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Hybrid battery and supercapacitor energy storage for enhanced performance of retrofitted e-motorcycles: Case study of Rwanda

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Abstract

Nowadays, the increase in air pollution and fuel costs has made the usage of electric vehicles (EVs) more dominant. However, EVs face a major challenge due to the impact of high charge-discharge currents on battery lifespan, leading to performance degradation over time. Supercapacitors (SCs) present a promising solution to address these issues and improve battery longevity. By combining SCs with batteries, the stress on the battery during high current demand can be transferred to the supercapacitors, reducing the heat generated in the battery and ultimately extending its lifespan. SCs can store significant amounts of energy and provide high power output without significantly affecting their lifespan. The purpose of this research is to enhance energy storage performance in retrofitted electric motorcycles. This was achieved through modelling and simulating a hybrid system that integrates both batteries and supercapacitors using MATLAB. According to the conducted survey, 90% of respondents preferred gasoline-powered motorcycles due to the longer driving range offered by a full tank of fuel compared to the limited range of a fully charged electric motorcycle. To address this issue and promote the adoption of electric motorcycles, the study developed a hybrid model that combines batteries and supercapacitors to extend the driving range. The simulation results showed a 35.76% increase in average power, indicating a significant improvement in energy storage and overall performance. This suggests that hybrid systems incorporating supercapacitors and batteries could play a vital role in enhancing the performance and feasibility of electric motorcycles.

Keywords: Energy efficiency, Gasoline motorcycle, Hybrid storage, Retrofitted motorcycle, Supercapacitor.

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1. Introduction

The widespread use of gasoline-powered vehicles worldwide has resulted in severe environmental and health issues. These vehicles emit harmful pollutants such as carbon monoxide and hydrocarbons, which contribute to air pollution and global warming [1]. In many developing countries, motorcycles have become a popular mode of transportation. They are well-known for their flexibility, speed, affordability, convenience for short travel, and ease of parking, making them an ideal choice for short-distance transportation. In Rwanda, especially in Kigali, these motorcycles are vital in the transportation system. They offer affordable mobility solutions in areas that are not covered by other public transportation types and enable swift and convenient last-mile travel. Additionally, they are high in demand among urban citizens as their mode of transportation comes in a smaller size, and at the same time enable riders to avoid hassles such as traffic congestion and parking insufficiency.

However, with rapid industrialization and growth, the number of motorcycles has increased significantly, resulting in a substantial amount of pollution emissions and noise [2, 3]. Therefore, reducing pollution emissions from motorcycles has become a pressing issue that cannot be ignored [4]. In transportation systems, electric motorcycles are being adopted to mitigate these pollution emissions issues [5, 6]. Sustainable and improved transportation relies heavily on electric traction. Battery Electric Vehicles (EVs) are one of the most promising options. In the case of EVs, greater emphasis is placed on the specific power, which is associated with acceleration and hill-climbing abilities. Additionally, the longevity of the main energy-storage system (ESS) is a crucial consideration [7]. However, these motorcycles present different problems related to their daily usage. Some of them include a shortage of charging stations, initial cost, and unsatisfactory driving range caused by the low capacity of the onboard battery, which is the main issue for the currently operating electrical motorcycles. For battery-based energy storage systems (ESS) in electric vehicles (EVs), high power density is essential to meet peak load requirements.

However, EVs that rely solely on battery energy storage systems (BESS) face challenges such as limited range, decreased battery lifespan, and insufficient power density [8, 9]. To address these issues, it is necessary to incorporate an additional ESS or buffer capable of managing sudden current surges more effectively [10, 11]. As a solution to these problems, researchers have proposed a hybrid energy storage system that incorporates supercapacitors (SC) [9]. It is indicated that this SC can be used in hybridization to improve the system performance of batteries and SCs, given that SCs have a high speed in charging and discharging [12, 13]. These devices offer a viable approach for managing power inconsistencies and energy-storage requirements. It is also indicated that a series connection of multiple SCs leads to a higher voltage, which is required in a hybrid system [14].

In this paper, instead of producing a new electric motorcycle, an existing traditional petrol-driven motorcycle was converted into an electric one by using the concept of retrofitting. Retrofitting consists of taking the petrol engine of the motorcycle and other key components out of the motorbike including motor transmission, combustion engine system, and exhaust system, and replacing them with electric ones [15]. Figure 1 shows the process of converting petrol-driven motorcycles into electric motorcycles conducted at Rwanda Electrical Mobility (REM) workshops.

Figure 1.
Retrofitting process: From original petrol-drive to full retrofitted at REM workshops.

After retrofitting, the motorcycle remains only with the motor, speed controller, frame, batteries with 2000 lifecycles, and brakes. This research investigates the integration of hybrid battery and supercapacitor energy storage systems to improve the performance of retrofitted e-motorcycles in Rwanda. Key questions include: How does the hybrid system affect efficiency, range, and overall performance compared to traditional battery systems? Additionally, how does it support sustainability given Rwanda's energy infrastructure and environmental policies? This work aims to enhance the performance of the energy storage system by modelling and simulation of the hybridization of battery and supercapacitor to increase the distance to be covered by e-motorcycle, which is the main contribution of this paper. Apart from this introduction section, this paper is organised into the following sections: 2) Related works, 3) Methodology, 4) Dynamic modelling of e-motorcycle, 5) Results and discussions, and finally, 6) Conclusion.

2. Related Works

2.1. Basic Characteristics of a Retrofitted Motorcycle

The electrical motor is needed to convert electrical to mechanical power to propel the two-wheeled motorcycle, the brushless DC motor (BLDC motors) are mostly used**.** The motor is used to drive rear wheels with a chain drive between the motor pinion and rear axle gear [16]. As the motor starts, the shaft of the motor starts to rotate, and due to this, the wheel of a motorcycle also starts to rotate [17]. In general, BLDC motors are faster and more powerful than conventional brushed motors, and they also make less noise [18]. For energy storage, the battery is used, and nowadays, Lithium-ion batteries are commonly used for portable electronics and electric vehicles due to their high energy and power density, long cycle life, low self-discharging, and fast-charging capacity compared to other types of batteries like Nickel-cadmium or lead acid batteries [18]. After retrofitting, the motorcycle remains with an electric motor, speed controller, frame, batteries, and brakes [16, 19]. A throttle allows driving an e-motorcycle from zero to rated speed. The throttle converts the DC voltage received from the battery to alternating voltage to facilitate speed control. This alternating voltage and a variable frequency drive the BLDC motor at different speeds [17].

Electric motorcycles provide the following advantages compared to petrol-driven ones: (i) Long-term money saving, (ii) Reduced maintenance costs, (iii) environment-friendly, (iv) More torque, (v) Quiet riding, and (v) No considered petrol costs. Apart from the mentioned advantages, electric motorcycles suffer from: (i) Charging times, (ii) High initial upfront cost, (iii) High cost of battery replacement (iv) Limited battery life [20, 21]. Therefore, considering all the above factors, e-motorcycles are more preferred than petrol-driven motorcycles [17].

2.2. Improving the Energy Storage System of E-Motorcycles

Adding a SC storage system to the existing battery storage extends the autonomy of the motorcycle. SCs are useful technologies for delivering high power, while batteries are used to transfer energy. SCs have a higher power response and a longer lifecycle than batteries do [22]. They can deliver a large amount of energy in a few seconds, and they can be fully discharged without degrading their lifecycle. In Zahedi, et al. [5] and Machedon-Pisu and Borza [23] an economic evaluation of the energy storage system for electric motorcycles was conducted using Federal Test Procedure driving cycles. The results indicated that employing a combined energy storage approach led to a reduction in the frequency of battery replacements over the vehicle's lifespan.

An optimally controlled hybrid system consisting of a supercapacitor and a battery was proposed to reduce the impact of peak current demands on the battery [24]. Furthermore, it has been found that e-motorcycles can save energy compared to gasoline motorcycles travelling the same distance, but the battery capacity of e-motorcycles is limited [25]. For this reason, to enable the e-motorcycles to travel long distances, the energy storage systems could be enhanced. However, due to the high initial cost of e-motorcycles, retrofitting [17] could offer a reliable solution to accelerate e-motorcycle adoption and satisfaction.

3. Methodology

This study employed a survey questionnaire to capture the behavior, experiences, and performance of gasoline and electric motorcycles from motorcycle riders. In addition to the survey, design, modeling, and simulation were conducted using MATLAB to further analyze e-motorcycle performance. A key component of this research was the use of a driving cycle [26] a velocity-time profile that simulates real-world driving conditions, and reflects vehicle speed values over time, which is crucial for simulating realistic traffic scenarios. For determining load power requirements, it helps predict the expected power demand during various driving conditions. This prediction allows for efficient power management, particularly for electric motorcycles, by optimizing the allocation of power between the battery and supercapacitor [14].

Through the combination of rider feedback and simulation models, this study provides a comprehensive understanding of the factors influencing the performance of gasoline and electric motorcycles, contributing valuable insights into optimizing e-motorcycle performance in diverse conditions. Two categories of driving cycles are commonly used in traffic simulations: the European and the American driving cycles [27]. In this case, a European driving cycle shown in Figure 10a was used to model the performance of the e-motorcycle.

3.1. Design and Dynamic Modelling of E-Motorcycle

A typical model that shows various subsystems of an e-motorcycle such as the battery, electric motor, controller unit, and transmission system [28] is shown in Figure 2. Battery packs consist of battery modules, with multiple battery cells in series and parallel configurations within each battery module. Series battery cell connections result in higher pack voltage, while parallel cell connections result in larger current and power capacities, which in turn lead to higher pack capacities [29].

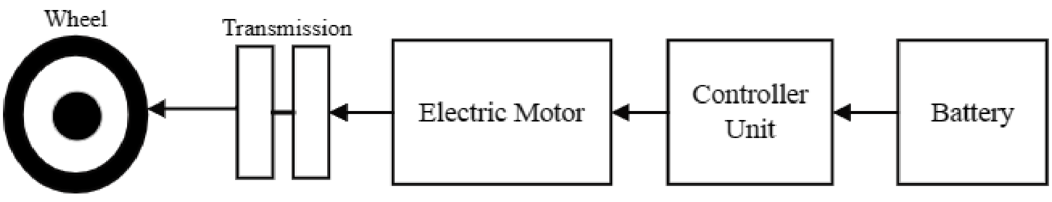

Figure 2.
Topology of a retrofitted motorcycle.

The discharging current (i_g) was calculated (from the propulsion power required to propel the e-motorcycle) to be able to compute the battery voltage (V_b) as shown in (1), while the power of the battery pack (P_b) is expressed in (2) and the battery parameters [30]. The battery parameters used in this work are shown in Table 1.

$$V_b = V_{OC} - R_{bat} \times i_g + A \times \exp(-B \times i_g) - K \frac{Q(i_g - I_{FC})}{Q - i_g} \quad (1)$$

$$P_b = V_b \times i_g \quad (2)$$

where:

V_{OC} is constant voltage from battery (V), K is polarization constant (V/Ah) or polarization, resistance (Ω), Q is battery capacity (Ah), A is exponential zone amplitude (V), B is exponential zone time constant inverse (Ah-1), R_{bat} is internal resistance (Ω), and I_{FC} is filtered current at low frequency (A).

Table 1.
Battery Parameters.

Parameters	Units	Values
Battery constant voltage (Voc)	V	72
Polarization constant (K)	V/Ah	0.0076
Battery capacity (Q)	Ah	2.3
Exponential zone amplitude (A)	V	3.5949
Exponential zone time constant inverse (B)	Ah^{-1}	1.5256
Internal resistance (R_{bat})	Ω	0.012
Filtered current (I_{FC})	A	0.1

3.1.1. Battery Supercapacitor Hybridisation

A parallel combination of battery and supercapacitor is involved to improve the storage system of the e-motorcycle. This supercapacitor is a capacitor with a capacitance of very high value [31]. Hybrid energy storage (HES) results from the integration of two or more different storage technologies into one system, and the basic components of HES are shown in Figure 3. The combination of the advantages and characteristics of different storage methods is performed to achieve specific requirements and improve the whole system's performance. SCs have a high power rate and short discharge duration, but limited energy density. Also, batteries have high energy rates and long duration of storage, but limited power. This hybridization provides high energy and power ratings, fast response, and both short and long discharge duration. In this paper, the total power to the motor (P_t) shown in Figure 3 is calculated using (3).

$$P_t = P_{sc} + P_b \quad (3)$$

where P_{sc} is the power of the supercapacitor.

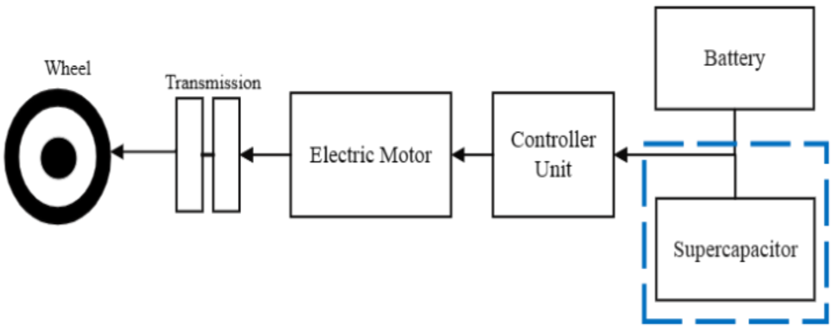

Figure 3.
Consideration of both battery and supercapacitor.

Output voltage of the supercapacitor (V_{SC}) is expressed in (4).

$$V_{SC} = N_S(V_{OSC} - R_1 \frac{i_g}{N_P}) \quad (4)$$

where N_S and N_P are the number of supercapacitor cells in series and parallel connection, respectively. Also, V_{OSC} is the voltage of a single cell supercapacitor and i_g is the current of the supercapacitor module. The P_{sc} is calculated using (5), where the values of the parameters to be used are shown in Table 2.

$$P_{sc} = V_{sc} \times i_g \quad (5)$$

Table 2.
Supercapacitor parameters.

Parameters	Units	Values
Capacity	F	310
Voltage (single cell)	V	2.7 V
Ns	-	5
Np	-	1
Internal resistance	mΩ	0.0055
Nominal capacitance	F	210
Cv	F/V	80

3.1.2. Forces Acting on E-Motorcycle and Power to the Motor

To propel the e-motorcycle, it must overcome all resisting forces. Referring to Figure 4, the total tractive force provided by the motor $F_{tr}(t)$ is calculated in (6) [25] and the estimated values for e-motorcycle weights are shown in Table 3.

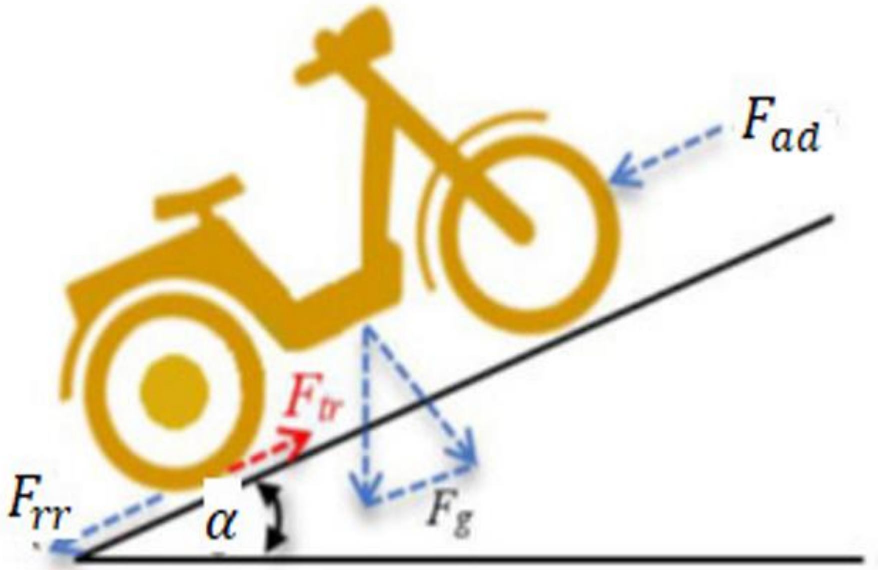

Figure 1.
Forces acting on the e-motorcycle.
Source: Shirima, et al. [25].

$$F_{tr}(t) = M \times \frac{dv_{d(t)}}{dt} + F_{rr}(t) + F_{ad}(t) + F_{\alpha}(t) \quad (6)$$

where:

- M is the total mass of the EV rider, passenger, and the weight of the e-motorcycle (kg) and $v_{d(t)}$ is the driving velocity (m/s).
- $F_{rr}(t) = M \times g \times f_{rr} \times cos\,\alpha$ is the rolling resistance, "g" is the gravity constant and f_{rr} is the rolling resistance Coefficient between the tyres and the road.
- $F_{\alpha} = M \times g \times \sin\alpha$ is the gradient resistance force
- $F_{ad}(t) = \frac{1}{2}\rho_a C_{ad} A_f v_d^2(t)$ is aerodynamic drag resistance, "ρ_a" is the air density, "C_{ad}" is the aerodynamic drag coefficient, and "A_f" is the frontal area, where the corresponding parameters are in Table 4 .

Table 3.
Estimated values for e-motorcycle weights.

Parameters	Mass in kg
E-motorcycle Weight	90
Passenger	60
E-motorcycle rider	75

Table 4.

Parameters for the aerodynamic drag force of e-motorcycle [25].

Symbol	Road angle(θ)	ρ_{air}	A_f	f_{rr}	C_{ad}	η_{SYS}
Quantity	1.72 rad	1.2 kg/m^3	0.50m^2	0.48	0.60	0.93

The total net electrical input power (P_{t_net}) to the motor required is calculated using (8).

$$P_{t\_net} = \frac{P_t}{\eta_{SYS}} = \frac{F_{tr} \times V_d}{\eta_{SYS}} \quad (8)$$

where η_{SYS} is the system's efficiency.

3.3. Survey-Based Data Collection

The research model was developed based on a survey conducted in two key locations: Musanze District and Kigali City. This study aimed to evaluate and compare the performance of both gasoline-powered and electric motorcycles in these areas. The research targeted a sample of 50 motorcycle riders, including those using electric motorcycles and those relying on traditional petrol-driven ones. The selection of respondents was based on the availability of e-motorcycles in Kigali and the likelihood of finding the required number of motorcycle riders in Musanze District. This approach ensured a balanced representation of both regions, allowing for a comprehensive evaluation of electric and gasoline motorcycles under different conditions. The study aimed to capture diverse experiences, environmental conditions, and factors influencing motorcycle performance by selecting riders, considering their choice and usage of gasoline and electric motorcycles in varying terrains and infrastructures.

4. Results and Discussion

This section describes the results found during the data collection and those from software simulation for combined battery and supercapacitor.

4.1. Motorcycle Riders' Perception of the Usage of Gasoline and E-Motorcycles

In this paper, the technical challenges for both gasoline motorcycles and e-motorcycles are discussed. According to Figure 5 most frequent problems of gasoline motorcycles are related to engine functionality, which takes 39% of all mentioned technical challenges indicated by responders. Contrary to the e-motorcycle, the main technical challenges are based on the control unit (30%). However, the lighting system and the quality of bearing are shown to be less problematic by 4% compared to other indicated technical problems for both gasoline and electric motorcycles respectively.

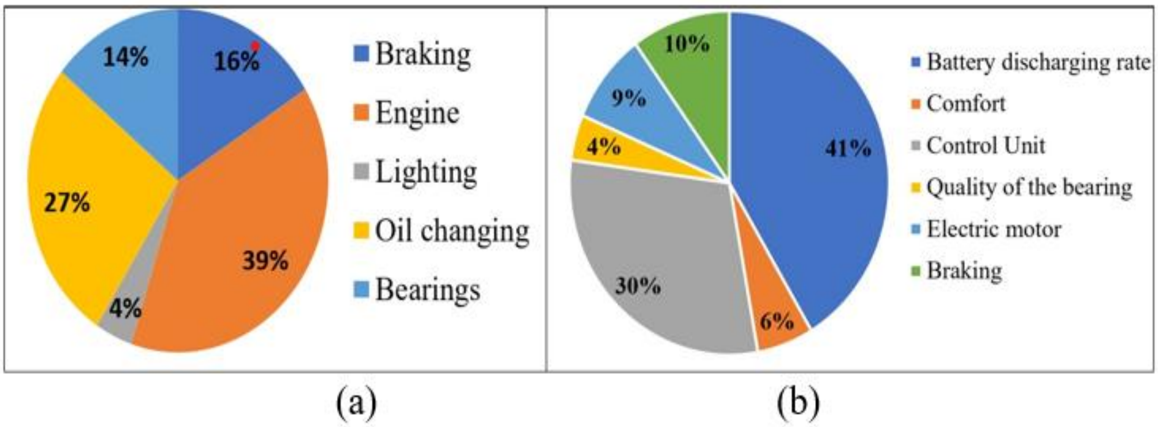

Figure 5.
The main technical problems of (a) gasoline motorcycles and (b) electric motorcycles.

In general, gasoline motorcycles require more maintenance as they have more mechanical parts, which can wear out. This results in additional operating costs of ownership. It has also been observed that the speed of gasoline motorcycles is low. However, according to the responders (6%), e-motorcycles are not comfortable compared to petrol-driven ones as shown in Figure 5. Thus, modifications can be made to the structure of these electric motorcycles to meet the customers' needs.

4.1.1. Impact of Distance During Fuelling Motorcycles

It has been observed that 78% of the riders live far away from the fuelling stations, as shown in Figure 6a. Based on their responses in Figure 6b the riders living at a distance of 2 km or more are assumed to live far away from the fuel stations. It can be inferred that many riders must travel a long distance to reach the fuel stations. This has a significant impact on their living conditions, as they must bear additional costs.

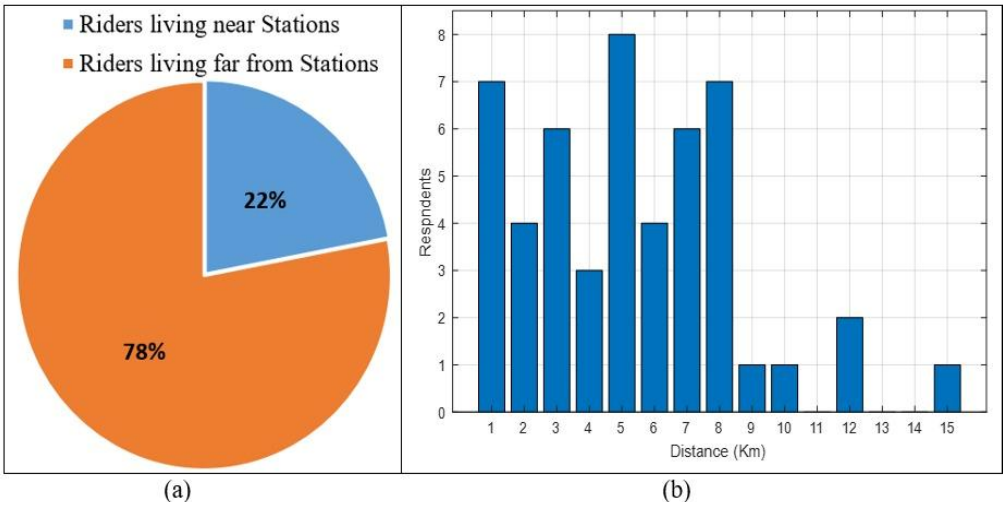

Figure 6.
Distance from moto riders' homes and fuelling station.

The longer distance to the fuelling stations, the more the fuel costs to operate a motorcycle. This can be an important point to be considered while sensitizing petrol-driven motorcycle riders to shift to the use of electric motorcycles after the installation of possible infrastructures related to electric mobility.

4.1.2. Environmental Impacts of Gasoline Motorcycles

As discussed above, gasoline motorcycles are among the sources of gas emissions that affect the environment. It was found that the transportation sector contributes around 27 % of greenhouse gases (GHGs) emissions [32]. As a consequence, gasoline motorcycles in Kigali emit ten (10) times more GHG emissions per kilometer travelled than e-motorcycles [33]. In this work, even though motorcycle riders in the selected sectors of Musanze district are not aware of gas emissions, 54% of them are convinced that petrol-driven motorcycles emit gases as shown in Figure 7, and 34% of them have no idea about the negative impacts of motorcycles. This indicates that a campaign for motorcyclists about these impacts is required, especially for rural areas including the Musanze district where the survey was conducted.

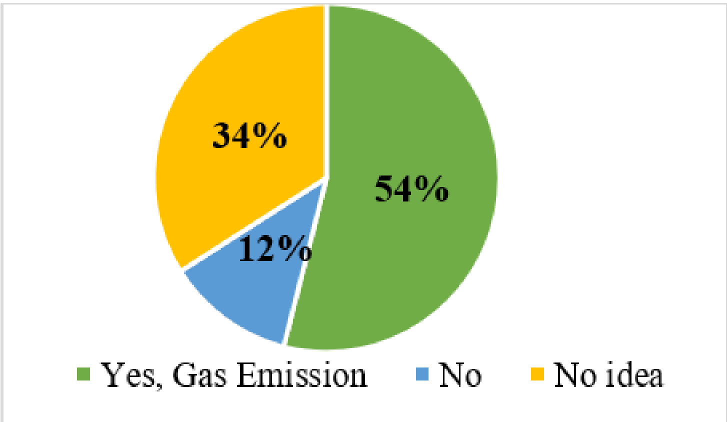

Figure 7.
Impacts of gasoline motorcycles on global life.

4.1.3. The Status of E-Motorcycles in Rwanda

Currently, three companies offer electric motorcycles: Ampersand Inc.,(REM [34] and SPIRO [35]. While Ampersand Inc. and SPIRO exclusively produce and distribute electric motorcycles, REM focuses on converting gasoline motorcycles into electric ones.

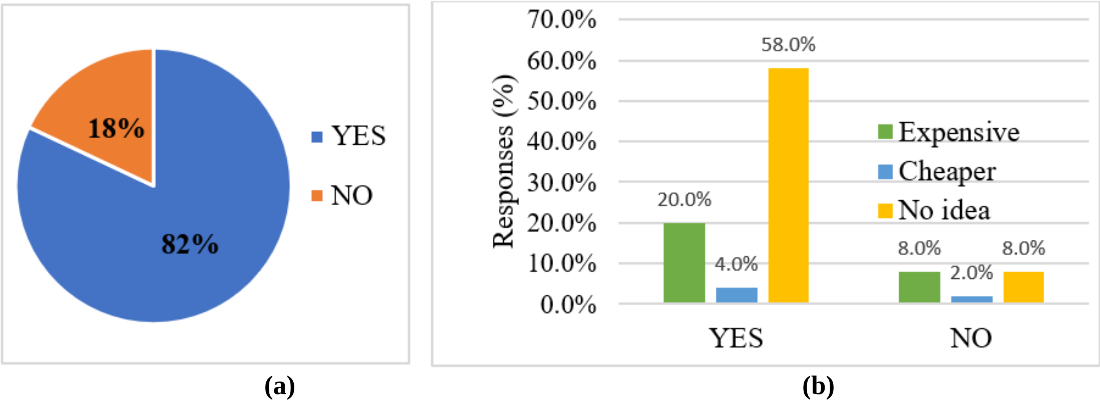

Figure 8.
(a) Availability of e-motorcycles and (b) Cost information).

However, a survey in the Musanze district revealed that although 82% of motorcyclists are aware of e-motorcycles, 18% have no idea about them as shown in Figure 8a and Figure 8b. Additionally, 58% lack information on the cost of using e-motorcycles, as they currently use gasoline ones. This underscores the need for better education campaigns to convey the existence and benefits of e-motorcycles, as some may perceive the cost as prohibitive. Rwandan policy [36] aims to transition all gasoline motorcycles to electric ones.

4.1.4. Choice of Motorcycles

This part discusses the preferences of motorcycle riders when it comes to choosing between e-motorcycles and gasoline-dependent motorcycles. E-motorcycles generally have a higher upfront purchase price than gasoline motorcycles; however, they prove to be more economical in terms of operating costs per kilometer. Despite Rwanda's relatively high electricity rates, the energy expenses associated with electric motorbikes are considerably lower than those of traditional motorcycles. As a result, e-motorcycles emerge as a more cost-effective transportation choice over time [33]. According to Figure 9 52% of motorcyclists stated that fuel cost was high as compared to the battery swapping cost. Additionally, when it comes to distance coverage, 90% of them preferred gasoline-dependent motorcycles as they can cover longer distances as compared to e-motorcycles that are fully charged.

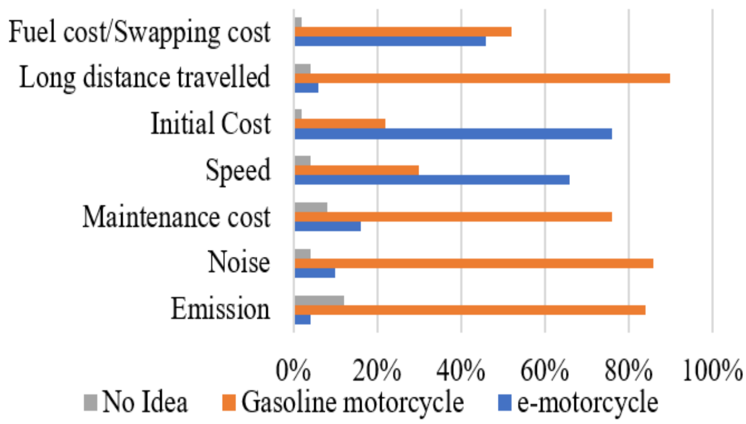

Figure 9.
Reasons for motorcycles' preferences: gasoline vs. e-motorcycles.

By considering motorcycle cost, 76% responded that the initial cost of e-motorcycles is higher than that of gasoline motorcycles, and this can be a major challenge for some riders to adopt these types of EVs. According to these respondents, the maintenance cost for gasoline is higher than that for electric energy-dependent ones. In addition, 84% of the respondents confirmed that gasoline motorcycles emit more greenhouse gases into the atmosphere. It was found that the performance of e-motorcycle storage is not sufficient (to cover sufficient distance) compared to the gasoline ones. This is important to improve the storage system of e-motorcycles to satisfy the energy demand for motorcycle riders.

4.1.5. Battery, Supercapacitor and Hybrid Powers

Figure 10b shows the generated electrical current used to analyse the performance of the storage system for a chosen driving cycle shown in Figure 10a. It is indicated that the used urban dynamometer driving schedule (UDDS) [37] ranges for a time of 2798 seconds, and the speed varies from 0 to 10 m/s. This UDDS has been chosen because it is commonly used in the city test and represents city driving conditions [38, 39].

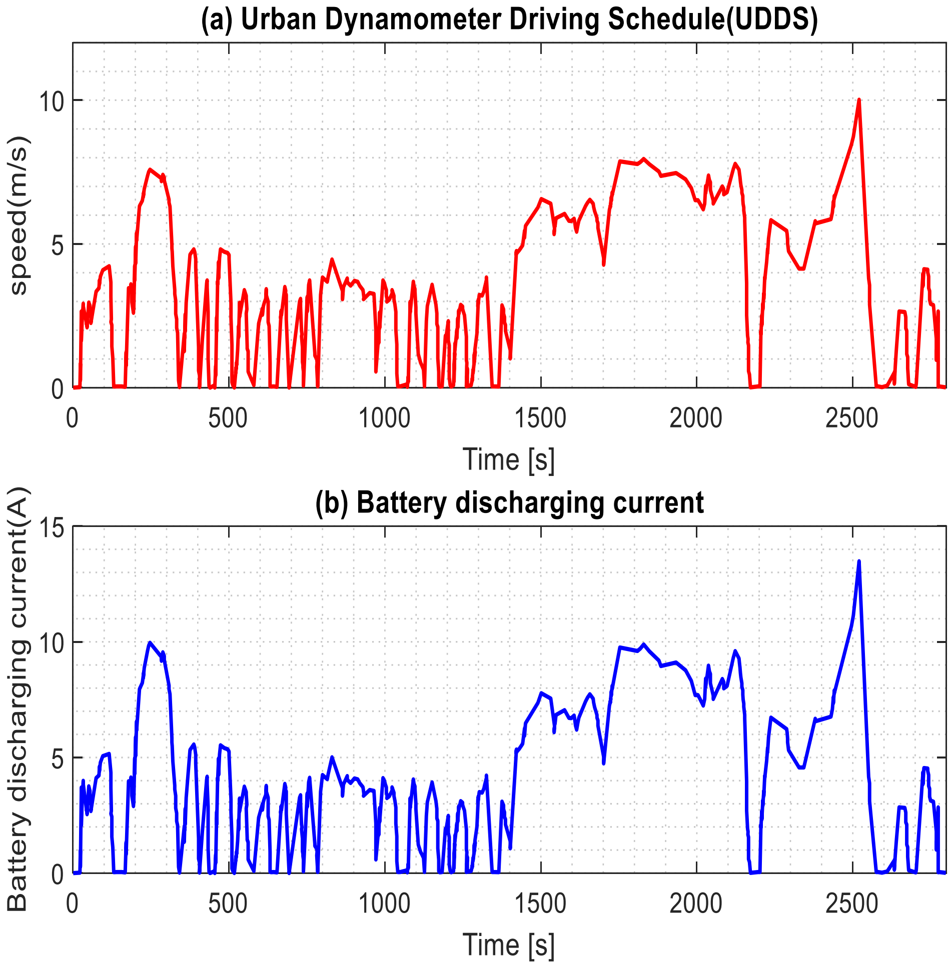

Figure 10.
Extracted current from the battery and the driving cycle.

The more the speed increases, the more the extracted current from the battery increases, indicating a high-power consumption. In Figure 12, it is evident that combining the battery with the supercapacitor results in an increase in power input to the motor by 35.76%. This, in turn, helps to enhance the driving range of the electric vehicle (EV). In addition, a supercapacitor provides the effectiveness to mitigate rapid power fluctuations in and out of the battery of an electric vehicle [40]. Comparing the riding speed in Figure 10a and the power consumed in Figure 12 it is recommended to maintain an average speed to reduce the power consumption from the storage system. The discharge pattern of supercapacitors is characterized by a linear decline in voltage over time as energy is released by comparing to Figure 11a and Figure 11b. This voltage is directly related to the amount of charge that remains in the device. In contrast to batteries, supercapacitors do not maintain constant voltage during discharge. Instead, the voltage began to decrease immediately and continued to fall throughout the entire discharge process, resulting in a sloping discharge curve rather than a flat one.

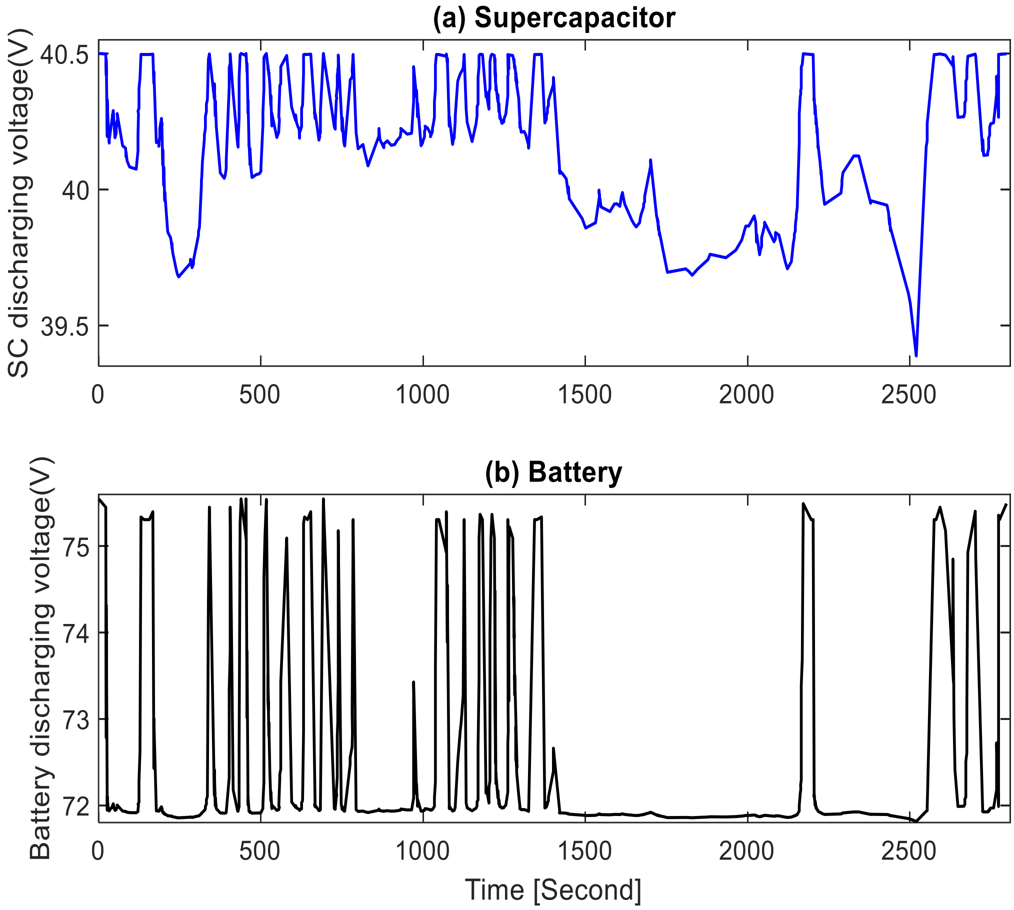

Figure 11.
Discharge voltages for (a) supercapacitor and (b) battery storage.

Battery storage maintains a relatively constant voltage during discharge, with a slow decrease as energy is depleted. However, when subjected to high current demands, these batteries experience a moderate voltage reduction due to internal resistance. While batteries excel at long-term energy storage, they are less effective at managing brief, high-power outputs without compromising efficiency or experiencing degradation. In contrast, supercapacitors display a linear voltage decline during discharge. Their low internal resistance allows for the delivery of extremely high currents, making them well-suited for short, intense power requirements, such as quick acceleration. However, supercapacitors have a significantly lower energy density compared to batteries, resulting in a reduced overall energy storage capacity.

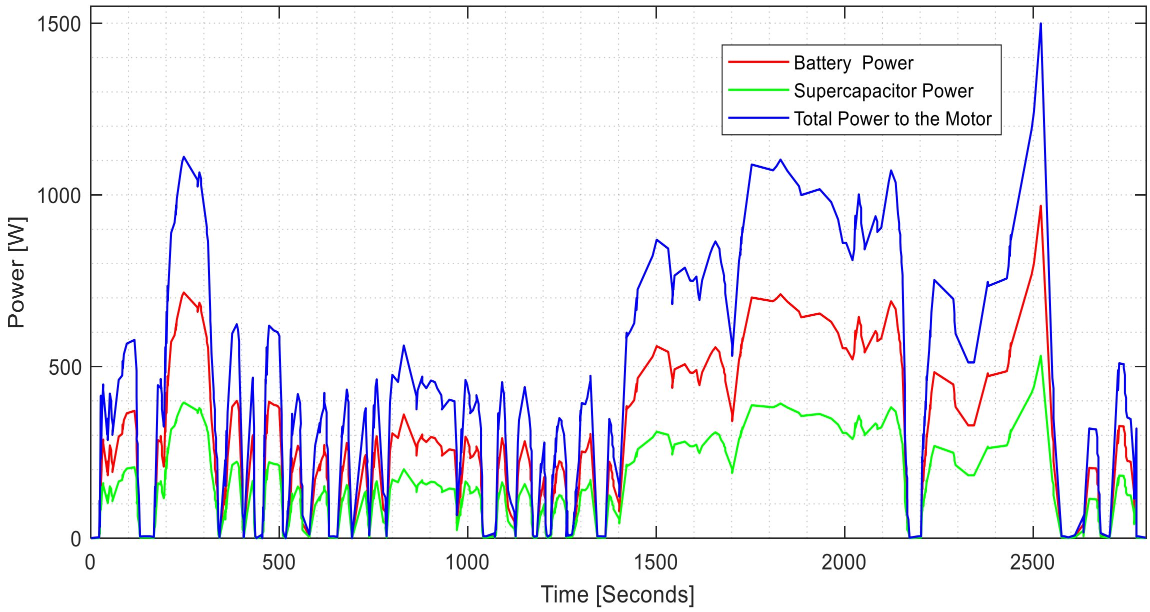

Figure 12.
Battery power, SC power and bus power.

Battery stress can be decreased with a direct parallel connection, while its life span can be increased [41]. It was found that once the supercapacitor is added to the battery storage system, the overall charging cost is reduced by curtailing the charging cycles, which proves that this combination contributes to the increase of the electrical vehicle's travelling range [42]. In this paper, it was found that the average power at the time of 2520 seconds, a peak power of 35.4% as shown Figure 12 has increased after incorporating the supercapacitor in the system. This result points to an improvement in the performance of the e-motorcycle energy storage.

5. Conclusion

In conclusion, the efficiency improvement of the energy storage system of electric motorcycles is crucial for advancing the viability and sustainability of electric mobility. During this research, data collection was done to assess how motorcycle riders understand the working principle and behavior between gasoline motorcycles and electric motorcycles. Referring to the survey conducted, it was found that 90% preferred the use of gasoline-based motorcycles, because these motorcycles cover long distances compared to e-motorcycles. To enhance the usage of e-motorcycles, modelling and simulation of a hybrid battery and supercapacitor storage system was done to improve the performance of energy storage of e-motorcycles to cover a higher driving range. The simulation shows that the average power of 35.76% has increased after incorporating the SC in the system, indicating the possibility of improving the storage system of retrofitted motorcycles. Also, due to the lack of information regarding e-motorcycles, sensitization related to the advantages of using e-motorcycles is needed in remote areas of Rwanda. For the future research, the studies will be concerned with the analysis of a retrofitted motorcycle to be charged with renewable energy resources.

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