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Development of an Emulator of the Sustainable Energy Harvesting Pad System on a Bike Lane for Charging Lithium Batteries

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Abstract-

In response to the urgent imperative of combating global warming and advancing sustainable energy solutions, an innovative approach has emerged, capitalizing on bicycles and road bike lane infrastructure. This solution integrates a Smart Lithium Battery Charging System with a Sustainable Energy Harvesting Pad (SEHP) designed for cyclists. The SEHP harnesses piezoelectric energy from mechanical vibrations and kinetic energy from lightweight vehicles. It produces clean, renewable electricity as an alternative to traditional power sources. Comprehensive assessments of the SEHP's energy generation performance at various proficiency levels have revealed impressive capabilities. An electronic emulator system is developed to support academic and research communities, simulating scenarios on bike lanes to efficiently charge 36.36 Wh lithium batteries at various cycling proficiency levels. The study involved specific circuit design, seamless integration with the custom Smart Lithium Battery Charging System, and optimization using Microcontroller hardware and software solutions. Practical prototypes verified the emulator's functionality and real-world applicability, making it an authentic replica of the SEHP's outcomes. This innovative technology enhances our understanding of SEHP and enables comparative analysis against other energy sources, contributing to a more sustainable future.

Index Terms

SEHP; Alternative Energy; Emulator, Electronic Module;

I. INTRODUCTION[1]

The SEHP emulator represents an innovative response to the pressing need for clean, sustainable energy sources, particularly in urban mobility [1]. In the contemporary world, energy sustainability and environmental preservation challenges have accentuated the demand for renewable energy sources and inventive energy conversion technologies. This introduction sets the stage for understanding the significance of SEHP, emphasizing its potential impact and underscoring the imperative for a comprehensive scientific evaluation and adaptation of this groundbreaking technology.

Roadways, ubiquitous components of global infrastructure, offer substantial potential as energy conversion platforms due to their expansive surface area [2]. This extensive expanse, subject to dynamic forces from vehicular traffic and abundant solar insolation, presents a unique opportunity for various energy harvesting technologies, including piezoelectric, thermoelectric, and photoelectric systems [3]. Harnessing the potential of these technologies can significantly reduce our reliance on fossil fuels and enhance sustainability. Roads, once considered passive elements of infrastructure, have the potential to evolve into one of the largest sources of clean energy in the foreseeable future.

The recent surge of interest in energy harvesting from pavement reflects the growing recognition of roads as platforms for energy generation [4]. Extensive research endeavors have been dedicated to comprehending energy conversion mechanisms, designing efficient energy harvesting facilities, and conducting thorough laboratory and field assessments to gauge practical applications [5]. Among various energy harvesting technologies developed for renewable energy, piezoelectric energy harvesting (PEH) has gained considerable attention, particularly in light of the rapid advancements in piezoelectric materials over the last two decades [6-7]. Various types of PZT sensors and electrical signal generators by sizes and shapes have been developed.

Recent research has explored diverse designs and testing methods for piezoelectric energy harvesting from roadway traffic, unveiling the technology's potential [10]. Innovative designs and concepts have surfaced, such as the integration of Cymbal prototypes into asphalt [11], disk-array harvesters designed for heavy trucks [12], and PVDF film-based modules [13]. These studies underscore that roadways' kinetic energy can be efficiently harnessed for electricity generation. For instance, another study focused on integrating PZT disks into conductive pavement [14]. Another study devised a PEH module featuring a bridge-type displacement amplification mechanism to reduce vertical displacement [15]. Another researcher designed an energy harvester composed of 64 layered bridges, demonstrating its capability to produce energy under dynamic loading conditions [16-17].

Challenges and Innovations in Road-Compatible PEH Devices: While PEH has made substantial progress, there remains ample room for improvements in terms of efficiency, road compatibility, and practical application. Road engineering, once exclusively focused on accommodating vehicular traffic, is now evolving into a source of energy production [18-19]. Road-based technologies, including photovoltaic pavement, thermoelectric, magnetic, and piezoelectric pavement, have gained momentum.

This research addresses the challenges of developing road-compatible piezoelectric power generation devices by introducing a novel force amplification mechanism (FAM) and a cone-flat contact design. These innovations are meticulously crafted to optimize energy generation while minimizing the device's impact on the road infrastructure [20]. Extensive laboratory and road tests unveil the potential for large-scale energy generation, with higher vehicle speeds demonstrated to be particularly beneficial [21]. This research lays the foundation for integrating piezoelectric power generation technology into the smart highways of the future, facilitating cleaner and more sustainable transportation [22].

Innovative solutions are imperative in the present energy landscape, characterized by fossil fuel depletion and ecological challenges [23]. The SEHP emulator emerges as a promising option, primarily tailored for bikers and urban mobility [24]. While this technology holds the potential for energy generation, its practical application necessitates comprehensive scientific analysis, environmental impact assessment, and adaptability [25].

This paper contributes to advancing our understanding of the SEHP technologies' efficiency and adaptability, promoting the realization of a cleaner, smarter, and more sustainable urban transportation future. An electronic module known as the Sustainable Energy Harvesting Pad (SEHP) emulator has been developed to facilitate learning and analysis of the Sustainable Energy Generating Pad (SEGP) technology [26-33] for academic and research purposes. This emulator allows students and researchers to understand how cycling speed varies electricity generation for the SEGP, making it an invaluable tool for studying and advancing sustainable energy solutions. The combination of cycling skill levels, mph, and the SEGP technology, along with the SEHP emulator for academic and research exploration, underscores the dynamic and ever-evolving nature of bike riding and its potential to contribute to a greener, sustainable future.

II. Analysis of Prototype SEGP for the Biker

The research team developed a few innovative Sustainable Energy Generating Pads (SEGP), also known as Energy Generating Pads (EGP), designed to cater to the specific needs of cyclists [26-29]. Two other distinct versions, the 1XSEGP and the 2XSEGP, were created. A dual-stage smart charging system was developed [30] to collect the produced no-sinusoidal AC-DC energy into a 90 Wh lithium-ion battery (18V and 500 mAh) and subjected to comprehensive laboratory testing, with the results presented in Table I [26-29] and Fig. 2. The 2XSEGP stood out by generating nearly double the amount of power compared to the 1XSEGP, making it a more promising choice for energy generation.

Both versions of the energy-generating pads incorporated a thin film made of lead zirconate titanate (PZT) cells. In the laboratory setting, an energy harvester was constructed to measure the energy produced by these PZT cells. This energy was generated by applying bending pressure and stress, as shown in Fig. 1. The PZT cells could generate an acyclic high peak no-sinusoidal AC signal in response to the applied force. This non-sinusoidal AC energy converted into DC energy through an AC-to-DC conversion system was implemented to harness this energy effectively, as shown in Fig. 1 [33]. This technology holds tremendous potential to revolutionize sustainable energy generation, from transportation to cycling.

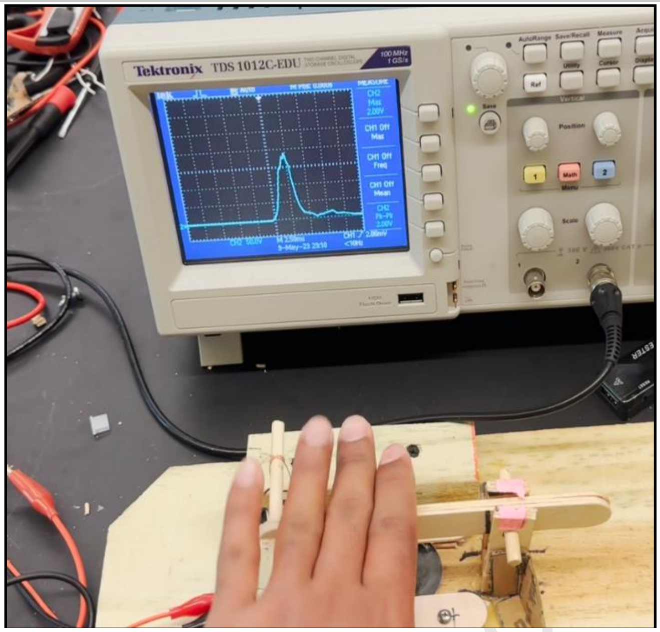

Fig. 1. Harvest Energy Signal from a PZT Cell.

The summarized data from Table I [29] reveals crucial performance characteristics of the 1XSEGP and 2XSEGP. Both pads are optimized for speeds ranging from 10 to 12 mph and can accommodate a weight load of 150-160 lbs. Notably, the 2XSEGP offers a wider voltage range, spanning from 82-85V, while the 1XSEGP operates within the 68-76V range. Additionally, both pads produce current outputs ranging from 4.8 to 7.8 mA. When it comes to power output, the 2XSEGP consistently outperforms the 1XSEGP, delivering a range of 0.54-0.67 W/ride/0.34s, compared to the 1XSEGP 0.33-0.41 W/ride/0.34s. These figures underscore the superior energy-generation capabilities of the 2XSEGP, making it an exciting advancement for sustainable energy solutions by utilizing the bikers.

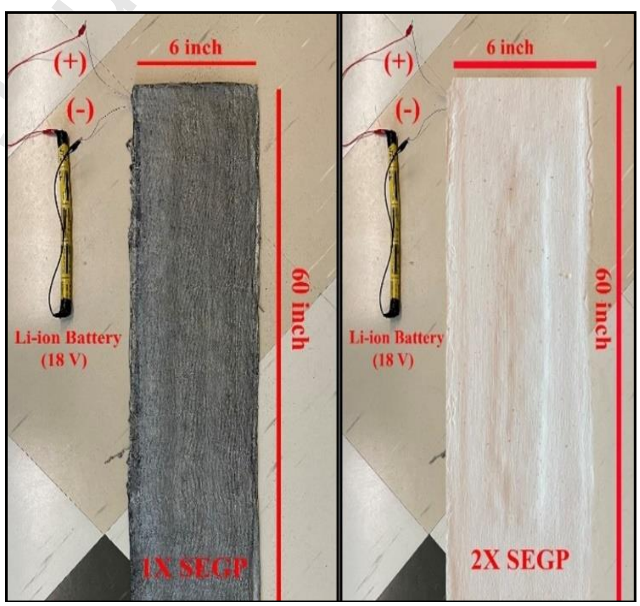

Fig. 2. Prototype of the Developed SEGPs with 1X and 2X Layers.

TABLE I. TESTED RESULTS OF THE PROTOTYPED SEGPS.

Type	*Speed (mph)*	*Weight (lbs.)*	*Voltage (V)*	*Current (mA)*	*Power (W/ride/0.34s)*	*90 Wh Li-ion Battery full charging time (min)*
1XSEGP- (5-foot)	10-12	150-160	68-76	4.8-5.4	0.33-0.41	1.54-1.24
2XSEGP- (5-foot)	10-12	150-160	82-85	6.60-7.80	0.54-0.67	0.94-0.76

III. ANALYSIS OF 1XSEHP EMULATOR FOR 1XSEGP

An exciting technology has been developed to generate electricity using SEGPs. The potential for generating sustainable energy varies based on a cyclist's skill level [31-32]:

Beginner Level: Novice riders typically maintain speeds ranging from 8 to 12 mph, as shown in Fig.3., as each wheel can touch 3.5 inches on the SEGP at a time. While their contribution to electricity generation is present, it is modest due to their lower speeds.

Intermediate Level: Cyclists at the intermediate level maintain speeds ranging from 13 to 18 mph. Their proficiency in pedaling at moderate speeds significantly enhances their contribution to the sustainable energy source.

Advanced Level: Advanced riders are capable of reaching speeds from 13 to 25 mph or even higher. Their expertise in maintaining higher speeds means they have the potential to generate substantial amounts of electricity. Their proficiency level in paddling at a moderate speed can significantly enhance the sustainable energy from the SEGP sources.

This innovative technology promotes eco-friendliness while encouraging cyclists to push their limits, generating more electricity as they progress from one skill level to another. Additionally, to facilitate academic and research understanding of prototype SEGP technology on a test bench environment, an electronic module called the SEHP emulator has been developed, making it an invaluable tool for studying and advancing sustainable energy solutions.

Fig. 3. Analysis of Standard Adult bike with rider.

The mathematical model for generating electricity for the SEHP for different levels of bike riders with constant weight (around 160 lbs, including a bike with a bike rider) is expressed below:

$$P_{1XSEHP} = Wh \times D \times P \times Pl \times AP \quad (1)$$

Where,

P_{1XSEHP} = The power produced from 1XSEHP (W/Sec), Wh = No of wheels, D = Average Distance (feet/sec), P = No. of PZT cell, Pl = No of Pulse, and AP = Average power per Pulse.

TABLE II. 1XSEHP GENERATED POWER ANALYSIS BASED ON SPEED.

Biker Level	*Speed (mph)*	*Wh (pcs)*	*D (feet/Sce)*	*P (pcs)*	*Pl (pcs)*	*AP (mW/Pulse)*	*P_{1XSEHP} (W/Sec)*
Beginner	8-12	2	14.6	6	2	14	4.9
Intermediate	13-18	2	20.5	6	2	14	6.8
Advanced	19-25	2	29.3	6	2	14	9.8

Based on the findings in Table II, a novice cyclist with around 160 lbs consistent weight on a 1XSEHP generates 4.9 Watts per second (W/Sec) for the beginner-level speed. An intermediate cyclist produces 6.8 W/Sec, while advanced riders reach 9.8 W/Sec. This data highlights the connection between skill level, speed, and power output for the same weight applied on the 1XSEHP, which is vital for sustainable energy research and applications.

IV. Development of 1XSEHP Emulator

Addressing the data and results from the Prototypes of SEGP from Section II, the SEHP emulator with a 36Wh lithium-ion battery charging system is developed. All emulators are developed using the conceptual framework shown in Fig. 4.

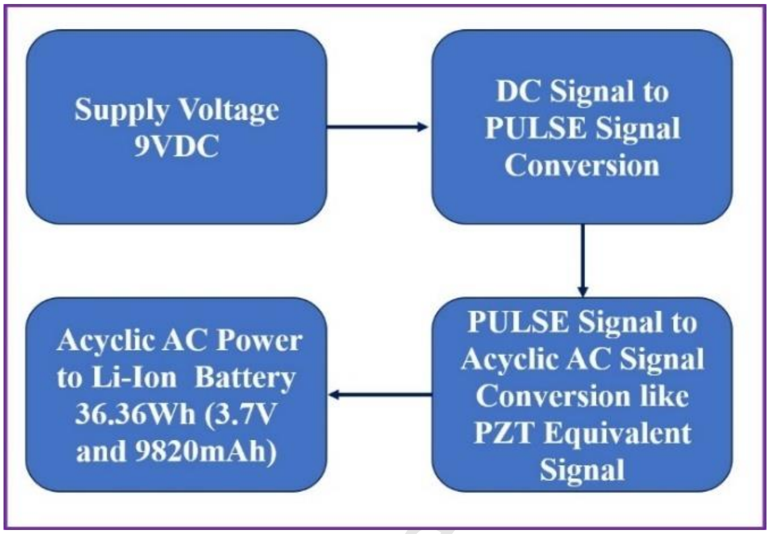

Fig. 4. The conceptual framework of SEHP Emulator

A. Design and simulation of 1XSEHP Emulator

Based on the 1XSEGP experimental data, an electronic module called the 1XSEHP emulator is designed and analyzed by using Proteus software, as shown in Fig.5-6. In Fig.6, the red signal represents the pulse signal, the blue signal is the output signal added to capacity, and the yellow signal is the charging signal on the Li-ion battery.

The mathematical model for designing the 1XSEHP Emulator for different levels of bike riders (around 160 lbs) is expressed below:

$$Pulse_1 = \frac{1.44}{(R1+2R2)\times C} \qquad (2)$$

and

$$D_1 = \frac{T1}{T} \qquad (3)$$

Where,

$Pulse_1$ = The No. of time press on the 1XSEGP (Hz), D_1 = The duty cycle of the generating Pulse.

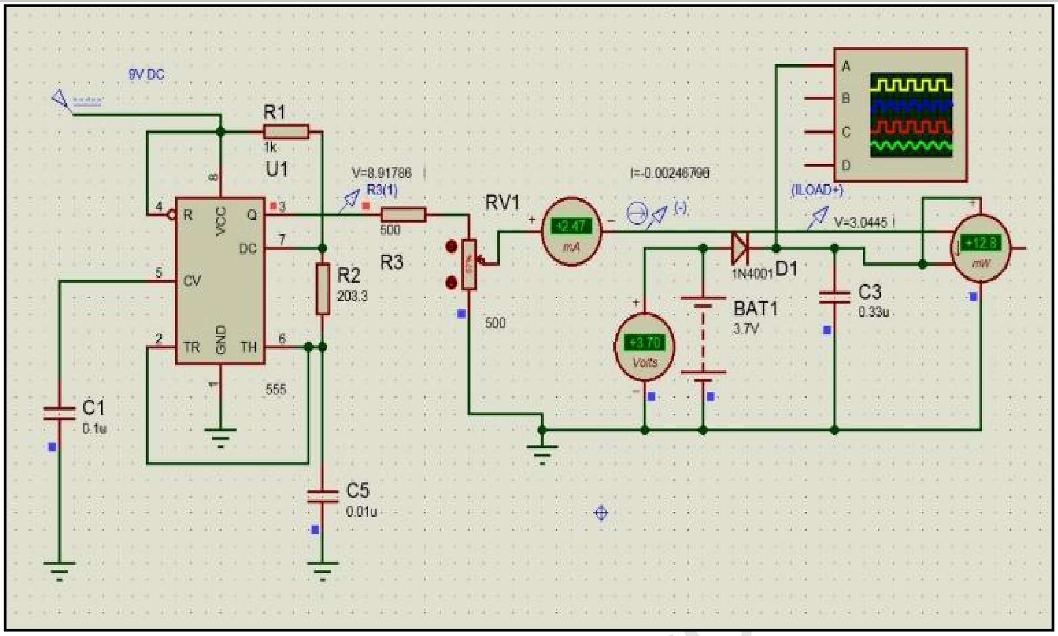

Fig.5. Design of a 1XSEHP Emulator

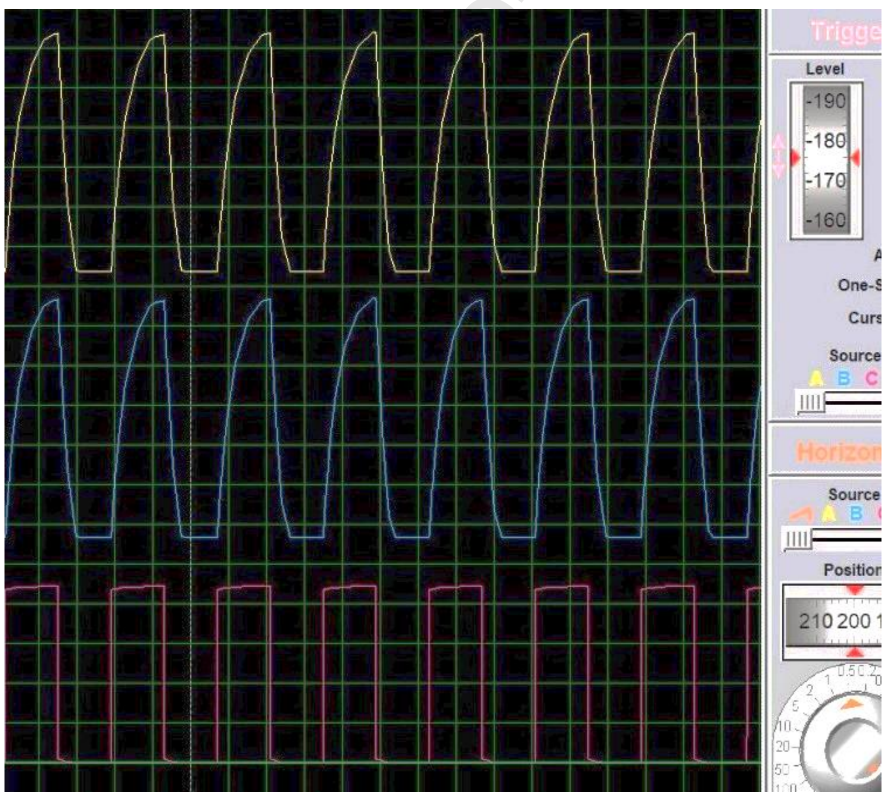

Fig.6. Output Signal of a 1XSEHP Emulator like 1XSEGP

TABLE III. 1XSEHP EMULATOR ANALYSIS.

Biker Level	**Beginner**	**Intermediate**	**Advanced**
Speed (mph)	8-12	13-18	19-25
R1 (kΩ)	1	1	1
R2 (kΩ)	203.3	147	102.2
C (uF)	0.33	0.33	0.33
Pulse (Hz)	354.024	489.15	703.2
D_1 (%)	50.1	50.1	50.2
Voltage (volt/Pulse)	3.7	3.7	3.7
Current (mA/Pulse)	2.47	2.47	2.47
P1XSEHP (mW/Pulse)	12.8	12.8	12.8
TP1XSEHP (W/Sec)	4.57	6.26	9.2
Li-ion Battery Voltage (V)	3.8	3.8	3.8
36Wh Battery Fully Charging time from 1XSEGP (min)	131.2	95.8	65.2

The 1XSEHP emulator's simulation data are described in Table II, considering three biker skill levels: beginner, intermediate, and advanced. The parameters include a consistent resistance of 1 kΩ (R_1), variable resistance levels (203.3 kΩ for beginners, 147 kΩ for intermediates, and 102.2 kΩ for advanced) as R_2, a constant capacitance of 0.1 uF (C), and increasing pulse frequency with skill level (354.024 Hz for beginners, 489.15 Hz for intermediates, and 703.2 Hz for advanced). The duty cycle (D_1) remains relatively consistent at around 50%. Voltage and current per Pulse are constants at 3.7 volts and 2.47 mA, respectively. Power per Pulse (P_{1XSEHP}) is consistent at 12.8 mW, while the total power per second (TP_{1XSEHP}) increases with skill level (4.57 W/Sec for beginners, 6.26 W/Sec for intermediates, and 9.2 W/Sec for advanced) for the same around 160 lbs. weight. A Li-ion battery voltage of 3.70 V and signal (yellow color in Fig.6), the corresponding full charging times from the 1XSEHP are included for each skill level (131.2 minutes for beginners, 95.8 minutes for intermediates, and 65.2 minutes for advanced) for 160 lbs of weight applied on the SEHP.

B. Prototype and results of 1XSEHP Emulator

Based on the simulation of the 1XSEHP emulator, a prototype of 1XSEHP was developed in the lab. As shown in Fig. 7. The 1XSEHP Emulator consists of an emulator, a smart charging system with a 36Wh lithium battery. The tested data are analyzed in Table IV. Furthermore, different levels of 1XSEHP signal are shown in Fig. 8-10.

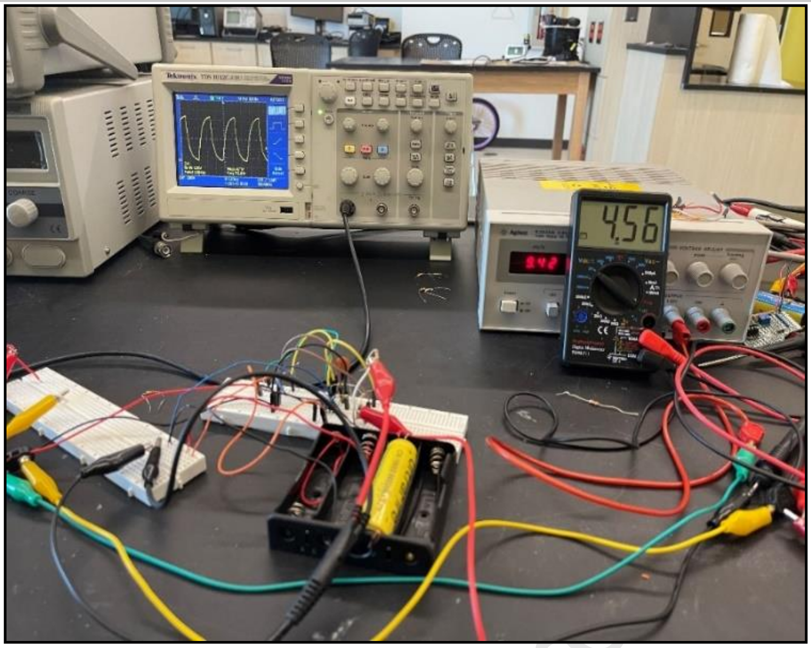

Fig. 7. Prototype of 1XSEHP Emulator

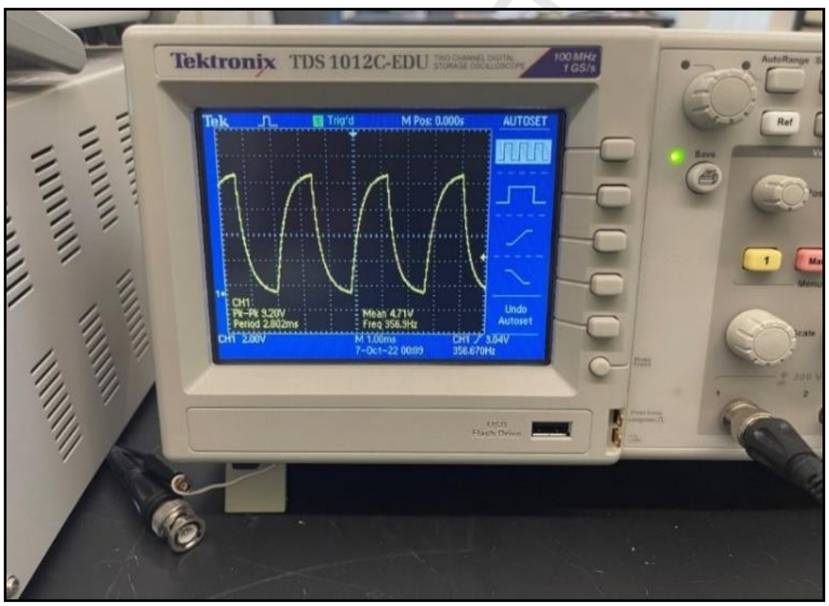

Fig.8. Beginner level the 1XSEP Emulator Signal like 1XSEGP

The 1XSEHP emulator's Prototype data are presented in Table IV, focusing on three distinct biker skill levels: beginner, intermediate, and advanced. The key parameters encompass a consistent resistance value of 1 kΩ (R_1), variable resistance levels (203.3 kΩ for beginners, 147 kΩ for intermediates, and 102.2 kΩ for advanced) as R_2 and a constant capacitance of 0.1 uF (C). Pulse frequency increases with skill level (356.47 Hz for beginners, 485.15 Hz for intermediates, and 715 Hz for advanced).

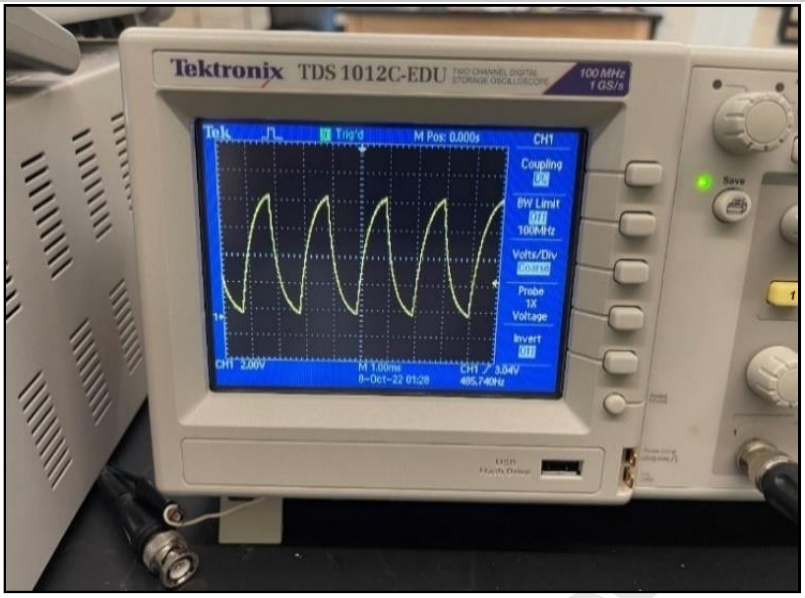

Fig.9. Intermediate level of the 1XSEP Emulator Signal like 1XSEGP

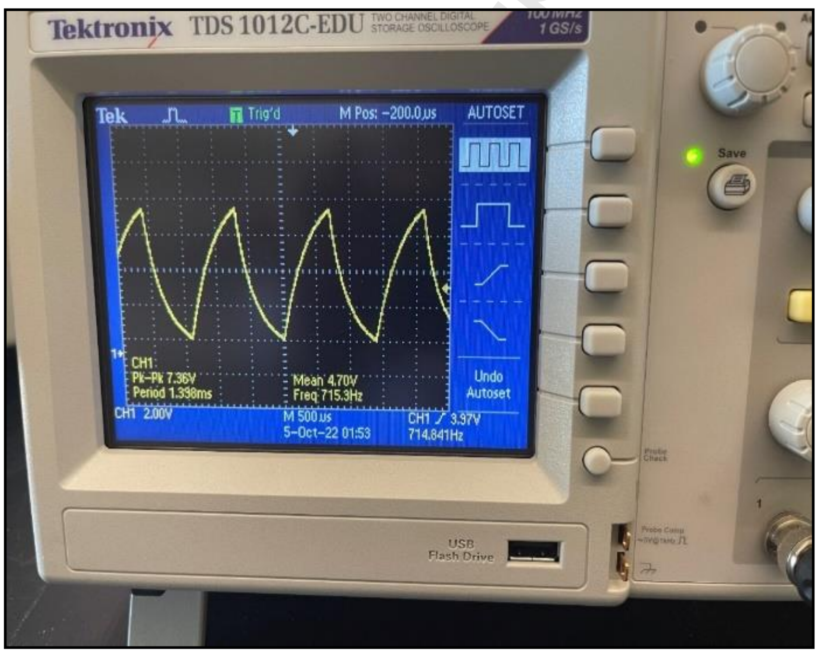

Fig.10. Advanced level the 1XSEP Emulator Signal like 1XSEGP

TABLE IV. PROTOTYPE 1XSEHP EMULATOR ANALYSIS.

Biker Level	**Beginner**	**Intermediate**	**Advanced**
Speed (mph)	8-12	13-18	19-25
R_1 (kΩ)	1	1	1
R_2 (kΩ)	203.3	147	102.2
C (uF)	0.33	0.33	0.33
$Pulse_1$ (Hz)	356.47	485.15	715
D_1 (%)	50.1	50.1	50.1
Supply Voltage (volt/Pulse)	9	9	9
Emulator Output Voltage (mA)	4.7	4.7	4.7
Emulator Output Current (mA)	2.5	2.5	2.5
P_{1XSEHP} (mW/Pulse)	11.75	11.75	11.75
TP_{1XSEHP} (W/Sec)	4.19	5.71	8.41
Li-ion Battery Voltage (V)	3.8	3.8	3.8
36Wh Battery Full Charging time from 1XSEHP (min)	143	105	71.34

The duty cycle (D_1) remains consistently at around 50 %. Both the supply voltage and emulator output voltage are set at 9 volts, while the emulator output current is constant at 2.5 mA. Power per Pulse (P_{1XSEHP}) is uniform at 11.75 mW, and the total power per second (TP_{1XSEHP}) exhibits an ascending trend with skill level (4.19 W/Sec for beginners, 5.71 W/Sec for intermediates and 8.41 W/Sec for advanced). A Li-ion battery voltage of 3.8 V and the corresponding full charging times from the 1XSEHP are included for each skill level (143 minutes for beginners, 105 minutes for intermediates, and 71.34 minutes for advanced).

V. ANALYSIS OF 2XSEHP EMULATOR FOR 2XSEGP

The 2XSEHP emulator with a 36Wh lithium-ion battery charging system is also developed in the following conceptual framework shown in Fig. 4.

A. Design and simulation of 2XSEHP Emulator

Based on the 2XSEGP experimental data, an electronic module called the 2XSEHP emulator is designed and analyzed by using Proteus software, as shown in Fig.11-12. The mathematical model for designing the 2XSEHP Emulator for different levels of bike riders (around 160 lbs) is expressed below:

$$Pulse_2 = \frac{1.44}{(R1+2R2)\times C}) \tag{4}$$

and

$$D_2 = \frac{T1}{T} \tag{5}$$

Where,

$Pulse_2$ = the No of time pressed on the 2XSEGP (Hz), D_2 = The duty cycle of the generating Pulse.

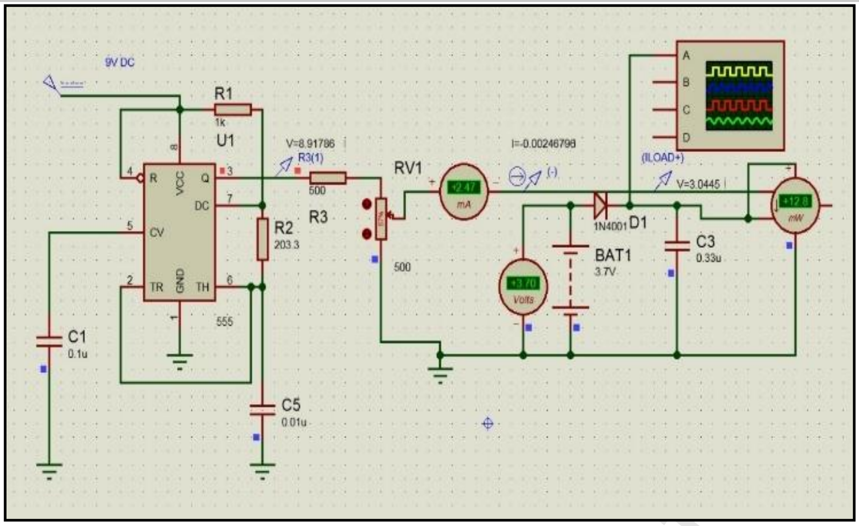

Fig.11. Design of a 2XSEHP Emulator

Power per Pulse ($P1_{XSEHP}$) is uniform at 12.8 mW, while the total power per second (TP_{1XSEHP}) shows an ascending trend with skill level (8.99 W/Sec for beginners, 12.6 W/Sec for intermediates, and 17.99 W/Sec for advanced). Additionally, it includes a Li-ion battery voltage of 3.8 V and the corresponding full charging times from the 1XSEGP for each skill level (66.74 minutes for beginners, 47.6 minutes for intermediates, and 33.35 minutes for advanced) for 160 lbs of weight applied on the SEHP.

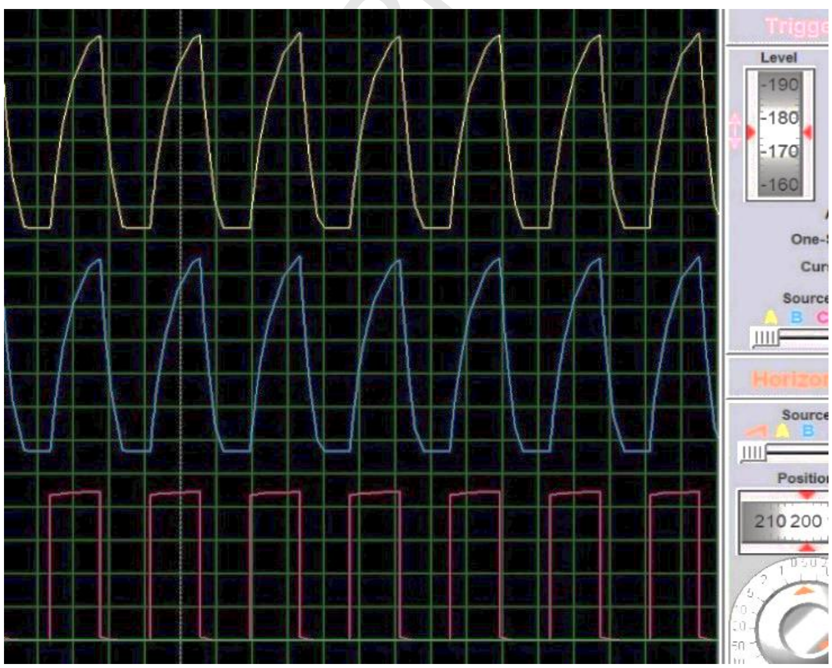

Fig.12. Output Signal of a 2XSEHP Emulator like 2XSEGP

TABLE V. 2XSEHP EMULATOR ANALYSIS.

Biker Level	Beginner	Intermediate	Advanced

Speed (mph)	8-12	12-18	19-25
R_1 (kΩ)	1	1	1
R_2 (kΩ)	102	72.7	51
C (uF)	0.33	0.33	0.33
Pulse (Hz)	702.5	985.6	1406
D_2 (%)	50.1	50.1	50.2
Voltage (volt/Pulse)	3.7	3.7	3.7
Current (mA/Pulse)	2.47	2.47	2.47
P_{2XSEHP} (mW/Pulse)	12.8	12.8	12.8
TP_{2XSEHP} (W/Sec)	8.99	12.6	17.99
Li-ion Battery Voltage (V)	3.8	3.8	3.8
36Wh Battery Fully Charging time from 2XSEGP (min)	66.74	47.6	33.35

B. Prototype and results of 2XSEHP Emulator

Based on the simulation of the 2XSEHP emulator, a prototype of 2XSEHP was developed in the lab. As shown in Fig. 13. The 2XSEHP Emulator consists of an emulator and a smart charging system with a 36 Wh lithium battery. The tested data are analyzed in Table VI. Furthermore, different levels of the 2XSEHP signal are shown in Fig. 14-16.

Table VI provides an analysis of the Prototype 2XSEHP emulator for three distinct biker skill levels: beginner, intermediate, and advanced. The key parameters include a consistent resistance of 1 kΩ (R1), variable resistance values (203.3 kΩ for beginners, 147 kΩ for intermediates, and 102.2 kΩ for advanced) denoted as R2, and a constant capacitance of 0.1 uF (C). Pulse frequency increases with skill level (706.2 Hz for beginners, 984.3 Hz for intermediates, and 1401 Hz for advanced).

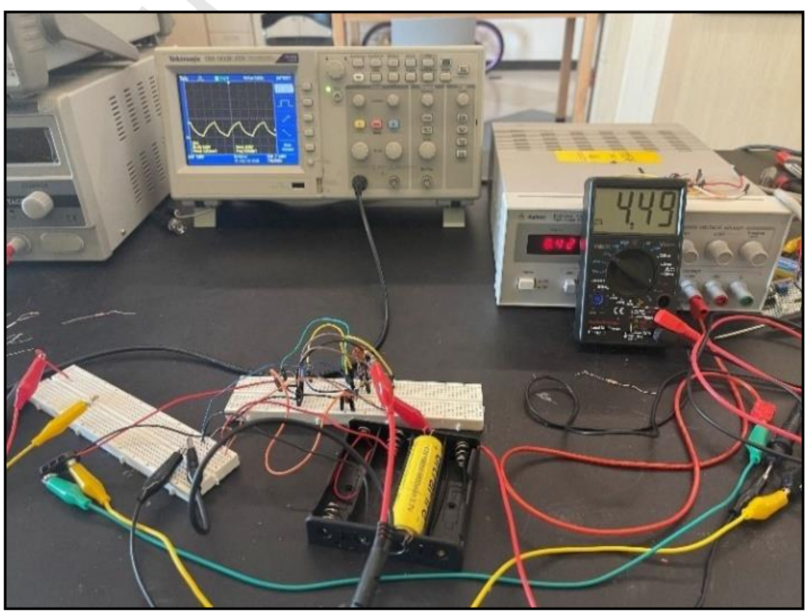

Fig. 13. Prototype of 2XSEHP Emulator

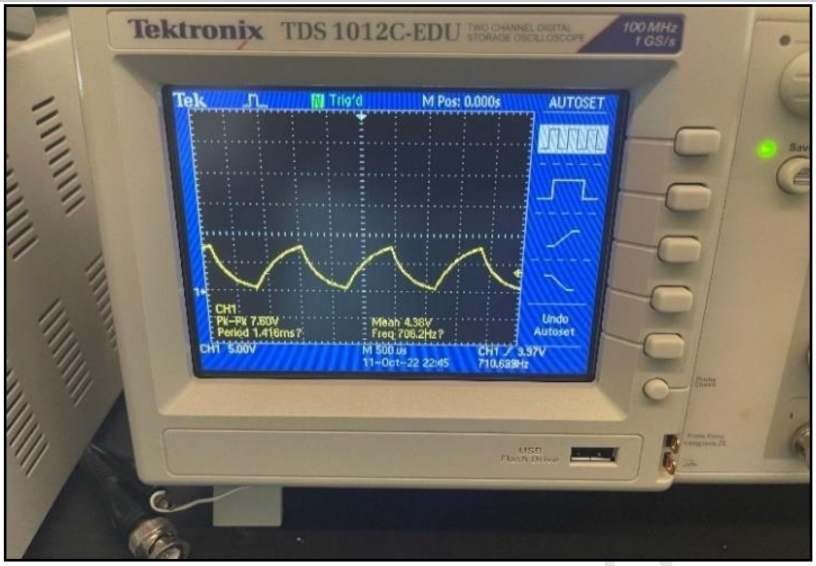

Fig.14. Beginner level the 2XSEP Emulator Signal like 2XSEGP

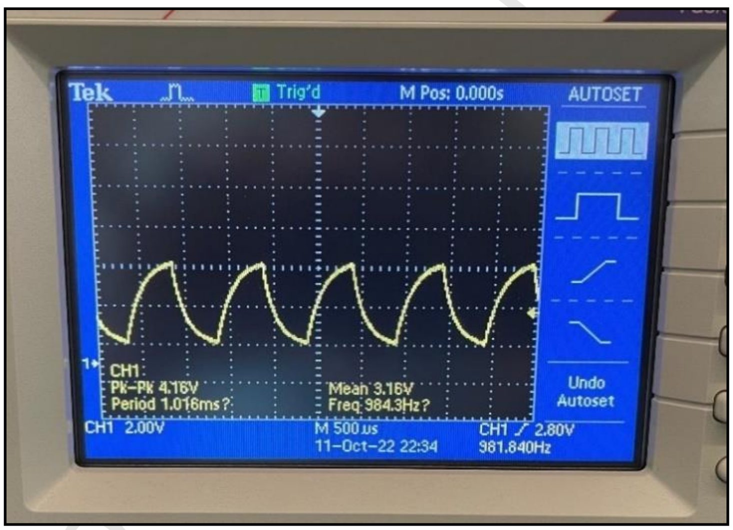

Fig.15. Intermediate level the 2XSEP Emulator Signal like 2XSEGP

The duty cycle (D_2) remains constant, staying close to 50%. Both the supply voltage and emulator output voltage are set at 9 volts, and the emulator output current is a consistent 2.6 mA. Power per Pulse (P_{1XSEHP}) remains steady at 12.22 mW, while the total power per Pulse (TP_{2XSEHP}) increases with skill level (8.62 W/Sec for beginners, 12 W/Sec for intermediates, and 17.12 W/Sec for advanced). The data includes Li-ion battery voltage at 3.8 V and the corresponding full charging times from the 1XSEHP for each skill level (69.5 minutes for beginners, 50 minutes for intermediates, and 36.04 minutes for advanced).

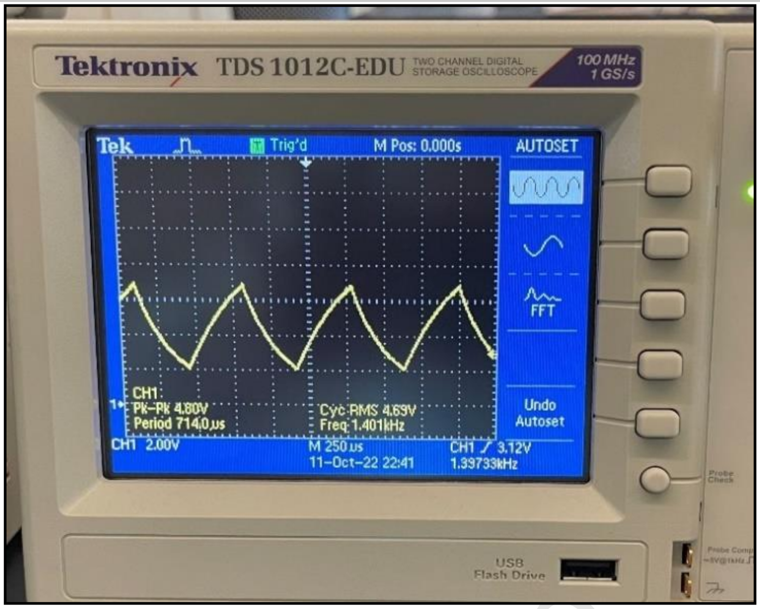

Fig.16. Advanced level the 2XSEP Emulator Signal like 2XSEGP

TABLE VI. PROTOTYPE 2XSEHP EMULATOR ANALYSIS.

Biker Level	**Beginner**	**Intermediate**	**Advanced**
Speed (mph)	8-12	13-18	19-25
R_1 (kΩ)	1	1	1
R_2 (kΩ)	203.3	147	102.2
C (uF)	0.33	0.33	0.33
$Pulse_2$ (Hz)	706.2	984.3	1401
D_2 (%)	50.1	50.1	50.1
Supply Voltage (volt/Pulse)	9	9	9
Emulator Output Voltage (mA)	4.7	4.7	4.7
Emulator Output Current (mA)	2.6	2.6	2.6
P_{2XSEHP} (mW/Pulse)	12.22	12.22	12.22
TP_{2XSEHP} (W/Sec)	8.62	12	17.12
Li-ion Battery Voltage (V)	3.8	3.8	3.8
36Wh Battery Full Charging time from 2XSEHP (min)	69.5	50	36.04

VI. DISCUSSION & COMPARISON

The real-time simulation results highlight the significant energy generation and efficiency differences between the 1XSEGP and 2XSEGP systems. The 1XSEGP generates between 0.33–0.41 W per ride over 0.34 seconds, with variations depending on factors like rider speed and weight. In contrast, the 2XSEGP shows much better efficiency, generating 0.54–0.67 W per ride in the same time frame. This clear difference emphasizes the superior energy production capacity of the 2XSEGP system. When comparing the charging times for a 36Wh lithium battery, the 1XSEHP takes 65.2–131.2 minutes, depending on the rider's skill level. On the other hand, the 2XSEHP emulator charges the same battery much faster, taking only 33.35–69.5 minutes. These shorter charging times highlight the practicality and efficiency of the 2XSEHP emulator in real-world use. It's also important to note the role of rider skill in electricity generation. For example, advanced cyclists using the 2XSEGP can generate up to 0.67 W per ride over 0.34 seconds, compared to just 0.41 W per ride for novice riders on the 1XSEGP. The advantages of the 2XSEGP system are clear, with better performance and faster charging times (33.35–69.5 minutes) when paired with the 2XSEHP emulator. Based on the real-time implementation, simulation, and prototype results, a comprehensive analysis of energy generation from SEHPs has been provided, as described in Table VII and Fig.17-18. The Table outlines the expected power generation from SEGPs at different speed levels: Beginner, Intermediate, and Advanced, considering various parameters, such as running time, Distance covered, and power output in kilowatt-hours per day for both TP_{1XSEGP} and TP_{2XSEGP} systems.

TABLE VII. EXPECTED GENERATION ANALYSIS FROM SEGPS

Speed Level	Running Bike/day	Riding time (hr)	Distance Cover (mile)	TP_{1XSEGP} (kWh/day)	TP_{2XSEGP} (kWh/day)
Beginner	1	0.5	5	0.00102	0.00210
		1	10	0.00210	0.00422
	2	0.5	5	0.00210	0.00422
		1	10	0.00422	0.00844
	10	0.5	5	0.0102	0.0210
		1	10	0.0210	0.0422
	100	0.5	5	0.12	0.21
		1	10	0.21	0.42
Intermediate	1	0.5	7.5	0.00158	0.00316
		1	15	0.00316	0.00636
	2	0.5	7.5	0.00316	0.00317
		1	15	0.00636	0.00127
	10	0.5	7.5	0.0158	0.0316
		1	7.5	0.0316	0.0636
	100	0.5	7.5	0.158	0.316
		1	15	0.316	0.636
Advanced	1	0.5	10	0.00212	0.00422
		1	20	0.00422	0.00844
	2	0.5	10	0.00422	0.01688
		1	20	0.00422	0.00844
	10	0.5	10	0.0212	0.0422
		1	20	0.0424	0.0844
	100	0.5	10	0.212	0.422
		1	20	0.424	0.844

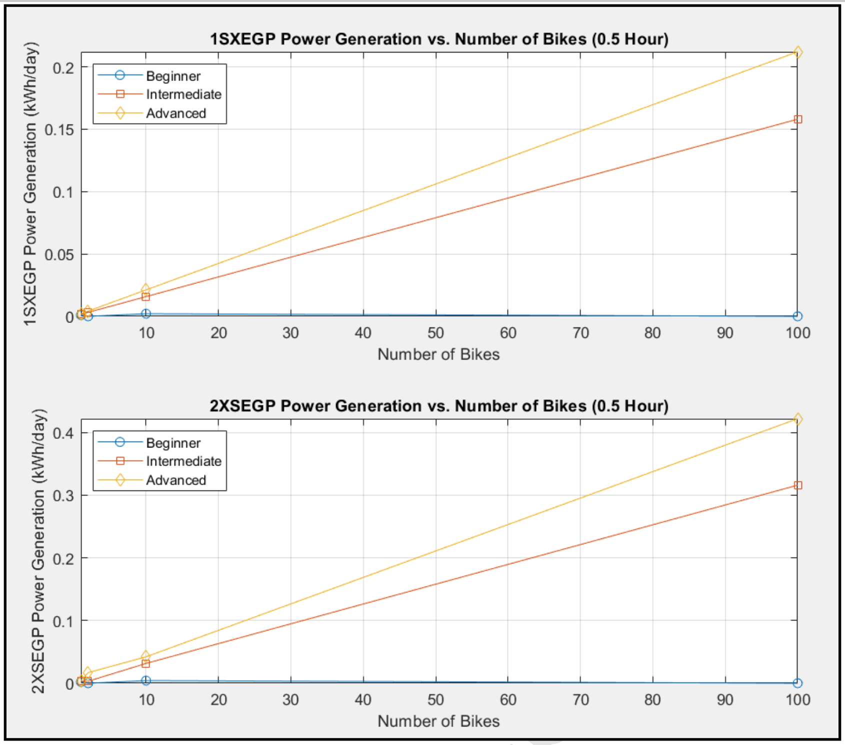

Fig. 17. Expected power generation Vs. No. Bike for 30 min riding.

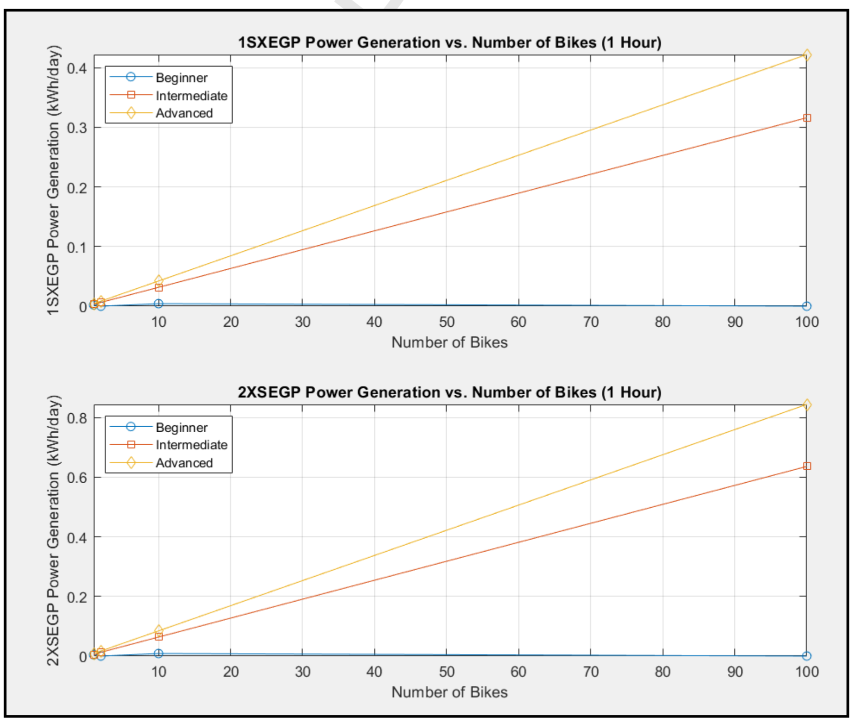

Fig. 18. Expected power generation Vs. No. Bike for 60 min riding.

At the Beginner level with 160 lbs weight, power generation varies with running time (min/day) and Distance (miles), with TP_{1XSEGP} producing between 0.00102 kWh and 0.21 kWh per day and TP_{2XSEGP} ranging from 0.0021 kWh to 0.42 kWh per day.

Intermediate-level with the same weight results follow a similar pattern but with longer riding times, with TP_{1XSEGP} generating between 0.00158 kWh and 0.316 kWh and TP_{2XSEHP} producing between 0.00316 kWh and 0.636 kWh per day. Advanced-level people with the same weight performance see even higher power generation, ranging from 0.00212 kWh to 0.424 kWh for TP_{1XSEGP} and from 0.00422 kWh to 0.844 kWh for TP_{2XSEGP}. The power generation is positively correlated with riding time and Distance, with the most significant power output observed at the highest speed and longest duration. The specific power output values for Total Generated Power of 1XSEGP (TP_{1XSEGP}) and Total Generated Power of 2XSEGP (TP_{2XSEGP}) at different scenarios are provided for each speed level, offering valuable insights into the energy production capabilities of these SEHP systems.

VII. CONCLUSIONS

The SEGP represents a significant breakthrough in sustainable transportation and clean energy technology. Its key achievements include converting mechanical vibrations and kinetic energy into electricity, enabling cyclists to actively participate in clean energy generation, and reducing reliance on grid charging. Additionally, the SEGP provides real-time insights into road usage and traffic conditions, supporting the development of smart energy infrastructure. Prototype results revealed a notable performance difference between the 1XSEGP and 2XSEGP systems. The 2XSEGP system generates 0.54–0.67 W per ride over 0.34 seconds, nearly doubling the output of the 1XSEGP, which ranges from 0.33–0.41 W. In this context, developing a SEHP emulator system represents a significant advancement, replicating SEGP technologies and opening up new research possibilities. The emulator is vital for advancing academia and research, offering benefits such as controlled experiments with compact electronic modules, risk-free innovation, and bridging the gap between theoretical knowledge and practical applications. This research reinforces the credibility of SEGP technology for bike lanes and cyclists at different speed levels. Prototypes of the 2XSEHP emulator charge a 36Wh lithium battery in 33.35–69.5 minutes, markedly faster than the 65.2–131.2 minutes required by the 1XSEHP. Advanced cyclists with the 2XSEGP can achieve an impressive 0.67 W per ride, compared to 0.41 W with the 1XSEGP. Daily energy generation reaches up to 0.844 kWh for the 2XSEGP, significantly outperforming the 0.424 kWh from the 1XSEGP. This research highlights the potential of SEGP and SEHP technologies to drive sustainable urban energy solutions, offering substantial gains in efficiency and performance, especially for e-bike riders.

VIII. FUTURE WORKS RECOMMENDATIONS

After successfully developing an emulator for the SEHP for bikers, the next phase of this endeavor involves the development of comprehensive software tailored to meet the needs of academic researchers, students, and industrial partners. This software will encompass the Simulation and analysis of SEGP, facilitating tasks such as planning, budgeting, performance assessment, and technical and techno-economic analysis. It is designed to handle various energy sources, whether used individually or in combination, including renewable, non-renewable, and alternative sources. The primary objective of this software is to outperform currently available solutions, such as HOMER, RETScreen Expert, ETAP, PVSyst, and MATLAB, or that software can also add another module for SEHP analysis. Additionally, a key aim of this software is to consolidate diverse analytical requirements into a single, all-encompassing platform, providing a one-stop solution for various types of analyses.

Furthermore, Researchers also established a complete emulator system setup and a SEHP site for bikes to run in the large-sized lab of the SMART center at Prairie View A&M University so other researchers can visit and train about this newer energy generation applications. Additionally, collaboration of academic and industrial partnerships can form for manufacturing and deploying the technology on bike lanes that can reduce fossil fuel consumption in the long run and save the environment.

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Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

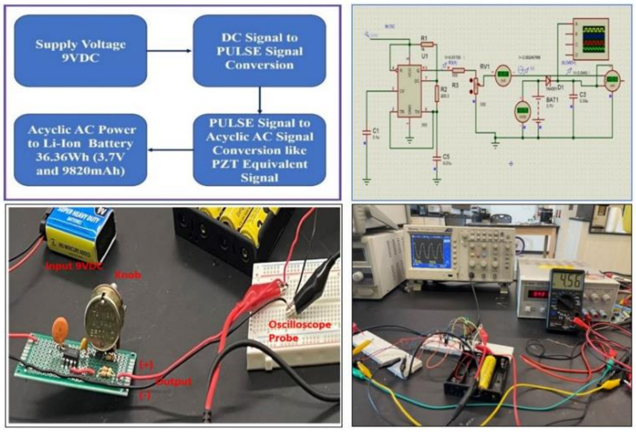
Kazi Meharajul Kabir reports financial support was provided by Prairie View A&M University. Kazi Meharajul Kabir reports financial support was provided by National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author's Credit Statement

☒ The authors declare the equal contribution of this work

Graphical abstract

Graphical abstract of a SEHP Emulator for the SEGP Technology



Highlights:

1. Introducing a groundbreaking emulator for SEHP, a unique tool facilitating real-world validation of innovative energy-generation technology.

2. A comprehensive resource for SEHP emulator design, simulation, and prototyping insights.

3. The prototype verifies the emulator's functionality, establishing its credibility as an authentic SEHP system replica.

4. Illustrating the emulator's crucial contribution to the progress of sustainable energy technology.

5. To the development of greener and more environmentally conscious energy solutions by focusing on the viability of the SEHP system