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Development and Techno-Economic Analysis of a Large-Scale Speed Bump Power Generation System

Baribuma Gbaarabe*, Barinyima Nkoi

Department of Mechanical Engineering, Faculty of Engineering, Rivers State University, Port Harcourt, Nigeria

Email address:
buma3g@gmail.com (Baribuma Gbaarabe)
*Corresponding author

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Abstract: This study explores the practicability of a large-scale power generation from road speed bumps by harvesting moving vehicle energy using mechanical speed bump (MSB). It includes conceptual design of a large-scale speed bump power generation system (SBPGS), analysis of the power generating capacity, and techno-economic analysis of the system. The system is designed with 8 mechanical speed bumps that are installed sequentially on the road with its linked DC generators connected together in parallel to the energy storage system (ESS) via the low voltage bus bar. To analysed the power generating capacity, performance data of the mechanical speed bump fabricated-prototype simulated under traffic condition was collected, and traffic survey was conducted for the proposed installation road. The analysis carried out on the system shows that with the passage of 16,949 vehicles per hour on the road, the power generating capacity of the system is 2MW, of which 8MWh of usable energy would be harvested in 6-hours period of continuous traffic flow per day. The harvested energy would be stored in a 15MWh capacity battery storage system, contains 375 batteries of 24V, 1500Ah capacity each, wired into 3 parallel strings, from which it would be withdrawn for use and also transmitted into the gird. The techno-economic analysis carried out shows that the system can be implemented at a cost of ₦250,518,000, with levelized cost of energy generation of ₦5.58/kWh, a payback period of 3years, and would mitigates 1,281,880kg of CO_2 emissions and its accrued carbon bon tax of ₦4,486,580 annually. The proposed system design would enable addition of more renewable power generated to the national gird, and despite its initial investment cost, the lowest value of the levelized cost of energy guarantee is it an economic feasible source of renewable power generation.

Keywords: Energy Harvesting, Energy Storage System (ESS), Speed Bump Power Generation System (SBPGS), Levelized Cost of Energy (LCOE), Mechanical Speed Bump (MSB), Moving Vehicle Energy, Traffic Flow

1. Introduction

Energy access in Africa is a key policy priority, given the strict inter-relation between energy, economic growth and sustainability. The persistent energy crisis in Africa is hindering the continent's ability to transition economically [1]. The challenge in overcoming this energy crisis required urgent needs for alternative energy sources [2]. According to Rhodri speed bump is the latest alternative energy source [3]. The speed reduction of vehicle when encountering speed bumps on our road ways results in energy wastages [4]. An electro-mechanical system that is capable of harvesting this wasted energy and converting it to electricity is the proposed SBPGS [5]. The input energy into the system is the moving vehicle energy, which is abundantly available on our roadways daily, thus considered a renewable and alternative energy system [5, 6].

SBPGS utilizes both mechanical and electrical technologies for the power generation and its storage. It comprises of two basic parts, mechanical speed bump (MSB) and energy storage system (ESS). The MSB is capable of harvesting moving vehicle energy using various mechanisms described as speed bump mechanism which includes rack and pinion mechanism [7]. The ESS uses different electrical components that stored and amplified the power generation, which include battery storage system, inverter, charge controller and other installation hardware [8]. Power is generated from the system as each vehicle drive over the MSB. Thus, the power generation is proportional to the traffic flow. The output of the system is intermittent and the intermittence of the power generation necessitated the ESS that stored energy generated in moments [9].

Rhodri presented a report on speed bumps to get new role as a source of renewable energy, in the report, Peter Hughes the designer behind the idea proposed that a steady flow of traffic passing over the speed bump can generate 10 - 36kW of power and four of the speed bump would be enough to power all the street lights, traffic lights and road signs for a mile-long stretch of road [3].

Dey et al. presented a paper on roadside power harvesting for auto Street light. In their paper vehicle pressurized the speed breaker causes potential energy to be converted into rotary energy by rack and pinion mechanism. The rotary energy rotates dynamo that generates electrical energy which is being stored through battery using charging circuit. They concluded that the amount of electrical energy generated depend on spring constant, displacement of rack, gear ratio, weight of the vehicle and number of vehicles [8].

Todaria et al. proposed a speed bump energy harvester that is expected to provide sufficient electricity for many road side devices, in their work an in-field test was done by driving a vehicle through the speed bump energy harvester prototype at 2km/h and a power output of 200W was achieved [4].

Olugboji et al. worked on modelling and design of an auto-street light generation speed breaker mechanism. The speed breaker mechanism was developed using a static analysis of the spring and computational fluid dynamics (CFD) analysis of the air flow using SolidWorks software. The test results revealed that the mechanism generated an average of 6VDC, an indication that the speed breaker mechanism is a feasible source of renewable energy and will be beneficial on a larger scale [10].

Wang et al. developed a speed bump energy harvester (SBH) to harness electrical energy from impulse excitation when a vehicle passes through a speed bump. In their work, a prototype was fabricated and tested using a passenger car. The result showed that power output up to 1.27kW was harvested when one-wheel axle of vehicle passes through the SBH at low speed. The analysis carried out on the SBH showed the effectiveness of the SBH and the capability of generating large-scale electrical power [11].

Gholikhani et al. developed an electromagnetic speed bump harvester (ESE) prototype to harvest energy of passing vehicles and simultaneously control the speed of vehicles. In their work, the ESE absorbs the deflection generated by a passing vehicle and converts it to a rotating shaft that triggers an embedded generator. A laboratory tests conducted to simulate the traffic conditions and evaluated the performance of the prototype in generating electrical power showed that a maximum average power of 3.21mW was generated, an indication that the proposed ESE prototype would generate substantial power under actual traffic loading conditions [12].

Gbaarabe et al. designed and fabricated prototype of a speed bump power generation system. In the work, experimental test and theoretical energy assessment were conducted to simulate the actual traffic loading condition, and evaluated the performance of the fabricated prototype in generating electrical power. The results showed that an average weight of 10.91kN acting on the tyres of vehicles, transmitted to an input mechanical power of 5420W that generated an average output electrical power of 32.52W. The results showed the capability of generating large-scale electrical power from the system when installed in a high traffic flow location [13].

Having reviewed literatures, it was observed that speed bump is a feasible source of renewable energy and will be beneficial on a larger scale. Thus, this study takes the concept of speed bump power generation a step further by developing a large-scale SBPGS to improve the speed bump power generation capacity and analyse its economic feasibility.

2. Materials and Methods

The materials for this study include performance data of MSB-fabricated prototype, traffic flow data of Market Junction (proposed installation road) obtained through traffic survey conducted by the authors, and the road layout of the Junction extracted from Port Harcourt google satellite map. The methods that have been used in the study are discussed in the following sections:

2.1. Description of a Large–Scale Speed Bump Power Generation

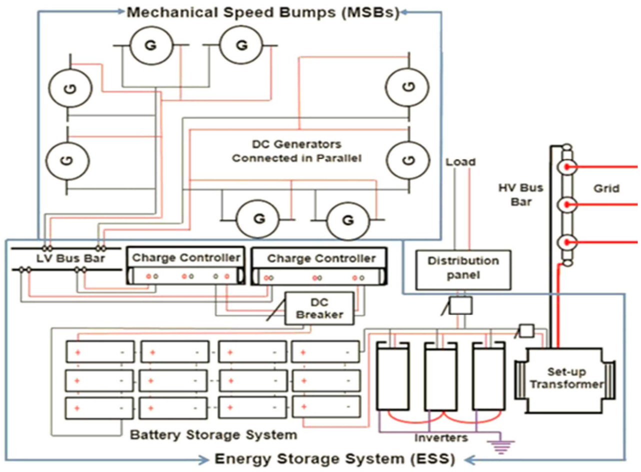

Figure 1. *Conceptual Design of the Large-Scale SBPGS.*

Figure 1 is the schematic description of the large–Scale SBPGS, which illustrate the transmission of the weight exerted on the MSB into electrical energy and its storage in the ESS from where it is withdrawn for use and also transmitted into the grid. The key components within the system include:

2.1.1. Mechanical Speed Bump

The MSBs are arranged sequentially on the road layout, with its link DC generators connected together in parallel which help to maintain continuity of the power generation. Table 1 show the summary of the performance analysis carried out on the MSB-fabricated prototype by the authors. A total of eight (8) MSBs are use in this study.

Table 1. Performance data of mechanical speed bump fabricated-prototype.

Parameter	Value
Average weight acting on MSB	10.91kN
Average power input	5420W
Average power output	32.52W
Energy conversion efficiency	0.6%
Generated emf	0.186V
Rotational speed of generator	31rad/s
Generator voltage constant	0.00634Vs/rad

Source: [13].

2.1.2. Battery Storage System (BSS)

The SBPGS operates intermittently. To mitigate fluctuations associated with the power generation due to the intermittent nature, battery storage system is required to store the energy generated in moments [9].

2.1.3. Inverter

The inverter converts the DC power from the DC generators to AC and reduces voltage fluctuation. The inverter also transferred the power generated to a step-up transformer, that step the power up to a frequency that is feasible and standardized for the grid. Three identical power inverters are stacked into parallel configuration to increase the amperage capacity to draw power from the BSS as shown in Figure 1.

2.1.4. Charge Controller

Charge controller manages the flow of energy into the BSS from the low voltage busbar. Two charge controllers are connected in parallel to each other across the BSS through a DC breaker as shown in Figure 1.

2.2. Mechanical Speed Bump Installation

Figure 2 is the schematic description of the MSB installation on the road layout of Market Junction. The MSBs are installed sequentially on the road layout fitted in precast trenches buried on the road. Port Harcourt is known to be one of the most populated cities in Nigeria and traffic congestion is observable virtually along all major roads [14]. Thus, creating the possibility for a large-scale SBPGS. Q_1, Q_2, Q_3 and Q_4 shows the traffic flow on each road layout per hour, and is summarized in Table 2.

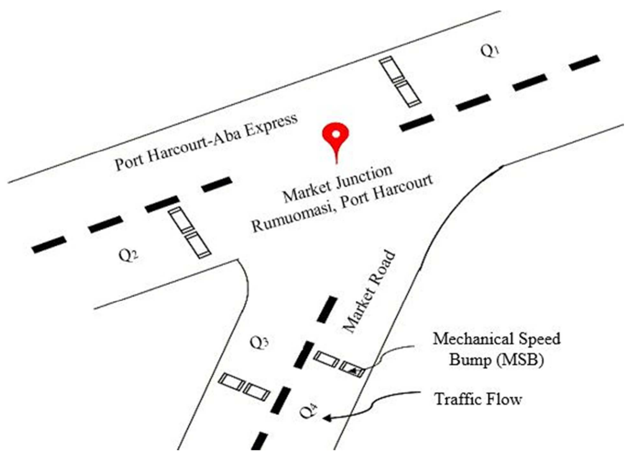

Figure 2. Mechanical Speed Bump Installation.

Table 2. Summary of traffic flow on each road layouts.

Day	Q_1 (veh/h)	Q_2 (veh/h)	Q_3 (veh/h)	Q_4 (veh/h)
Monday	5500	7000	3200	1380
Wednesday	5000	7600	3040	1190
Friday	6415	6900	2610	1050
Saturday	4128	4780	2800	5200
Average	5261	6570	2913	2205

Source: Traffic flow survey for Market Junction, Port Harcourt conducted by the authors

2.3. Power Generating Capacity

Power is generated from the system as each vehicle drives over the MSB. The power generating capacity of the system under actual traffic loading conditions is estimated from the power output of each MSB and the traffic flow [8-13]. Thus, power generating capacity (P_g) of the system would be calculated by

$$P_g = P_{veh} \times Q \times t \quad (1)$$

where P_{veh} = average power generated per vehicle passing on the MSB (W), Q = traffic flow (veh/h), t = survey period (h). From the traffic survey conducted, the traffic count data per direction was recorded based on 15-minute intervals, which summed up to a survey period of 1 hour from the 4-traffic flow configuration on the road under study as shown in Figure 2.

2.4. Energy Harvesting

Energy harvesting is the capture and conversion of small amounts of readily available energy in the environment into useful form of energy such as electricity [15]. The energy harvested from a system is defined in term of net capacity factor, which is a measure of the efficiencies of the energy transducers [16]. The energy transducers in the designed large-scale SBPGS include batteries, charge controllers and inverters as shown in Figure 1. Thus, the capacity factor is calculated by

$$C_f = \eta_i \times \eta_c \times \eta_b \quad (2)$$

where η_i = efficiency of inverter (%), η_c = efficiency of charge controller (%), η_b = battery charge efficiency (%).

The energy harvested (E_h) from the system is given as [16].

$$E_h = P_g \times T \times C_f \quad (3)$$

T = period of traffic flow (h). From the traffic flow survey conducted, an average of 6 hours of continuous traffic flow was experience at the Market Junction, Port Harcourt each day.

2.5. Sizing of the Battery Storage System

The harvested energy would be stored in a BSS. The specifications of the battery are shown in Table 3. The size of the BSS is determined as follows:

2.5.1. Capacity of Battery Storage System

The required capacity of the battery storage system expressed in Watt-hour (Wh) and Ampere-hours (Ah), respectively, and are given as [17].

$$C_{Wh} = \frac{E_h}{DOD \times \eta_b \times \eta_i \times \eta_c} \tag{4}$$

and

$$C_{Ah} = \frac{C_{Wh}}{V_r} \tag{5}$$

where DOD = battery depth of discharge, η_b= battery efficiency (%), V_r = net resultant voltage of the system (V).

2.5.2. Number of Batteries in the Storage System

The number of batteries to be connected in series and parallel of the BSS are given respectively as [18].

$$N_S = \frac{V_r}{V_b} \tag{6}$$

and

$$N_P = \frac{C_{Ah}}{C_b} \tag{7}$$

where N_S = number of batteries to be connected in series, V_b = voltage rating of a single battery (V), N_P = number of batteries to be connected in parallel, C_b = energy capacity of a single battery (Ah).

The total number of batteries (N_B) required for the BSS is then given as [18].

$$N_B = N_P \times N_S \tag{8}$$

2.6. Sizing of Inverter

Inverters are connected in parallel, and the number of inverters (N_i) required for the system is given as [18].

$$N_i = \frac{P_g \times Pf}{P_i} \tag{9}$$

where Pf = power factor, P_i = Capacity of a single inverter (kVA).

2.7. Sizing of Charge Controller

Charge controllers are connected in parallel to meet high power charging requirements, the number of charge controllers (N_c) required is given as [18].

$$N_c = \frac{P_g \times Pf}{V_r \times I_c} \tag{10}$$

where I_c = current rating of a single charge controller (A). The specifications of the battery, inverter and charge controller used are listed in Table 3.

Table 3. *Specifications of battery, inverter and charge controller.*

Component	Parameter	Value
Battery	Voltage	24V
	Capacity	1500Ah
	DOD	80%
	Efficiency	90%
Inverter	Capacity	800kVA
	Efficiency	85%
Charge Controller	Current	350A
	Efficiency	90%

Source: [19].

2.8. Techno-Economic Analysis

Techno-economic analysis is used to assess the value of a given system and guides investment and resource allocation decisions. The economic metrics commonly used for assessing energy systems, includes Levelized Cost of Energy (LCOE), Payback period and Carbon emission mitigation [20].

2.8.1. Levelized Cost of Energy (LCOE)

LCOE is an economic assessment of the net present value of a unit cost of energy and is given in the units of currency per kilowatt-hour. It is defined as the ratio of lifetime costs to the power generation over that lifetime. The life time cost elements include total installation cost, fuel cost, operating and maintenance cost [21]. The annual maintenance cost of utility infrastructure which includes energy generation system is expressed as a percentage of its investment cost and optimum is assumed between 1.75% and 2.5% per year [22]. LCOE is calculated over an assumed design lifetime of a power generation system using the formula [23].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{11}$$

where; I_t = investment cost in the year t (₦), M_t = operation and maintenance costs in the year t (₦), F_t = fuel cost in the year t (N), E_t = energy generated in the year t (kWh), r = discount rate (%), n = expected lifetime of system (year).

2.8.2. Payback Period

Payback period determines the number of years for the energy savings from a renewable energy system to offset the initial cost of the investment. Payback is calculated using the formula [24].

$$Y_p = \frac{I_t}{E \times C - M} \tag{12}$$

where Y_p = payback period (year), E = energy generated per year (kWh/year), C = unit cost of energy (₦/kWh), M =

operations and maintenance per year (₦/year). The average cost of grid electricity in Nigeria is ₦32.87/kWh [25].

2.8.3. Carbon Emission Mitigation

Using renewable energy system for power generation is one of the effective strategies to mitigate carbon emission. The amount of carbon emission and its accrued carbon tax mitigated using speed bump for power generation are, respectively, calculated by [26].

$$A_{EM} = E \times EF_{grid} \tag{13}$$

and

$$C_{Tax} = A_{EM} \times CR \tag{14}$$

where A_{EM} = amount of carbon emission mitigation ($kgCO_2$), EF_{grid} = Electricity emission factor ($kgCO_2eq/kWh$), C_{Tax} = Carbon tax (₦), CR = carbon tax pricing rate (₦/$kgCO_2eq$). Nigeria's specific carbon emission factor for grid electricity is 0.439$kgCO_2eq/kWh$ and Nigeria's carbon tax pricing start modestly at ₦3.5/$kgCO_2eq$ [27-28].

2.9. Cost of Installation of the Large-Scale SBPGS

The cost of installation of large-scale SBPGS was conventionally divided into two parts: the cost of fabrication and installation of MSB, and the costs of ESS components which include cost of batteries, inverters, charge controllers and installation hardware as shown in Table 4.

3. Results and Discussion

The results of the study are presented and discussed as follows:

3.1. Analysis of Power Generating Capacity

From Figures 1 and 2 two identical MSBs would be installed together in series at a particular location and their total length amounts to the average width of a vehicle. Thus, at any given instance only one-tyre is passing on each MSB and the one-tyre exact an average weight of 10.91kN which is transmitted to an input power of 5420W that generated an average output power of 32.52W (from Table 1). But each vehicle has an average of four-tyres. Thus, the average power generated per vehicle (P_{veh}) = 32.52 x 4 ≈ 128 W.

Applying (1), power generating capacity of the large-scale SBPGS is determined as follows;

P_{veh} = 128W, Q = 5261 + 2205 + 2913 + 6570 = 16949 veh/h (from Table 2) t = 1h

$$P_g = 128 \times 16949 \times 1 = 2169472W \approx 2MW$$

3.2. Analysis of Harvested Energy

Applying (2), the capacity factor is determined as follows; η_i = 0.85, η_c =0.9, η_b = 0.9 (Table 3).

$$C_f = 0.85 \times 0.9 \times 0.9 = 0.6885$$

Applying (3), the harvested energy is calculated thus: P_g =2MW, C_f = 0.6885, T = 6h

$$E_h = 2 \times 6 \times 0.6885 \approx 8MWh$$

From the analysis, with the passage of 16,949veh/h, the power generating capacity of the system is approximately 2MW, of which 8MWh of usable energy would be harvested in 6-hours period of continuous traffic flow per day. Which is an indication that the proposed SBPGS would actually generates substantial power on large scale, and when installed in a high traffic flow location as reported in [8 -13].

3.3. Analysis of Capacity of the Battery Storage System SBPGS

Applying (4 and 5), where E_h = 8MWh, DOD = 0.8, η_i = 0.85, η_c =0.9, η_b = 0.9 (from Table 3), V_r = 0.186 x 16949 ≈ 3kV (from Table 2), the energy storage capacity in Watt-hour and Ampere-hour are respectively, calculated thus:

$$C_{Wh} = \frac{8}{0.8 \times 0.9 \times 0.85 \times 0.9} \approx 15MWh$$

and

$$C_{Ah} = \frac{15000}{3} \approx 5000Ah$$

Applying (6 and 7), where V_r = 3kV, V_b = 24V (from Table 3), C_{Ah} = 5000Ah, C_b = 1500Ah (from Table 3), the number of batteries to be connected in series and parallel are respectively, determined as:

$$N_S = \frac{3000}{24} = 125$$

and

$$N_P = \frac{5000}{1500} \approx 3$$

Thus, using (8), the required number of batteries is determined as: N_S = 125, N_P = 3.

$$N_B = 125 \times 3 \approx 375$$

From the analysis, the harvested energy would be stored in 15MWh capacity battery storage system, contains 375 batteries of 24V, 1500Ah capacity each, wired into 3 parallel strings.

3.4. Analysis of the Required Number of Inverters and Charge Controllers

Applying (9 and 10), where P_g = 2MW, Pf = 1.25, P_i = 800kVA (from Table 3), V_r = 3kV, I_c = 350A (from Table 3), the total number of inverters and charge controllers required for the system are respectively calculated thus:

$$N_i = \frac{2000 \times 1.25}{800} \approx 3$$

and

$$N_c = \frac{2000 \times 1.25}{3 \times 350} \approx 2$$

From the analysis, a total of 3 Inverters of 800kVA capacity, and a total of 2 charge controller of 350A capacity are required for the large-scale SBPGS

3.5. Analysis of the Levelized Cost of Energy

Applying (11), the Levelized Cost of Energy is determined as follows; I_t = ₦250,518,000 (Table 4), F_t = 0 (no fuel), r = 0 (no discount), n = 25years, E_t = 8000kWh/day x 365day/year x 25year = 73,000,000 kWh, M_t = ₦250,518,000 x 0.025 x 25 = ₦154261250.

$$LCOE = \frac{337690035 + 211056271.88}{264625000} = 5.58\text{₦/kWh}$$

3.6. Analysis of Payback Period

Applying (12), the payback period is calculated as: I_t = ₦250,518,000 (Table 4), E = 8000kWh/day x 365day/year = 2,920,000 kWh/year, C_t = ₦32.87/kWh, M_t = ₦250,518,000 x 0.025 = ₦6,262,950/year

$$Y_p = \frac{250518000}{2920000 \times 32.87 - 6262950} \approx 3 \text{ years}$$

3.7. Analysis of Amount of Carbon Emission Mitigation

Applying Eq. (13 and 14), the amount of carbon emission mitigation and its accrued carbon tax are, respectively, determined as follows; E = 2,920,000 kWh/year, EF_{grid} = 0.439kgCO_2eq/kWh, CR = ₦3.5/kgCO_2eq

$$A_{EM} = 292000 \times 0.439 = 1{,}281{,}880\text{kgCO}_2\text{eq/year}$$

and

$$C_{Tax} = 1281880 \times 3.5 = \text{₦}4{,}486{,}580\text{/year}$$

From the analysis, the large-scale SBPGS can be implemented at a cost of ₦250,518,000, with levelized cost of energy generation of ₦5.58/kWh, a payback period of 3years, and would mitigates an average of 1,281,880kg of CO_2 emissions and its accrued carbon bon tax of ₦4,486,580 annually. The SBPGS was found to be the most economically feasible renewable energy system with the lowest LCOE of ₦5.58/kWh ($0.013/kWh), when compared with other renewable energy system reported in International Renewable Energy Agency [21].

Table 4. *Summary of cost of installation of the Large-scale SBPGS.*

S/N	Description	Quantity	Rate (₦)	Cost (₦)
1.	Fabrication of MSB	8	80,000	640,000
2	Earthwork and Excavation		Lump sum	100,000
3	Low voltage bus bar	2	18,000	36,000
4	High Voltage bus bar	1	45,000	26,000
5.	Charge controller	2	100,000	200,000
6.	Inverter	3	220,000	660,000
7.	Battery	375	650,000	243,750,000
8.	Step-Up Transformer	1	1,000,000	1,000,000
9.	DC Breaker	3	3000	6,000
10.	Cable and Accessories		Lump sum	2,000,000
11.	Miscellaneous		Lump sum	100,000
12.	Installation Labour		Lump sum	2,000,000
	Total			250,518,000

4. Conclusion

This study put forth a conceptual framework for the development of a large-scale SBPGS, and analysis of its economic feasibility. The study is summarized as follows:

i. The large-scale SBPGS is designed with 8 MSBs that are installed sequentially on the road layouts, with its linked DC generators connected together in parallel to the ESS, and it consist of BSS, low voltage busbar, two charge controller, three inverters, set-up transformer and other installation hardware.
ii. The analysis carried out on the system shows that with the passage of 16,949 vehicles per hour, the power generating capacity of the system is approximately 2MW, of which 8MWh of usable energy would be harvested in 6-hours period of continuous traffic flow per day, which is an indication that the proposed SBPGS would actually generates substantial power on large scale, and under actual traffic loading conditions.
iii. The harvested energy would be stored in a 15MWh capacity battery storage system, contains 375 batteries of 24V, 1500Ah capacity each, wired into 3 parallel strings, from which it would be withdrawn for use and also transmitted into the gird.
iv. The techno-economic analysis carried out shows that the system can be implemented at a cost of ₦250,518,000, with levelized cost of energy

generation of ₦5.58/kWh, a payback period of 3years, and would mitigates an average of 1,281,880kg of CO_2 emissions and its accrued carbon bon tax of ₦4,486,580 annually.

In conclusion therefore, this study takes the concept of speed bump power generation a step further by developing a large-scale SBPGS to improve the speed bump power generation capacity. The proposed system design would enable addition of more renewable power generated to the national gird, and despite its initial investment cost, the lowest value of LCOE guaranteed is it an economic feasible source of renewable power generation.

5. Recommendations

The recommendations of this study are as follows:

i. Enthusiasts who are interested in renewable energy project could take on this project for further research to explore ways of improving the energy conversion efficiency of the MSB.

ii. The findings of this study are useful for sustainable energy for all action agenda, under electricity vision 30:30:30 which targets generation of at least 30GW of power by the year 2030 with 30% of generation from grid connected renewable energy technologies in the energy mix. Thus, Government could partner with academia, professional bodies and investors to provide standard and guideline for further development and implementation of this exciting technology in high traffic flow location.

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