0.082
Rolling Resistance Coefficient ()	0.018
Aerodynamic drag Coefficient ()	0.72
Round Trip Distance (d)	24 km
Number of Stops in Round Trip	20
Radius of Wheel	0.508 m
Efficiency	75%
Trips per year	190

$$F_{resist} = C_{roll}mg + \frac{1}{2}\rho C_d A v^2 + mgsin\theta \quad (31)$$

$$F_{drive} = \min\left(\frac{P_{motor}}{v}, F_{max}\right) \text{ where } F_{max} = \frac{T_{max}}{R} \quad (32)$$

$$a = \frac{F_{drive} - F_{resist}}{m} \quad (33)$$

$$v_{k+1} = \max(v_k + a_k t, 0) \quad (34)$$

$$x_{k+1} = x_k + v_{k+1} \Delta t \quad (35)$$

$$t_{k+1} = t_k + \Delta t \quad (36)$$

$$P_{batt} = \frac{P_{motor}}{\eta_{motor-controller}} \quad (37)$$

$$E_{Wh} = \sum_{x=0}^{x=d} \frac{P_{batt}}{3600} \quad (38)$$

4. Results and Discussion

4.1 PAYGO Model Ecosystem

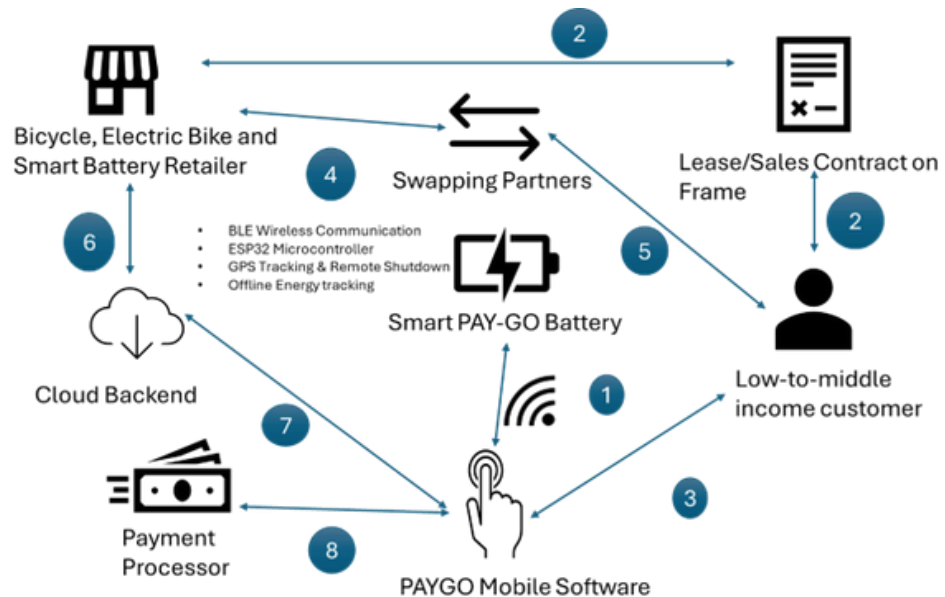


Figure 4: PAYGO Model Ecosystem

At the heart of the PAYGO ecosystem (Figure 4) is an embedded smart PAYGO battery management system (BMS) integrated with the battery pack's existing BMS. In (1), a dedicated mobile application connects to the smart BMS via Bluetooth Low Energy (BLE), enabling users to interact with the battery, validate tokens in the PAYGO application, and upload purchased energy credits to the battery. Once a token is paid for and obtained from the service provider on the application, the PAYGO application validates it using AES asymmetric encryption to decode and authenticate it and permanently invalidates the token to prevent replay attacks. Validated tokens are stored locally in the phone's onboard memory, and the burn list of used tokens is synchronised with an online server. The battery is physically secured to the bicycle frame to prevent tampering and unauthorised removal. Also, only the service provider can perform swaps or battery maintenance.

Users can choose between 3 PAYGO contract models shown in (2): Firstly, leasing the entire bicycle, including the battery, under a contract enforced by the BMS, which would be a time-based contract tied to recurrent lease payments, where ownership is transferred at the end of the contract. Secondly, leasing only the bicycle frame while paying a monthly subscription fee for access to a battery pool and home charger after which prepaid charging credits are bought to allow them to charge their batteries after discharging them. Finally, they can enter into a short-term rental contract of less than a month, where every month the BMS shuts off to remind the user of payment, however ownership is never transferred. In (2), users can swap depleted batteries at designated exchange points or charge at home if they have sufficient prepaid watt-hours uploaded to the battery. As the battery charges, energy entering the battery is tracked and decremented in real time. Once the prepaid energy allocation is exhausted, charging ceases automatically, and users must purchase additional watt-hours to continue charging the battery.

In (6) and (7), the entire PAYGO ecosystem is controlled by a back-end cloud-based server that stores customer data, account status, battery information, and contract data. Once a user logs in and is authenticated, the backend assigns the user a type (admin or basic user).

In (8), payments may be made via mobile money or in a physical store. When the payment is confirmed, the battery service provider creates an encrypted token payload containing the individual account ID and the purchased charge watt-hours. The timestamp is appended to this to generate unique tokens each time.

In (4) and (5), the PAYGO Battery provider can take advantage of the small and portable nature of e-Bike batteries. Any business willing to provide space and has the capacity could earn extra income by offering swapping services on its premises. The battery provider may either provide a modular swapping cabinet with an accompanying DC-DC charger and solar panels, or a number of basic AC chargers to charge the batteries directly from the grid. The swapping partner then earns an income from offering swapping services on their premises. With basic battery storage education, any business on major routes with high demand could be used to expand the battery swapping network. It incentivises other players to expand the network's reach for the battery provider, without large infrastructure investments or the need to secure land for their own battery-swapping infrastructure.

Figure 5 outlines the corresponding business model triangle for the PAYGO Battery-as-a-Service Model.



Figure 5: PAYGO Business Model Triangle

4.2 Total Cost of Ownership

Under the base case scenario, the commute time for one leg of the round trip (12 km) is 22 minutes at an average speed of 31.75 km/h. This has the same commute time as using a taxi in rush hour traffic. The depth of discharge of the entire round trip on the battery is 51%, consuming only 483.13 Wh. The specific energy consumption rate was 20.26 Wh/km.

After evaluating the model under the base-case scenario shown in Figure 6. The highest total cost per km under the base-case scenario was found to be car ownership at N\$ 1.75 per km, while the lowest total cost per km was the bus at N\$ 0.432 per km. This means that public transport remains the most cost-efficient way to move around in Namibia. However, the existing public transport system in Namibia is critically deficient, operating on a restricted weekday schedule with no weekend service and failing to meet peak-hour demand due to an ageing, unreliable fleet. Furthermore, the lack of integrated route interconnections within the city severely limits connectivity and overall commuter accessibility (SUTMP, 2013).

Analysis of the 10-year Total Cost of Ownership (TCO) per kilometre reveals that PAYGO leasing, outright purchase of an electric bike, and regular taxi use are closely comparable in long-term cost. While current short-term bike rental models, like the subsidised BushBike, are more expensive than taxi services over time. Based on a worst-case scenario—involving 100% Depth of Discharge (DoD) per cycle, a 6-month idle period at 100% State of Charge (SOC) and 32°C, and battery degradation to 80% of original capacity—the estimated levelized cost of energy for the Battery-as-a-Service model is N\$ 30.31 per kWh. However, real-world usage patterns would likely improve this cost efficiency. In practice, riders may pedal assist, adjust power levels, and experience shallower discharge cycles, all of which can increase total energy throughput before the battery reaches its end-of-life (EoL) threshold. This surplus in energy throughput over the rated worst-case-scenario energy throughput before the battery’s end of life leads to a surplus in revenue to the BAAS service provider.

Moreover, even after the battery degrades to below 80% of its beginning-of-life capacity, it typically retains sufficient energy—approximately double the daily commuting requirement of the base case scenario—to meet user needs. This effectively extends the battery's usable service life beyond its technical EoL, allowing users to continue benefiting from cost savings long after the provider has fully recouped the initial capital investment in the bike and battery system.

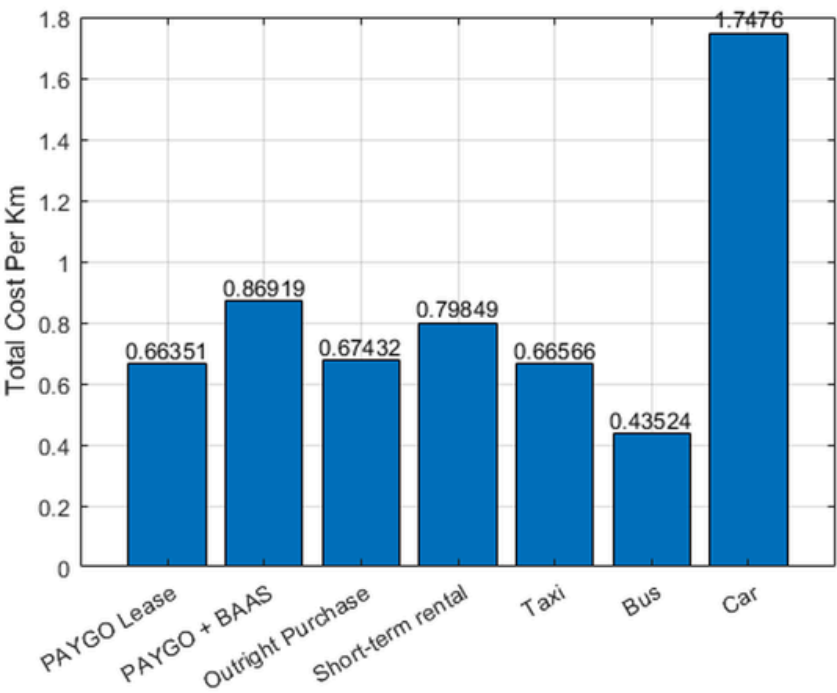


Figure 6: Graph of TCO of All Cases under Base Case Scenario Use Case

As illustrated in Figure 7, the dominant driver in reducing a user’s cost per kilometre in a PAYGO Battery-as-a-Service is the reduction in the capital expenditure of the bike frame and battery. Specifically, a 20% reduction in bicycle capital expenditure results in an approximate reduction of N\$0.09 per kilometre in user costs for PAYGO BAAS, while a 20% increase in your round-trip length leads to a N\$0.12 increase in cost per kilometre for PAYGO BAAS. However, compared to the lease model, the PAYGO BAAS configuration results in a difference of N\$8948 in the first year’s total cost, corresponding to a 28% reduction in the first year’s costs when commuting under the base case scenario. However, since ownership is never transferred, it is like paying for fuel at the pump. The recurring payment for energy eventually erodes the initial savings. In addition, under the PAYGO BAAS model, the cost per trip of the model is N\$14.73 per round trip (24 km), which is 43% lower than the cost per trip compared to taxis (N\$26) and only 13.4% (N\$2.27) lower compared to public buses. Electric bikes in any model, PAYGO BAAS, or lease have a lower long-term cost per kilometre when compared to owning a second-hand car/ICE motorcycle, with a 50% and 62% lower cost per kilometre, respectively.

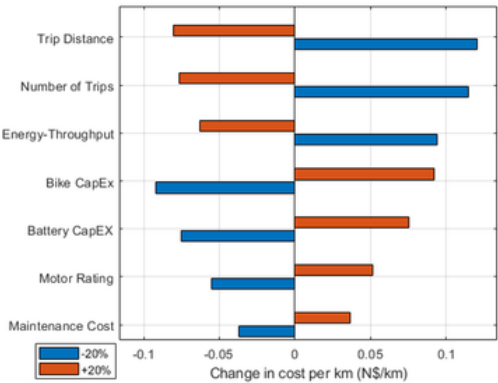


Figure 7: TCO Sensitivity Analysis of the PAYGO BAAS Relative to Base Case Scenario

Figure 9 shows that when benchmarked against the current bus and taxi costs, the lease model achieves total net present cost per kilometre parity with buses for this specific commuting case when the bicycle frame capital cost is N\$9500, excluding the battery component. It achieves net present cost per kilometre parity with taxis at a bicycle frame capital cost of N\$19000, excluding the battery component. On the other hand, the pure PAYGO BAAS model where the user is charged based on consumption, achieves total net present cost per kilometre parity with taxis for this specific commuting case when the bicycle frame capital cost is N\$10 700, excluding the battery component.

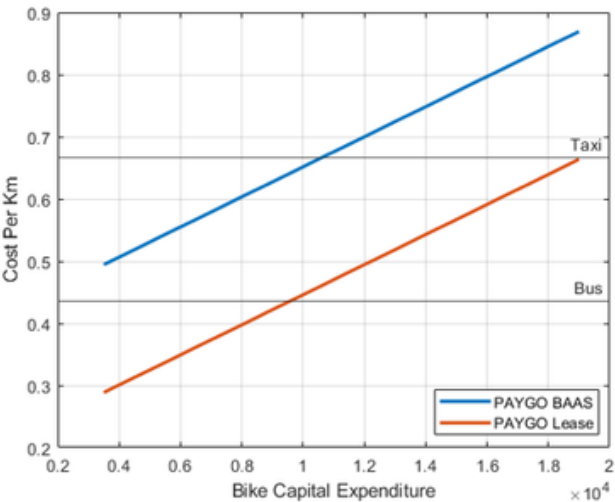


Figure 9: Change in Cost Per Km Against Bike Frame Cost (BAAS v.s Lease)

Importantly, the cost per kilometre by users grows inversely to revenue captured by the service provider; under this framing, the PAYGO model demonstrates significantly higher long-term revenue potential than standard leasing arrangements for the service provider, while simultaneously enabling higher market adoption due to an upfront cost that is approximately 30% lower for the user.

Read against this literature, the Namibian case adds a specific mechanism rather than a new general claim. Where the PAYGO solar literature manages income volatility through remote service-blocking on a discrete household appliance (Yadav et al., 2019), and the BaaS literature manages cost and degradation risk through provider ownership of a stationary or vehicle-mounted battery asset (Zhou et al., 2025), this study's contribution is to show what changes when payment enforcement is embedded directly in a small, portable, and individually mobile hardware unit — the e-bike battery — in a setting where formal credit infrastructure is weak and mobile-money-based collection is already established practice. This portability is what allows the same enforcement logic used in PAYGO solar to be repurposed for a transport asset without requiring a parallel loan product or a fixed point of service delivery. The resource-constrained business model literature's emphasis on reducing operational costs through the value-creation activities of the business model itself, rather than through new product development (Sharmelly & Ray, 2021), is consistent with what this study finds: the PAYGO BAAS configuration is not cost-competitive on a pure per-kilometre basis, but its value lies in the business model activity of enforced, incremental cost recovery, which is precisely the mechanism the fragmented BaaS literature has yet to examine in a resource-constrained, non-vehicular context (Haldar et al., 2026).

5. Conclusions

This paper shows that a PAYGO electric mobility model is most effective when used as an enforcement mechanism for transitional leasing rather than a permanent battery-as-a-service solution. While a pure PAYGO approach leads to higher long-run user costs per kilometre, it significantly lowers upfront barriers to access and provides strong revenue, enforcement, and risk-reduction benefits for service providers.

The results indicate that cost competitiveness depends primarily on bicycle capital cost and battery utilisation. A hybrid model—where PAYGO enables cost recovery and payment enforcement before eventual ownership transfer—offers the best balance between user affordability and commercial sustainability. Practically, PAYGO smart BMS systems are therefore best deployed as enabling infrastructure for scalable and inclusive electric mobility, rather than as a long-term substitute that prevents battery ownership.

6. Ethics

This study did not involve identifiable personal data or vulnerable participants. Consultations with electric bike providers were conducted with written informed consent, and ethical clearance was obtained from the Namibia University of Science and Technology.

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