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Abstract

Even though more people around the world have access to energy than ever before, the number of people without energy in Sub-Saharan Africa has increased. To address this issue, electrification through decentralized renewable-based solutions is gaining traction. There are very limited public transportation systems that rely primarily on diesel-powered vehicles, some of which are significant polluters, requiring a thoughtful approach that considers the tradeoff between economic growth and sustainable development. As a result, electromobility is high on the list of alternatives critical to Africa's long-term prosperity, especially for the continent's rural population, where transportation and energy infrastructure are typically unsustainable. In response to this dilemma, evidence is shown in this article that presents a feasible economic solution based on solar electric vehicles as part of a large-scale response to the continent's growing demands.

Keywords: Renewable Based Solutions; Solar Powered Tricycle; Electric Mobility; Photovoltaic Module (PV); Electric Vehicle (EV); Research and Development (R&D)

1. INTRODUCTION

1.1 COMPANY BACKGROUND

Solar-e-Cycles Kenya is a budding startup exploring vehicle integrated photovoltaics. The company began operating in Kenya in 2015 with the help of the Energy and Environment Partnership Trust Fund Africa. The company promotes the adoption of sustainable mobility and increased access to renewable energy for further productive use through its distinctive product design and in-house capacity building that maximizes the economic and social impact on consumers. The goal is to provide meaningful solutions that address both energy and mobility issues, while also empowering those in need. The venture designs and assembles solar-electric three-wheeled vehicles and electric two-wheelers that are affordable, accessible, and robust.

A solar electric vehicle is an electric vehicle that is entirely or partially powered by solar energy. Solar panels use photovoltaic (PV) cells to convert sunlight directly into electricity, which can then be stored in a battery and also used to power the vehicle's motor system.

1.2 Context of Study

The purpose of this section is to give a broad overview of Kenya's economic, social, and political performance within the electric automobile market. This will give context to the data SEC K will present from the field that their case study is within.

Kenya already has a thriving and dynamic e-mobility industry, with several electric vehicle assemblers, large-scale adopters in the delivery and taxi sectors, e-mobility-focused financiers, researchers, associations, and a national transition campaign. [1]

Startups spanning from small to medium-sized enterprises are currently occupying the space, testing products and services for the e-mobility industry. Internal combustion engines (ICEs) are being replaced with cost effective electric drive trains in the region through vehicle conversion.

The rise of electric vehicles represents an excellent opportunity for Kenyans and Africans at large to promote local manufacturing and distribution of their innovations. Motorcycles are one of the most representative methods of transportation in terms of sheer numbers and their environmental impact on the region. The Kenya Boda-Boda Safety Association predicts that the daily distance covered by a motorcycle is between 100 and 125 kilometers. [2] The sector is one of the country's most important economic drivers. The dominance of ICE motorbikes signals that more effort should be put into developing responsible alternatives that would help riders minimize their carbon footprint.

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During the early stages of the market's development, public sector stakeholders, research institutions, e-mobility entrepreneurs, energy sector stakeholders and private sector foundations have been critical in laying the groundwork for the e-mobility agenda.

More efforts are underway to champion the uptake of e-mobility for the transport sector in light of Kenya's national emissions reduction target as part of the Advancing Transport Climate Strategies project, which is a technical assistance project focused on institutionalizing climate change solutions within the State Department for Transport. [3] Electric mobility is one of the main targets for the Transport sector's Nationally Determined Contributions to reduce emissions by 32%. This is in Kenya's National Climate Change Action Plan (2018-2022).

If the government genuinely provides incentives and collaborates with stakeholders, the use of electric vehicles will increase accordingly.

To support lowering of importation duties and simplifying the shipping of electric vehicles, the Kenyan government in its efforts has incentivized local manufacturers to obtain an assembler's license or register bonded warehouses where upfront VAT payments are waived. In the 2019 Finance Bill, the excise tax on all cars with electric motors for propulsion (BEVs) was proposed to be reduced from 20% to 10%. [4] In addition, the Energy Bill of 2017 would promote investment in necessary infrastructure to scale up the industry, such as grid-tied EV charging stations. It was still being debated in parliament during the time of the case study presented in this article.

There are several government backed and independently financed research and development programs aimed at offering better knowledge of Kenya's e-mobility industry's developments. This is very encouraging, given the attention that this emerging industry is receiving and the potential to significantly impact modes of transportation in a new market.

1.5 Case Study

In order to establish how it could add value to its solutions for the marketplace SEC K needed to assess its capabilities to develop and operate solar electric vehicles.

As a result, SEC K built multiple electric tricycle prototypes to provide a low-cost medium of transportation for Africa's population.[5] The solar electric tricycle had to be produced and operated within its target users' budgetary guidelines. Hence the initial objective was to build a solar electric tricycle for less than $1,000.

Since 2014, 10 distinct prototypes of the Solar-e-Cycle have been developed. Experts in the fields of e-mobility, photovoltaics and tricycle design have further engaged in its proof of concept, which allowed Solar e-Cycles to participate in notable events, including the Solar Festival, Solar Race Challenge, COP22, Sun Trek Africa and more.

After the Uhuru prototype won the VALEO Innovation Challenge in 2018, it was decided to test it on several end-user-based pilot initiatives.[12] The Uhuru prototype is the featured model of Solar E Cycle within this article.

“Uhuru” means freedom in Swahili, the national language of Kenya. It was also the name of the President of the Republic of Kenya at the time of writing this article. The prototype was put to test through a year-long case study; much Research & Development (R&D) was invested to ensure its performance within the target market. After an analysis of the data collected from earlier prototypes necessary adjustments were made. The SEC K product development team finally adopted a delta shaped tricycle design featuring two brushless 350 watt (W) motors, 4x12 volt (V), 30 ampere hour (AH) valve regulated lead acid (VRLA) batteries connected in series and a 300W semi-flexible solar panel (PV). The Uhuru prototype used
a mountain bike frame to which a rear two-wheel cargo platform was attached to support the PV module.

SEC K was inquisitive about the prototype's potential design flaws, which were subsequently found throughout the testing protocol it was subjected to. During the one-year experimental study, SEC K showed that they could build a solar electric tricycle for less than $1,000 in capital expenditure (CAPEX), then identified the acts of maintenance and repair done on the vehicle over time to attribute a working operational expenditure (OPEX) to the vehicle (Table 1).

For the product to be successful in the African market, SEC K needed to prove that the vehicle was reliable and affordable. The OPEX costs were reduced over both distance and time (Graph 5) as the team learned about the nature between the reliability and affordability of components incorporated on the vehicle. After several pilot projects, SEC K reconsidered and furnished their approach to penetrate the market by developing a better product, Tryke, which is presented in the conclusion of this article.

2. Methodology
The study employed a quasi-experimental approach to detect relations between variables where SEC K had no prior expectations about the nature of interactions between them. The research was conducted in Nairobi, Kenya, and data was gathered via primary sources such as an online communication channel established for test drivers to send data to the testing manager. A hub-and-spoke business model was used in the case study. The activities in which SEC K engaged were coordinated from the ‘hub’ at Strathmore Energy Research Center, Strathmore University, out to different pilot projects. The study included both a descriptive and a quantitative method of data collection, with respondents sharing their experiences on the Uhuru prototype. Many features of the source data were then studied and compared in the search for patterns and correlations utilizing a multitude of approaches.

The research population consisted of a number of pilot projects, including entrepreneurs running businesses and riders who deliver food and household items to customers. There was no sampling because the target population was so small.

2.1 Pilot Projects
SEC K mandated all end users to participate in free training and testing on how to properly operate the vehicles, which contributed to the creation of capable drivers.

Kwanza Tukule is a business that supplies informal food vendors with raw or partially cooked foods and cooking supplies from its headquarters to various customers. The average recorded distance for the Uhuru prototype over a days’ activity was 35.2km. Within the vehicle’s range, SEC K transported items on Uhuru prototypes during the test period between the 11th of December 2019 to February 20th 2020. The test activities would start off very early in the morning when it was dark, and on a full charge the Uhuru tricycle could run 30-40 km before having to recharge the battery pack in the sun. Towards the end of the pilot phase the vehicle was only able to achieve less than half this range during low irradiance conditions. This prompted a research and development project investigating Lithium Ion technology instead of Lead Acid, as these types of batteries are better established for electric vehicles, with more duty cycles and a deeper depth of discharge in comparison to VRLA batteries.

M'l'o Zone was another business involved, it was located along Road A in the industrial area of Nairobi. They delivered cooked meals to blue collar workers and various business parks within the area. The idea was to get cooked meals to customers as fast as feasible. SEC K was a last-mile delivery partner, replacing motorcycles at a proposed rate of around 150 Kenyan Shillings (KES) per day. This was less than the claimed 500 KES per day for motorbike services.

The daily rate was subsequently put to the test in a similar pilot with TheFlea Online Megastore, which used bicycles to complete orders from its online marketplace. This was a student-run business that began at Strathmore University. They were able to improve their delivery speed and efficiency, carrying more goods and expanding their business into new routes. They had more capacity to provide their services by utilizing the Uhuru Prototype.

Finally, during the initial COVID 19 outbreak in Kenya, one of the company's in-house riders participated in a trial

Image 4: A fleet of 6 Uhuru prototypes were built in the Industrial area of Nairobi in August 2019.
2.2 Types of Data Collected
SEC K collected data on energy consumption, maintenance, distance traveled, drive time, R&D activities and expenditures from specific dates within the case study’s scope of activities. All data was collected from the pilot projects mentioned above to internal testing of the vehicles.

Given the prototype's primitive state and the need to correct all problems discovered throughout the case study, it was determined to separate R&D results from acts of pure maintenance within the analysis and exclude them from all speculated end-user OPEX.

R&D included any product change that was nurtured through the ongoing development of the prototype. A consumer would not normally encounter it during an actual use case of the vehicle. This was based on the cost of any equipment malfunctions caused by research and development during the case study period. It also included the cost of any design improvements such as trialing stator cooling fluids or switching to Lithium Ion battery technology. The fleet's OPEX accounted for a smaller portion of the fleet's total running cost.(Graph 4).

2.3 Data analysis
SEC K aimed to demonstrate that solar electric tricycles could be built for less than $1,000. Two prototypes were 15% over budget. They had a third motor installed on the front wheel as part of an all wheel drive study during R&D. This was the outcome of tests on an earlier, heavier prototype that had traction and driveability issues. SEC K discovered that the Uhuru prototype did not require the third motor because it was lighter and it was more in kin to a traditional in its scope of design than its predecessors. The initial cost that was used to base the total CAPEX for the Uhuru prototypes came from a bill of materials (BoM) that took original invoices from overseas shipments of parts and equipment into account as well as prices from local sources within Nairobi.

The cost of maintenance \(m\) is an indication of the OPEX. It is by definition the natural consequence of vehicle repairs after being driven over any distance. Given that these vehicles do not require the end users to purchase fuel, the OPEX defines the primary costs associated with acts of maintenance, such as puncture or structural repairs, or the costs of replacing components like-for-like on the Uhuru prototype. The frequency of the acts of maintenance and replacement was accounted for and then multiplied by the initial pricing as it was stated within the BoM.

2.4 Six-week period sensitivity Analysis
SEC K wanted to examine data from two separate cross sections of the case study’s time period in order to properly describe the overall expense of running the fleet of solar electric tricycles. This is a comparison analysis to the overall cost analysis across the entire study. The sub studies were divided into two six week periods that were aligned to exclude anomalies from the datasets of all pilot projects. The first step was a quantitative assessment of the fleet's maintenance profile by looking at the total cost per kilometer (cost/km) for each six-week sub study period (sensitivity 1). After that, the gray areas were defined in a qualitative analysis to differentiate between maintenance and R&D so that a second study (sensitivity 2) may be performed on the data set where some maintenance acts are transferred to R&D.

Sensitivity 2 has been applied in instances where the replacement of a part is necessary but not to any faults encountered whilst on the road; be it damage through fabrication, shipping or the necessity to investigate damages and subsequently running repairs to components whilst still keeping a vehicle active. The data and descriptions can be found in 3.3.

SEC K produced the data using the fleet's logged journey readings to calculate the total distance traveled and the frequency of maintenance during each of the time periods. Doing this provided the initial cost per km for each sub study. This was then assessed alongside the total accumulative cost per kilometer for the fleet over its entire distance, to arrive at a combined average which can then be used to compare with other vehicles, such as those with ICEs.

2.5 Analysis of Energy Efficiencies
To show the efficiency of the PV module attached to the vehicle we analyzed sample data from journeys with and without the solar panel connected. As a control, the datasets with the solar panel connected are from when the vehicle was active during full load hours (FLH) only, when the irradiance from the sun was equal to or greater than 1000 watts per meter squared.
In Image 5, the difference between the start and finish voltages of journey 1 above was 5.8v. The operating voltage range was rated between 52.08v and 43.2v, a 8.8v difference. We know this because a single VRLA cell is rated between 1.8v and 2.17v and a battery pack must have 24 cells connected in series to be rated at 48v.

A discharge of 65% of the batteries capacity is obtained by dividing 5.8(v) by 8.8(v) and multiplying by 100. The battery pack's stated capacity was (48v 30ah) 1440 watt hours (wh). In this instance the total energy lost would be 940wh. The amount is divided by the distance traveled in kilometers to arrive at a figure that is the total energy lost from the battery distributed over the entire distance traveled, shown as watt hours per kilometer (wh/km).

In Graph 2, some of the wh/km data is given in negative values. It means the vehicle's battery was charging more than discharging due to the solar panel generating energy as evidenced by a higher end voltage than starting voltage within a journey's log.

Graph 3 shows the overall case study's efficiency data in watt hours per kilometer. The data was analyzed using a normal distribution chart. This dataset's major peaks and troughs were regarded as anomalies. If presented, they would skew the results to unrealistic figures. These anomalies generally occurred as a result of riders misinterpreting journey readings, or falsely flagging data via the online communication channel. All anomalies within the efficiency data accounted for under 15% of the total efficiency dataset and were removed to allow SEC K the closest representation of accurate information from the core body of source data.

### 2.6 Elements of Analysis

These elements were shown using equations, tables and charts throughout section 3. They are given here in alphabetical order.

- \( a \) = daily energy consumption for a small rural household
- \( b \) = the cost of constructing the fleet
- \( c \) = capex
- \( d \) = total fleet mileage
- \( e \) = average cost of motorcycle servicing
- \( h \) = the comparable motorcycle's estimated fuel cost per kilometer
- \( i \) = average energy efficiency on the Uhuru prototype
- \( j \) = battery capacity at example of 60% depth of discharge
- \( m \) = cost of fleet maintenance during the case study
- \( q \) = opex/km for the Uhuru mode

\( r \) = cost of research and development within the case study

All monetary value were considered in US dollars

### 3. Results

#### 3.1 Energy and Efficiency

The difference in mean values of the upper and lower control limits (UCL, LCL) in Graph 1 and Graph 2 describe the nature of the benefit the photovoltaic module attached to the roof of the vehicle provides. In some cases after completing a journey, a vehicle had more energy than it did when it started the journey, indicating that it is capable of meeting further energy demands with the PV module integrated into its system design.
3.2 CAPEX and OPEX

The CAPEX to build and operate the fleet totaled \( c \) $13,016.4. 48.1 % of this amount, or $6263.8, was spent on the initial build of the fleet of Uhuru prototypes \( b \). Product R&D accounted for another 47.1% of spending, or $6129.06. The remaining 4.8 % \( m \), or $623.6, was spent on legitimate fleet maintenance and repair.

The percentage contribution of each vehicle to the total is shown in table 1 above. The vehicles are numbered from V1 (vehicle one) to V6 (vehicle six) in ascending order. The average running cost per kilometer traveled \( q \) was $0.052 and is shown in Eq. (2) The maintenance cost described as Eq. (1) was divided by the total distance traveled by all vehicles \( d \) 11,895 km.

\[
m = c - (b + r)
\]

\[
q = \frac{m}{d} \quad (1)
\]

\[
C = b + r + m \quad (2)
\]

<table>
<thead>
<tr>
<th>C</th>
<th>$13,016.4</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
<th>V5</th>
<th>V6</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>$6,263.8</td>
<td>$1,157</td>
<td>$987.3</td>
<td>$987.3</td>
<td>$1,157</td>
<td>$987.3</td>
<td></td>
</tr>
<tr>
<td>%b</td>
<td>48.1%</td>
<td>17.97%</td>
<td>16.02%</td>
<td>16.02%</td>
<td>17.96%</td>
<td>16.02%</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>$6,129.06</td>
<td>$846.6</td>
<td>$529.2</td>
<td>$972.6</td>
<td>$551.1</td>
<td>$1,168.9</td>
<td>$2,060.7</td>
</tr>
<tr>
<td>%r</td>
<td>47.1%</td>
<td>13.81%</td>
<td>8.63%</td>
<td>15.87%</td>
<td>8.99%</td>
<td>19.07%</td>
<td>33.62%</td>
</tr>
<tr>
<td>m</td>
<td>$623.6</td>
<td>$45.0</td>
<td>$49.7</td>
<td>$112.1</td>
<td>$92.7</td>
<td>$80.2</td>
<td>$243.9</td>
</tr>
<tr>
<td>%m</td>
<td>4.8%</td>
<td>7.22%</td>
<td>7.97%</td>
<td>17.98%</td>
<td>14.87%</td>
<td>12.86%</td>
<td>39.11%</td>
</tr>
<tr>
<td>d</td>
<td>11,895 km</td>
<td>768 km</td>
<td>787 km</td>
<td>2446 km</td>
<td>2424 km</td>
<td>2273 km</td>
<td>3198 km</td>
</tr>
<tr>
<td>%d</td>
<td>100%</td>
<td>6.46%</td>
<td>6.62%</td>
<td>20.56%</td>
<td>20.38%</td>
<td>19.11%</td>
<td>26.89%</td>
</tr>
</tbody>
</table>

The second sub study ran from 10/01/20 to 21/02/20. Sensitivity 1: The overall cost of the maintenance during this timeframe was $207.41, and the fleet logged a total distance of 1772.4km, resulting in a cost per km of $0.122. The significant costs associated were another fault in a charge controller, wire damage to a display and a battery unit overheating.

3.3 Sub Study Data and Sensitivity Analyses

Sensitivity 1: During the first sub study between 07/11/2019 and 19/12/2019 the total logged distance was 1270.3 kilometers. Within the timeframe, the total fleet maintenance cost was $128.43. This includes a charge controller's replacement cost. A charge controller is used to maintain the battery's state of charge and stop it from over charging or discharging. When the cost during this substudy was divided over the distance of the dataset, the cost per kilometer was $0.101.

According to the maintenance logs, "smoke was noticed when opening the battery box one morning, and after examination, it was determined that one of the capacitors within the charge controller had blown... Given that this vehicle had just been removed from an engineering workshop, it was most likely damaged there, or before during shipping." This descriptive data guided SEC K to deem it was an anomaly in hindsight.

Sensitivity 2: When examining the maintenance profile for this particular act, it does not appear to be a legitimate act of maintenance arising from natural vehicle usage. Because this seems more of an abnormal product fault, changing the charge controller could be considered R&D and as such, it may not be included in the maintenance costs. If the charge controller replacement is not included in maintenance profile, then the fleet's cost per km during this time period then becomes $0.050, which is closer to the benchmark of the overall fleet cost over distance mentioned above \( q \) of $0.052.
The display was repaired and reused in house. According to our descriptive dataset, the “charge controller did not seem to be charging, the vehicle’s state of charge had been stuck at 47.5v for a week.” The controller was removed for analysis and potential repair. It was replaced with a working one, not only as part of a test to see if the fault actually came from the charge controller but also to keep the fleet active.

On the other hand, overheating had caused a pack of lead acid batteries to become unbalanced, necessitating the replacement of a single VRLA unit. It was most likely an older unit at a different stage of its life cycle than the other units in the battery pack, and it was considered genuine maintenance.

Sensitivity 2: If the charge controller faults are accounted for as part of R&D in the maintenance logs, the overall maintenance cost will be $142.61US and $0.080 per kilometer. If the display replacement cost is also excluded and exchanged for a simple repair fee according to local prices, which was achieved through R&D, the total cost becomes $113.61, and $0.064 the cost per kilometer respectively.

In summary, after establishing the figures for cost per km, they were combined to find their average and then evaluated to see whether they were in support of the fleet’s total cost/km. If some ingenuine acts are removed from the cost of maintenance as explained, the average cost per km for the fleet compared with the cost from the two sub-studies should be within the scope of the overall figure. The costs of the total fleet and the averages across the combined figures using sensitivity 2 were within 4% of each other (Table 2).

<table>
<thead>
<tr>
<th>cost per km</th>
<th>sensitivity 1</th>
<th>sensitivity 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>average</td>
<td>$0.093</td>
<td>$0.055</td>
</tr>
<tr>
<td>total fleet</td>
<td>$0.052</td>
<td>$0.052</td>
</tr>
<tr>
<td>07/11-19/12/19</td>
<td>$0.101</td>
<td>$0.050</td>
</tr>
<tr>
<td>10/01-21/02/20</td>
<td>$0.122</td>
<td>$0.064</td>
</tr>
</tbody>
</table>

3.4 Cost Indicators
The activities for R&D were successful, through research and the development of the Uhuru prototype, SEC K learnt how to reduce the frequency of maintenance on the fleet of vehicles, which is directly associated with managing the costs of operational expenditure (Graph 6).

SEC-K had to then verify its cost by comparing the OPEX of the fleet of prototypes within the distance of the case study to that of a motorcycle, which is one of Kenya's most popular modes of transportation and a key competitor. The chosen motorcycle was a model that SEC K had in house, with a fuel cost around ($h$) $0.03/km. This figure was calculated using market rates for petroleum in Nairobi as of March 2022. If the fuel cost per kilometer is multiplied by the distance ($d$) covered by the fleet of prototypes during the case study, the total estimated fuel cost is $356.9.

\[ h \times d = \$356.9 \]  

The servicing schedule for the in-house motorcycle was postulated to occur initially within the first 500 kilometers of its life, followed by a second service 1000 kilometers later, and then ongoing every 2000 kilometers after that. This means that, based on the distance traveled by the Uhuru Prototype fleet ($d$), the motorcycle would need to be serviced up to 7 times (Table 3).

Each service is estimated to cost between $10 and $20. The extra cost of servicing the motorcycle over a similar distance to the solar tricycle’s case study was calculated by multiplying the average cost of servicing ($e$) by 7. It was then added to the total estimated cost of fuel across the distance ($d$) of the case study to arrive at a comparable estimated OPEX figure.
Table 3: showing estimated Fuel ($f$) and Servicing ($e$) accumulative costs of the in house motorcycle over ($d$) distance

<table>
<thead>
<tr>
<th>$d$</th>
<th>$f$</th>
<th>$e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 km</td>
<td>$15</td>
<td>$15</td>
</tr>
<tr>
<td>1500 km</td>
<td>$45</td>
<td>$30</td>
</tr>
<tr>
<td>3500 km</td>
<td>$105</td>
<td>$45</td>
</tr>
<tr>
<td>5500 km</td>
<td>$165</td>
<td>$60</td>
</tr>
<tr>
<td>7500 km</td>
<td>$225</td>
<td>$75</td>
</tr>
<tr>
<td>9500 km</td>
<td>$285</td>
<td>$90</td>
</tr>
<tr>
<td>11500 km</td>
<td>$345</td>
<td>$105</td>
</tr>
<tr>
<td>11895 km</td>
<td>356.85</td>
<td>OPEX: $462</td>
</tr>
</tbody>
</table>

As shown in Eq. (4) below, the estimated cumulative motorcycle OPEX of $462 was divided by the fleet's distance to yield a cost per kilometer of $0.04.

$\frac{\left(15\text{US}^\circ\text{d}^\circ7 e+ f\right)}{d} = 0.04/\text{km}$

(4)

Based on these operating cost indicators, a motorcycle's cost per kilometer over the same distance traveled as the fleet of electric vehicles was 23% less than the Uhuru prototype's cost of $0.052.

Another unit of measure was the average fuel cost per kilometer for a small car, which ranged between $0.09 and $0.1/km. [7] Under sensitivity 2 of the Uhuru prototype's analysis this was around 45% higher than the presumptive OPEX of the solar electric tricycle. A small car's operating costs includes not only fuel but also other significant cost drivers such as maintenance, insurance, and utility service charges which have not been factored in here. This is an indicator that the small cars OPEX may well in fact be higher than the metrics shown here, which are built on a small car's fuel cost alone.

3.4 Efficiency Indicators

When a PV module was connected to the tricycle, it was more efficient (Graphs 1&2). According to a feasibility study for rural parts of Kenya, on average a small household with a grid tie implemented had an assumed daily consumption rate of 249wh ($a$). [8] This consumption rate is determined to be found in remote areas and informal settlements, with low energy demand since their power use is often limited to lights, charging phones and playing small electronic appliances.

The average efficiency on the Uhuru prototype comes to a figure of 15.7 wh/km ($i$) (Graph 3). The full capacity of the battery pack on the prototype was 1440wh. If we set an example depth of discharge on this battery pack of 60% then the energy available to us within one cycle is 864wh ($j$)

SEC K subtracted the daily estimate of energy consumption for a rural household ($a$) from the capacity of our battery pack ($j$) and divided the remaining amount of energy available over the Uhuru prototype's average energy efficiency, measured in watts per kilometer ($i$). From this it was indicated that the Uhuru prototype would be able to travel a distance around 39km at the same time as providing the necessary small rural household load profile of 249wh on a daily basis. Accordingly, the more energy a household consumes, the less distance in kilometers the Uhuru prototype will be able to cover in a day. In the same respect, the deeper the depth of discharge from the battery pack, the greater the potential supply of energy will be.

$(a-j)/i = 39\text{km}$

(5)

4. Conclusions

SEC-K has proved that they can build a solar powered tricycle for under $1000 with the Uhuru prototype case study. Managing the fleet over a distance of 11895km revealed that this vehicle can be maintained for an average base cost of $0.052 per km. Nevertheless, this is 23% more than the estimated OPEX cost of a motorcycle over the same distance, thus it is not more cost-effective in that regard.

It was deduced that the maintenance cost was too high. To bring value to an end user, there was a need to reduce the cost of maintenance per kilometer to something less than the opex of a motorcycle. This meant that to be effective the solar electric tricycle should be saving a higher percentage on the dollar per kilometer compared to using a motorcycle. It is clear that SEC K over nurtured the Uhuru prototype during this case study since the pilot projects were structured around the research and development of the product. Thus a large portion of the expenditures came from experimenting with the prototype and its sub assemblies throughout the case study in order to work on improvements to the design.

4.1 Interventions

The company developed a much improved version of the solar electric tricycle known as the Tryke based on the data from the Uhuru prototype case study (Image 6). Plans are already underway to test the product in a new case study within a rural setting.

In order to reduce the cost further with the Tryke, SEC K had to learn from the failings within the Uhuru prototype. They processed the maintenance dataset to build an improvement threshold. The threshold acts as the standard to be built upon by the Tryke. This threshold clearly indicates where the majority of maintenance was carried out, and signals to the areas that must be improved upon in the evolution from the Uhuru prototype to the Tryke. The improvement threshold draws a line through the list of all
vehicle components within the master maintenance profile. Anything that went over this line in terms of maintenance frequency would be brought into question during the Tryke’s new design. Any item that was maintained within the fleet distance which remained below the improvement threshold was considered generally fit for its purpose.

The items above the threshold included the Batteries, Charge Controllers, Motors, Tires, Brake Cables, Brake Pads, Rims, Chain and Front Forks as indicated in the data. All of these things have been upgraded or improved upon in the newer Tryke prototype, some of which have been explained further below.

One key shift was from lead acid batteries to Li-ion technology for energy storage since it has a higher number of duty cycles and a deeper depth of discharge.

Charge controllers were removed as they frequently blew up or malfunctioned. SEC K are adopting the idea of connecting the solar PV directly into a battery management system (BMS) which manages the Li-ion battery. There has also been testing of integrating Maximum Power Point Technology in place of the Pulse Width Modulation charge controllers, in an effort to boost the efficiency and optimisation of the PV module.

Motors: were a big part of R&D and contributed to a lot of the failures on the Uhuru prototype. This was down to them being overworked and overheated in addition to accelerating to high speeds, hitting potholes and tearing up of the internal gear sets which were made of a cheap plastic material. The key improvement here was the removal of the “sun” gear which produced the higher, faster gear ratio within the motor. This ultimately meant limiting the top speed to a safe 20km/h, to prevent the motors from being overworked and overheated. The motors on the Tryke have been proven to be reliable when going up a hill or carrying a heavy load. The best part is that there is enough torque even in low gear to climb hills and carry heavy loads while keeping the motor cool and the vehicle safer at low speeds.

Tires and Rims: In the new design, SEC-K utilized 20*4” fat tires and their corresponding rims. This allowed for greater weight distribution, lower ground clearance and a safer, more controlled ride that put less stress onto the steel frame, which in turn no longer requires frequent welding repairs.

The bicycle disk brakes which required a lot of management in alignment and replacement on the Uhuru prototype were upgraded to hydraulic scooter brakes. From these improvements and looking ahead, SEC K propose that they have created a more reliable and therefore more affordable vehicle in the Tryke. You can request to view any of the datasets that we have based our results on within this article, or any further information on our current operations by contacting the authors of this article directly through the channels provided.

5. References