Leveraging electric transport for rural energy access

A techno-economic study for integrated transport and community energy access in Kenyan Wildlife Conservancies

Thesis to obtain the M.Sc. in Energy Engineering by the Polytechnic University of Catalonia and M.Sc. in Energy by the Catholic University of Leuven through a double-degree framework of the EIT Innoenergy M.Sc. in Energy for Smart Cities

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The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand.

It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known.

-- Carl Sagan, Pale Blue Dot, 1994

Abstract

This thesis argues transportation systems and access to energy as key solutions to rural poverty alleviation and human development. The low population densities and weak buying power of remote communities in Sub-Saharan Africa prompts for unconventional means of transport, namely the motorcycle taxi. The demand for rural motorcycle taxi services has generated a new industry in remote communities that employs young adults and improves transport efficiency. However, operators are subject to premiums on the price of fuel, due to the logistical costs on transporting the fuel to remote locations. Novel electric transportation technologies offer a solution that is detached from the price of fuel and a comparable quality of service. Additionally, stimulating the electric demand in off-grid communities improves the conditions for mini-grid development. This thesis sought to examine the technical and economic thresholds of introducing an electric vehicle fleet to a potential mini-grid site in the Olkirimatian conservancy of Kenya. The study compared results with status quo motorcycle taxi operations and business as usual mini-grid development. The results demonstrated that introducing the electric vehicles in rural communities lowered the cost of electricity, but increased the costs of the mini-grid. Additionally, the proposed electric vehicle had a capital expense that yielded unfavourable financial performance for motorcycle taxi operations. However, decreasing the price of the electric vehicle to 1,820 -2,120 USD achieved NPV parity with the status quo. Additionally, fueling costs were found to be 78.8% lower for electric motorcycles, compared to their internal combustion-based counterpart. Ultimately, the capital expenditure of the electric vehicle will determine whether it is possible to decrease the cost of rural transport, while providing enough income for the operator. Fortunately, there is reason to believe that electric motorcycle cost reductions are possible, as manufacturers improve their operations to cater for the growing global appetite for electric vehicles.

Preface

This work is based on a Green Mini Grid Facility that provided Technical Assistance to African Solar Designs (ASD) for a proposal on “Leveraging Energy Access in Maasai Mara Off-Grid Tourism Sites and Communities”. The Green Mini Grid Facility Kenya (GMG Facility) is a DFID funded programme that provides grants and technical assistance for promoting private sector mini grid developments in Kenya. The original proposal is the product of ASD’s collaboration with local leaders and stakeholders in the Naboisho, Olare Orok, Olderkesi, Olkirimatian, and Shompole conservancies.

Acknowledgements

I would like to thank God Almighty for affording me with the health, intellect, and fortitude that led me to this far in life and put me on track towards this rewarding educational experience. Special thanks to the EIT Innoenergy programme for their funding support and facilitating such a remarkable Masters School. I'd like to convey a sincere gratitude to Mark Hankins and Isaiah Gitau of African Solar Designs (ASD) Ltd. for granting me the opportunity to come to Africa and work on valuable development projects, a role I've dreamt of working in ever since I was a child. To my M.Sc. supervisor, Prof. Oriol Gomis Bellmunt, thank you for your support and the knowledge you've shared with me on energy technologies that prepared me for this role. Further thanks to all the teachers and professors that have enriched my intellectual and personal growth. My reverent gratitude to *Pani* Szulc, your resolute attitude towards my education made an invaluable impact on my life, I wish you could still be here to witness my academic journey, God bless you and rest in peace.

The body of work that constitutes this thesis has benefited from the insights and experiences that I have had with individuals during my tenure at African Solar Designs and the Innoenergy programme. My most sincere thanks to the communities of the Naboisho, Olare Orok, Olderkesi, Olkirimatian, and Shompole conservancies for welcoming me to your communities during the site assessment phase. Thank you to Benard of ASD, the knowledge you've shared with me on mini-grid design and power systems has been pivotal in making me a well-rounded engineer. To Samy, thank you for taking my mind off the thesis from time-to-time and helping me understand basic financial principles. To Amrita, thank you for your positive messages that kept me going and for your support with proof-reading my final draft. Further thanks to my close friends Thomas, Carlos, Beatriz, Nuria, David, and the ASD team for supporting me throughout this Masters program either through laughs or lending a sympathetic ear.

Finally, on a personal note, I wish to thank my parents who have invested so much of their time, effort, and faith in me. I am truly blessed to have the life I have, and I owe it all to you.

Dedicated to my parents,

Mirosława and Jacek Zasępa

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List of Acronyms

AC – Alternating Current
ASD – African Solar Designs
BEV – Battery Electric Vehicle
BLAC – Brushless Alternating Current
BLDC – Brushless Direct Current
BOP – Base of the Pyramid
COE – Cost of Electricity
DC – Direct Current
DCF – Discounted Cash Flow
DFID – UK Department for International Development
EIT – European Institute of Innovation and Technology
EU – European Union
EV – Electric Vehicle
FCEV – Fuel Cell Electric Vehicle
GHI – Global Horizontal Irradiance
HEV – Hybrid Electric Vehicle
HGV – Heavy Goods Vehicle
HH - Household
IC – Internal Combustion
ICT – Information and Communications Technology
IRR – Internal Rate of Return
IFRTD – International Forum for Rural Transport and Development
IMT – Intermediate Means of Transport
KES – Kenyan Shilling
KSH – Kenyan Shilling
LCOE – Levelized Cost of Electricity
LGV – Light Goods Vehicle
NPV – Net Present Value
O&M – Operation and Maintenance
PV – Photovoltaic
RECP – Renewable Energy Cooperation Programme
SDG – Sustainable Development Goal
SORALO – South Rift Association of Land Owners
SSA – Sub-Saharan Africa
USAID – United States Agency for International Development
USD – United States Dollar
UNDP – United Nations Development Programme

1. Introduction

1.1. Motivation

Transportation and energy access are key elements necessary for sustainable human development and are crucial for rural communities in Sub-Saharan Africa (SSA) to emerge from poverty. Compared to urban areas, rural communities pay more for transportation and energy services because of expensive logistical costs and inefficient technologies. Energy access through mini-grid development is a proven and effective means of serving communities, however developers face many challenges regarding financial sustainability. The low ability to pay and low electric demand of rural dwellers typically restricts revenue from household consumers to below cost-recovery levels. Therefore, developers seek opportunities for productive uses of electricity that could improve the financial performance of the project. However, not every community has the capacity to support industries that would require productive use appliances. This work sought to integrate novel transportation technologies with mini-grids to improve the commercial viability of the project and provide a solution to local transportation problems. Transportation is a universal need for all populations that is often overlooked in rural development efforts and new technologies, such as electric vehicles, have rarely been applied to off-grid settings in SSA. Therefore, this thesis investigated the impact of electric transport as a productive use of energy for a potential mini-grid site in the Olkirimatian conservancy in Kenya. The work was done under the scope of larger project seeking to provide energy access for several off-grid communities in wildlife conservancies around the Maasai Mara and Lake Magadi regions of Kenya.

1.1.2. Conservancies in Kenya

Under the Kenyan Wildlife Act of 2013, conservancies are a legally recognized land use and are defined as:

> *"An area of land set aside by an individual land-owner, body corporate, group of owners or a community for the purposes of wildlife conservation [1]"*

This recognition is attractive for land owners and communities as it offers improved land, resource rights and access to government incentives [2]. Although conservancy land is dedicated for wildlife conservation, other compatible land uses that include human settlement, grazing, and tourism are accepted. These conditions offer a valuable way to address critical issues (poverty, wildlife loss, resource conflicts, environmental degradation, and weak local governance), through a common approach and framework. While wildlife protection is the core objective of a conservancy, it has played an integral role in livelihood development, peace and security, good governance, pastoral management, and providing community social services, such as health and education. Three types of conservancies exist based on land-ownership and land-use arrangements. These are private, community, and group conservancies. Collectively, they account for 6.36 million Ha of land in Kenya and represent the voices of roughly 707,460 households.

The conservancy considered in this thesis was formed from the Olkirimatian group ranch. The group ranch is on the western border of Kajiado county in Kenya as shown in Figure 1 and belongs to the South Rift Association of Land Owners (SORALO). The region is mostly inhabited by the roughly 20,000 indigenous Maasai pastoralists and their livestock [3]. The area is subject to hot semi-arid and dusty conditions. The sensitive ecosystem in the conservancy supports the migratory behaviour of large herbivores, 21 species of carnivores (including the lion), 420 species of birds, and a growing population of elephants.

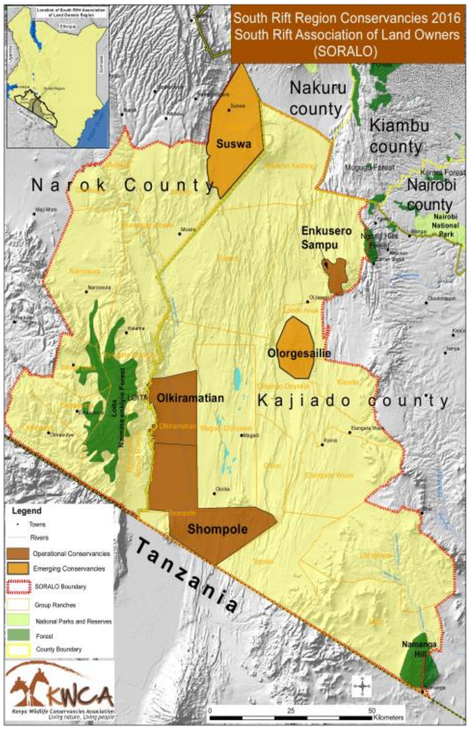


Figure 1: Map of Olkirimatian conservancy [4]

The group ranch is a unique land rights agreement in Kenya from the "Land Adjunction Act of June 1968" [5]. A group ranch is owned jointly by all members in equal and undivided shares. Under the Land Act, each group ranch must elect a group of representatives to safeguard and act on the behalf of the collective benefit of the community. Therefore, the Olkirimatian conservancy's plans for human wildlife cohabitation involves setting aside areas for (Figure 2) [3]:

a) Conservancy, a seasonally grazed grass bank, with no permanent settlement allowed
b) Livestock rearing area, the main wet season grazing area
c) Buffer Zone, area of seasonal settlement

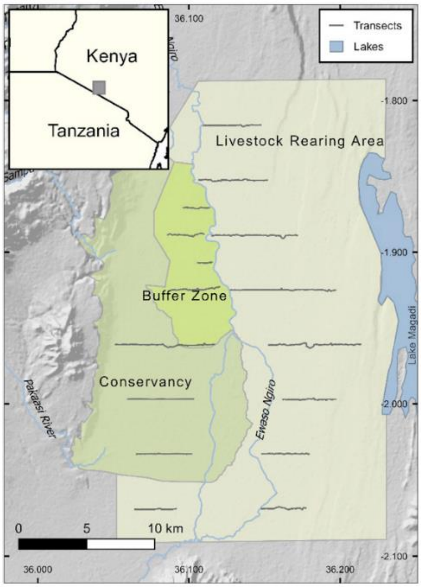


Figure 2: Different land use areas in the Olkirimatian conservancy [3]

1.2. Objective

The overall objective of this thesis was to assess the technical and economic feasibility of electric transport in an off-grid setting. However, to do so, the work relied on the outputs of the following interconnected sub-objectives:

- Identify and understand the key challenges and opportunities in rural human development regarding transportation and electricity access
- Develop a technical and financial model that reflected the conditions present in a realistic pilot site
- Evaluate the models and compare the results of the electric vehicle solution with the status quo
- Draw conclusions based on the results from the analysis that would gauge the technical and economic viability of the project

1.3. Research questions

The research questions this work sought to address are:

What are the technical and economic thresholds for facilitating an electric transport service in an off-grid remote setting?

What impact does an electric transport application have on the mini-grid?

Can electric transport solutions decrease the cost of transport for a rural community?

2. Methodology

The research methodology in this thesis follows a top-down approach where relevant information is presented on a macro-level, and then refined towards a realistic case study. Figure 3 illustrates the research process, which begins with an overview of the status quo and challenges in rural transport. Following, an income-generating transportation scenario is isolated, and an appropriate electric vehicle solution is discussed. The discussion will be centered around a potential pilot site suitable for a mini-grid. The analysis will deconstruct the problem into two models; technical and financial. The technical model will assess the impact of an electric transport application on the design of a mini-grid. This model will rely on the HOMER software and the results will be compared to a mini-grid design without electric transport. The financial model will employ an excel-based *Discounted Cash Flow* spreadsheet, to compare the economic performance of the shortlisted electric transportation scenario against the status quo. Both models will assess varying scenarios regarding potential fleet sizes and expenses. Afterwards, general conclusions will be discussed as well as next steps.

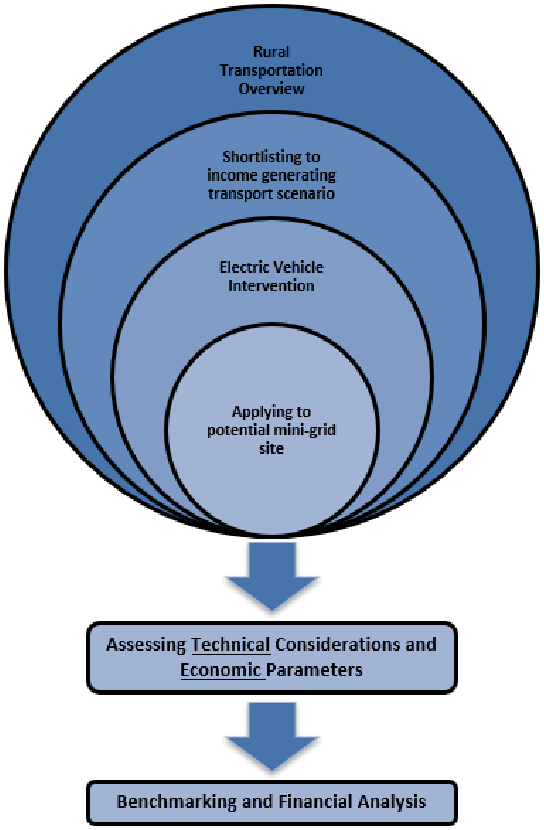
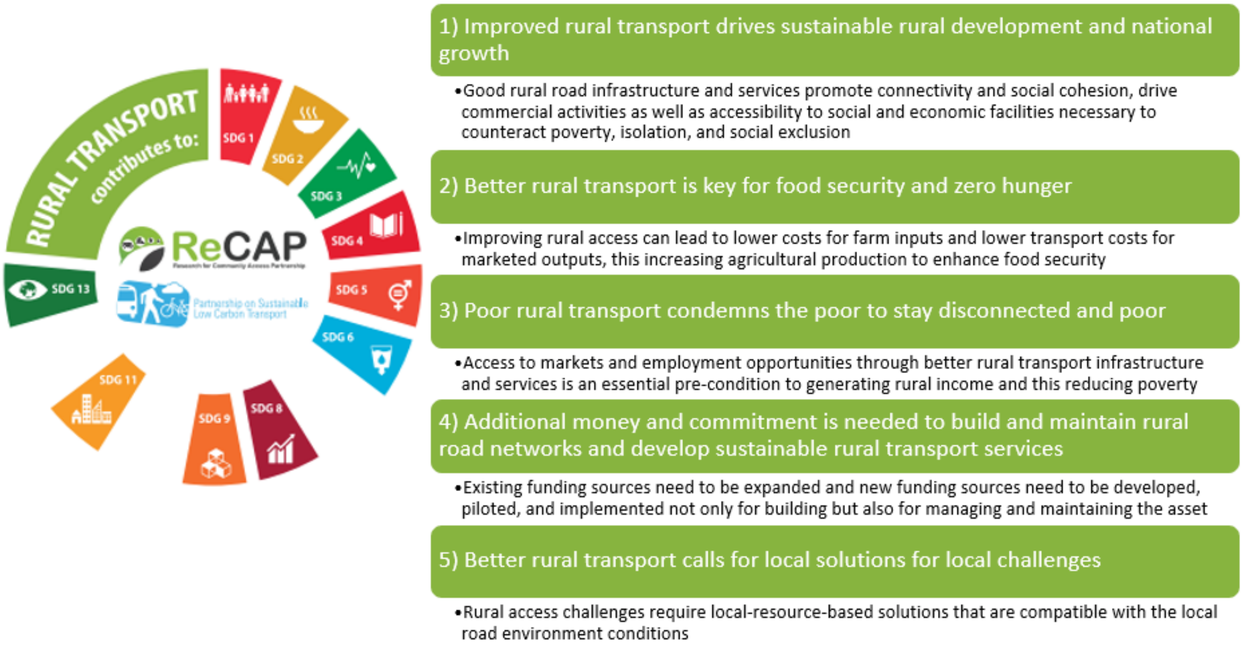


Figure 3: Thesis research methodology

3. Background Information

3.1. Rural transportation

Transportation systems in rural communities are an essential and often under-valued component of human development. Only 56% of the rural population in Kenya, comprised of 36.5 million individuals, live within two kilometers of a rural road that is in good condition [6][7]. Additionally, it is estimated that 49% of Kenya's rural population lives below the poverty line [8]. Although not explicitly listed in the UNDP's SDGs, rural transport contributes to 10 of the 17 SDGs through 5 key messages, as illustrated in Figure 4.



1) Improved rural transport drives sustainable rural development and national growth

- Good rural road infrastructure and services promote connectivity and social cohesion, drive commercial activities as well as accessibility to social and economic facilities necessary to counteract poverty, isolation, and social exclusion

2) Better rural transport is key for food security and zero hunger

- Improving rural access can lead to lower costs for farm inputs and lower transport costs for marketed outputs, this increasing agricultural production to enhance food security

3) Poor rural transport condemns the poor to stay disconnected and poor

- Access to markets and employment opportunities through better rural transport infrastructure and services is an essential pre-condition to generating rural income and this reducing poverty

4) Additional money and commitment is needed to build and maintain rural road networks and develop sustainable rural transport services

- Existing funding sources need to be expanded and new funding sources need to be developed, piloted, and implemented not only for building but also for managing and maintaining the asset

5) Better rural transport calls for local solutions for local challenges

- Rural access challenges require local-resource-based solutions that are compatible with the local road environment conditions

Figure 4: Rural transports contribution to the UNDP's SDGs (Adapted from [9] *and* [10]*)*

Rural areas typically have low population densities which are compounded with low income levels that do not foster an environment where economies of scale could facilitate affordable transport. Inadequate transportation systems and poverty in rural areas form a vicious cycle, where limited mobility limits income generation and economic demand. Low demand then constrains the facility of affordable transport and use of IMTs, which ultimately restricts mobility (Figure 5) [11].

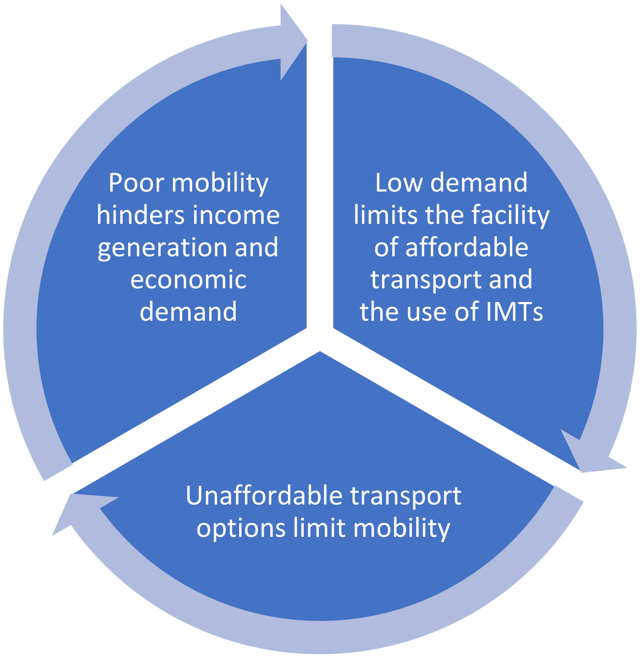


Figure 5: Viscous cycle of poverty and poor transportation systems

Rural transportation systems are complex, multi-stakeholder systems that are composed of three basic elements [12]:

1. Transportation infrastructure
2. Location and quality of facilities
3. Rural transport services and means of transport

Transportation infrastructure refers to rural roads, tracks, and paths that are present in rural settings, on which the population performs its transport activities. This element has typically been the focus of national transport strategies and investments in improving rural transportation [13]. Historically, governments and foreign investors in SSA dedicated funds to building all-weather road networks in rural areas to strengthen the agricultural sector, a prevalent source of income for rural communities. These investments are capitally intensive and often subject to political factors and corruption. Additionally, studies have shown that the development of all-weather roads in rural areas seems to benefit the "non-poor" while the poor continue to walk. Despite Kenya's investments in rural road networks, less than half are in good condition [14]. From observations in the field, the communities rely on informal tracks and paths, as well as on one formal unpaved road – linking the conservancy to Magadi town which ultimately provides a gateway to the capital, Nairobi (Figure 6). Furthermore, the poor conditions and often narrow dimensions of these transportation networks presents obstacles that are almost impossible for conventional cars to maneuver through. Therefore, local communities rely on unconventional vehicles and modes of transport that can circumvent such conditions.

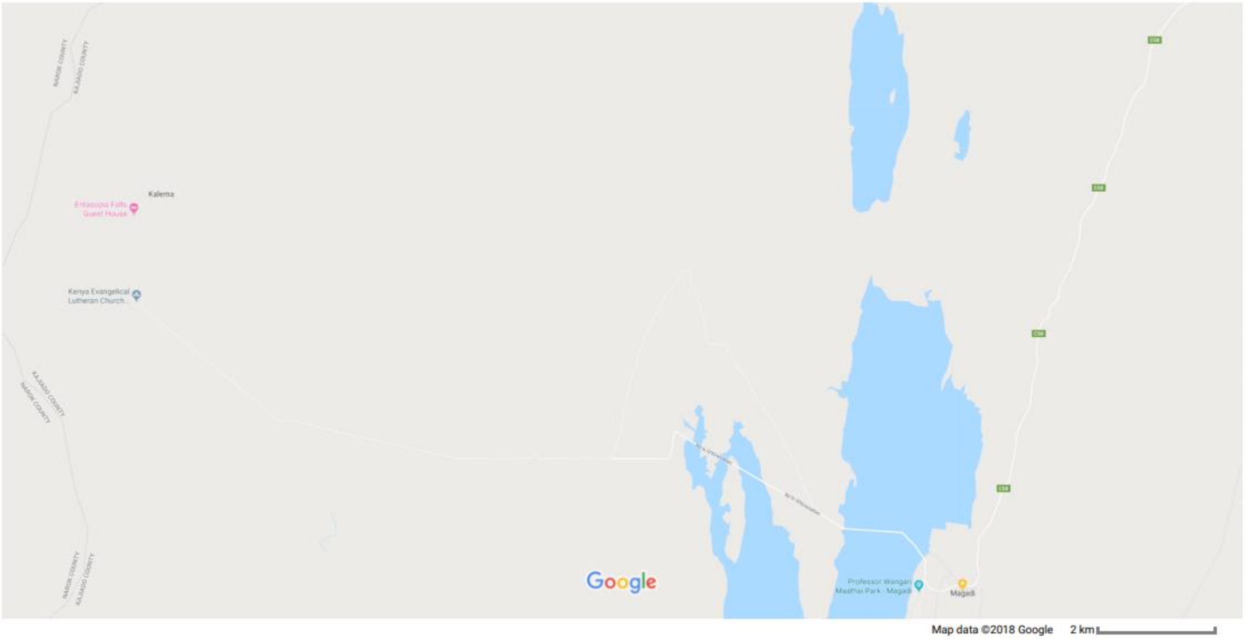
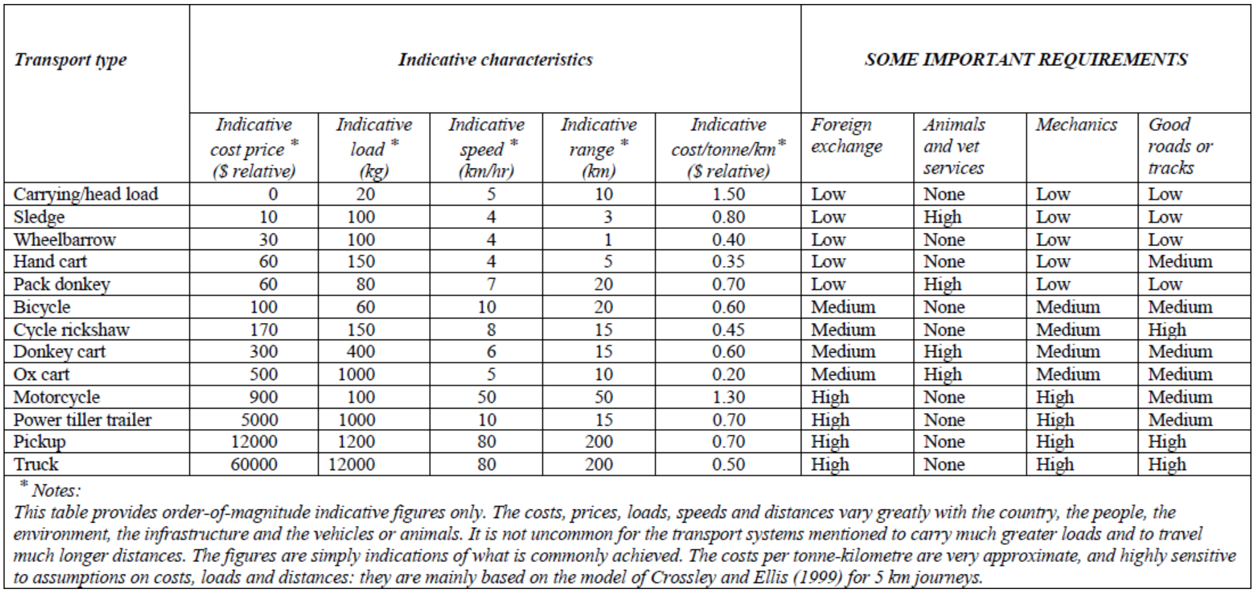


Figure 6: Formal road map of Olkirimatian conservancy

Location and quality of services relates to the distance between a rural dweller and facilities such as water points, forests, health centers, schools, markets, and others. The distance and quality of the facility dictates the amount of time or money a dweller would need to dedicate to reach that facility. In some communities, subsistence necessities such as water and energy (through firewood) are distant from settlement areas. Time-consuming commutes, which reduce productivity, are practiced almost daily. Similarly, the location and quality of educational and health facilities factors into an individual's decision-making in seeking out those services. If persons choose to abstain from these services due to the distance, this can have adverse effects on the wellbeing of the community. Increasing the number of service providers in rural areas would effectively reduce the distance from dwellers, but low population densities would likely leave these facilities underutilized. Alternatively, promoting affordable and effective means of transport would make these services more accessible, without affecting the supply and quality of health and educational facilities.

The means of transport refers to the method in which community members commute (e.g. Walk, bicycle, motorcycle). While, rural transport services refer to the informal and formal services available to them (e.g. Taxi service, intercity bus service). This element is crucial for empowering and developing rural communities [15]. However, the primary challenge in promoting affordable and effective means of transport is the low demand caused by low population densities. The most commonly used method is walking, which is efficient for short distances, but taxing for longer trips and large payloads. In most of rural SSA, people walk or head-load regularly for distances up to 5 kilometers, and in some cases, 20 kilometers [16]. This leads to drudgery, which ultimately compromises a community's ability to boost its economic status. Therefore, rural communities rely on motorized and non-motorized transportation technologies to mitigate the burden of long-distance travel or moving cumbersome objects. An overview of transport technologies most common in rural communities worldwide is presented in Table 1.

Table 1: Overview of transport technologies present in rural settings [17]



Transport type	*Indicative characteristics*					*SOME IMPORTANT REQUIREMENTS*			
	*Indicative cost price * ($ relative)*	*Indicative load * (kg)*	*Indicative speed * (km/hr)*	*Indicative range * (km)*	*Indicative cost/tonne/km* ($ relative)*	*Foreign exchange*	*Animals and vet services*	*Mechanics*	*Good roads or tracks*
Carrying/head load	0	20	5	10	1.50	Low	None	Low	Low
Sledge	10	100	4	3	0.80	Low	High	Low	Low
Wheelbarrow	30	100	4	1	0.40	Low	None	Low	Low
Hand cart	60	150	4	5	0.35	Low	None	Low	Medium
Pack donkey	60	80	7	20	0.70	Low	High	Low	Low
Bicycle	100	60	10	20	0.60	Medium	None	Medium	Medium
Cycle rickshaw	170	150	8	15	0.45	Medium	None	Medium	High
Donkey cart	300	400	6	15	0.60	Medium	High	Medium	Medium
Ox cart	500	1000	5	10	0.20	Medium	High	Medium	Medium
Motorcycle	900	100	50	50	1.30	High	None	High	Medium
Power tiller trailer	5000	1000	10	15	0.70	High	None	High	Medium
Pickup	12000	1200	80	200	0.70	High	None	High	High
Truck	60000	12000	80	200	0.50	High	None	High	High

* *Notes:*
This table provides order-of-magnitude indicative figures only. The costs, prices, loads, speeds and distances vary greatly with the country, the people, the environment, the infrastructure and the vehicles or animals. It is not uncommon for the transport systems mentioned to carry much greater loads and to travel much longer distances. The figures are simply indications of what is commonly achieved. The costs per tonne-kilometre are very approximate, and highly sensitive to assumptions on costs, loads and distances: they are mainly based on the model of Crossley and Ellis (1999) for 5 km journeys.

From the table above, it is apparent that different technologies have unique characteristics and varying values for cost, load, speed, and range. This observation leads to an understanding that the available means of transport in a community can be arranged and viewed as a spectrum. On one end of this spectrum, there are solutions appropriate for simple transportation needs. On the other, there are the large-scale means of transport for long distances and heavy payloads. In Figure 7, this spectrum is illustrated, and it is important to note that the two extremes differ based on their distance covered and utilization rate. Basic means, like walking, are used more frequently because it is inexpensive and effective for mobility within a farm or village. Large-scale transport technologies (e.g. intercity busses and minivans) for inter-district travel can only reach economies of scale if used for long and lengthy distances. However, the demand for such high-volume transport services is low since community members do not travel long distances frequently - rendering large-scale transport technologies economically nonviable for short trips. In between, there is a vast array of intermediate means of transport (IMT) that cater for trips that are too time-consuming for walking and more frequent for large-scale technologies to efficiently manage.

Basic

- Walking and carrying
- Simple, cheap, and efficient for short distances, difficult terrain, and small payloads
- Generally done to collect water and firewood, and tending crops and livestock
- Time-consuming activity, typically burdened onto females
- <5km

Intermediate

- Both non-motorized (bicycle, donkey cart) and motorized (motorcycle, tractor) solutions
- Locally-based, good availability
- Suitable for difficult terrain and larger loads
- Important for on-farm, within-village, and village-to-market, and other short trips near village surrounding
- Reduces drudgery at affordable rate
- 50m to 20 km

Large-scale

- Trucks, buses, automobiles, trains, airplanes, and ships
- Low availability
- Good for moving people and goods over long distances with large roads (typically between towns, districts, and counties)
- Complicated and expensive technologies
- With efficient operation and high capacity utilization, economies of scale can yield low cost per km
- 5 to 5000 km

Figure 7: Means of transport spectrum

IMTs bridge the gap between short- and long-range commutes. They have the ability to increase transport capacity and reduce drudgery at a relatively low cost, solving local transport problems [17]. Locally based IMTs can include wheelbarrows, hand carts, bicycles, tricycles, animal-powered carts, motorcycles, and trucks. In an ideal transportation system, there should be a variety of diverse and flexible IMTs to effectively cater to a local transport problem. In addition to solving niche transport problems, IMTs can operate as a profitable service. These transport technologies generate income, save time, and could assist in profitable ventures. Nevertheless, a necessary provision for IMTs to thrive in rural settings is to reach a “critical mass” of users. Most means of transport require maintenance and supporting infrastructure sustain its continuous usage. For instance, a study in a rural Madagascan village found that within the community, there was a number of bicycle users, but not enough to reach a “critical mass” that would prompt the formation of a local repair service [17]. Interestingly, the village did have an abundance of ox carts, which reached a “critical mass” to incentivize local artisans to engage in maintenance activities. Furthermore, these ox carts were used to transport bicycles in need of repairs to another village that had a bicycle mechanic.

The three elements of rural transport collectively influence a community's quality of life and capacity for prosperity. The following sections highlight the vital role of transportation systems on rural livelihoods.

3.1.1 Socio-economic impact

Transportation systems have a crucial role in accessing fundamental social services needed for human development. Education and health care are key elements to a community's growth and wellbeing – however, the ability to access these facilities ultimately dictates the service's effectiveness. Children in SSA typically need to walk long distances to primary school, which contributes to low enrollment rates and early dropouts. This issue is further amplified when children are tasked with household labour activities and are faced with the decision to either walk a long distance to be educated or help the family at home. This issue more so disproportionally affects girls, where gender attitudes in rural areas demand them prioritize subsistence activities over their education [18]. Apart from the pupil's experience, the quality of a rural community's transportation system also affects the teacher. In some cases, teachers are not attracted to remote and isolated communities, contributing to under resourced schools.

Accessibility is essential to the success of health services in rural areas. An efficient transportation system is essential in overcoming the fatal "three delays" in peri-natal care – the decision to seek care, travelling to reach healthcare, and then the treatment within healthcare systems, which includes referrals to other locations [19]. A study in Zambia found that systematic motorcycle management and health care delivery improved basic health-care delivery in rural villages through increased health worker productivity and greater geographical coverage [20]. The study particularly noted an increase in patient visits, measles immunizations, child growth assessments, and more people receiving health education.

A community's ability to access marketplaces and income-generating opportunities is also affected by its transportation system. The time and cost of a means of transport factors into an individual's decision to participate in any income-generating activity. Affordable modes of transport are valued by individuals, since it allows access to seek opportunities outside of their immediate surroundings regarding resources, employment, or social gatherings. Generally, analysts rely on a "rule of thumb" for valuing travel time at 50% of the prevailing unskilled wage rate [21]. Cook et al., determined that in Meru county (Kenya) random-parameters logit models implied that the average value of travel time was 18 KES/hour (0.18 USD/hour), which supported the 50% rule. However, a latent-class approach identified four classes of consumers: one class that values time very highly at 49 KES/hour, one poorer group that values time at less than 1 KES/hour, and two groups that value time at roughly 9 KES/hour.

3.1.2. Gender

As mentioned earlier, gender attitudes in rural areas demand that women look after a household's subsistence needs. In a rural Maasai homestead, the male assumes the responsibility of herding and marketing livestock, which ultimately means he collects and controls the income [22]. This setup leaves the woman with subsistence and on-farm duties. These duties include child rearing, collecting firewood and water, harvesting, and trips to the grinding mill. A study in a rural village in Tanzania found that women bear almost seven times the transport burden in comparison to men (Figure 8). The common means of transport for women to conduct these activities is walking. However, the time-consuming nature of walking results in time wasted on drudgery, rendering women to be less productive and generate little to no income. In addition to being placed in a patriarchal setting, where men have the authority over all income-related decisions, women will not have the money to afford reliable, transport service. Additionally, women are typically excluded from engaging as transport operators due to low vehicle ownership and cultural attitudes [16]. Not only do women not own bicycles, hand carts, and motorcycles, but the physical design of these technologies prohibit women from using them. In a rural Tanzanian case, the design of wheelbarrows challenged women's ability to carry their child and push the wheelbarrow concurrently, since it required both hands [16]. In some societies, bicycles and motorcycles have strong male associations and it would be considered inappropriate for a woman to straddle over such vehicles. Such factors in limited transport inhibits women's ability to thrive and creates a power divide between genders, where males control the means of transport and have greater access to income-generating opportunities. In some circumstances, this inequality results in women offering sexual services in exchange for transport [23]. Such situations increase the risk of sexually transmitted diseases and unwanted pregnancies. Given these challenges in vehicle utility, societal gender biases, and inaccessibility of affordable transport, there is a clear need to develop gender inclusive means of transport to empower women in rural communities and effectively cater to their needs.

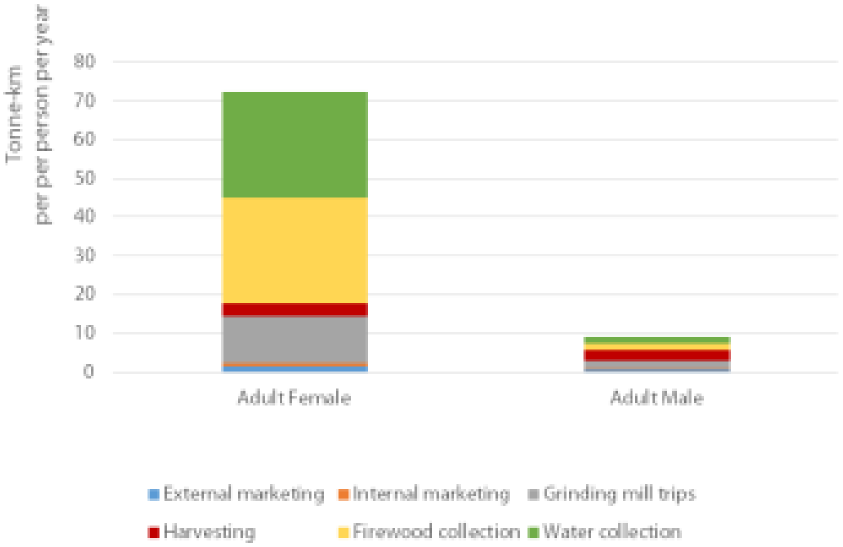


Figure 8: Transportation burden for men and women in Makete, Tanzania [24]

3.1.3. Agriculture

The primary source of livelihoods for the communities in Kajiado county and much of rural SSA is derived from agricultural and livestock activities [25] [26]. In the Olkirimatian conservancy, this pertains to the harvesting of corn and millet, as well as animal husbandry from cattle and goats. Historically, national transport strategies focused on developing rural roads so that farmers can move their products to larger markets. Although this has been successful, a study in rural Nepal concluded that roads benefited the poor but were not enough in reducing inequalities [27]. The benefits of a good transportation system are often undermined. Proper transportation can lead to lower marketing costs, more efficient agriculture, and less food wastage [11]. The cost of transport in rural areas far exceeds its urban counter-parts. Vehicle scarcity, as well as the high cost of maintenance and fuel due to expensive logistics in remote areas, increases operating costs which manifests to burden the farmer. Following the produce value chain in Figure 9, the “first mile” is the segment of transport that links the farmer to the nearest rural road, collection point, or market. This “first mile” is an important step as it is the bridge between the farmer’s labour and financial reward. Depending on the area this first mile can range from 0.25 to 5 km, and is typically done through human portage, animal carts, bicycles, animal carts, motorcycles, and in some cases trucks and tractors [28]. Head loading is the most commonly used means of transport, but it is also the most expensive (Figure 10) [28]. IFRTD claims that this expensive “first mile” transport method accounts for 10 to 30 % of the produce income to the farmer. In addition to bringing products to markets, a study in Laikipia East Sub-County in Kenya found that motorcycle-taxis were responsible for transporting agricultural inputs to the farmers [29]. The study found that out of the inputs transported by the taxis, 66% were fertilizer, 10% manure, 7% herbicide, 4% maize seeds, and 2% agro-chemicals. The weather-sensitive nature of the fertilizer required they be transported quickly to the fields.

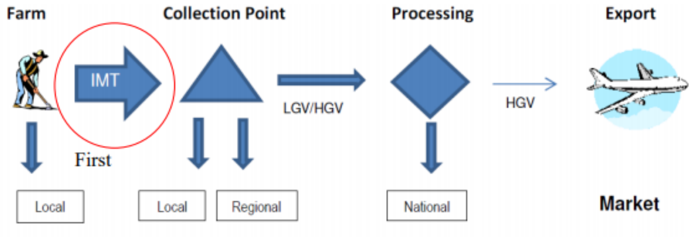


Figure 9: Produce value chain [28]

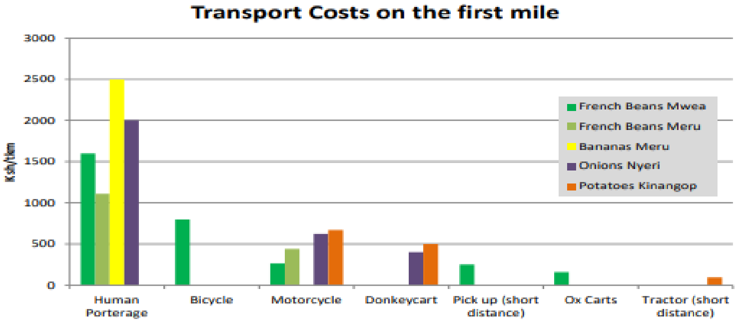


Figure 10: First mile transport costs for crops in different locations [28]

3.1.4. Motorcycle taxis

Motorcycle taxis (Also referred to as moto-taxis or "*Boda-bodas*" in East Africa) are a unique phenomenon in SSA, that fill a gap caused by African governments divest public transportation services due to economic and political factors [30]. In colonial times, the governing authorities instilled national transportation services that served urban and to some extent rural communities. With countries in SSA slowly gaining independence in the 1960s, governments took over the responsibilities of managing public services. However, with the economic downturn in the 1980s and additional political factors, some governments struggled to support public transport services and opted to cut spending and decentralize the service. Despite the economic downturn and downfall of public transport, the transportation demand of the population did not waver. This void presented an opportunity for the private sector to fill through cost-effective technologies such as motorcycles. Since the 1970s, motorcycle taxis as a transportation service began springing up in SSA to cater for this unsatisfied demand. This trend in adopting motorcycles was further catalyzed by the influx of inexpensive motorcycle brands from China and India [31]. In 2003, the Kenyan government acknowledged the value of motorcycles to the population and enacted a zero-rating[1] policy on the sale of motorcycles below 250cc [32]. This prompted an exponential growth in motorcycle registrations, as illustrated in Figure 11.

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[1] When a commodity is zero rated, the government does not tax its sale. The manufacturers can claim credits for the value-added tax (VAT) paid on inputs.[80]

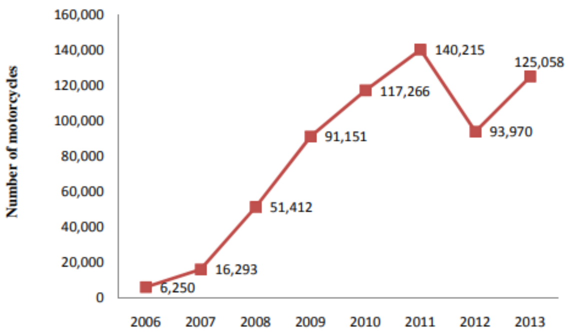

Figure 11: Number of motorcycles registered in Kenya, 2006 – 2013 [33]

In addition to the favourable macro-economic conditions, moto-taxi services provided a convenient, fast, and flexible light transport solution which was valued by both urban and rural populations. Table 2 shows a series of factors that influence the growth of motorcycles in SSA.

Table 2: Factors influencing the growth of motorcycles in SSA [34]

Positive		Negative	Push	Pull
Demand	Supply			
• Time savings • Door-to-door service • Improve mobility • Easy access • Demand Responsive • Easy maneuverability • Employment generation/Increase in income	• Easy availability • Limited street space (More applicable to urban settings)	• Congestion • Pollution • Accidents • Safety/crime • Unregulated	• Urban sprawl • Poor secondary road network • Poor road quality • Low density • Uncontrolled growth • Absence of safe, secure, affordable alternatives (especially for women)	• Inexpensive • Easy credit • High unemployment • Low car ownership • Unregulated

Rural areas particularly stand to gain from the influx of motorcycles through direct and indirect employment opportunities, as well as improved transport efficiency. The emerging moto-taxi sector in rural areas has directly led to the employment of young male adults, predominantly aged between 21 and 30 [30]. This activity offers a pathway for young adults to become economically-active and contribute to their local economy. Additionally, individuals seeking supplementary income or to boost their financial status tend to engage as operators due to the relatively lucrative potential of this service. Apart from direct employment opportunities, the presence of moto-taxis facilitates other income-generating activities that diversify and strengthen the rural business ecosystem. In Laikipia East Sub-County, it was found that the presence of motorcycle taxi operations prompted the promotion of activities which include: roadside kiosk construction, spare parts sales, mechanics, petrol filling stations, garages, poultry keeping, and the formation of self-help groups that finance members through soft loans [29]. The study also found that the moto-taxis were used as ambulance services, as they transported patients in and out of the hospital. Furthermore, the emergence of ICT technologies has also aided motorcycle operators and customers by facilitating “on-call” and door-to-door convenience, which has greatly benefited the rural elderly and disabled [35]. Motorcycles also have the advantage of maneuvering through difficult terrain with obstacles and narrow paths.

Motorcycle activities in SSA tend to follow two ownership models; Owner-operator or Renter-operator [30]. In the owner-operator case, an operator buys a motorcycle through their own savings through a credit union, and operates as a self-employed entity. Conversely, the renter-operator rents or buys the vehicle on hire-purchase for a daily fee from a fleet owner. A fleet owner owns multiple vehicles and, in most cases, is either a government official or other actor with capital to invest and become a profit seeker. The fleet-owner is not involved in the day-to-day operations of the service and only takes care of major repair works. In both cases the operator is responsible for the regular fuel and maintenance costs. However, in the renter-operator case, the operator is pressured to both cement his own income and pay the daily rental fee. This arrangement can lead to risky behaviour by the operator to secure his own income and the rental fee. Despite the commercial viability of moto-taxis, rural operators are faced with high costs for fuel and spare parts. The cost of petrol and spare parts increases with the remoteness of location due to logistical costs. The price of petrol can increase by up to 25% in comparison to the point of entry into the country, as shown in Table 3. Furthermore, the price of fuel fluctuates unpredictably and is often subjected to political events. Recently, the government of Kenya unexpectedly implemented a 16% VAT on all fuel products starting on September 1st, 2018 [36]. Moreover, the frequent maintenance of combustion engines also requires spare parts which are not always available in remote areas. Additionally, internal combustion (IC) motorcycles release greenhouse gases (GHGs) like CO2, through their tailpipe emissions and are gender-biased in design. Chen et al., found that rural driving habits can release up to 41.42 grams of carbon dioxide per kilometer and achieve a fuel performance of 40 km/L [37].

Table 3: Fuel price evolution from point of entry to conservancy

Cost of Petrol (May 15 – June 14, 2018)[2]		
Mombasa (Port)	**Nairobi**	**Olkirimatian conservancy[3]**
103.8 KES[4]/L	107.1 KES/L	130 KES/L

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[2] https://calculator.co.ke/erc-kenya-fuel-prices

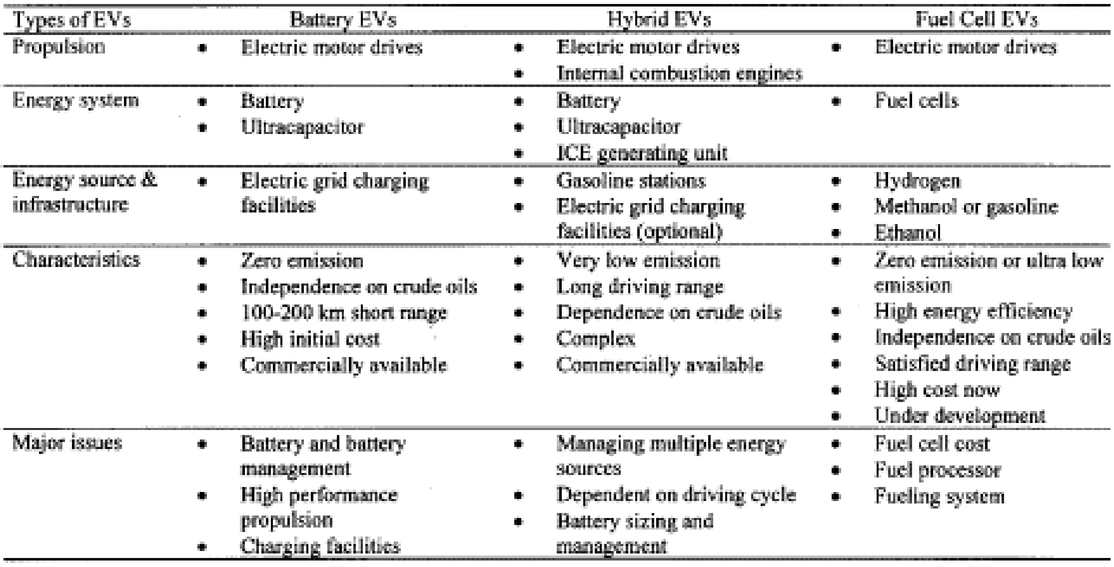
[3] Field visit on May 31, 2018

[4] 100 KES = 1 USD

3.2. Electric Vehicles

Electric vehicles (EVs) have been receiving a lot of attention in recent years due to the rising price of oil and global discussion on the environmental impacts of road transportation. This attention is reflected in the growing stock of EVs worldwide. The IEA estimated that in 2013, there were less than 0.5 million EVs worldwide [38]. However, this number grew to around 3 million EVs in 2017. EVs have the capacity to offer the same level of service as conventional combustion engine-based vehicles, but their drive-trains are powered entirely or partly by electrical energy. Table 4 highlights the three main types of EVs and their associated characteristics. In addition to EV's independence from fuel prices, another motivating factor for EV adoption is maintenance expenditure for BEVs can be 19% less compared to conventional IC vehicles [39]. This is mainly because EVs do not require frequent oil changes and the brakes wear out less frequently, due to energy recuperation systems.

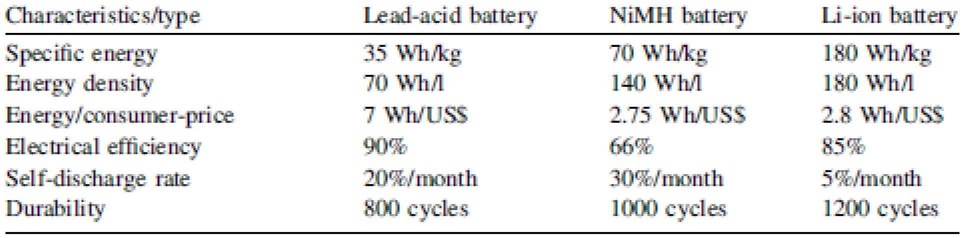
Table 4: Characteristics of the three main types of EVs [40]



Types of EVs	Battery EVs	Hybrid EVs	Fuel Cell EVs
Propulsion	• Electric motor drives	• Electric motor drives • Internal combustion engines	• Electric motor drives
Energy system	• Battery • Ultracapacitor	• Battery • Ultracapacitor • ICE generating unit	• Fuel cells
Energy source & infrastructure	• Electric grid charging facilities	• Gasoline stations • Electric grid charging facilities (optional)	• Hydrogen • Methanol or gasoline • Ethanol
Characteristics	• Zero emission • Independence on crude oils • 100-200 km short range • High initial cost • Commercially available	• Very low emission • Long driving range • Dependence on crude oils • Complex • Commercially available	• Zero emission or ultra low emission • High energy efficiency • Independence on crude oils • Satisfied driving range • High cost now • Under development
Major issues	• Battery and battery management • High performance propulsion • Charging facilities	• Managing multiple energy sources • Dependent on driving cycle • Battery sizing and management	• Fuel cell cost • Fuel processor • Fueling system

The key components of any BEV or HEV is the battery, motor, transmission, control system, and in the hybrid case, the IC engine. It is important to note that the battery represents around 75% of the total cost of an EV powertrain [41]. The most common types of batteries for EV applications are Lead-acid, Nickel-metal hydride (NiMH), and Lithium ion (Li-ion) [42]. A comparison of the three types of batteries is shown in Table 5. Lead-acid batteries are the oldest of the three types, but Li-ion batteries are likely to meet the needs for energy storage for future EVs [43]. Li-ion batteries dominate the other technologies because of their improved specific energy, volumetric energy density, cyclability, charging rate, stability, and safety. However, a major drawback of Li-ion batteries is their cost and dependence on scarce material inputs. Fortunately, with the global growth in Li-ion battery consumption, experience rates could drastically reduce the cost and make EVs cost competitive with IC vehicles by reaching a price point of 150 USD/kWh sometime between the year 2022 and 2034 [44].

Table 5: Comparison of the three most common EV battery technologies [42]



Characteristics/type	Lead-acid battery	NiMH battery	Li-ion battery
Specific energy	35 Wh/kg	70 Wh/kg	180 Wh/kg
Energy density	70 Wh/l	140 Wh/l	180 Wh/l
Energy/consumer-price	7 Wh/US$	2.75 Wh/US$	2.8 Wh/US$
Electrical efficiency	90%	66%	85%
Self-discharge rate	20%/month	30%/month	5%/month
Durability	800 cycles	1000 cycles	1200 cycles

3.2.1. Electric two-wheelers

Although most of the attention around EVs centered around cars, two-wheelers present a substantial and cost-effective solution for transportation needs. The growth in electric two-wheeler adoption is mainly led by China, which has an estimated 250 million units on the road [38]. Similar growth is also expected to occur in India and in other South-East Asian countries [45]. In these markets, there are three distinguishable types of two-wheeled vehicles that are present. These include: e-bicycles (or pedelecs), mid-size electric two-wheelers known as e-mopeds or small e-scooters, and large electric two-wheelers known as e-motorcycles and large e-scooters. A description of the technical features of each two-wheeler is presented in Table 6.

Table 6: Comparison of three types of electric two-wheelers [46]

Powertrain component	Electric bicycle	Mid-size electric two-wheeler	Large electric two-wheeler
Traction source motor	• Electric motor assisting human pedalling • DC motors	• BLDC or BLAC (synchronous machines) motors	
Max. continuous rated motor power (kW)	• ≤0.25	• 0.25 – 4	• >4
Transmission	• Mainly direct or in combination with reduction gearing at the wheel-hub • OR through a separate gear at the bicycle chain • OR through a helical gear box at the bottom bracket	• Direct-drive configuration or in combination with a multi-speed gear box	
Energy storage	• Rechargeable lead-acid, nickel-metal hydride, or lithium-ion batteries	• Predominantly rechargeable lithium-ion batteries (in Europe and the USA); to a minor extent lead-acid, nickel-metal hydride, lead/sodium-silicate batteries	
Battery capacity (kWh)	• 0.3 – 0.6	• 0.5 – 15	
Indicative charge time (80% battery capacity)	• 8 hours through wall outlets • 3 hours to less than 1 hour through fast charging		
Battery swapping	• Mostly standard	• Possible for several models but not standard	
Recent trends	• Market diversification • Retrofitting • Battery weight reduction • Energy recuperation • Hybridization of power trains		
Image			

Although electric two-wheelers do not produce any tailpipe emissions, it is necessary to look through a wider lens of system boundaries to accurately assess their environmental impact. From a tank-to-wheel perspective, electric two-wheelers can achieve a 50-90% energy savings compared to conventional IC technologies [46]. However, a well-to-wheel perspective is subject to the associated environmental impact of the electricity mix powering the EVs. A largely fossil fuel based electricity mix can lead to efficiencies comparable to IC technologies, as was the case in a study of electric scooters in Taiwan [47]. This issue becomes more grave when assessing the full lifecycle emissions of electric two-wheelers, which includes the environmental impact from the production and end-of-life treatment of the vehicle. The electricity mix of the country, namely China, producing components such as the battery, can greatly increase the overall lifecycle impact of the electric two-wheelers [46]. Despite the complexity of an EV's environmental impact, some general conclusions can be made. EVs shift their environmental impact to concentrated point sources that are typically away from settlement areas and have an advantage over IC vehicles by not emitting any tailpipe emissions.

3.3. Mini-grids for rural electrification

In 2016 the estimated rural electricity access rate for Kenya was 39.3%. This represents a population of around 21.8 million people that do not have access to modern electrical services. Kenya Power (the national utility) has had much success in extending the grid in recent years, going from a national electrification rate of 19.2% in 2010, to 56% in 2016. Despite this success, many rural communities are far away from existing infrastructure and remain disconnected from the national grid. Electricity access is a vital service that has a strong link to human development and is an essential step in poverty alleviation for rural communities [48]. Poverty is a vicious cycle that traps communities in a state where they have low incomes and are unable to afford proper food, shelter, healthcare, education, and electrical appliances. This translates into a low ability to pay for goods and services, as well as a low demand for electricity since appliance ownership is almost negligible. These factors combined are unfavourable for any projects regarding grid extension since the national utility would likely not recover its capital expenditure. This is because grid extension is an expensive means of electricity access that requires large-scale civil works and infrastructure. Additionally, the utility would be required to sell electricity at the national tariff rate, which would be below project cost recovery levels. A 2008 study concluded that 15 out of 21 countries in SSA had utilities operating at a loss because they were required to sell electricity at below cost-recovery limits [49]. These conditions present an opportunity for affordable off-grid solutions to fill.

One solution that has a history of catering to this opportunity is electrification through mini-grids. Mini-grids (or Micro-grids in some literature), in an off-grid setting, are a decentralized electricity generation and distribution facility that can serve a town/community, factory, or other type of client that is distant from the national grid and has a concentrated electricity load[5]. It is important to mention, that mini-grids can also be present within the domain of grid-connected systems, however this case is not relevant to this thesis. At its most basic, mini-grids are composed of the following elements: an electricity generation unit, energy storage unit, power

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[5] There is no universally adopted definition for mini-grids, this is the author's best attempt to give a clear understanding of what mini-grids are

conditioning units, control system, distribution system, and load (Figure 12). Other means of off-grid electrification are stand-alone solar home systems such as solar lanterns and "plug and play" systems which typically power low power DC appliances (LED lights, radios, fans, and custom TVs and Refrigerators). However, mini-grids have an advantage because they can support high power AC appliances that can promote a wide array of productive use business activities [50]. Additionally, the distribution system can be integrated in the future with the national grid.

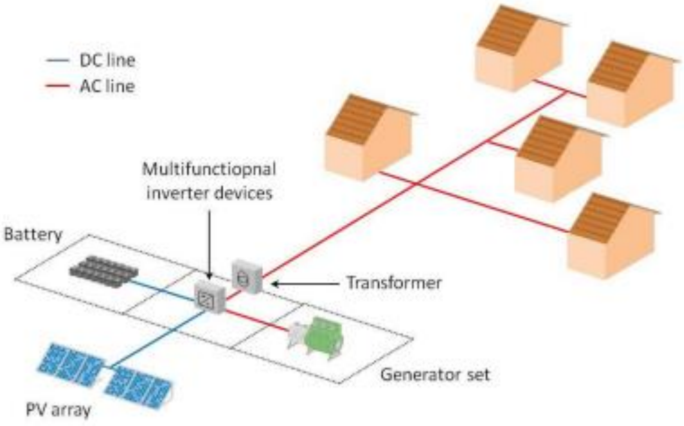

Figure 12: Mini-grid illustration [51]

Kenya's is well-endowed with an abundance of solar energy due to its positioning on the equator. The country has an average of 5-7 peak sun hours a day and an average daily insolation of 4-6 kWh/m^2 [52]. The Africa-EU RECP estimates a yearly photovoltaic (PV) potential of 23,046 TWh. PVs are an electricity generating technology that convert sunlight into electric energy through the "photo-electric effect" of silicon semi-conductor materials [53]. PV cells are comprised of silicon wafers that are arranged together to form a module that would produce more energy. The capacity to generate electric energy can be integrated with mini-grids and form a "green energy" system, which means it does not have the tailpipe emissions a diesel generator would have. However, the nature of PV cells is to produce direct current (DC) electricity that is vulnerable to changing environmental conditions. To provide stable alternating current (AC) power, a PV-based "green" mini-grid needs a charge controller, inverter, and some form of electrical storage, typically a battery bank. An intelligently programmed charge controller would support the system through overcharge protection, deep discharge protection, system power management, and user alerts. As mentioned in an earlier section, batteries are expensive, thus provisions should be made to minimize their size and extend their usable lifetime. Charge controllers can be programmed to make sure that batteries are not damaged by deep-discharges from over-use of the load and overcharging from the PV modules. Furthermore, inverters increase system voltage and convert DC power to AC. However, in doing so, the inverter consumes energy with a typical efficiency of above 90%. Although inverters discount the system efficiency, they can boost system voltages to 110 or 230 V, which is convenient for users that would like to run high power appliances such as water kettles, power tools, computers, etc. Batteries offer a form of energy storage necessary to regulate fluctuating electricity production from PV modules and provides a source of energy during the night and periods of overcast. Batteries convert electric energy to chemical energy when charging, and vice-versa when discharging. The most common types of battery chemistries for mini-grid applications are lead-acid, lithium ion, nickel metal hydride, and nickel cadmium. Lead-acid batteries are mature technologies that are available, cost-effective, and suitable for all but the smallest solar power systems. For added reliability however, system designers often hybridize the green mini-grid through the integration of a diesel generator to the system architecture (Figure 13).

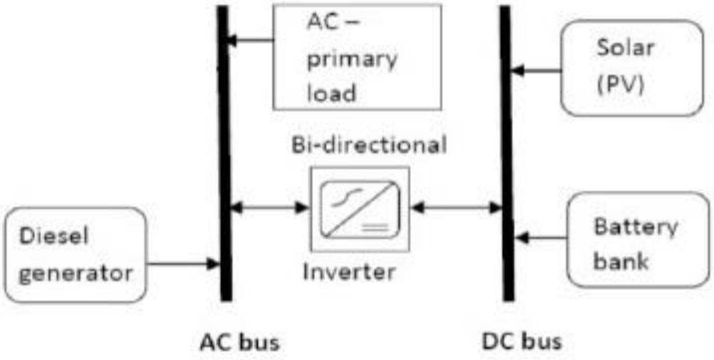

Figure 13: Hybrid mini-grid system architecture (Adapted from [54]*)*

The advantages and disadvantages of green, hybrid, and fully diesel generator-based system is presented in Table 7: Comparison of green, hybrid, and diesel mini-grids *[51] [55]*. Mini-grid developers can design the system to meet a certain degree of hybridisation based on their preferences and project constraints. The degree of hybridisation would effectively dictate the level of renewable energy penetration and [55]. A low degree of hybridisation would require the diesel generator to run full time while the opposite would reduce the diesel generator run time at the expense of a sophisticated control system.

Table 7: Comparison of green, hybrid, and diesel mini-grids [51] [55]

<table>
<tr><th></th><th>DIESEL</th><th>HYBRID</th><th>GREEN</th></tr>
<tr><td rowspan="4">Advantages</td><td colspan="3">Higher capacity to sustain wide array of productive use activities</td></tr>
<tr><td colspan="3">Can support energy intensive appliances (ie. Refrigerators, Electric kettle, etc.)</td></tr>
<tr><td colspan="3">Supports future connection with national grid</td></tr>
<tr><td>• Adequate reliability
• Low capital expense
• Good load following capabilities and operational flexibility
• Common servicing skills</td><td>• Moderate capital and operating expense
• Good reliability</td><td>• Emission free
• Quiet</td></tr>
<tr><td rowspan="3">Disadvantages</td><td colspan="3">Regular maintenance required</td></tr>
<tr><td colspan="3">Weak financial and ownership models in the past failed in recovering project costs</td></tr>
<tr><td>• Excessive emissions
• High operational expenses
• Poor part load efficiency
• Vulnerable to fluctuating fuel prices
• Noisy</td><td>• Moderate emissions
• Need for control system depending on degree of hybridization</td><td>• Vulnerable to fluctuating weather patterns, poor reliability</td></tr>
</table>

In addition to the technical aspects of mini-grids discussed before, considerations need to be made on the ownership of the system. Ownership models answer questions on operations and maintenance, role of private sector involvement, tariffs and subsidies, and capacity building and training [56]. These factors are critical to the long-term sustainability of a mini-grid project. Table 8 compares the four most common ownership models from USAID's experiences in mini-grid development. As mentioned in Table 7, weak financial models in the past have led to project failure. This failure arises from setting tariffs that are not affordable for the consumers. Generally, it is difficult to collect payments from *"Base of the Pyramid (BOP)* [6]*"* consumers. BOP consumers have a low ability to pay and mini-grid electricity units are often too expensive for them to afford. This is an unfavourable characteristic that could compromise the financial performance of a mini-grid project because electricity sales are the core revenue stream. Therefore, developers rely on clever business models and promote the productive use of electricity on mini-grid sites. Productive use of electricity can support the potential for sustained poverty reduction through the creation and improvement of income generating activities [57].

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[6] Base (or Bottom) of Pyramid is a socio-economic concept that refers to the largest but poorest group of the world's population [81].

Table 8: Comparison of mini-grid ownership models [58]

	PRIVATE INVESTOR/DEVELOPER	NATIONAL UTILITY	LOCAL COMMUNITY	HYBRID
Advantages	- Operations, maintenance and management is usually more efficient. - If the investor has a stake in another business in the region (like a manufacturing plant), they are more likely to maintain a high-quality of electricity services. - Faster than utilities in breaking ground. - Easier to scale up operations if investment is profitable.	- Utilities have relevant experience. - Established technical expertise, maintenance capacity, and financial management systems. - Good access to legal services to manage regulations. - Can easily connect mini-grids to main grids. - Can cross-subsidize mini-grid consumers through tariffs collected from grid-connected customers. - Charge national uniform tariff which is usually less than actual cost of energy from mini-grid, advantage for mini-grid consumers	- Can serve remote areas where projects are not cost-effective for utilities and private sector, and therefore satisfy needs of community. - Communal ownership can facilitate proper management and delivery of high-quality services, which benefits the local community. - Projects can create local jobs and training opportunities. - Communities can use profits from mini-grid projects to support other community development projects.	- Combines advantages of other ownership models. - Well-designed models maximize effectiveness and impact. - Collaboration leverages each partner's strengths and decreases the need for capacity building. - Collaboration can address the weaknesses of one partner with the strengths of another.
Disadvantages	- Without supportive policies, regulations and financing for mini-grids, rural electrification may not be cost-effective or be too risky for private actors. - Failure to engage with local communities and promote a sense of ownership leads to botched projects - Adequate technical and financial management capacity is not guaranteed with each developer. - Vulnerable to regulations and/or fixed tariffs that could jeopardize project success. - Exhaustive mini-grid regulations could delay project through lengthy approval times.	- Slow and inefficient. - Vulnerable to political agendas. - Profit-driven utilities in have little incentive to electrify poor communities. - Failure to engage with local communities and promote a sense of ownership leads to botched projects - The project might not receive as much attention since mini-grids are not the utility's core activity. - The utility's large corporate structure might not effectively serve smaller projects. - Satisfying costly regulations can strain limited budgets.	- Lack the financial and technical capacity to develop a mini-grid. - Tariffs are sometimes too low to recover project costs, compromising the financial viability of the project. - If an effective mechanism to monitor consumption is not in place, some members might misuse electricity. - Vulnerable to corruption in certain cases, which would divert resources or decrease community support. - Local politics could affect project success. - Enforcement and ensuring payment can be challenging	- Multiple stakeholder agreements can be difficult to establish and maintain. - Differences in management styles across partners can cause friction and increase transaction costs. - Careful planning is needed to meet the needs of all stakeholders in the local context. - Disagreements between partners can lead to defaulting of contracts. - One weak partner's financial problem could affect the whole venture.

As discussed before, the financial viability of a mini-grid project relies on the consumer's buying power for the electricity produced. Developers have the flexibility to set different tariffs for the various consumer groups but the governing parameter from which the tariff is derived is the levelized cost of energy (LCOE). The LCOE can be characterized as the fictitious average price of electricity seen by the generation technology, that breaks even all costs (capital, replacement, and operational) for the owner/operator over its lifetime [59]. The formula defining the LCOE is shown below [60]:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{T}(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) \times (1+r)^{-t}}{\sum_{t=1}^{T} MWh_t (1+r)^{-t}}$$

Where,

$Capital_t$ is the capital construction costs in year t,

$O\&M_t$ is the operation and maintenance costs in year t, excluding fuel and possible carbon tax,

$Fuel_t$ is the fuel costs in year t,

$Carbon_t$ is the carbon-tax costs in year t, if applicable,

D_t is the decommissioning and waste management costs in year t,

MWh_t is the amount of electricity generated in MWh in year t,

$(1+r)^{-t}$ is the discount factor for year t, with r being the discount rate,

T is the considered project lifetime.

Figure 14 shows the range of expected LCOE's for different mini-grid electricity generation technologies. It is important to note that the study was done by ESMAP in 2007, thus the projected costs for 2015 may have not fully captured the technological developments in that time frame. Also, the cost of electricity is subject to local conditions regarding resource availability and load. Nevertheless, the LCOE of a 25 kW PV mini-grid are expected to be roughly 0.42 USD/kWh [61]

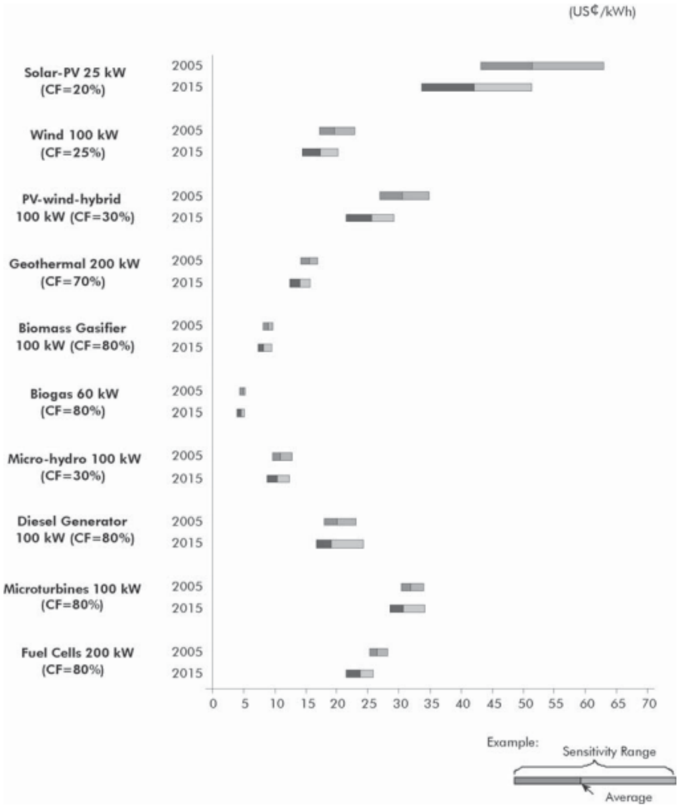

Figure 14: Mini-grid forecast LCOE [61]

3.4. Summary

This discussion addressed the challenges faced by rural communities regarding sustainable human development. Inadequate transportation systems and access to electricity has an adverse effect on a rural population’s socio-economic status. These conditions form a vicious cycle of poverty that is difficult to emerge from without external intervention through aid or new technology. The previous discussion touched on the emerging motorcycle taxi industry that is creating employment opportunities and helping rural communities solve a local transportation problem. However, the technology (IC motorcycles) itself is faced with expensive operational costs and is vulnerable to unforeseen political decisions. An electric alternative would isolate the industry from volatile fuel prices and lower operational expenses for the operator that could potentially translate to lower transportation fares. Additionally, introducing EVs to the community would boost demand for electricity. This is an essential element for rural electrification efforts because it presents a favourable condition for developers to recover project costs. The next section will detail a proposed model for an integrated approach to electrify motorcycle taxi operations with the assistance of a hybrid mini-grid that would also serve the community’s electrical needs. In a further section, this model will be assessed based on its technical thresholds and financial performance.

4. System modelling

The following section will detail the technical and economic model used in this study to assess an integrated electricity access and transport approach to rural community development. The model will use data from relevant literature, field observations, and key informant interviews. This model will be based on information from a potential pilot site and will evaluate the technical and economic thresholds for varying scenarios regarding the price of fuel and number of vehicles.

4.1. Site information

The town of Oloibototo (1°48'41.4"S, 36°03'20.9"E) has been selected as a potential site for a mini-grid through a demand assessment study orchestrated by African Solar Designs Ltd (ASD) and the GMG Facility Kenya[7]. The community is located roughly 29 km west of Magadi town and is on the western edge of Kajiado county as shown in Figure 15.

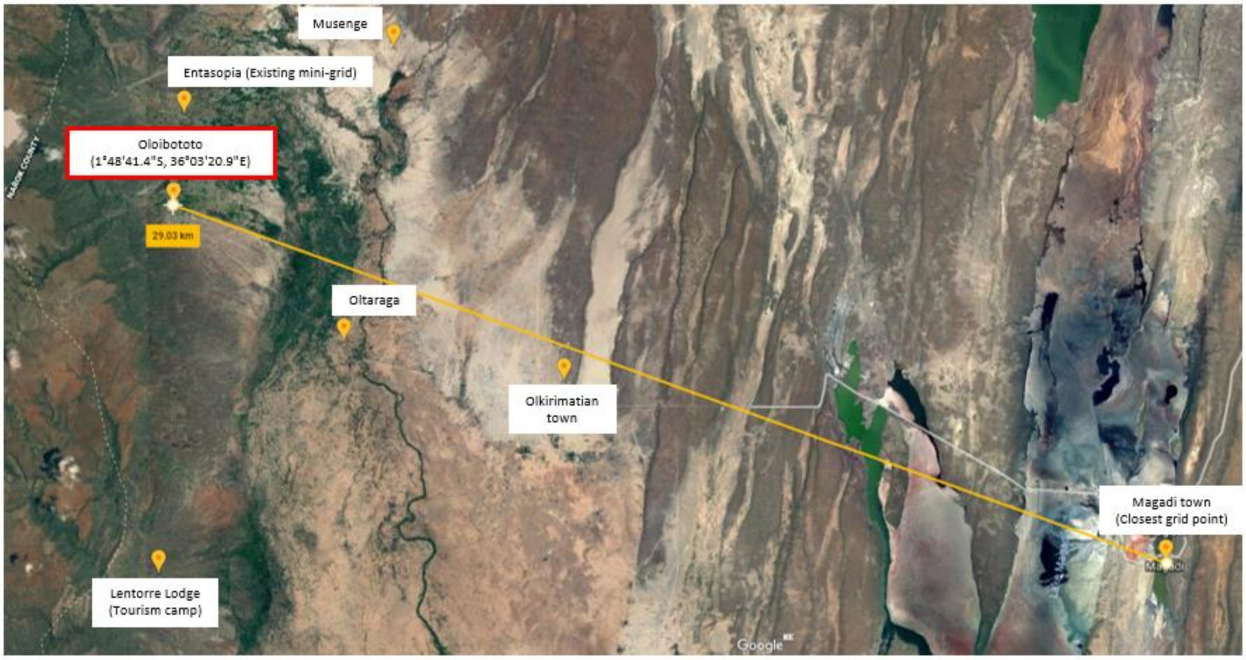

Figure 15: Location and positioning of pilot site in Olkirimatian conservancy

The town has a population of around 1,000 people and hosts a wide variety of institutions and businesses that do not have access to electricity or rely on pico-solar and/or solar home systems. From discussions in the field, community leaders welcomed the idea of a mini-grid and believed it would improve their socio-economic status. However, to design a mini-grid it is recommended to accommodate for future growth and cater for the anticipated load in 2-3 years [62]. Table 9

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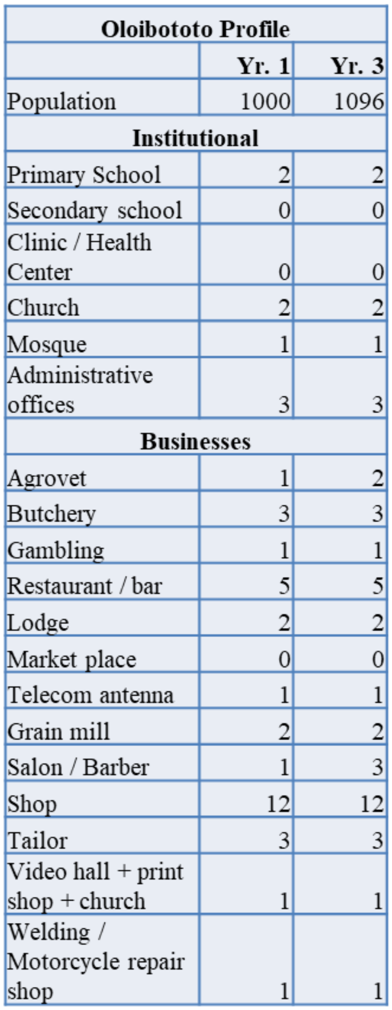
[7] https://www.gmgfacilitykenya.org/

shows a list of activities present at the time of visit (May 2018) as well as the projected activities for the year 2020.

Table 9: Population, businesses, and institutional activities in Oloibototo town [63]



Oloibototo Profile		
	Yr. 1	**Yr. 3**
Population	1000	1096
Institutional		
Primary School	2	2
Secondary school	0	0
Clinic / Health Center	0	0
Church	2	2
Mosque	1	1
Administrative offices	3	3
Businesses		
Agrovet	1	2
Butchery	3	3
Gambling	1	1
Restaurant / bar	5	5
Lodge	2	2
Market place	0	0
Telecom antenna	1	1
Grain mill	2	2
Salon / Barber	1	3
Shop	12	12
Tailor	3	3
Video hall + print shop + church	1	1
Welding / Motorcycle repair shop	1	1

Translating these activities in terms of their electrical consumption yields a load profile resembling Figure 16. The community is projected to have a daily electricity consumption of 171 kWh [63].

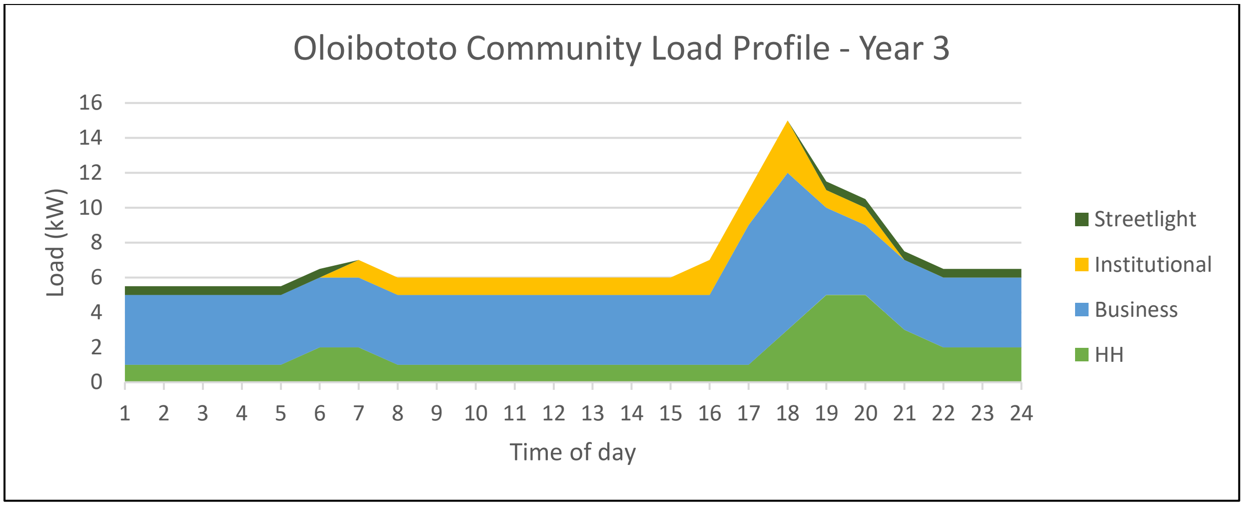


Figure 16: Projected load profile for the Oloibototo community in year 2020 [63]

The main assumptions the GMG Facility team used in their analysis are:

- Connection rate in year 1
    - 75% for households
    - 85% for businesses
    - 85% for institutional
- Consumption growth rate 2018 – 2020
    - 2% for households
    - 2% for businesses and institutional
- Coincidence factor of 0.9
- Seasonality not modeled

4.2. Motorcycle taxi modeling

4.2.1. Motorcycle taxi state-of-the-art and benchmark

The state of the art for the moto taxi activities in Oloibototo was formulated through a combination of literature review, key informant interviews, and observations in the field. A key informant interview was conducted on July 2018 with a representative of the Lentorre Tourism Lodge in Olkirimatian. The individual was an active member of the conservancy and had insights on the operations of the motorcycle taxi industry in Olkirimatian. The questions asked are attached in Appendix A and the key findings can be summarized as follows:

- The average income for an operator is 150 USD/month
- The approximate fare in Olkirimatian is 0.33 USD/km
- Operators spend on average 10 – 15 minutes in the town center, at the taxi stage, waiting for clients

- Hours of operation are on average are 10 hours per day on a "busy" day
- There are 50 motorcycle taxi operators in the entire Olkirimatian conservancy area
    - 30 based in the town of Entasopia alone (Note: Entasopia has a 5.6 kW green mini-grid)
    - Other towns have less than 10
- The rental fee for a motorcycle is 3 USD/day
- The average purchase price for a motorcycle is between 900 to 1,100 USD and they are typically low-cost models from Chinese or Indian manufacturers
- The community has never seen or heard of electric motorcycles
- Conservancy dwellers use motorcycle taxi transport for trips related to work, health, agriculture, dairy, and to transport people to the bus stop
- It is not common to commute by motorcycle taxi to school or to transport meat products
- Tourists and researchers in the conservancy use motorcycle taxis but not at a high rate
- There is no registered motorcycle taxi association

Although not all the questions during the interview could be answered, the key findings above can be considered accurate. The information on income is in line with other studies that supported a 2 to 7 USD daily income for moto-taxi operators in Kenya [29][64][65][32][33]. Furthermore, a daily rental fee of 3 USD is within the range of 2 to 5 USD, based on previous research [33][31][66][64]. A fare of 0.33 USD/km is within the range of 0.13 to 0.34 USD/km found in [31]. Although the distance traveled per month is not explicitly mentioned, an approximation using the fare and income would reveal operators travel approximately 455 km per month. However, to account for seasonal variability, a monthly average of 400 km was assumed for modelling. Fare elasticity is difficult to determine without a comprehensive survey or pilot study. Despite this lack of information, a study in a rural area of Kenya revealed that a 1% reduction in fares led to a 0.6% increase in journeys [67]. Therefore, a fare sensitivity of -0.6 was assumed for this model. Additionally, a study in rural Tanzania found that on average there were 8 to 10 motorcycle taxi operators per town as well [68]. From observations in the field and in literature, the most popular motorcycle brands in Kenya are Jingchen, TVS, Ranger, Bajaj motors, Star, Hero, Lion, Panther, and Haojin [69]. These motorcycles vary in price depending on whether they are used or new, but their purchase price in rural areas can range from 750 to 1,100 USD [33]. Monthly maintenance fees can be approximated to be between 10 and 30 USD [64]. Information on the technical characteristics of three models commonly found in Kenya is presented in Table 10. It is important to point out that the efficiency listed in Table 10 is from the manufacturer website and does not reflect rural driving habits. For modeling purposes, an efficiency of 40 km/L was used to reflect rural driving habits [37]. The interview revealed that operators tend to wait in the town center, though there was no mention on the time of day of their operations. However, a study in another rural area in Kenya surveyed the operators and found that most operate anytime on demand but the most common time of day was morning and evening [64]. Conversely, the least common time to operate was midday and at night. Additionally, a study found that operators typically engage in moto-taxi activities for 2 to 4 years [64].

Table 10: Technical characteristics of commonly found motorcycle models Kenya [70][71]

Vehicle	Boxer 100	Boxer 150	TVS Star HLX 150
Price	$750 - $1,200 USD		
Off-road?	Yes		
Manufacturer	Bajaj motors (India)	Bajaj motors (India)	TVS (India)
Engine	4 stroke, Natural air cooled, SI engine		
Engine displacement	99.27 cc	144.8 cc	147.99 cc
Max Power	6.03 kW @ 7500 RPM	8.83 kW @ 7500 RPM	8.9 kW @ 7500 RPM
Max Torque	8.05 Nm @ 4500 RPM	12.26 Nm @ 5000 RPM	12.3 Nm @ 5000 RPM
Frame	Steel	Steel	Steel
Fork	Hydraulic	Hydraulic	Hydraulic
Kerb Weight	109 kg	123 kg	119 kg
Fuel tank	9.3 L (2.2 L Reserve)	11.0 L (2.5 L Reserve, 1 L unusable)	12 L (2L reserve)
Fuel efficiency	55 km/L		60 km/L

4.2.2. Proposed electric vehicle solution

After reviewing several models and versions of electric two-wheelers the author proposes the UBCO 2x2 as a viable vehicle for rural motorcycle taxi operations. Technical and non-technical characteristics of the vehicle from the manufacturer are presented in Table 11. This model was selected based on its high range and gender-inclusive design. Although the UBCO 2x2 cannot reach a top speed that is comparable to an IC motorcycle, a max speed of 50 km/h is on par with the indicative speed of motorcycles in Table 1. The electric two-wheeler was treated as a typical AC appliance since it comes with a 100 – 220 V wall charger. Throughout the time that the EV is plugged in and charging, the power drawn was set to 350 W. Using the rated battery capacity, the energy that can be stored in the EV is 2.4 kWh. With a range of 120 km per charge, for modelling purposes the efficiency was assumed to be 50 km/kWh. Furthermore, the manufacturer does not list the expected maintenance expenses, so a value of 5 USD/day will be used [45]. Additionally, a lifetime of 50,000 km was used for modelling [72] [73].

Table 11: Technical and non-technical characteristics of UBCO 2x2 [74]

Vehicle	**UBCO 2x2**
Price	$5,300 USD
Off-road?	Yes
Manufacturer	Ubco Bikes (New Zealand)
Motor	Two 1 kW BLDC motors on each wheel
Max speed	50 km/h
Max Torque	184 N.m
Frame	Aluminum alloy
Fork	Hydraulic / Spring
Kerb Weight	65 kg
Carrying capacity including rider	150 kg including rider
Battery[1]	Li-ion 52.2 Ah (48Ah rated), 50 V
Charge time	6 – 8 hours
Charger type	100 – 240 V, 350 W, wall or bench mount
Range	120 km (depends on terrain and load)
Additional	✓ Gender inclusive design ✓ Removable battery ✓ Brake regeneration ✓ USB charger ✓ Handles gradients of up to 30% ✓ Water resistant (up to foot pegs) ✓ Very low maintenance (5% of the purchase price per year) ✓ No oil changes or engine specific replacements
Image	

Regarding the charging profiles, the author proposed a schedule that will restrict charging to daylight hours. Operators will understand that charging overnight would draw power from reserves dedicated to the welfare of the community. Enforcement methods are out of the scope of this thesis, but it is likely that operators would not want to compromise the wellbeing of their community members. Reducing the demand for electricity during the night will effectively reduce the size of batteries needed for the mini-grid. This will reduce the capital expenditure for the mini-grid, which will reduce the cost of electricity for the consumers. Therefore, the author set a charging schedule between 7 am and 5 pm. Mini-grids will be designed for the worst-case scenario, where all vehicles are charged all day. Furthermore, four scenarios with varying quantities of EVs will be assessed to examine the effect on technical and economic performance of the model. The five models from now on will be referred to as follows:

- No electric vehicles
- Small fleet: 5 vehicles
- Medium fleet: 10 vehicles
- Large fleet: 20 vehicles
- Conservancy wide: 50 vehicles

The corresponding charging profiles are illustrated in the figure below.

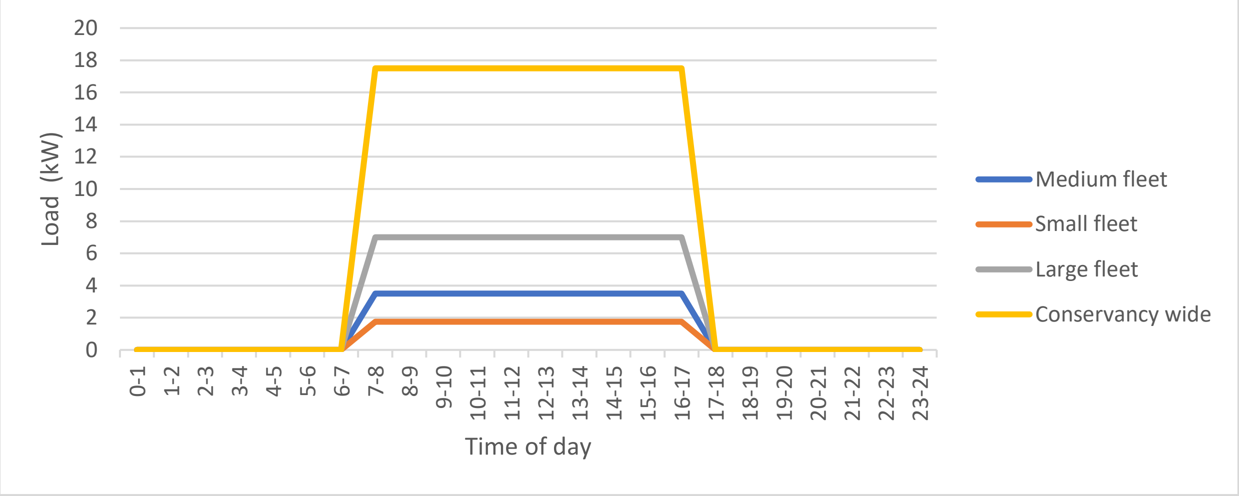


Figure 17: Electric load profiles for considered EV fleet sizes

4.3. Technical modelling

The mini-grid for the community was hybridized and has the following components: PV panels, lead-acid battery bank, inverter, and diesel generator. The system constraints are as follows:

- High share of renewables
- Greater than 24 hours of battery autonomy for community loads (excluding electric transport)
- 50% battery depth of discharge
- 40% minimal diesel generator load factor

This analysis will design 5 different mini-grids to compare the differences between the scenarios. The first mini-grid was designed without electric transport and served as a benchmark. The following mini-grids were designed to cater for the small, medium, large, and conservancy wide EV fleets. The author relied on the HOMER software to model the mini-grid and compare the technical and economic characteristics of each design. HOMER is a well-known software in the mini-grid industry developed by NREL, that is used to design, evaluate, and optimize off-grid and on-grid power systems. The user sets the components and necessary constraints into the model and the software generates an array of options based on the resources considered. The author used the generic components available in the software and followed the topology presented in Figure 18. Although, the figure presents two diesel generators, these are only included in the modelling process and ultimately a design that only has one of the generators was selected. Additionally, “Electric Load #2” refers to the EV power consumption. Appendix B details the load profiles for all mini-grid scenarios; no fleet, small fleet, medium fleet, large fleet, and conservancy wide fleet.

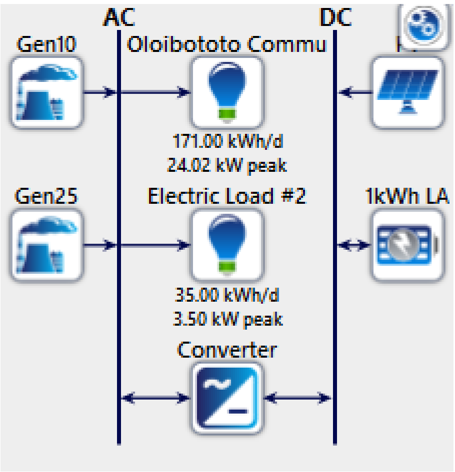


Figure 18: Mini-grid component topology in HOMER software

As mentioned earlier, the mini-grid should have a battery autonomy of at least 24 hours. Designers follow this protocol because it would ensure the community would have at least one day’s worth of electricity in the event of abnormal supply and/or demand behaviour. To ensure the system in Oloibototo has this reliability, a calculation of the community’s daily demand is used to find the necessary battery capacity to do so (Appendix C). With a daily load of 171 kWh, the generic lead-acid battery was set to 86 strings of 48 V.

In addition to the user’s decisions on sizing components, the HOMER software uses weather data to optimally size components according to the resources available. In this thesis, the author used meteorological data from NASA that is available in the HOMER software. Figure 19 presents the daily solar radiation and clearness index by month for Oloibototo. Additional technical and economic parameters of the components are presented in Appendix D.

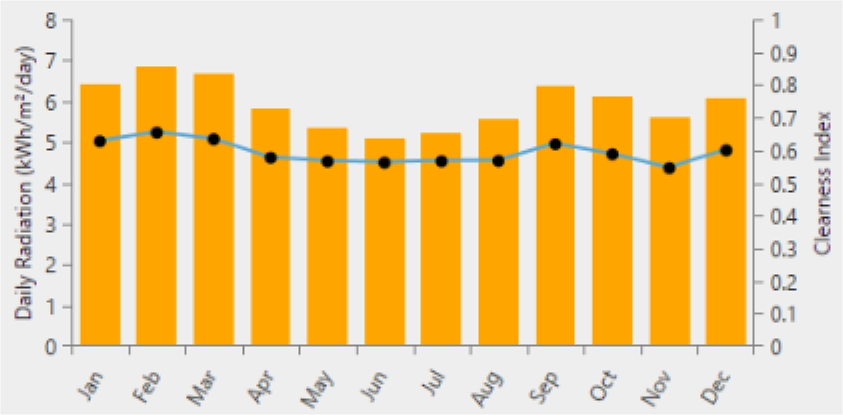


Figure 19: Monthly average solar GHI data for Oloibototo community

4.4. Financial model

This thesis examined the financial performance of the proposed solutions through a *Discounted Cash Flow Analysis*. DCF Analysis is used by investors to evaluate the attractiveness of an opportunity [75]. This method estimates the net present value of a project through discounting future cash flows with an annual discount rate. The *net present value* is derived using the following formula.

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o$$

Where,

C_t is the net cash inflow during a period t,

C_o is the total initial investment,

r is the discount rate,

t is the number of time periods.

The summation term in the above equation is referred to as the discounted cash flow. The present value is then interpreted by investors to gauge a project's potential and attractiveness. A positive NPV would indicate that the projected earnings by a project exceeds the anticipated costs. Generally, investors look for a positive NPV because it would indicate a project could be profitable. A project with a negative NPV will result in a net loss for the investor. An additional metric to measure a project's economic attractiveness is the *internal rate of return*. The IRR is the discount rate that would make the NPV of all cash flows equal to zero. It relies on the same formula above, but the NPV is set to zero and solved for the discount rate. When comparing projects, an investor would find the project with the highest IRR more desirable. The IRR reflects the rate of growth a project is expected to generate. This is useful when project developers need to decide between options of either establishing new operations or expanding existing ones. Alongside the NPV and IRR, investors also evaluate the project's *payback period*. The payback period is the length of time required to recover the project's investment. Projects with long payback periods are undesirable because investors typically want to recover their investment as soon as possible.

This thesis evaluated three different DCF models for both IC and electric motorcycles. A breakdown of the models and their respective cash flows are presented in Table 12. It is important to note that insurance and registration fees were excluded from the cash outflows because Kenya has not yet set regulations regarding EV use. To simplify the analysis, those expenses are assumed to be constant for both IC and EV scenarios and therefore excluded from the DCF model. Furthermore, the operator's venture lifetimes were set to four years because most operators tend to engage in moto-taxi activities for a maximum of four years, due to the physically strenuous nature of the profession. The fleet owner venture lifetime is derived from the expected lifetime of the electric motorcycle of 50,000 km, factored with an average of 400 km covered each month. This suggests a lifetime of over ten years but to account for uncertainties, the author assumed a lifetime of eight years.

Table 12: Overview of motorcycle taxi financial models

Financial model	Cash outflows	Cash inflows	Venture lifetime
Owner-operator	• Capital expenditure • Fuel costs • Maintenance	• Taxi fare	• 4 years
Renter-operator	• Rental fee • Fuel costs • Maintenance	• Taxi fare	• 4 years
Fleet owner	• Capital expenditure • Maintenance	• Rental fee collection	• 8 years

The DCF analysis in this thesis broke down the monthly cash flows and employed an annual discount rate of 8%. Additionally, operators were considered to only work 24 days of the month while fleet owners collected payments everyday of the month (30 days). Analysis in further sections assessed the sensitivity of the system regarding the fuel price, cost of electricity, fare price, and cost of EV. However, the benchmark for the distance covered per month, fare, and daily rental fee are 400 km, 0.33 USD/km, and 3 USD, respectively. When changing the fare price, the model will adjust the distance covered per month accordingly based on an elasticity of -0.6.

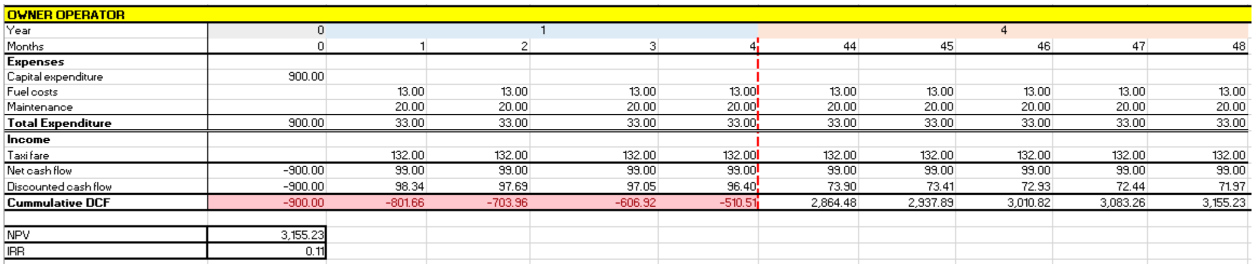
4.4.1. Owner-operator model

The owner-operator DCF model reflected a scenario in which an operator bought a motorcycle with their own savings and operated as a self-employed entity. The owner-operator was responsible for the full capital cost of the vehicle, as well as the recurring fuel and maintenance costs. Values and calculation methodology for the cash flows prescribed to the owner-operator are presented in Table 13.

Table 13: Parameters for owner-operator financial model

Parameter	Value
OWNER-OPERATOR	
Fare	0.33 USD/km
Distance covered per month (Δ)	400 km
Taxi fare cash inflow	$Fare * \Delta$
IC Motorcycle	
Capital expense	900 USD
Monthly maintenance	20 USD
Fuel efficiency (η_{IC})	40 km/L
Petrol price (PP)	1.1, 1.3, 1.5, and 1.7 USD/L
Fuelling costs	$\frac{PP * \Delta}{\eta_{IC}}$
Electric Motorcycle	
Capital expense	5,300 USD
Monthly maintenance	5 USD
Motor efficiency (η_E)	50 km/kWh
Cost of electricity (COE)	Depends on results from HOMER
Fuelling costs	$\frac{COE * \Delta}{\eta_E}$

Figure 20 illustrates the DCF model for an owner-operator in an excel spreadsheet.



OWNER OPERATOR										
Year	0	1				4				
Months	0	1	2	3	4	44	45	46	47	48
Expenses										
Capital expenditure	900.00									
Fuel costs		13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00
Maintenance		20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Total Expenditure	900.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Income										
Taxi fare		132.00	132.00	132.00	132.00	132.00	132.00	132.00	132.00	132.00
Net cash flow	-900.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
Discounted cash flow	-900.00	98.34	97.69	97.05	96.40	73.90	73.41	72.93	72.44	71.97
Cummulative DCF	-900.00	-801.66	-703.96	-606.92	-510.51	2,864.48	2,937.89	3,010.82	3,083.26	3,155.23
NPV	3,155.23									
IRR	0.11									

Figure 20: Owner-operator financial model in Excel spreadsheet

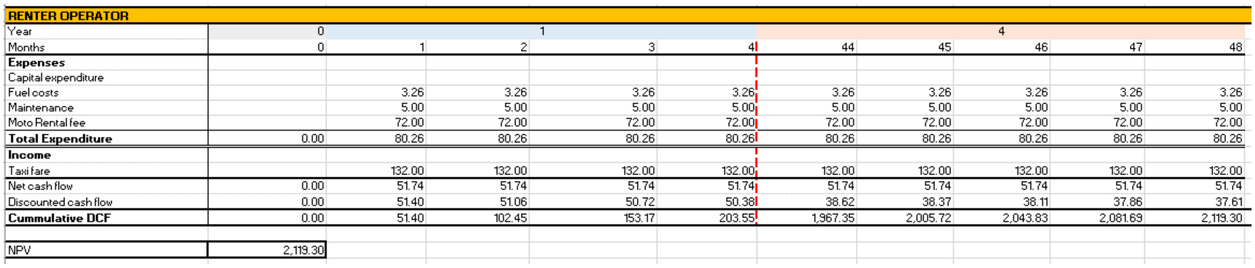
4.4.2. Renter-operator model

The renter-operator DCF model reflected a scenario in which an operator rented a motorcycle from a fleet owner for a daily rate. The owner-operator was responsible for recurring fuel and maintenance costs as well as the rental fee. Values and calculation methodology for the cash flows prescribed to the owner-operator are presented in Table 14.

Table 14: Parameters for renter-operator financial model

Parameter	Value
RENTER-OPERATOR	
Fare	0.33 USD/km
Distance covered per month (Δ)	400 km
Taxi fare cash inflow	$Fare * \Delta$
Days worked per month	24
Daily rental fee	3 USD
IC Motorcycle	
Monthly maintenance	20 USD
Fuel efficiency (η_{IC})	40 km/L
Petrol price (PP)	1.1, 1.3, 1.5, and 1.7 USD/L
Fuelling costs	$\frac{PP * \Delta}{\eta_{IC}}$
Electric Motorcycle	
Monthly maintenance	5 USD
Motor efficiency (η_E)	50 km/kWh
Cost of electricity (COE)	Depends on results from HOMER
Fuelling costs	$\frac{COE * \Delta}{\eta_E}$

Figure 21 illustrates the DCF model for a renter-operator in an excel spreadsheet.



RENTER OPERATOR										
Year	0	1				4				
Months	0	1	2	3	4	44	45	46	47	48
Expenses										
Capital expenditure										
Fuel costs		3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26
Maintenance		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Moto Rental fee		72.00	72.00	72.00	72.00	72.00	72.00	72.00	72.00	72.00
Total Expenditure	0.00	80.26	80.26	80.26	80.26	80.26	80.26	80.26	80.26	80.26
Income										
Taxi fare		132.00	132.00	132.00	132.00	132.00	132.00	132.00	132.00	132.00
Net cash flow	0.00	51.74	51.74	51.74	51.74	51.74	51.74	51.74	51.74	51.74
Discounted cash flow	0.00	51.40	51.06	50.72	50.38	38.62	38.37	38.11	37.86	37.61
Cummulative DCF	0.00	51.40	102.45	153.17	203.55	1,967.35	2,005.72	2,043.83	2,081.69	2,119.30
NPV	2,119.30									

Figure 21: Renter-operator financial model in Excel spreadsheet

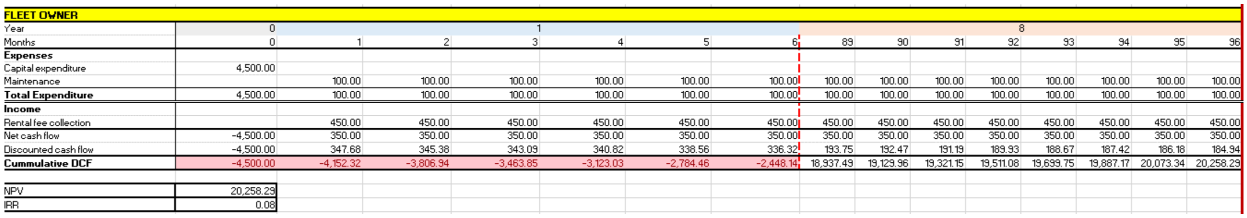
4.4.3. Fleet owner model

The fleet owner DCF model reflected the scenario in which an individual or organization has capital to invest in a profitable venture. The capital was used to purchase a fleet of vehicles and the costs were recovered through the collection of rental fees. Although the operator is responsible for maintenance, the fleet owner had to take care of major repair works. Values and calculation methodology for the cash flows prescribed to the owner-operator are presented in Table 15.

Table 15: Parameters for fleet owner financial model

Parameter	Value
FLEET OWNER	
Fleet size	5, 10, 20, and 50 vehicles
Fee collection days per month	30
Daily rental fee per vehicle	3 USD
IC Motorcycle	
Monthly maintenance per vehicle	20 USD
Electric Motorcycle	
Monthly maintenance per vehicle	5 USD

Figure 22 illustrates the DCF model for a fleet owner in an excel spreadsheet.



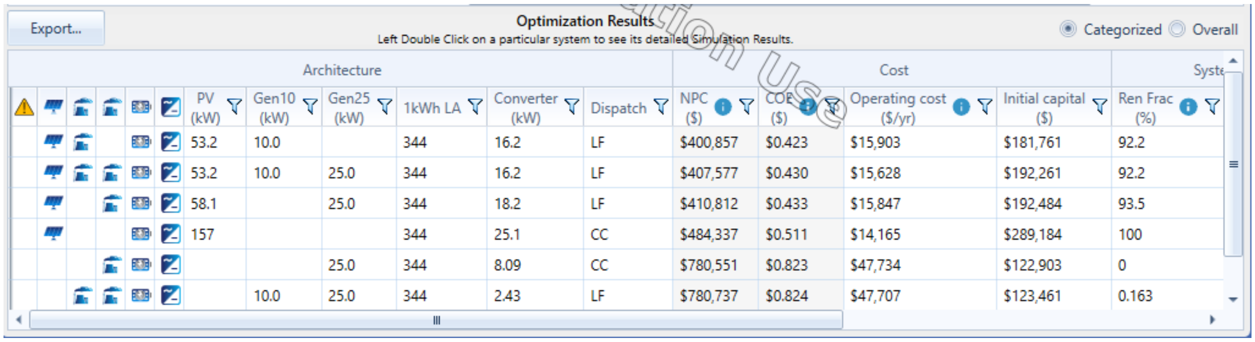
FLEET OWNER															
Year	0	1						8							
Months	0	1	2	3	4	5	6	89	90	91	92	93	94	95	96
Expenses															
Capital expenditure	4,500.00														
Maintenance		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Total Expenditure	4,500.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Income															
Rental fee collection		450.00	450.00	450.00	450.00	450.00	450.00	450.00	450.00	450.00	450.00	450.00	450.00	450.00	450.00
Net cash flow	-4,500.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00
Discounted cash flow	-4,500.00	347.68	345.38	343.09	340.82	338.56	336.32	193.75	192.47	191.19	189.93	188.67	187.42	186.18	184.94
Cummulative DCF	-4,500.00	-4,152.32	-3,806.94	-3,463.85	-3,123.03	-2,784.46	-2,448.14	18,937.49	19,129.96	19,321.15	19,511.08	19,699.75	19,887.17	20,073.34	20,258.29
NPV	20,258.29														
IRR	0.08														

Figure 22: Fleet owner financial model in Excel spreadsheet

5. Results and discussion

5.1. HOMER results

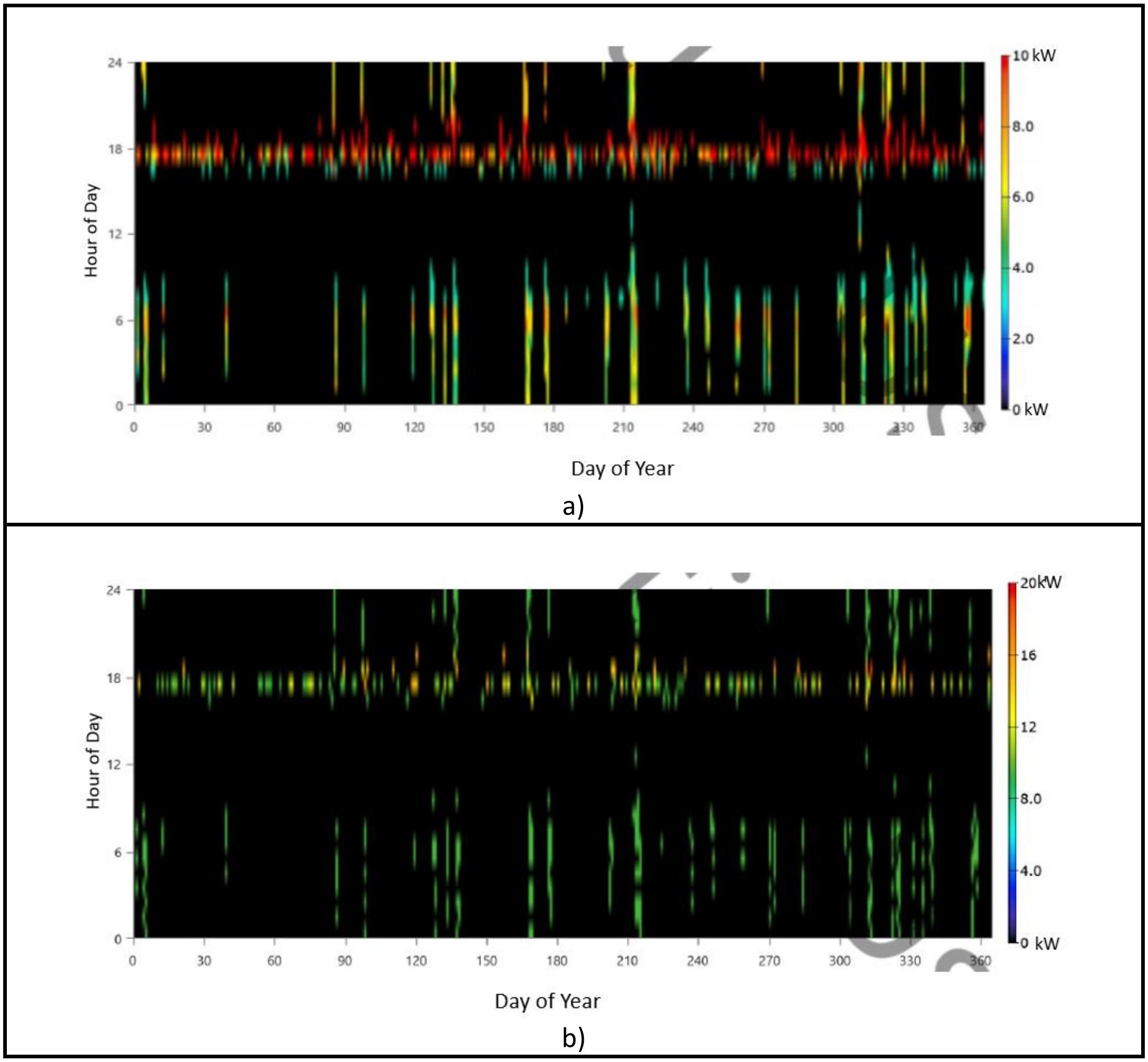
After constructing the technical models in the HOMER software, simulations analyzed various scenarios and presented them in a list of increasing COE (Figure 23). The developer is free to choose any design but generally results with a low COE are favoured.



Architecture												Cost				Syste
⚠						PV (kW)	Gen10 (kW)	Gen25 (kW)	1kWh LA	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
	●	●		●	●	53.2	10.0		344	16.2	LF	$400,857	$0.423	$15,903	$181,761	92.2
	●	●	●	●	●	53.2	10.0	25.0	344	16.2	LF	$407,577	$0.430	$15,628	$192,261	92.2
	●		●	●	●	58.1		25.0	344	18.2	LF	$410,812	$0.433	$15,847	$192,484	93.5
	●			●	●	157			344	25.1	CC	$484,337	$0.511	$14,165	$289,184	100
			●	●	●			25.0	344	8.09	CC	$780,551	$0.823	$47,734	$122,903	0
		●	●	●	●		10.0	25.0	344	2.43	LF	$780,737	$0.824	$47,707	$123,461	0.163

Figure 23: Small fleet HOMER optimization results list

In this case, the author selected the mini-grid with the lowest COE and only one diesel generator. However, the author assessed the diesel generator output of the designs to avoid the genset running at peak output for an extended period. Figure 24a presents the generator output for the design with the lowest COE for a small fleet case. Despite the low COE, this design required the genset to operate almost everyday between 17:00 and 18:00 at 10 kW. In an off-grid setting, this is unfavourable because it will shorten the lifespan of the genset and require more frequent maintenance which is costly for remote areas where access to spare parts is limited. Therefore, the author selected a design that had favourable diesel generator behaviour, as illustrated in Figure 24b.



a)

b)

Figure 24: Generator output for small fleet design with a) 10 kW genset and b) 25 kW genset

Similar trends were observed across all proposed mini-grids designs and ultimately the 25 kW generator was chosen over the 10 kW option. Figure 25 summarizes the capacity of the system components for all mini-grid designs. PV and converter capacity for the no fleet case was found to be 52.9 kW and 16.6 kW, respectively. Intuitively, it was observed that introducing EVs increased the PV and converter capacity for the mini-grid. For a small fleet the PV capacity was found to be 58.1 kW and for the conservancy wide case 116 kW. This increase in capacity is caused by the increased electrical load in the system. Although the batteries are excluded from the figure, from the discussion in the previous section each mini-grid had 86 strings of batteries with a nominal capacity of 83.4 Ah.

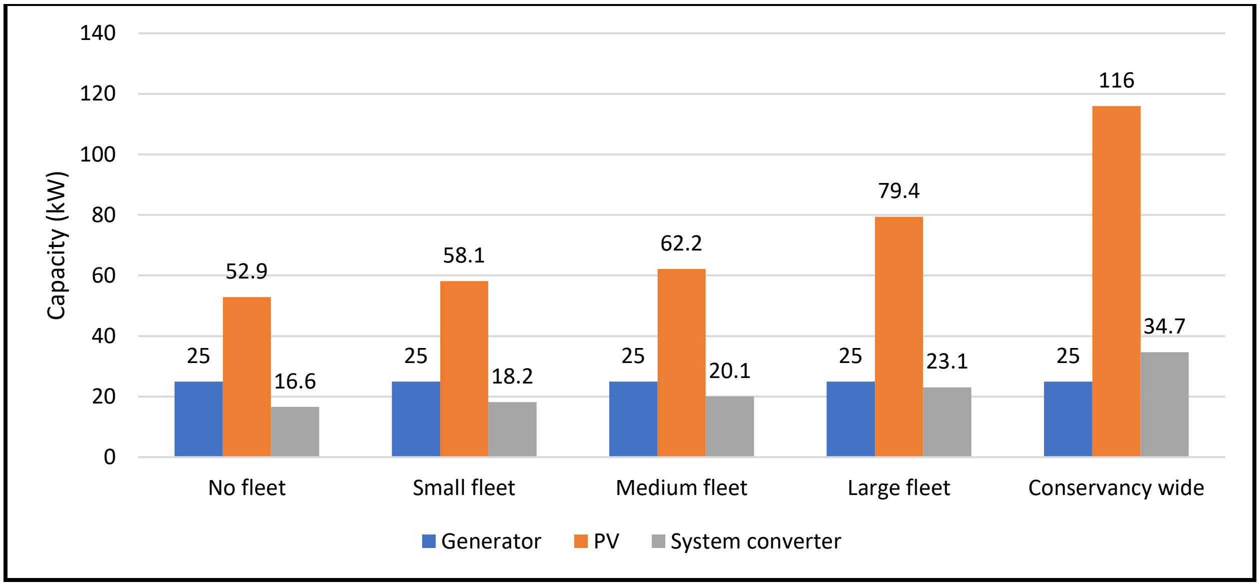


Figure 25: Mini-grid component capacities summary

Furthermore, the proposed component capacities are expected to have energy production behaviour illustrated in Figure 26. Total annual generation for the no fleet case was found to by 93,914 kWh, while the conservancy wide case was 200,899 kWh. On average, each additional vehicle reflected an increased annual production of roughly 1,888 kWh ± 17.4%. Notedly, each design had a renewable energy fraction above 90%, which can be considered as "high share" and therefore satisfies this system constraint.

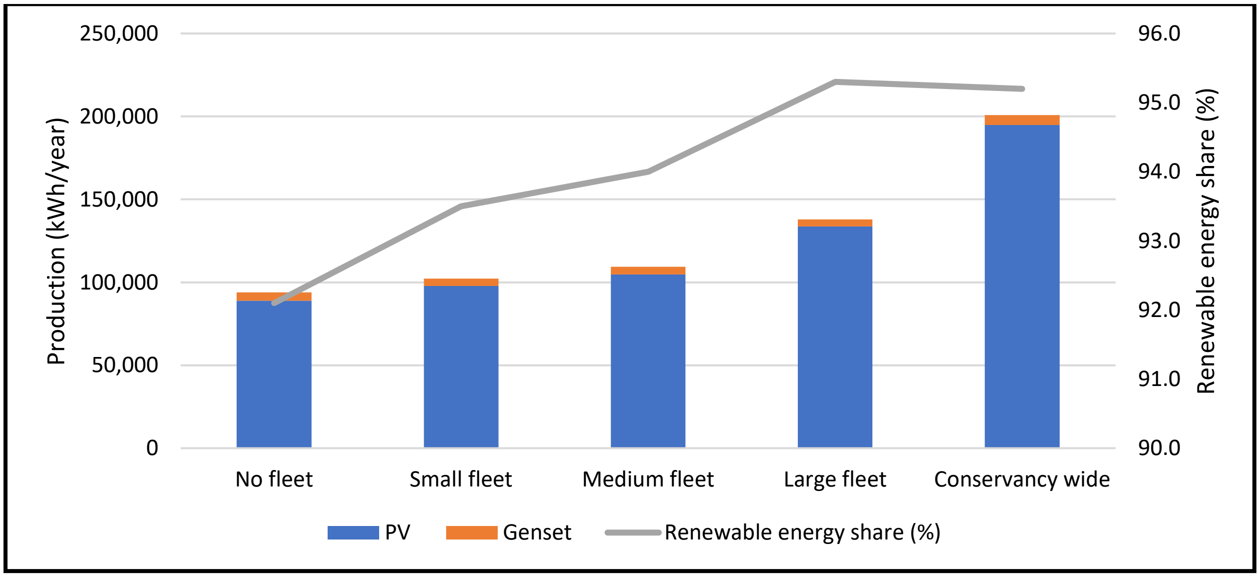


Figure 26: Annual electricity production and renewable energy share summary

Given the system is designed to have a high share of renewable energy, the battery autonomy was assessed in case of days with poor PV generation. From Figure 27, autonomy in the no fleet scenario has 24-hour reliability, which is expected from the calculations in Appendix C. However, since the battery size was fixed for all designs, the increasing EV fleet was detrimental to the autonomy. This was the result of limitations in the software that prohibited isolating the EV load from battery sizing. With a fleet size of 50 vehicles, the results from HOMER suggested the community will have an autonomy of roughly 12 hours. Realistically, all motorcycle taxi operators will not be charging their vehicles everyday. With a range of 120 km per charge and monthly travel distance of 400 km, a single charge should last an operator over a week. This means that the operators are unlikely to be charging all the vehicles everyday, however with limited data on the travel patterns and behaviour of rural moto-taxis the author opted for designing for the “worst case scenario”. For a future study, it would be interesting to investigate the behaviour of “Vehicle 2 Grid” communication. This way, the batteries from the EVs can also be used as a storage solution for the mini-grid itself.

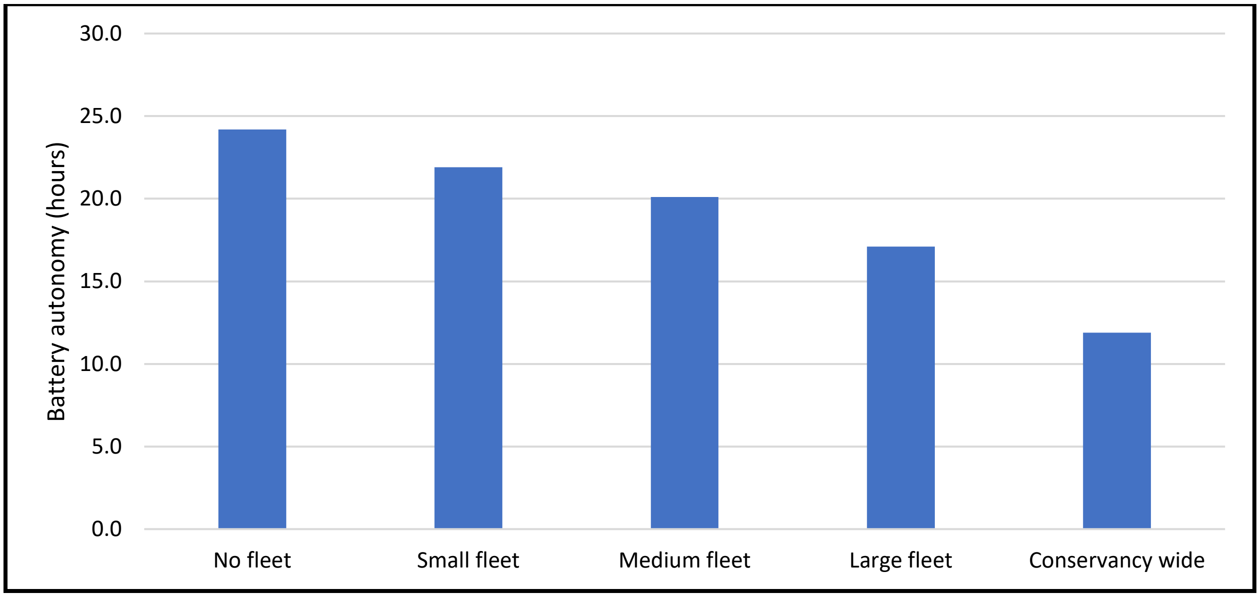


Figure 27: Battery autonomy summary

In addition to the technical performance of the mini-grid, it is important to assess the financial outputs of the HOMER designs. Figure 28 illustrates and summarizes the key financial metrics of each design. From the figure, the total net present cost, capital, and operating costs increase with increasing fleet size. The net present cost for the benchmark case was found to be 400,469 USD – of which 185,398 USD is capital and 59,651 USD is operating expenses. Intuitively, installing the system capacity needed to cater for the EVs increased the capital and operating costs. Introducing 5 EVs increased the net present cost, capital costs, and operating costs to 410,812 USD, 192,484 USD, and 60,139 USD, respectively. While a conservancy wide electrification scenario resulted in 525,069 USD, 268,806 USD, and 69,543 USD for net present, capital, and operating costs, respectively. Generally, full electrification of the conservancy’s moto-taxis reflected a 31.11%, 44.99%, and 16.58% increase in net present, capital, and operating costs in comparison to the no fleet case. Interestingly, the LCOE decreased with increasing fleet size. With no EVs the LCOE was found to be 0.466 USD/kWh, while in the conservancy-wide case 0.302 USD/kWh. The difference between the LCOE between the no fleet scenario and conservancy wide case is roughly 35.19%. Following the equation for LCOE in Section 3.3, this decrease in LCOE can be explained by the increase in electricity production through a cost-effective technology, which in this case is PV. This is a drastic decrease in the cost of electricity, which is favourable to a community with a low ability to pay. With a lower LCOE, it is likely that more residents of the Oloibototo will be able to afford access to electricity, which could improve the wellbeing of the community.

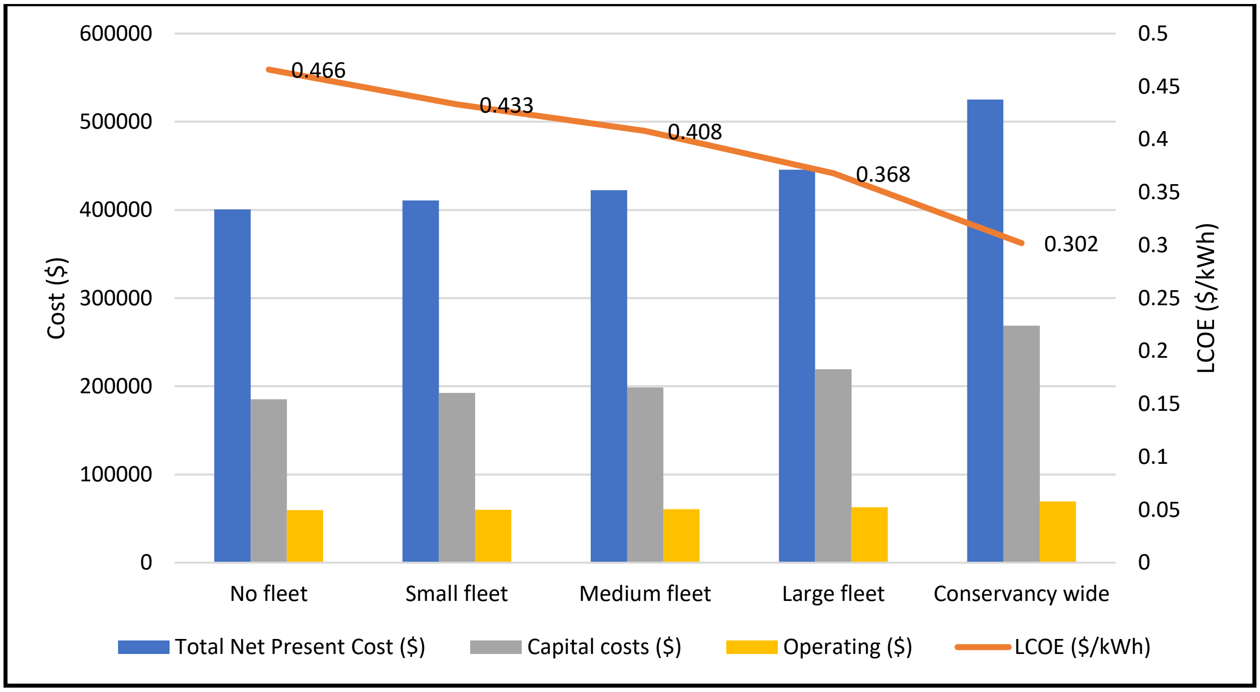


Figure 28: Mini-grid cost and LCOE summary

Although much of the energy generated in the mini-grid is from emission-free solar resources, the diesel generator produces CO2 which compromises the environmental impact of the system. The CO2 emissions and genset operational hours for each design is illustrated in Figure 29. The no fleet case yielded 4.46 tonnes of CO2 per year, while the small and conservancy wide case yielded 4.12 and 5.54 tonnes of CO2 per year, respectively. From the figure, there is no clear correlation between fleet size and CO2 emissions. However, it is observed that higher hours of operation correlate to more CO2 emissions.

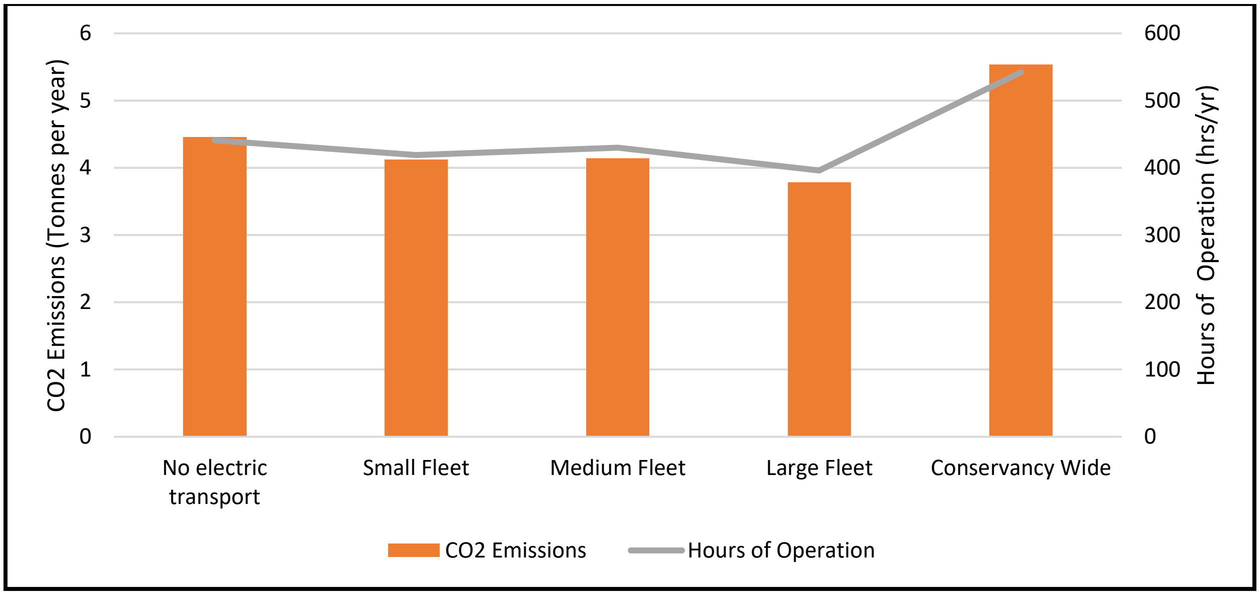


Figure 29: CO2 emissions summary

Although the charging schedule for the EVs was designed to capitalize on the solar energy from daylight hours. Comparing Figure 30a with 30b the diesel generator was used to charge the EVs. In Figure 30b, between 6:00 and 12:00 the diesel generator is engaged to serve the system load. To avoid this, a more detailed study on the daily routine of moto-taxis is needed to develop an optimal charging schedule. Alternatively, a smart charger can be programmed and implemented into the system to make sure only solar energy is charging the EV batteries. However, this was out of the scope of this thesis and not covered. However, it would be valuable for a further study on this issue.

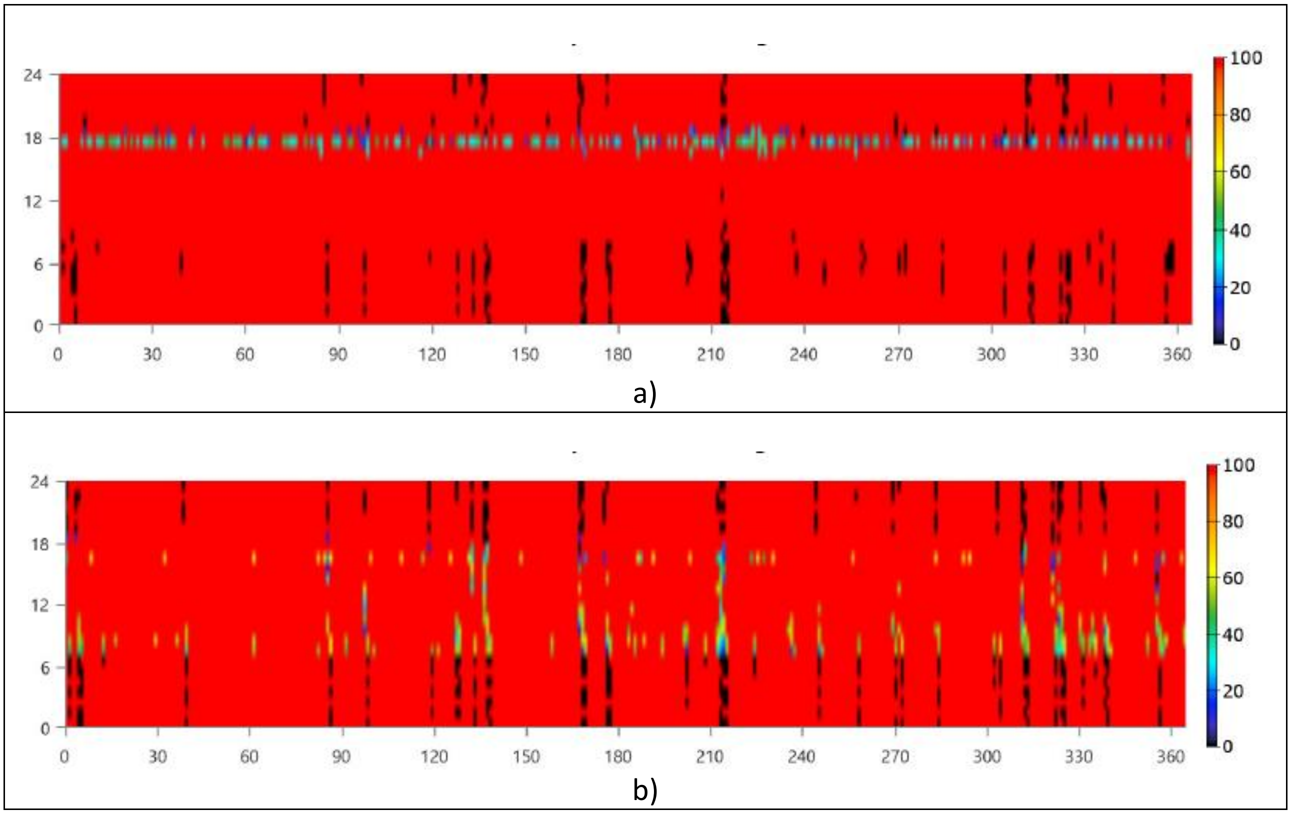


Figure 30: 100% minus instantaneous non-renewable output as percentage of total load for a) no EV case and b) conservancy wide case

5.2. Motorcycle taxi results

5.2.1 Operator benchmarking

This section will present the results of the DCF analysis detailed in Section 4.4.1. and 4.4.2. As discussed, the NPV of a project is used to gauge its attractiveness and potential. Figure 31 presents a comparison of the NPV as a function of the price of fuel and cost of electricity for the IC motorcycle and electric motorcycle case, respectively. Although the results vary based on the fuel price, they indicated an NPV for the IC motorcycle owner and renter of 3,114 USD ± 3.4% and 1,065 USD ± 9.9%, respectively. Furthermore, for the electric case, the owner had an NPV of -222 USD ± 8.5% and for the renter 2,129 USD ± 0.9%. It is clear that in the case of the IC motorcycle, the owner-operator benefits over the renter-operator – with a higher NPV for all fuel prices. This is because the owner-operator does not have to pay the daily rental fee. With a motorcycle cost of 900 USD, the owner-operator can recover the capital expenditure within ten months. Afterwards, the operator is no longer burdened with the cost to own the vehicle. In the renter case however, the operator must continually pay a fee for using the vehicle on top of the fuel and maintenance costs. Conversely, in the electric motorcycle case the owner-operator exhibits a negative NPV that is roughly 110% lower than the NPV of the renter-operator. This is because the electric motorcycle is relatively expensive, and the operator does not recover the capital costs within four years. However, the renter-operator experiences an NPV that is almost double the NPV of the IC motorcycle renter-operator case. Since the rental fee in both cases is constant, this trend can be attributed to the lower fuel and maintenance costs of the electric motorcycle. Notedly, in both electric cases the NPV improved with a decrease in COE which is the result of lower operating costs.

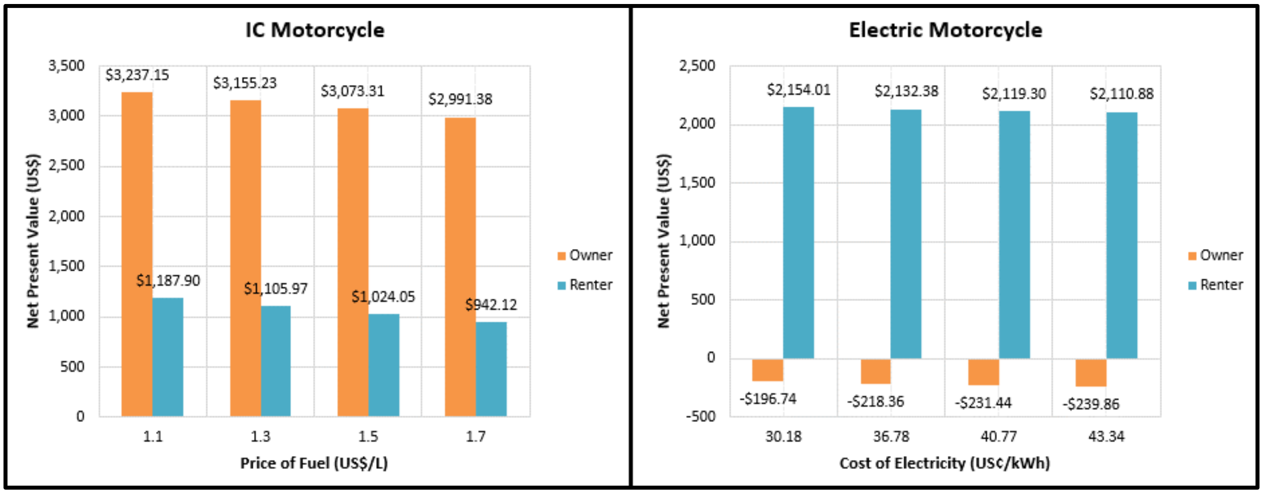


Figure 31: NPV for IC and electric motorcycles

The operational costs for a motorcycle can be broken down into two components; the maintenance and fueling. Both are a function of the distance traveled and driving habits of the operator. Maintenance for a combustion motorcycle is cumbersome and involves frequent check ups on various components, some of which includes; replacing the clutch, syncing the throttle and idle speed, changing filters (for engine oil, fuel, and air intake), checking/changing engine oil, lubricating choke cables, adjusting valve clearances, replacing the timing belt, checking external fuel hoses, replacing spark plugs, adjusting clutch cables, and checking the clutch fluid level. In comparison to an EV, the maintenance of the UBCO 2x2 is much simpler. With an EV all maintenance regarding combustion or the bike chain is omitted. Additionally, the electric motorcycles in this study employ regenerative braking which slows the wear on the brake pads. However, the motor and battery components do require regular cleaning, which can easily be incorporated into the operators' existing cleaning regiment. A potential risk that could drastically increase the cost of maintenance would be replacing the battery and to a lesser extent, the motor. On the manufacturer's website, a spare battery for the UBCO 2x2 is roughly 1,300 USD [74]. If the battery would need to be replaced within the four years, it would have a significantly negative impact on the financial performance of the venture. Furthermore, it is important to note that the assumptions on maintenance fees for the EV were based on a case in an urban area, where there was an abundance of electric motorcycles [45]. Given that EV technologies have not yet entered the rural African market at first, the actual costs for spare parts will be higher since a supply chain from the manufacturer to the market has not been established. The model in this thesis assumed a scenario in which EV technologies were as common in SSA as they are in other countries with a mature electric motorcycle market. To reach a price point for maintenance that is on par with the assumptions, a critical mass of users would need to be reached. An additional study into the necessary critical mass and barriers to entry in a rural SSA context would be necessary.

The second component of the operational costs is the fueling. Fueling costs are related to the price of fuel and price of electricity for the IC motorcycle and EV, respectively. An IC motorcycle converts chemical energy from a fuel (petrol) to mechanical energy through a combustion process in the vehicle's engine. This process is limited by the laws of thermodynamics to a maximum of 60% (The Carnot Efficiency) due to thermal losses that cannot be recovered [76]. Alternatively, an EV converts chemical energy from a battery to electric energy that powers a motor that ultimately propels the vehicle with mechanical energy. This process capitalizes on technological advances in power electronics and electric motors to reach efficiencies upwards of 89%. A comparison of the fueling costs as a function of the distance traveled for IC and EV motorcycles in the Oloibototo case study are illustrated in Figure 32. From the results, the fueling costs for an electric motorcycle are 78.8% cheaper compared to the IC motorcycle. This difference is a major advantage for the electric motorcycle operator since the price of fuel is much higher in remote areas and subject to volatile and unpredictable fluctuations. Recently, the government of Kenya implemented a 16% VAT on all fuel products starting on September 1st, 2018 [36]. This decision came as a surprise to many Kenyans and will disproportionally affect impoverished rural dwellers, where the price of petrol is already at a premium due to the logistical costs of transporting the fuel to their communities.

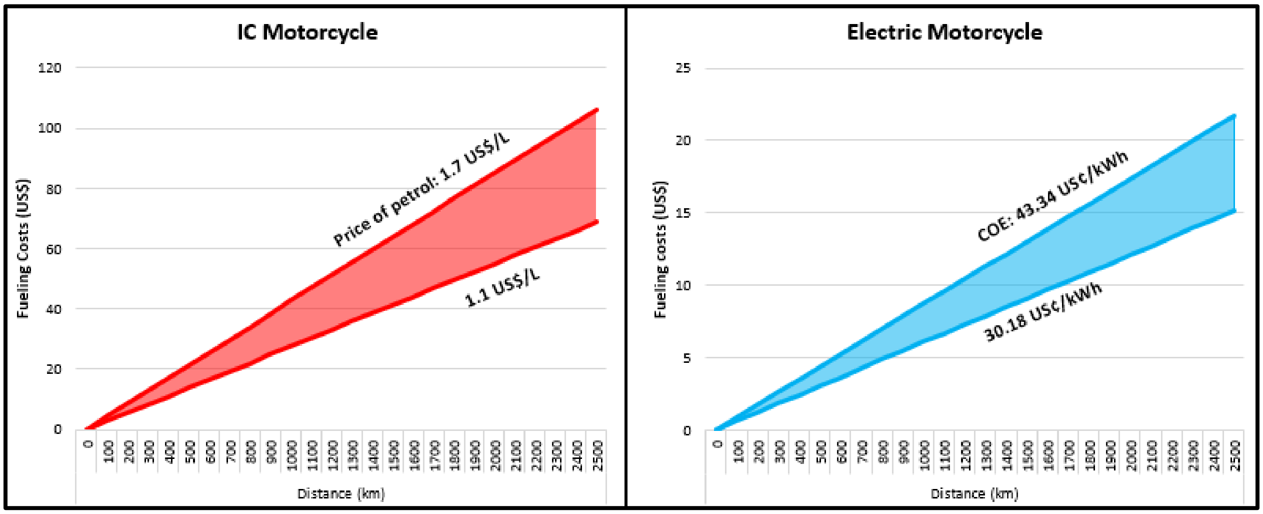


Figure 32: Fueling costs for IC and electric motorcycles

5.2.1.1. Owner-operator analysis

In the previous section, it was evident that an owner-operator with an IC motorcycle achieved a positive NPV while the electric case had a negative NPV. Since the income for both cases remained constant an examination of the cumulative expenses over the project's lifetime would provide insight into the cause of this observation. Figure 33 illustrates a breakdown of the cumulative expenses over an owner-operator's venture lifetime for both the IC and electric motorcycle case. Between the two options for vehicles, it is clear that the cumulative expenses for an electric motorcycle are greater than the IC motorcycles, by a factor of 2.3. However, the cost breakdown for both cases is drastically different. In the IC motorcycle case, the cumulative expenses are almost evenly split across the capital expenditure, fueling costs, and maintenance. However, in the electric motorcycle case, the capital expenditure accounts for 94% of the cumulative expenses. This expenditure is roughly six times greater than that of the IC motorcycle. Conversely, when comparing the costs for fueling and maintenance, the IC motorcycle operator pays roughly four times more than the electric motorcycle counterpart.

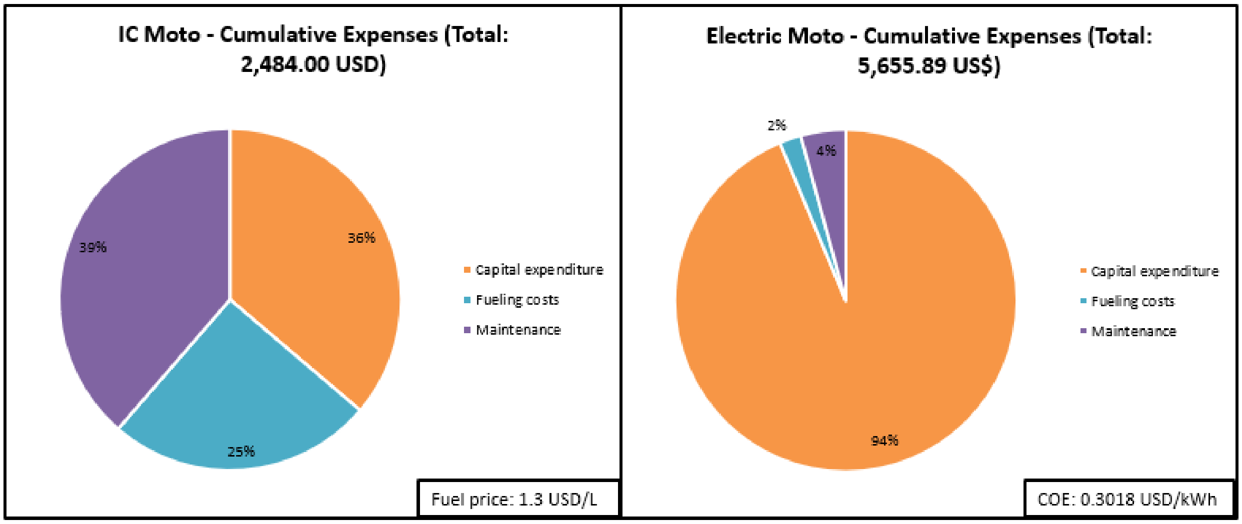


Figure 33: Cumulative expenses for IC and electric motorcycles

From the previous discussion, the initial cost of an electric vehicle is too high to be profitable for an owner-operator. Despite this inconvenience, from the discussion in Section 3.2, there is reason to believe that the price of EV technologies is likely to decrease as the technology matures. Therefore, it is important to establish the EV price point that would achieve NPV parity with the IC motorcycle operator. Parity occurs when the NPV of the IC motorcycle case is equal to the electric case. Figure 34 presents the NPV parity price for the electric motorcycle as a function of the cost of electricity, for varying fuel price scenarios. Generally, the results indicated that the price of electric motorcycles should decrease by 60 – 65 % to yield the same NPV as an IC moto-taxi owner-operator. This translates to price points between 1,820 USD and 2,120 USD. In a scenario with conservancy-wide moto-taxi electrification and the price of fuel from May 2018, an EV with a price of 1,948 USD would achieve the same NPV as an IC moto-taxi operator. From the author's experience, there are electric two-wheelers available on the market that reach these price points and lower. However, these other models had limited data and worse performance than the model selected for this analysis. Nevertheless, this proves that it is possible for electric motorcycles to reach this price point and that a further study should develop a vehicle that would specially cater to the needs of a rural SSA context. Additionally, the analysis done by Berckmans et al., it is possible that the cost of batteries, which drives the cost of EVs, can decrease by 60% as early as the year 2025. However, these projections to vulnerable to a wide array of events and scenarios that could hinder or accelerate these speculations.

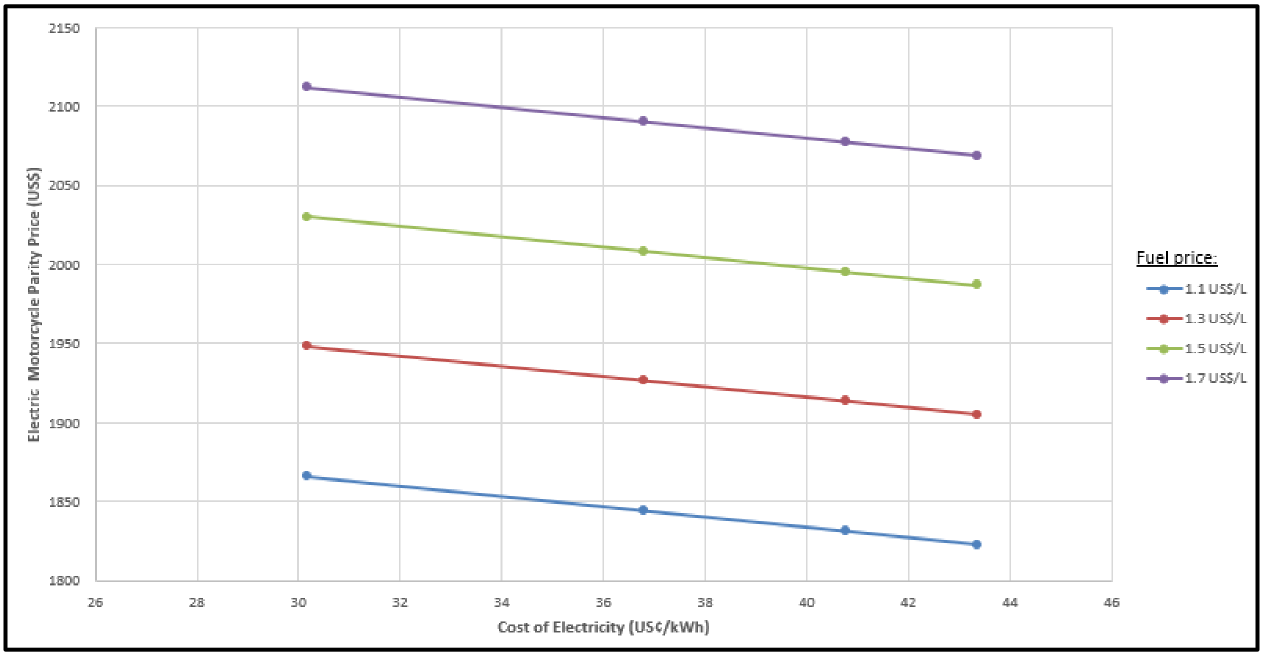


Figure 34: NPV parity price for electric motorcycle

Lastly, it is important to assess whether electric motorcycles could decrease the cost of transport for rural communities. To do so, the fare price should be lower so that more people could afford the transport service. However, from an operator's perspective, it is important that the venture is still profitable, meaning that the NPV is positive and high enough to be attractive. From the discussion above, it was established that the electric motorcycle was expensive and led to a negative NPV. Considering that a lower fare price would worsen the NPV, Figure 35 illustrates the NPV for varying fares as a function of the electric motorcycle price. As expected, with the electric motorcycle price of 5,300 USD, lowering the fare to 0.15 USD/km worsened the NPV to less than -2,000 USD. However, if the price of the motorcycle were halved the owner-operator could achieve a positive NPV for fares of 0.15 USD/km or more. From the previous discussion, the NPV parity electric vehicle price was found to 1,948 USD for a conservancy-wide electrification scenario at May 2018 fuel prices. At this EV price, an owner-operator could achieve an NPV of 1,776 USD while charging a fare of 0.20 USD/km. This NPV exceeds the NPV of an IC renter-operator which would suggest that operators could consider EVs as an option should they reach lower price points.

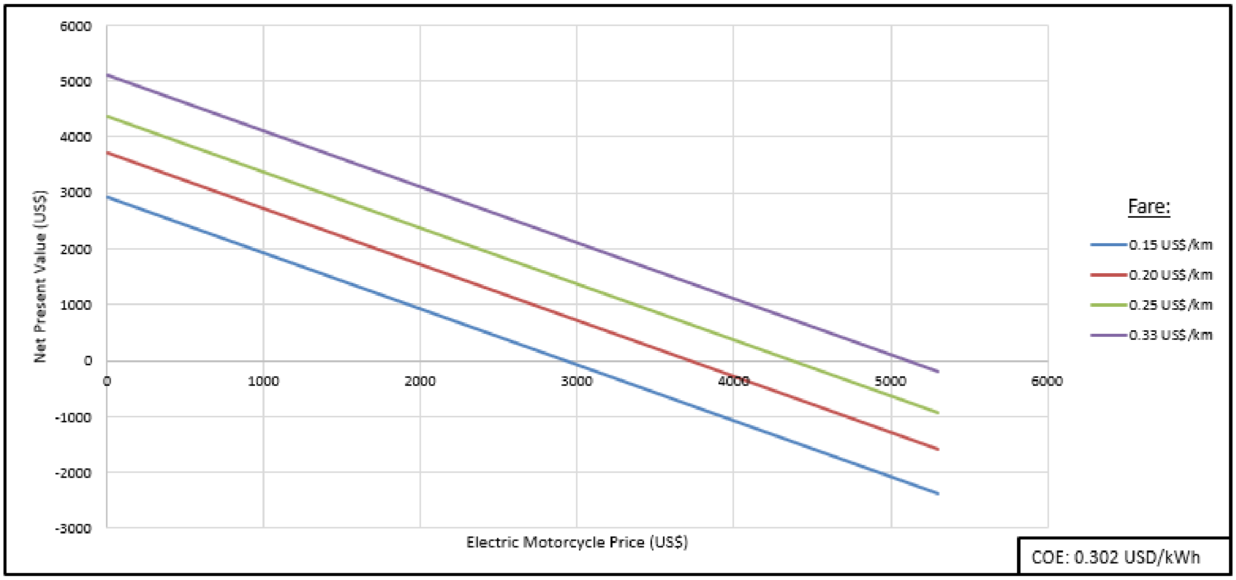


Figure 35: NPV for varying fares in owner-operator case

5.2.1.2. Renter-operator analysis

Comparing the graphs in Figure 36, it is apparent that the NPV for an electric moto-taxi renter-operator is roughly double the IC case. With the fare and rental fee constant for both cases, this difference in NPV can be attributed to the fueling and maintenance costs, like the owner-operator case. Figure X presents a breakdown of the monthly expenses experienced by renter-operators for both cases. In both cases, the rental fee accounts for majority of operator's monthly expenses. However, the total monthly expenses for the IC motorcycle are greater than the electric case by a factor of 1.3. This is because the fueling and maintenance costs for the IC motorcycle are roughly 4.5 times higher than that of the electric motorcycle.

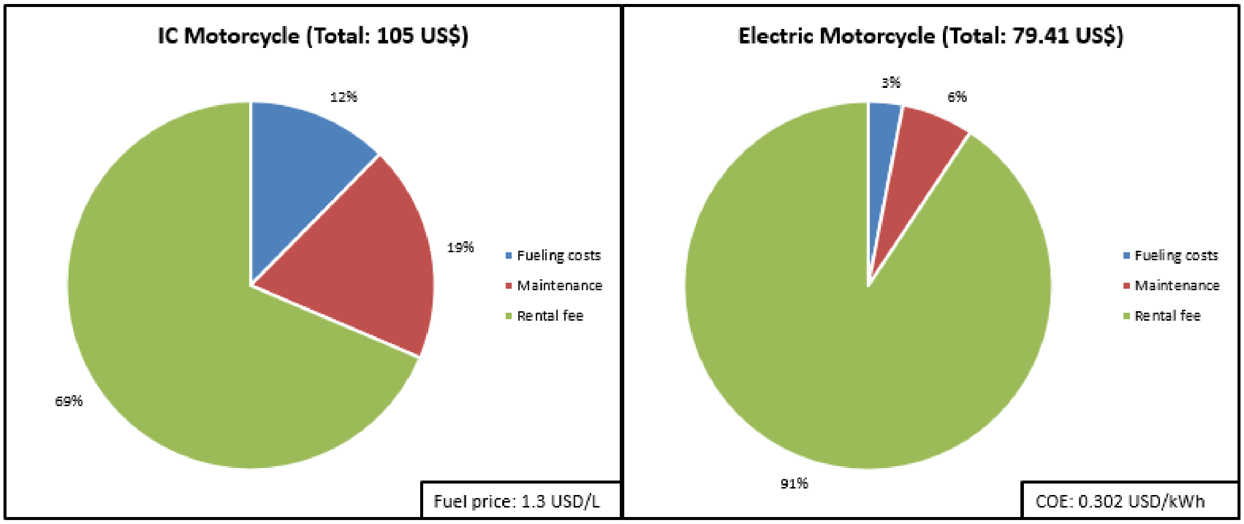


Figure 36: Monthly expenses for IC and electric motorcycles

Furthermore, like the owner-operator case, it is important to assess whether a renter-owner model could facilitate lower transportation fares for the community. However, to do so, the renter-operator would need to secure a salary that is equal to or greater than what was earned before. As a benchmark, a renter-operator with an IC motorcycle and an electric motorcycle earned a net monthly salary of 27 USD and 52.59 USD, respectively for a fuel price of 1.3 USD/L and COE of 0.3018 USD/kWh. As discussed, the rental fee accounts for a major portion of the operator’s monthly expenses, therefore changing the fare would require the rental fee to change as well. Figure 37 presents the rental fee as a function of the fare price for varying monthly incomes. Generally, as the operator’s income were to increase, the rental fee would need to decrease to remain attractive to the operator. From discussions in the field, a monthly salary of around 50 USD is enough to cover the basic living expenses for a resident of the Olkirimatian conservancy. Following the trendline for a 50 USD salary, reducing the fare to 0.20 USD/km would require a daily rental fee of 1.71 USD. Similarly, for a salary of 70 USD the same fare would require the daily rental fee to be 0.87 USD.

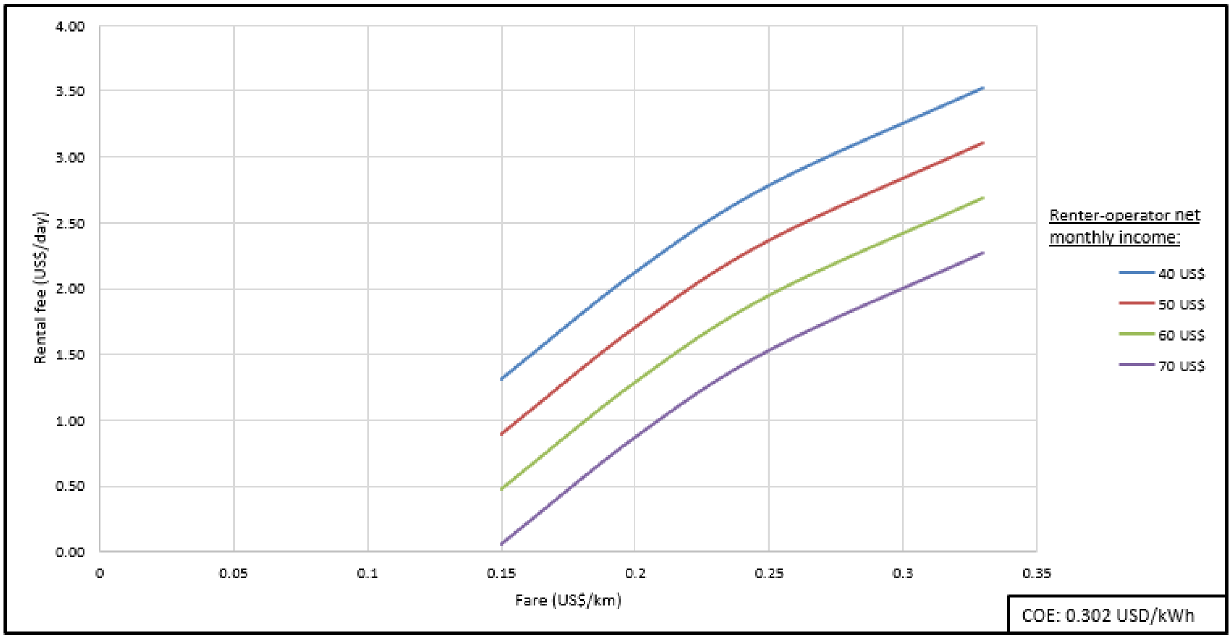


Figure 37: Rental fee as a function of fare for varying monthly incomes for renter

5.2.2. Fleet owner benchmarking

This section will present the results of the DCF analysis detailed in Section 4.4.3. Fleet owners are typically profit-seeking individuals with capital to invest in ventures that boost their financial status. They do not operate vehicles themselves and rely on individuals in a community seeking employment to rent the vehicles from them for a daily fee. This means that the fleet owner is indifferent to the daily operations of the moto-taxi service and is not directly affected by the price of fuel and fare. Nevertheless, before a fleet owner chooses to invest in a fleet of motorcycles, it is important to estimate the attractiveness and profitability of the venture. As discussed, one method to do so is to assess the estimated cash flows and establish the NPV of the venture. Figure 38 presents the NPV as a function of fleet size for both the IC and electric motorcycle case. Comparing the results for a 50 vehicle fleet, the IC and electric options yield NPVs of 202,583 USD and 35,636 USD. Clearly, the IC motorcycle fleet is more profitable than an electric fleet. The NPV for the IC case is roughly 5.7 times greater than that of the electric fleet. Furthermore, the DCF analysis projected a payback period for IC and electric motorcycles of 14 and 81 months, respectively. Additionally, the IRR for the IC and electric case was found to be 7.77% and 0.97%, respectively. These results are unfavourable for a fleet owner looking to buy electric motorcycles. Like the discussions before, the high capital expense for an electric vehicle has a significant adverse effect on the profitability on the moto-taxi business. Therefore, it is vital to the success of an electric moto-taxi business that there is either a decrease in EV price or a capital subsidy.

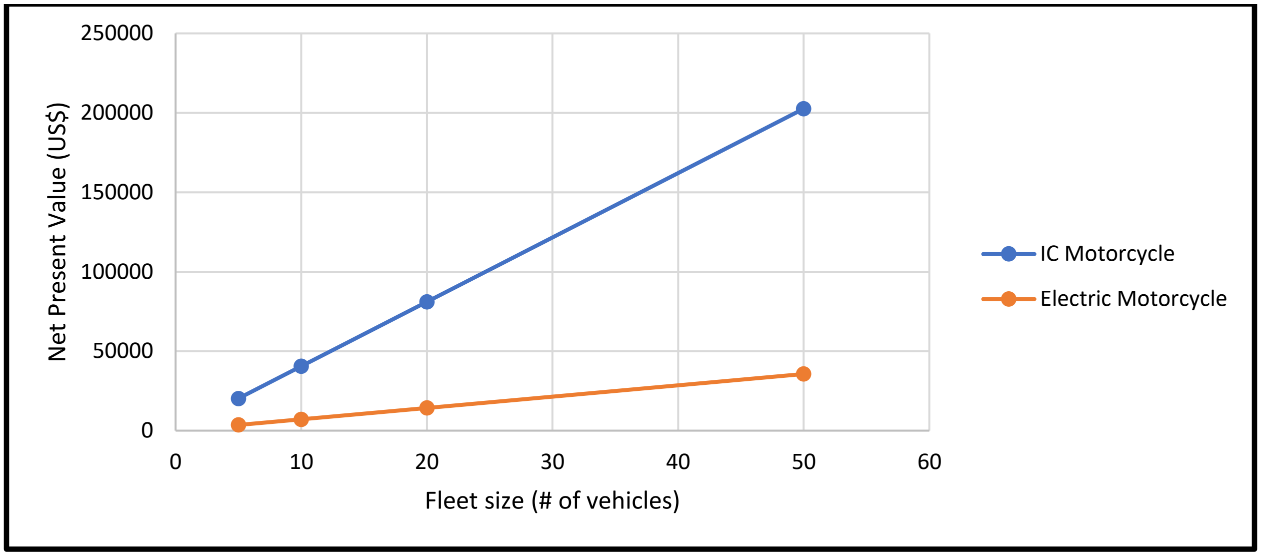


Figure 38: NPV as a function fleet size for IC and electric motorcycles

In SSA, there is a lengthy history of foreign governments and organizations extending aid through grant support for development efforts. Therefore, it is hypothetically possible for the conservancy to form an electric moto-taxi enterprise that would own and operate a fleet of EVs for the benefit of the community that could qualify for grant support. However, the details and dynamics of such a venture are out of the scope of this thesis but would be interesting for a future study. Nevertheless, it is interesting to examine the relation between grant support and an electric moto-taxi venture's profitability. Figure 39 demonstrates the NPV as a function of fleet size for varying degrees of capital discounts. Evidently, even a 25% discount on the capital expenditure could improve profitability and boost the NPV by a factor of 2.8. Furthermore, discounts between 50-75% can achieve NPV's that are on par with the IC motorcycle scenario.

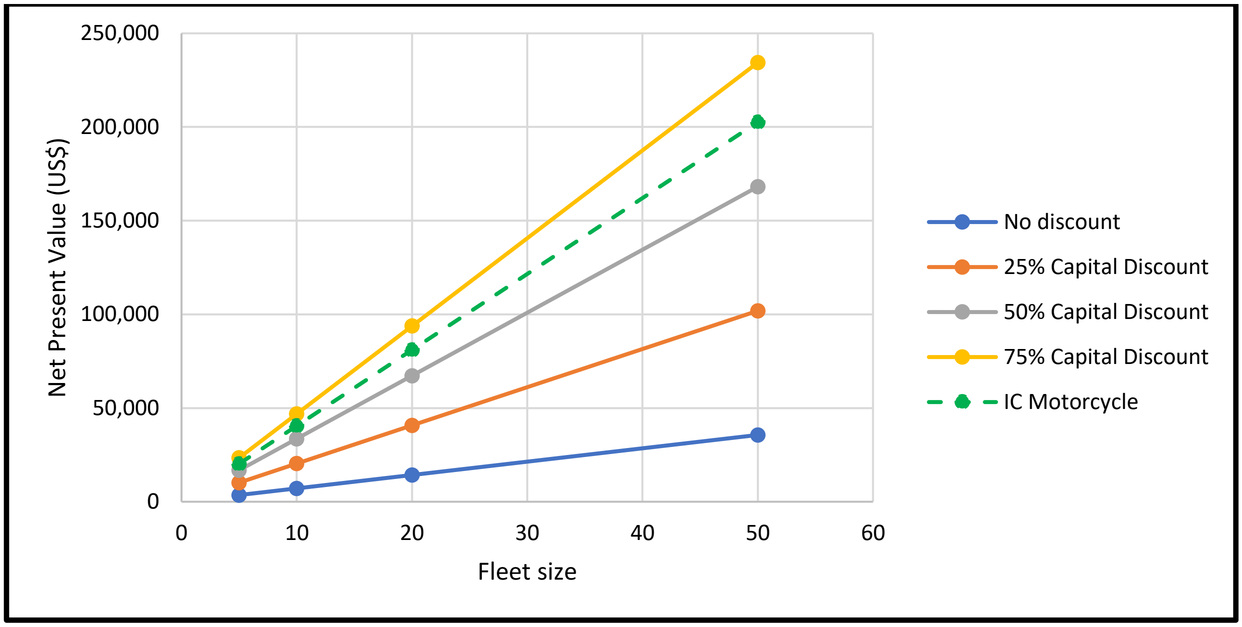


Figure 39: NPV as a function of fleet size for electric motorcycle capital discounts

Clearly, a capital discount can greatly improve the profitability of an electric moto-taxi venture for a fleet owner. From the discussion above, the corresponding capital grant to facilitate this financial performance is illustrated in Figure 40. For a conservancy wide moto-taxi electrification scenario, a grant of 166,947 USD would allow for the fleet owner to have a financial performance like the IC motorcycle case. In addition to improving the venture's NPV, a capital discount would improve the IRR and payback period for the fleet owner. Table 16 shows the IRR and payback period for different levels of capital discounts. Generally, higher capital discounts increase the IRR and decrease the payback period. For a grant of 166,947 USD, the fleet owner would have to invest 98,054 USD which would yield an IRR and payback period of 4.26% and 26 months.

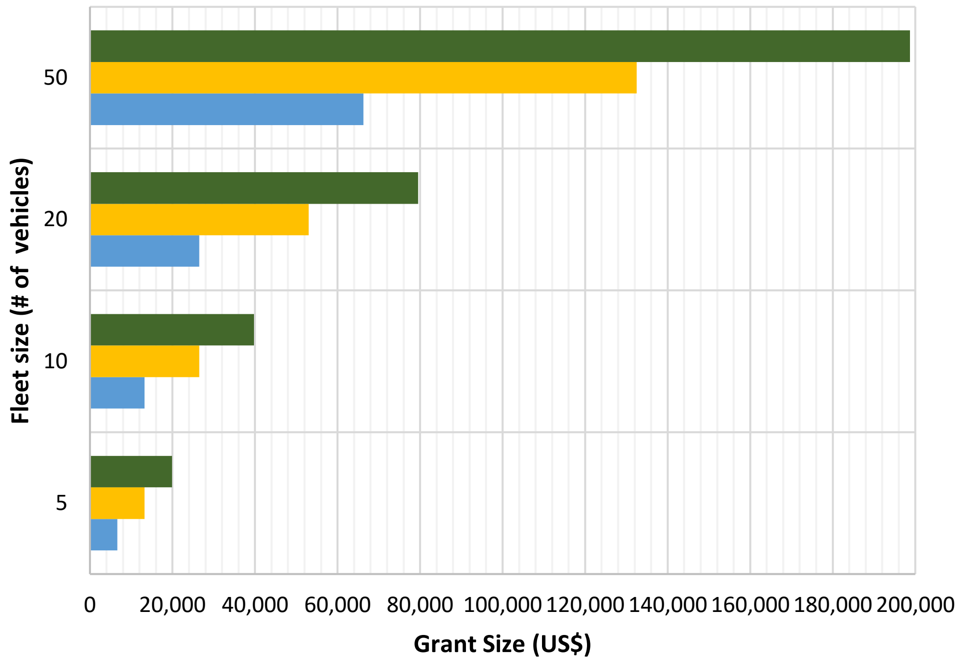


Figure 40: Equivalent grants for corresponding capital discounts

Table 16: IRR and payback period for varying degrees of capital discount

Capital Discount	Internal Rate of Return	Payback Period (Months)
0%	0.97%	81
25%	1.72%	57
50%	3.02%	36
75%	6.40%	17

Continuing the discussion in Section 5.2.1.2. on changing the rental fee for the operator, it is important to evaluate the effect this would have on the fleet owner. Currently, the cost of the electric motorcycle is expensive and yields an unfavourable NPV, therefore decreasing the rental fee would require a cheaper vehicle. Figure 41 presents the trends for different rental fees on the NPV as a function of the electric motorcycle price for a 5 vehicle and 50 vehicle fleet. For both cases, the intercepts on the EV price axis at which the NPV becomes positive is the same. Generally, a decreasing EV price yields a higher NPV. Additionally, charging a daily rate of 1.71 USD would require an EV price of at least 3,275 USD to yield positive NPVs. From previous analysis, this daily rate would secure a monthly salary of at least 50 USD for the operator while charging a 39% lower fare than before.

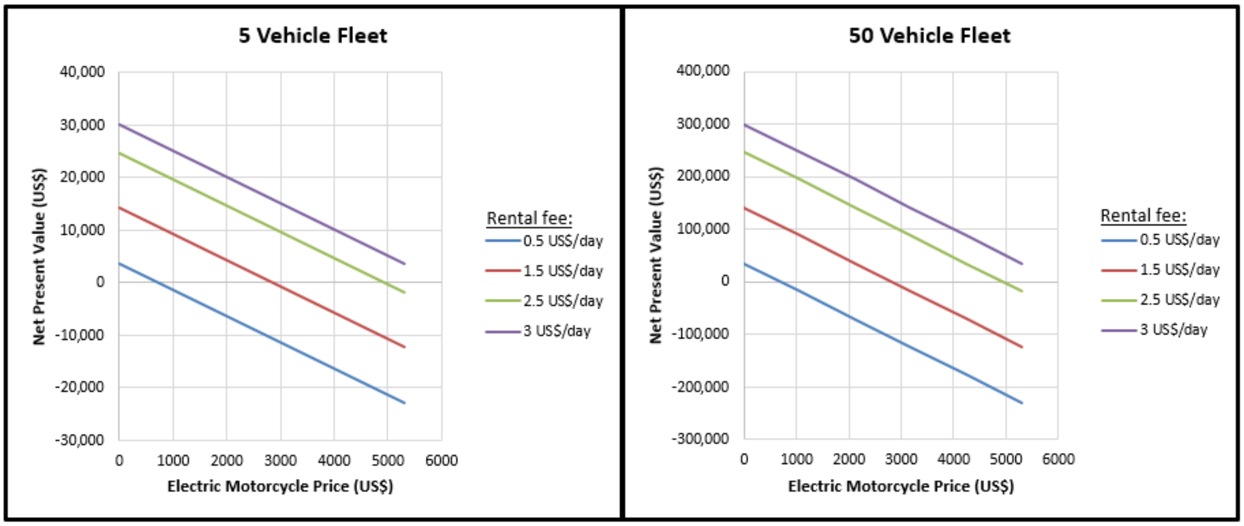


Figure 41: NPV as a function of electric motorcycle price for varying rental fees

5.2.3. Environmental impact

As discussed before, EVs have an advantage over IC vehicles regarding environmental impact because they do not produce any tailpipe emissions. Chen et al., determined that rural motorcycle driving habits emit around 42.42 g/km [37]. Figure 42 translates these emissions for the fleet sizes considered in this study. In a business as usual scenario, with 50 IC motorcycles in Olkirimatian traveling an average of 400 km per month, the moto-taxi sector produces roughly 10 tonnes of CO2 per year. This is almost equivalent to the CO2 emissions produced by 5 tonnes of burning coal [77].

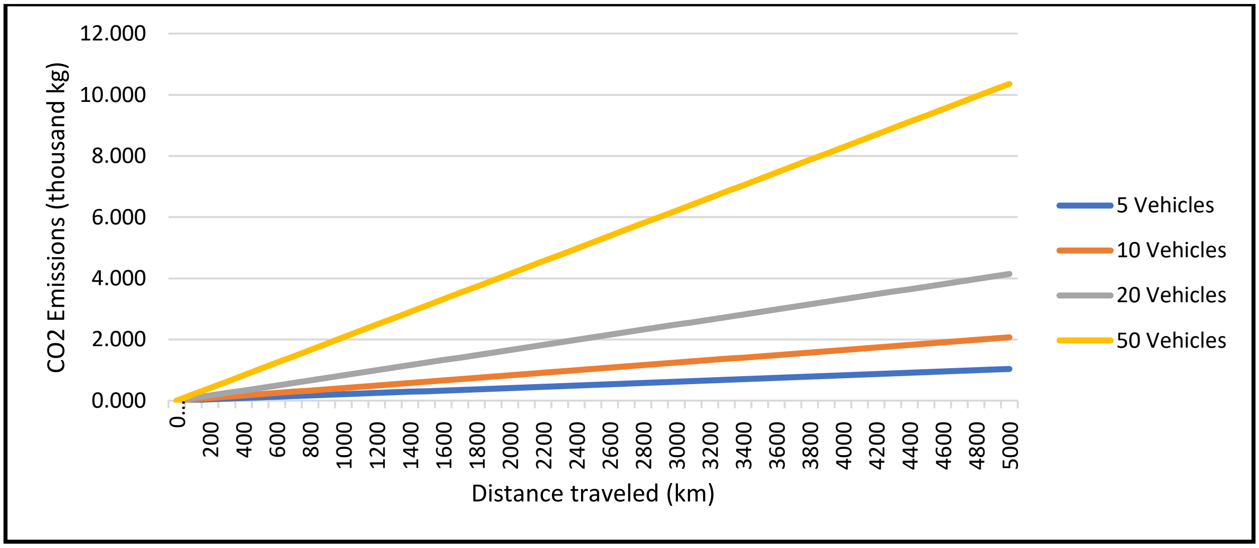


Figure 42: CO2 emissions for IC motorcycle fleets

6. Conclusion

This work investigated an integrated approach to electricity access through electrifying the emerging rural motorcycle taxi industry present across SSA. The work focused on a remote community based in the Olkirimatian conservancy area of Kenya and sought to improve the commercial viability of mini-grid projects and solve local transport problems. The model was tailored to a potential pilot site and the technoeconomic performance was compared to a business as usual (BAU) scenario. The BAU scenario represented a case with no EVs and mini-grid designed for community needs only. The proposed solution introduced electric motorcycle fleets with restricted charging times as an alternative to the conventional IC technology. Models for both the technical and financial aspects were developed and assessed. The results generally indicated:

- Introducing EVs to a potential mini-grid site increased the system capacity and overall costs but decreased the LCOE
- The high capital cost of the proposed EV compromised the financial performance of motorcycle taxi operations
- Fueling costs for EVs were 78.8% lower compared to IC motorcycles
- A 60 – 65% capital discount on the proposed electric motorcycle or selecting an EV priced between 1,820 and 2,120 USD would achieve the same NPV as status quo moto-taxi operations.
- EV intervention could mitigate the carbon footprint of rural motorcycle taxi operations

Ultimately, replacing IC motorcycles with EVs has the potential to decrease the cost of rural transport and reduce the cost of electricity. However, the EV chosen in this analysis had an unfavourable capital expenditure and a less expensive alternative would improve the financial performance of electric motorcycle taxi operations. Fortunately, there is reason to believe that electric motorcycle cost reductions are possible as manufacturers improve their operations to cater for the growing global appetite for EVs.

6.1. Recommendations for future research

This analysis relied on assumptions and limitations to streamline the work so that a general understanding of the impact of EVs on remote mini-grids can be conceived. Therefore, the following list of potential research topics would hold significant value in the ultimate implementation of the project:

- A detailed account and assessment of rural motorcycle taxi behaviours. This information could be used for developing an accurate load profile for the electric moto-taxis. Additionally, this information could be integrated with an intelligent control strategy that would only charge the moto-taxis with renewable energy.

- An assessment of the most appropriate implementation strategy and business model suitable for an electric transport service. Particularly focusing on capacity building, gender inclusion, tariffs, social impact, and enterprise organization.
- An analysis of “Vehicle 2 Grid” capabilities, this could potentially lead to additional cost savings as EV batteries are used as a storage mechanism for the mini-grid. This would decrease the required battery capacity for the mini-grid and effectively decrease capital and operational expenditure.
- A social impact assessment of empowering women as transport service providers in pastoral Maasai homesteads.

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8. Appendix

Appendix A: Key Informant Interview Questions

Olkirimatian Key Informant Interview Questions

1. What is the average monthly income of a "Boda-boda" operator?
2. What is approximate fare for motorcycle taxi transport?
3. How much time does a "Boda-boda" operator spend waiting for customers in the town center?
4. What is the average fuel expenditure per day?
5. What is the yearly maintenance expenditure?
6. What are the hours of operation for a "Boda-boda" operator?
7. Motorcycle ownership
    a. If renting from an owner, what is the daily rental fee?
    b. If a self-owner, what is the purchase price for a motorcycle?
8. How many "Boda-boda" operators are there in Olkirimatian conservancy?
9. Is there a "Boda-boda" association?
10. What motorcycle models are there?
11. What is the distance traveled on market days?
12. What is the perception of electric motorcycles?
13. How many trips are taken for the following reasons (per day or week)?
    a. Taking people to and from work?
    b. Taking people to and from school?
    c. Taking people to and from the health clinic?
    d. Emergency medical transport?
    e. Transporting of agricultural inputs to farmers?
    f. Transporting dairy products?
    g. Transporting meat products?
    h. Transporting people to bus stop?
    i. Transporting tourists/researchers?

Appendix B: Mini-grid load profiles

Table B. 1: Load profiles for community and all electric vehicle scenarios

Time	Household	Business	Institutional	Streetlight	Community total	Small fleet	Medium fleet	Large fleet	Conservancy wide
0-1	1	4	0	0.5	5.5	0	0	0	0
1-2	1	4	0	0.5	5.5	0	0	0	0
2-3	1	4	0	0.5	5.5	0	0	0	0
3-4	1	4	0	0.5	5.5	0	0	0	0
4-5	1	4	0	0.5	5.5	0	0	0	0
5-6	2	4	0	0.5	6.5	0	0	0	0
6-7	2	4	1	0	7	0	0	0	0
7-8	1	4	1	0	6	1.75	3.5	7	17.5
8-9	1	4	1	0	6	1.75	3.5	7	17.5
9-10	1	4	1	0	6	1.75	3.5	7	17.5
10-11	1	4	1	0	6	1.75	3.5	7	17.5
11-12	1	4	1	0	6	1.75	3.5	7	17.5
12-13	1	4	1	0	6	1.75	3.5	7	17.5
13-14	1	4	1	0	6	1.75	3.5	7	17.5
14-15	1	4	1	0	6	1.75	3.5	7	17.5
15-16	1	4	2	0	7	1.75	3.5	7	17.5
16-17	1	8	2	0	11	1.75	3.5	7	17.5
17-18	3	9	3	0	15	0	0	0	0
18-19	5	5	1	0.5	11.5	0	0	0	0
19-20	5	4	1	0.5	10.5	0	0	0	0
20-21	3	4	0	0.5	7.5	0	0	0	0
21-22	2	4	0	0.5	6.5	0	0	0	0
22-23	2	4	0	0.5	6.5	0	0	0	0
23-24	2	4	0	0.5	6.5	0	0	0	0
Daily KWH	41	106	18	6	171	17.5	35	70	175

Appendix C: Community battery size calculation

The formula to calculate the battery size is as follows:

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} (1 - \frac{q_{min}}{100})(24\frac{h}{d})}{L_{prim,ave} (\frac{1000Wh}{kWh})}$$

Where,

A_{batt} is the battery autonomy

V_{nom} is the nominal voltage of a single string in Volts (V)

Q_{nom} is the nominal capacity of a single storage unit in amp-hours (Ah)

q_{min} is the minimum state of charge of the storage bank as a percent (%)

$L_{prim,ave}$ is the average daily load in kilowatt-hours per day (kWh/day)

N_{batt} is the number of batteries in the storage bank

Since one of the constraints for the system design are to guarantee 24-hour autonomy, the value for battery autonomy will be set accordingly. Using the information available for the "Generic 1 kWh Lead Acid" battery from HOMER, the values for the rest of the parameter is as follows,

A_{batt} = 24 hour

V_{nom} = 48 V

Q_{nom} = 83.4 Ah

q_{min} = 50%

$L_{prim,ave}$ = 171 kWh/day

Solving for the number of batteries yields a value of

$$N_{batt} \cong 86$$

Appendix D: HOMER model values

Table D. 1: General project parameters for HOMER model

PARAMETER	VALUE
GENERAL	
Discount rate (%)	8.00
Inflation rate (%)	4.00
Annual capacity shortage (%)	0.00
Project lifetime (years)	20.00

Table D. 2: Load parameters for HOMER model

PARAMETER	VALUE
COMMUNITY LOAD RANDOM VARIABILITY	
Day-to-day (%)	10
Time step (%)	20
EV LOAD RANDOM VARIABILITY	
Day-to-day (%)	0
Timestep (%)	0

Table D. 3: Genset parameters for HOMER model[62] [78] [79]

PARAMETER	VALUE
GENERAL	
Minimum Load Ratio (%)	40.00
Heat Recovery Ratio (%)	0.00
Lifetime (hours)	15,000.00
Minimum Runtime (minutes)	0.00
Fuel ($/L)	1.33
10 KW FIXED CAPACITY GENSET	
Initial capital ($)	7,00.00
Replacement ($)	5,000.00
O&M ($/op. hour)	0.500
25 KW FIXED CAPACITY GENSET	
Initial Capital ($)	10,500.00
Replacement ($)	8,000.00
O&M ($/op. hour)	0.800

Table D. 4: Converter parameters for HOMER model [78]

PARAMETER	VALUE
COSTS	
Capacity (kW)	10
Capital ($)	$11,370.00
Replacement ($)	$11,370.00
O&M ($/year)	$5.00
CAPACITY OPTIMIZATION	
HOMER Optimizer	Yes
INVERTER INPUT	
Lifetime (years)	15.00
Efficiency (%):	98.00
Parallel with AC generator?	Yes
RECTIFIER INPUT	
Relative Capacity (%)	100.00
Efficiency (%)	95.00

Table D. 5: Generic 1kWh Lead Acid parameters for HOMER model [78]

PARAMETER	VALUE
BATTERIES	
Quantity	1
Capital ($)	300.00
Replacement ($)	300.00
O&M ($/year)	10.00
LIFETIME	
Time (years)	10.00
Throughput (kWh)	800.00
QUANTITY OPTIMIZATION	
HOMER Optimizer	No
Search Space	86
SITE SPECIFIC INPUT	
String size	4
Initial State of Charge (%)	100.00
Minimum State of Charge (%)	50.00

Table D. 6: Generic flat plate PV parameters for HOMER model [78]

PARAMETER	VALUE
PV	
Capacity (kW)	1
Capital ($)	1,000.00
Replacement ($)	1,000.00
O&M ($/year)	10.00
Lifetime (years)	20.00
CAPACITY OPTIMIZATION	
HOMER Optimizer	Yes
SITE SPECIFIC INPUT	
Derating Factor (%)	80.00
Electrical Bus	DC
MPPT	
Explicitly model MPPT	No
ADVANCED INPUT	
Ground Reflectance (%)	20.00
Tracking system	No Tracking
Panel slope (degrees)	15.00
Use default azimuth	Yes
TEMPERATURE	
Consider temperature effects?	No