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Designing a Spring-Powered Generator Prototype as an Alternative Power Source

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ARTICLE INFO	ABSTRACT
Article history: Received 13 October 2025 Received in revised form 30 October 2025 Accepted 2 November 2025 Available online 4 November 2025 Keywords: Generator; spring energy; flywheel; renewable energy; prototype	Most renewable energy sources such as solar and wind power rely heavily on environmental conditions, which limits their consistency and availability. Conventional small-scale mechanical generators, meanwhile, often suffer from low efficiency and limited adaptability for portable applications. This study aims to design and evaluate a spring-powered generator prototype capable of generating electricity independently of external conditions. The system uses four helical springs arranged in a zig-zag configuration (0°–180°–0°–180°) connected to a main shaft and flywheel to produce rotational motion, which is then converted into electrical energy using a 12 V DC generator. Experimental results show a maximum output voltage of 5.3 V and a rotation duration of approximately 9 seconds. The overall energy conversion efficiency reaches about 6.4%, indicating moderate performance that can be further enhanced through optimization of spring stiffness and flywheel mass. These findings demonstrate the feasibility of spring-based mechanical systems as compact, low-cost, and environmentally friendly power sources for small-scale, off-grid, or educational applications.

1. Introduction

1.1 Background

A generator is an electrical machine that converts mechanical energy into electrical energy based on the principle of electromagnetic induction. In the development of renewable energy technology, the use of generators with alternative energy sources is very important. One of the latest innovations is the development of generators that utilize spring force as a source of mechanical energy to generate electricity efficiently and in an environmentally friendly manner. Similar approaches have been reported in recent spring-based energy harvesting studies [1,2].

Recent advances in spring-based energy harvesting have demonstrated promising results as alternative renewable energy sources. For example, Su *et al.*, [3] proposed a 3D spring-based piezoelectric energy generator with cost-effective fabrication and high performance suitable for

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small-scale renewable devices [3,4]. Similarly, Chen *et al.*, [5] introduced a gas spring design that enhances output power and efficiency in electric generators by minimizing frictional losses [5]. More recently, Parashar *et al.* experimentally demonstrated spring-powered systems that convert stored potential energy in wound springs into usable electricity with efficiencies of up to 40%, suitable for powering small devices [6,7]. These innovations support the concept of using spring-powered generators as practical and eco-friendly solutions for low-power electricity needs, especially in remote or off-grid locations with limited access to conventional energy sources.

This spring generator offers a cost-effective power generation solution that can be applied on a small scale, such as LED lighting, with sufficient power output for such needs. With the increasing demand for sustainable and environmentally friendly electricity, this project aims to develop a spring generator model as a practical and economical alternative renewable energy source. As the population grows, technology advances, and electricity demand increases across various sectors of life, the need for reliable and sustainable sources of electrical energy continues to rise. Access to electricity remains a major problem in many places, especially in remote areas with poor infrastructure. This situation calls for energy generation solutions that are not only affordable and efficient, but also easy to use without relying on specific natural resources, such as wind or solar power, on a regular basis. This concept aligns with recent advancements in mechanical energy storage and conversion systems that utilize spring-flywheel integration [8,9].

One innovative alternative that has emerged to address this problem is a spring-based electricity generator. Mechanical spring components, which can store and release elastic potential energy, can be used to generate rotational motion, which is then converted into electrical energy through a generator system. This process is similar to how mechanical toys or analog watches that use spring energy work, but it has been modified so that it can be used as a low-power electricity source. Some of the main advantages of this innovation are that it does not require fuel, can operate at any time regardless of weather conditions, and is easy to maintain and install. Spring generators are also suitable for applications such as emergency lighting, charging small devices, and teaching energy conversion techniques to the general public and students. In addition, this system does not produce emissions or waste, supporting the agenda of carbon reduction and clean energy transition around the world. Although it sounds simple, the design and calculation of spring power generator systems require knowledge of rotational dynamics, material elasticity, and the efficiency of mechanical energy transmission to electrical energy. Parameters such as spring constants, flywheel mass, and gear ratios are important components that greatly affect the overall performance of the system. However, only a few studies have focused on purely mechanical spring-based energy systems that operate independently of external environmental conditions. Therefore, this research aims to address that gap by designing and experimentally testing a compact spring-powered generator prototype for small-scale electrical applications.

1.2 Research Objectives

The main objective of this research is to design and develop a prototype generator that utilizes spring energy as a source of mechanical energy for electricity generation. This study aims to measure, compare, and analyze the electrical output capacity generated by the spring-powered system under controlled experimental conditions. In addition, it seeks to identify and address technical challenges that arise during prototype operation, such as energy loss, torque imbalance, and spring fatigue, through a series of repeated test cycles. Furthermore, this research evaluates the system's performance degradation over time by examining the relationship between spring stiffness reduction, rotational duration, and voltage output. The findings from this study are intended to serve

as both a proof of concept and a foundation for the future development and optimization of modular or large-scale spring-based power generation systems.

1.3 Benefits of Research

It is anticipated that the findings of this study will offer an economical and ecologically friendly electrical energy source that can aid in the shift to sustainable power generation. By presenting a workable and affordable system that uses mechanical spring energy to generate electricity, this study advances the technology of renewable energy. Furthermore, in isolated or off-grid locations with restricted access to conventional power, the created prototype may be a workable alternative for small-scale electrical demands. Beyond its usefulness, this research has educational value as well. It can be used as a guide for creating emergency generators for homes or public spaces and as an interactive learning tool to help people comprehend the fundamentals of energy conversion, mechanical motion, and electrical systems. This approach also supports the development of resilient, off-grid power solutions for low-demand environments.

1.4 State of the Art

Recent developments in mechanical energy storage and conversion research focus on optimizing energy accumulation mechanisms, such as the use of springs and flywheels, which can efficiently store and stabilize kinetic energy. Flywheel Energy Storage Systems (FESS) have regained interest as an attractive technology due to their highpower density, long cycle life, fast response, and low environmental impact. Recent studies highlight improvements in rotor design, bearing technology (including magnetic and low-friction bearings), and integration with digital control systems to increase system efficiency and durability.

In terms of flywheel design, various studies have focused on increasing energy density and reducing stress concentration, for example, by optimizing the rotor-shaft structure and using composite materials. Increased flywheel inertia has been shown to extend rotation duration and maintain torque stability, which is particularly relevant for small-scale prototypes [10,11]. Meanwhile, recent research on spring mechanisms emphasizes cyclic energy accumulation and the ability of springs to store and release energy repeatedly with high efficiency [12]. introduced advanced spring mechanisms capable of cyclic energy accumulation.

Mechanical energy conversion systems utilizing springs and flywheels have gained increased attention. Zhang et al. developed a compact mechanical energy harvester that efficiently converts traffic-induced vibrations into electrical energy through resonant spring-mass systems, while Nishanth et al. combined piezoelectric and reverse dielectric effects to maximize energy harvest [13,14]. Kang *et al.*, [15] reviewed hybrid energy harvesting systems, emphasizing the optimization of spring mass-damping configurations near resonant frequencies to enhance generator performance [15]. Additionally, Mohankumar and Jayaramaiah reviewed bio-mechanical energy harvesting methods, including piezoelectric and electromagnetic techniques, illustrating broad potential for mechanical-to-electrical energy conversion [16]. Such studies provide a solid foundation and rationale for the design choices made in this spring-powered generator prototype.

Several studies also combine spring systems with flywheels to obtain more stable energy output. Optimization is carried out in three main aspects: (1) increasing flywheel inertia, (2) using the right gear ratio to increase generator speed, and (3) selecting spring materials with high fatigue resistance [8,17,18]. This research is in line with recent recommendations emphasizing the importance of cyclic testing to analyze performance degradation due to material fatigue and loss of mechanical efficiency

over time. Based on this review, this study contributes by developing a zig-zag configuration (0° – 180° – 0° – 180°) spring-powered generator prototype combined with a flywheel and DC generator. In addition to testing the system's performance in generating voltage and rotation duration, this study also conducted cyclic testing to evaluate performance degradation due to reduced spring stiffness, providing a new contribution to the study of small-scale mechanical energy conversion. This design concept corresponds to previous experimental prototypes tested by Rahman [19]. However, most studies focus on electromagnetic coupling or magnetic spring models, while little attention has been given to purely mechanical spring-driven flywheel generators at a laboratory scale.

2. Methodology

2.1 Research Method

This section describes the methods used in this study, which include literature review, tool design, and experimental testing. To accomplish its goals, this study uses both experimental and literature-based methodologies. In order to investigate the basic concepts of electrical generators, flywheel mechanisms, and the application of spring force in mechanical-to-electrical energy conversion, a through literature research was initially carried out. These results led to the design and construction of a spring-powered generator prototype using a gear-based rotational speed amplification system and a spring driving mechanism. After that, the prototype's performance was assessed using the experimental approach through repeated cycle testing, which measured efficiency, rotation duration, and voltage output under various operating situations. Guo *et al.*'s [20] work on elastic energy storage technology with spiral springs further informs the development of efficient mechanical energy storage and release mechanisms employed in this study [20]. The experimental results were validated by comparing the gathered data with earlier research, and then the performance degradation over time as a result of mechanical wear and spring fatigue was examined.

2.2 Research Approach

This study uses an experimental approach involving the design, manufacture, and testing of a physical prototype of a spring-powered generator. This flowchart in Figure 1 illustrates the overall stages of the research process, beginning with identifying the problem of alternative energy needs, followed by a literature review, conceptual design, and prototype development. The experimental setup was designed to test the performance of the spring-powered generator, followed by data collection, analysis, and evaluation. The final stage involves drawing conclusions and proposing future improvements, such as developing a hybrid magnet-spring system to increase energy efficiency.

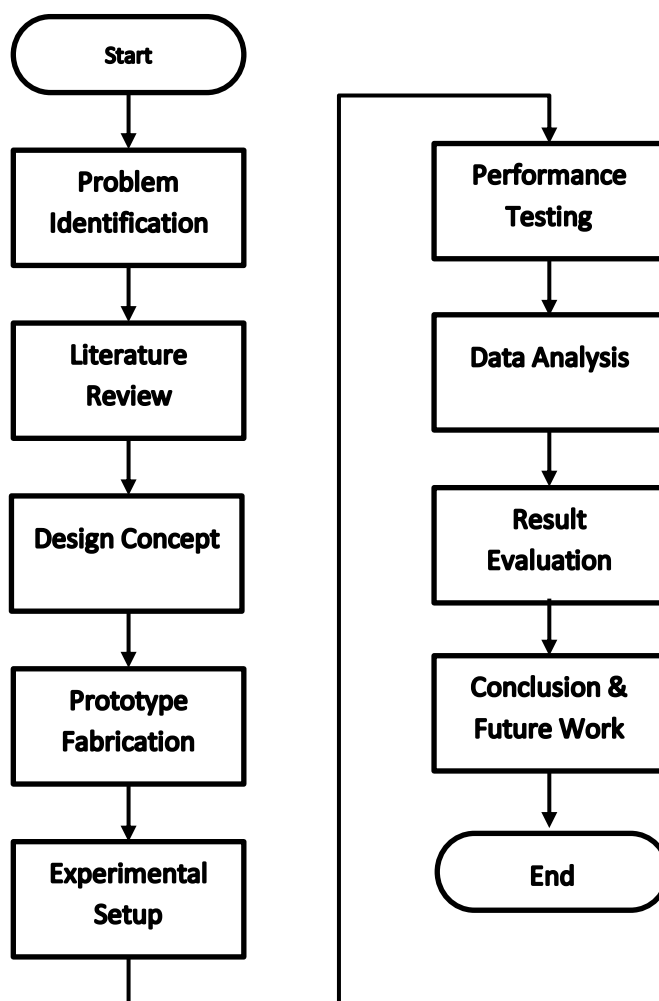


Fig. 1. Research flowchart of the spring-powered generator study

2.3 Working Principle of Springs in Energy Conversion

Springs store elastic potential energy that can be converted into kinetic energy when released. Similar mechanisms have been discussed in the works of Xiong *et al.*, [21] and Bijak *et al.*, [9] regarding spring-coupled electromagnetic energy systems. This mechanism enables repetitive motion that can be used to generate electricity continuously. Spring power generators work by utilizing the potential energy stored in springs. When the springs are pulled and released, the energy is converted into rotational motion that is transmitted to the flywheel and shaft to drive the generator.

According to Hooke's law, the force acting on a spring is directly proportional to the increase in the spring's length. ($F = -k \cdot x$), where F is the force, k is the spring constant, and x is the increase in length. The elastic potential energy stored in the spring can be calculated using the formula:

$$E = \frac{1}{2} k x^2 \quad \text{Eq. (1)}$$

Types of springs include coil springs, compression springs, and tension springs, each of which has specific characteristics in terms of energy storage and release.

Spring stiffness has a significant effect on the amount of electrical energy generated. Research shows that the greater the spring stiffness (high k value), the less electrical energy is generated from the speed bump prototype. Springs that are too stiff tend to absorb force without producing sufficient deflection to turn the generator efficiently. A spiral spring with a stiffness of 3.68 N/mm produces a maximum power of 0.093 Watts, while a spring with a stiffness of 13.08 N/mm only produces 0.0495 Watts. This demonstrates the importance of selecting the appropriate spring stiffness value in systems that convert mechanical energy into electrical energy.

The type of material used to make springs also affects their performance. Carbon steel, stainless steel, and copper alloys are some examples of materials that are excellent for mechanical energy storage systems due to their durability and high elasticity. Temperature is a very important factor. High temperatures can cause the elastic modulus to decrease, causing the spring to lose some of its stiffness and reduce the energy produced. Spring systems are often used in conjunction with torque amplification mechanisms such as levers or cams to increase electrical output. This is because small movements of the spring can be converted into larger rotations of the generator.

2.4 Flywheel Mechanism in Energy Storage

Flywheels help maintain rotational momentum, ensuring stable rotation and reducing energy loss due to load fluctuations in generators. A flywheel is a mechanical component that stores kinetic energy in the form of rotational momentum. According to the flywheel principle, energy is stored during acceleration and released during deceleration, maintaining the stability of the mechanical system. With sufficient mass and diameter, a flywheel is able to maintain rotation and reduce fluctuations in electrical output.

Flywheels are also used in speed bump-based mechanical energy conversion systems. Flywheels are installed in gearboxes to increase the rotational speed of alternator rotors, thereby generating higher electrical voltage. The use of flywheels has been proven to help maintain rotational stability and strengthen kinetic energy for more stable electrical output. A flywheel is a mechanical component that stores kinetic energy in the form of rotational momentum. This principle has been widely discussed by Xu et al. and Li & Palazzolo [11,19,22,23]. According to the working principle of a flywheel, energy is stored during acceleration and released during deceleration, maintaining the stability of the mechanical system. Suppose we have a spring constant $k = 100 \text{ N/m}$, the spring is pulled to a distance of $x = 0,05\text{m}$ (5 cm).

$$E = \frac{1}{2} \times 100 \times (0,05)^2 \quad \text{Eq. (2)}$$

$$0,5 \times 100 \times 0,0025 = 0,125 \text{ Joule} \quad \text{Eq. (3)}$$

where I is the moment of inertia and ω is the angular velocity. With sufficient mass and diameter, flywheels are able to maintain rotation and reduce fluctuations in electrical output.

The distribution of flywheel mass relative to the axis of rotation also affects how effective the flywheel is. Flywheels with more mass at the edge have higher inertia, which means they store more energy. By using materials such as steel or aluminum, you can balance structural strength and weight. In addition, magnetic bearings—also known as magnetic bearings—can be used in modern flywheels to reduce friction, allowing for longer and more stable rotation. In some advanced systems, flywheels can even be placed in a vacuum chamber to reduce air resistance and improve energy efficiency.

2.5 Conversion of Mechanical Energy to Electricity

The rotational motion generated by the spring system is transmitted to an electric generator, which converts it into electrical energy. The efficiency of the system depends on the quality of the springs, the gear ratio, and the flywheel design. A generator is a device that converts mechanical energy into electrical energy based on the principle of electromagnetic induction. This principle was first proposed by Michael Faraday, who stated that when a conductor moves in a changing magnetic field, an electromotive force (EMF) is generated in the conductor.

The generator used is alternator-based. This system is powered by a flywheel mechanism connected to a gear, producing an electrical voltage of up to 16.7 volts at 650 RPM. Energy efficiency depends on the initial torque produced by the spring mechanism and the rotational speed of the generator rotor. The use of direct current (DC) generators is more suitable for small and portable scales because they can directly charge batteries without the need for a rectifier. Due to the ease of charging batteries or capacitors directly, generators used in spring power systems are usually direct current (DC) generators. In practical scenarios, rectifiers and voltage regulators are needed to produce stable voltage and current, especially if the generator produces alternating current (AC).

The main formula for the electrical power generated is as follows:

$$P = V \times I \quad \text{Eq. (4)}$$

where P is power (watts), V is voltage (volts), and I is current (amperes). By increasing torque and controlling the load, system efficiency can be improved. Similar systems have achieved up to 16.7 V output in small-scale prototypes [24].

2.6 Energy and Mechanics Analysis Model

A simple model is used to describe the relationship between spring energy, flywheel inertia, and electrical output energy. The total mechanical energy stored in four identical springs is

$$E_m = 4 \times \frac{1}{2}kx^2 \quad \text{Eq. (5)}$$

This energy is converted into rotational energy

$$E_f = \frac{1}{2}I\omega^2 \quad \text{Eq. (6)}$$

Where $I = \frac{1}{2}mr^2$. The conversion of electrical energy is obtained from the integral of the generator's output power over one cycle. This model helps determine parameters such as spring stiffness, flywheel mass, and gear ratio to increase system efficiency.

2.7 Mechanical Design and Angle Determination

In addition to basic theories about springs, flywheels, and generators, the design of mechanical spring power generator systems also requires an understanding of spring stiffness, spring angle distribution on the shaft, and frame structure stability. Spring (the distance between spring coils) affects spring stress distribution and deflection. The smaller the spring pitch, the greater the number of coils, causing increased deflection, which also affects energy storage and release efficiency. In addition, the spring constant is influenced by the number of coils and the diameter of the wire. The greater the number of coils and the diameter of the spring, the lower the spring constant tends to be, which means that the spring is more flexible and capable of producing greater deflection.

This aspect is crucial in the design of spring-powered generators because springs that are too stiff tend to absorb force without generating optimal rotational motion, while springs that are too flexible may fail to return to their original position quickly, thereby reducing the system's overall efficiency and stability. The optimal combination of spring stiffness and flywheel inertia has been emphasized in studies by Ahamed *et al.*, [17]. To improve efficiency, this system integrates several key design considerations. The frame is designed to be rigid and sturdy to minimize vibration, ensuring stability during operation. The springs are arranged at angles of 0° – 180° – 0° – 180° in a zig-zag configuration to balance the forces on both sides of the mechanism. The shaft is equipped with an eccentric cam design so that each spring operates at a different phase, allowing for the alternating application of force. A flywheel with sufficient mass (15 cm in diameter) is used to store kinetic energy and stabilize rotational movement. The frame, made of wood or iron with dimensions of approximately 60×30 cm, supports all components and maintains structural integrity. The springs, each placed at an angle of 10 – 30° relative to the shaft, produce optimal tensile force, while the shaft, 1 cm in diameter and 60 cm in length, is equipped with grooves at 0° , 180° , 0° , and 180° to synchronize spring engagement. This zig-zag configuration, consisting of two pairs of opposing springs, is specifically designed to balance the torque from both sides and maintain smooth and stable shaft rotation.

In fact, the generator structure design must take into account the dynamic loads generated by flywheel rotation and spring tension. To ensure frame durability and stability, this force analysis can be performed using CAD software and finite element analysis (FEA) simulation. The distribution of spring installation angles (e.g., 0° – 180°) is very important to prevent unbalanced forces that can cause vibration or wear on the bearings. The tensile forces balance each other out with a symmetrical design and the rightangle selection, which allows for more efficient rotation. To protect sensitive parts from sudden impacts when the spring is released, you may also consider incorporating vibration dampers or shock absorbers. To ensure balance and torque stability, related designs have been numerically simulated in previous FESS optimization works [15,19,23].

2.8 Design and Planning

The placement pattern of the spring hooks on the shaft is designed in a zig-zag pattern (0° - 180° - 0° - 180°) so that the tensile force works alternately from the left and right sides. The springs are installed at an angle of 10 – 30° to the shaft to produce optimal tension and prevent the tensile force from working simultaneously from the same direction. To begin the initial design, working sketches are created using 2D design software such as AutoCAD and 3D simulation software such as SolidWorks. This is done to ensure that all components are properly installed without interfering with the mechanics. The main objective of the design is to create a system that is stable, modular, and easy to test in the laboratory. To achieve ideal traction without disrupting torque balance, the design considers the position of the shaft, flywheel, and springs relative to the main shaft. To reduce power loss due to misalignment, the generator or dynamo is positioned linearly with the shaft.

2.9 Materials and Tools

The selection of materials for the prototype was made based on cost efficiency, market availability, and ease of fabrication. High carbon steel spiral springs were chosen for their excellent fatigue resistance and durability. The main shaft was made of steel to withstand the torque generated by the springs, while the flywheel was constructed from solid cast steel to provide greater rotational inertia and smoother motion. Pillow block bearings were used to simplify assembly and minimize rotational friction. Additional components included an electric generator, iron or wooden

frame, bolts and nuts, and a V-belt for power transmission. Measurement instruments consisted of a digital multimeter to record voltage and current, and a stopwatch to measure the duration of flywheel rotation.

2.10 Dimensions and Specifications

The dimensions and specifications of the prototype are designed to ensure optimal performance and mechanical balance. The system uses four spiral springs, each measuring 9 cm in length and 1 cm in diameter. The main shaft measures 60 cm in length and 1 cm in diameter, providing sufficient space for even spring placement and stable rotation. A flywheel with a diameter of 15 cm and a weight of approximately 4 kg is installed to store kinetic energy and maintain consistent rotational movement. The support frame, made of wood, measures 60 cm in length, 30 cm in width, and approximately 25 cm in height, providing sufficient space for spring expansion and flywheel movement. To achieve balanced force distribution, the springs are installed at equal intervals of approximately 15 cm along the shaft, ensuring symmetrical loading and smooth rotational dynamics.

2.11 Steps for Making

The fabrication process of the spring-powered generator prototype involves several systematic steps. First, the spring system and flywheel mechanism are designed to ensure efficient energy transfer and stable rotation. Next, the frame and main shaft are installed to form the structural foundation of the device. The springs are then connected to the crankshaft in a zig-zag configuration to create alternating tension forces. Afterward, the flywheel system is assembled to maintain rotational momentum and smooth out fluctuations in torque. The shaft is subsequently connected to the electric generator to convert mechanical energy into electrical energy. Finally, the prototype is tested under various load conditions to evaluate its performance, output stability, and efficiency.

2.12 Design Schemes and Drawings

The design scheme of the spring-powered generator integrates mechanical and electrical components into a compact, functional system. The primary mechanism consists of a horizontal cylindrical shaft on which multiple springs are symmetrically arranged to ensure balanced operation. Each spring is connected at one end to an eccentric cam on the rotating shaft and at the other end to a fixed hook on the frame, allowing the spring to stretch and contract as the shaft rotates. This configuration enables the springs to alternately store and release mechanical energy. The main shaft is coupled to a flywheel and a generator (dynamo), where the flywheel serves to convert the intermittent spring force into smooth rotational motion. This continuous rotation is then transmitted to the generator, which converts the mechanical energy into electrical energy output. The overall design of the tool is shown in Figure 2, which displays the design scheme of the tool, including views from above, the right and left angles, as well as each part of the tool.

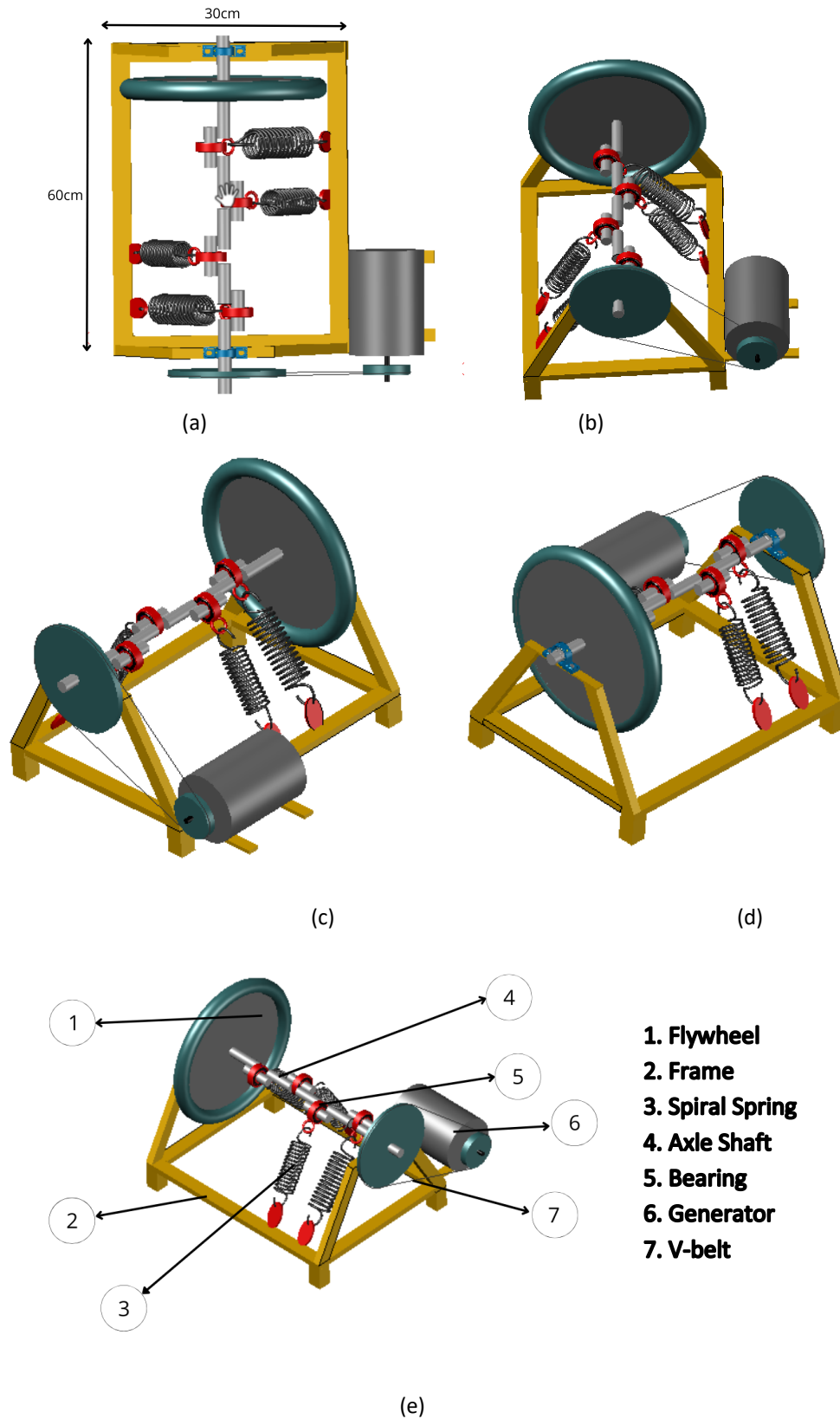


Fig. 2. Tool design scheme (a) Top view (b) Left top view (c) Right top corner view (d) Right top corner view (e) Each part of the tool

2.13 Prototype Design and Assembly

The finished prototype is shown in Figure 3, the image shows a completed prototype of a spring-powered generator that converts mechanical spring energy into electrical energy. The system consists of four high-carbon steel springs arranged in a $0^\circ\text{--}180^\circ\text{--}0^\circ\text{--}180^\circ$ zig-zag configuration mounted on a horizontal shaft. A 15 cm diameter flywheel is mounted on the main shaft to stabilize rotational movement, while a 12 V DC generator converts rotational energy into electrical output. A $60 \times 30 \times 25$ cm wooden frame supports all components and maintains structural stability during testing, ensuring balanced torque distribution and smooth operation throughout each energy cycle.

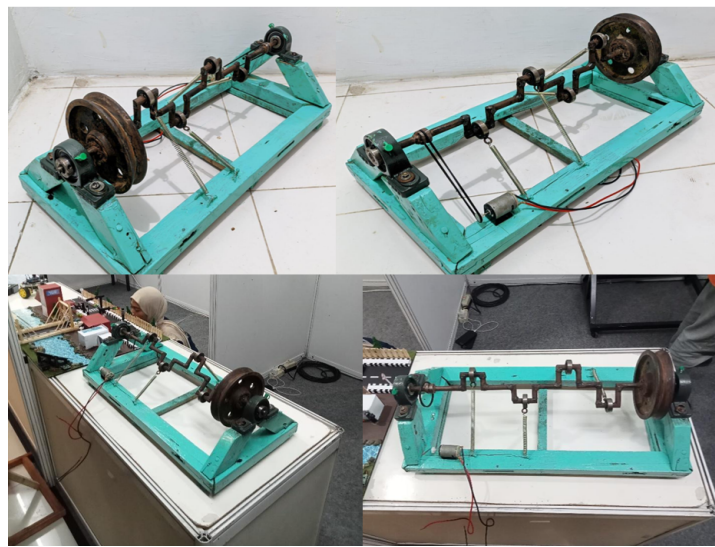


Fig. 3. Final prototype of the spring-powered generator system

3. Results

3.1 Performance Testing

The following section presents the experimental results obtained from the prototype testing. The test was conducted by pulling the four springs to their maximum position and then releasing them simultaneously. The shaft was rotated by the tensile force of the springs in a zig-zag pattern of $0^\circ\text{--}180^\circ\text{--}0^\circ\text{--}180^\circ$, causing the flywheel to rotate and drive the dynamo (12V DC generator). Table 1 shows the performance test results conducted on the spring-powered generator prototype. The data indicates that the flywheel is capable of completing approximately 13–15 revolutions after the spring is released, with an average rotation duration of approximately 9 seconds. During this period, the generator produces a maximum output voltage of approximately 5.3 V DC. These results indicate that the prototype is capable of effectively converting the mechanical energy stored in the spring into electrical energy in a short period of time. However, the relatively low output voltage and limited rotation time suggest that further optimization—such as increasing spring stiffness, increasing flywheel inertia, or applying a higher gear ratio—could improve energy conversion efficiency and extend operational time. Based on manual simulation and the mechanical characteristics of the springs and flywheel mass:

Table 1

Test results

Parameters	Results
Number of flywheel revolutions	±13–15 rotation after the spring is released
Round duration	±9 second
Maximum voltage of the dynamo	±5.3 Volt DC

The statement that this system “demonstrates potential” is supported by voltage and rotation duration measurements, which show that the elastic energy of the spring can be repeatedly converted into electrical energy. Compared to other small mechanical generator studies, the performance of this device is comparable, despite its much simpler construction. This indicates that spring-based systems are worth further development. Conversion efficiency is calculated by comparing the electrical energy produced and the elastic potential energy stored in the spring. Spring energy is calculated using the formula:

$$E = \frac{1}{2}kx^2 \quad \text{Eq. (7)}$$

While electrical energy is calculated from the product of voltage, current, and time

$$(E = V \times I \times t) \quad \text{Eq. (8)}$$

Based on the test results ($V = 5.3 \text{ V}$, $I = 0.1 \text{ A}$, $t = 9 \text{ s}$), the electrical energy produced is ± 3.15 joules, while the spring energy is around 20 joules, resulting in an efficiency of $\pm 15.8\%$. This value is comparable to the results of research on similar small-scale mechanical systems.

3.2 Efficiency Evaluation

An evaluation of the efficiency of spring-powered generators shows that the duration of rotation achieved is sufficient to generate a small but measurable amount of electrical energy. When a gear system is integrated to increase the RPM ratio, the voltage generated can be maintained at a higher and more stable level. However, continuous electricity generation requires repeated compression and release cycles of the spring, as the energy stored in the spring is limited per cycle. The overall efficiency of the system can be further improved through several enhancements, such as optimizing the gear ratio, using generators with higher sensitivity to low rotational speeds, and increasing the voltage or stiffness of the spring to store more mechanical energy per cycle. This approach aligns with hybrid spring-flywheel designs proposed in recent literature.

3.3 Results of Several Cycle Tests

To observe the performance of the device over time, 10 consecutive cycles of use were tested. Each cycle involved maximum pulling and spring release. Table 2 and Figure 4 below show graphs of the decline in tool performance based on the number of usage cycles. It is clear that both the maximum voltage and the number of flywheel revolutions decrease as the number of cycles increases, due to a decrease in spring stiffness. Voltage and revolutions decrease linearly as spring stiffness decreases. After ± 5 cycles, efficiency decreases dramatically. This is due to material fatigue in the spring, which reduces its elasticity and prevents the spring from storing maximum energy. Dara et al. and Wenjia et al., [26] similarly underscore the importance of selecting appropriate spring constants and flywheel design to avoid excessive force absorption or failure of spring recovery,

factors that significantly affect voltage output stability. These results highlight the need for ongoing optimization and material improvements [25,26]. The observed performance decline after several cycles is in agreement with studies on spring fatigue degradation under cyclic loading.

Table 2

Testing the performance of the tool with several cycles

Cycle No.	Maximum Voltage (V)	Round Duration (second)	Notes
1	5.3	9.0	Optimal springs
2	5.0	8.7	Slight decline
3	4.7	8.4	Normal
4	4.5	8.1	Springs begin to weaken
5	4.2	7.7	Performance decline begins to be noticeable
6	4.0	7.3	Spring stiffness begins to decrease
7	3.8	6.9	Pull begins to be less than optimal
8	3.5	6.5	Rotational energy decreases
9	3.2	6.1	Flywheel begins to lose inertia
10	3.0	5.8	Tension drops significantly

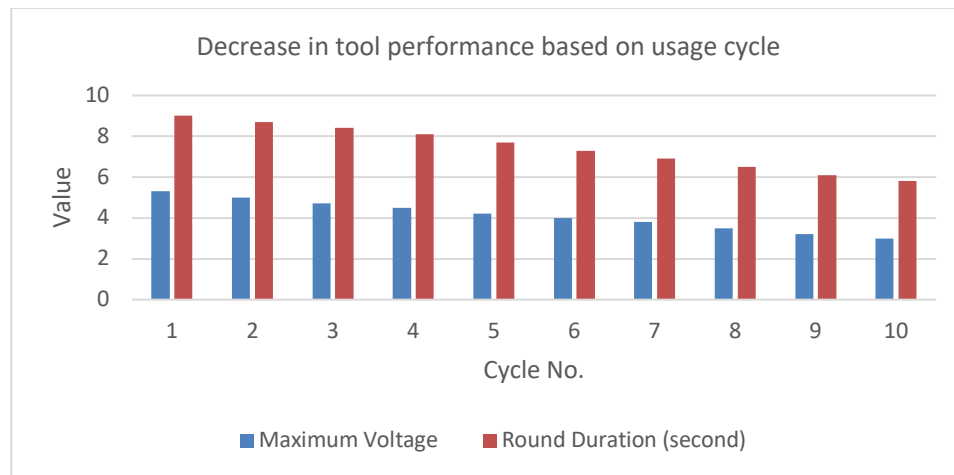


Fig. 4. Performance testing chart for the tool with several cycles

Table 3

Performance efficiency test results

Cycle No.	Electrical Energy Output (J)	Estimated Spring Energy Input (J)	Efficiency (%)
1	4.77	75	6.4
2	4.35	75	5.8
3	3.95	75	5.3
4	3.64	75	4.9
5	3.23	75	4.3
6	2.92	75	3.9
7	2.62	75	3.5
8	2.28	75	3.0
9	1.95	75	2.6
10	1.74	75	2.3

Table 3 summarizes the results of ten consecutive test cycles of the spring-powered generator. The electrical energy output and efficiency show a gradual decrease over time due to spring fatigue and increased internal friction. The highest recorded efficiency is approximately 6.4% in the first cycle, which progressively declines to around 2.3% in the tenth cycle. This trend confirms that spring stiffness degradation significantly affects the system's energy conversion performance.

3.4 Mechanical Principle and Design Optimization

The performance of the spring-powered generator is primarily influenced by the mechanical balance between spring stiffness, flywheel inertia, and rotational friction. Springs that are too stiff generate high torque but produce shorter rotation durations, while springs that are too flexible provide longer rotation but insufficient torque to sustain the flywheel. The flywheel plays a critical role in storing kinetic energy and stabilizing the system; however, excessive mass increases the moment of inertia and reduces initial acceleration. The optimal design, therefore, requires a moderate spring stiffness that allows adequate deflection without material fatigue, coupled with a flywheel of sufficient mass to maintain smooth rotation without overloading the shaft. Minimizing bearing friction and optimizing the pulley ratio between the shaft and generator can further enhance energy transfer efficiency. These mechanical considerations provide a foundation for improving future prototypes and scaling up the system for higher power output.

3.5 Relevance to Renewable Energy Applications

This prototype demonstrates the practical feasibility of using mechanical spring energy as a small-scale power source that operates independently of environmental conditions. Unlike solar or wind systems that rely on intermittent natural inputs, the spring-powered generator can function anytime, making it suitable for portable and emergency applications. The system's zig-zag spring configuration ensures torque balance and smoother rotational motion, which improves overall energy transfer stability. Although the electrical output is relatively small, the simple design and mechanical reliability make it ideal for educational purposes and low-power devices in remote areas. With further optimization of spring stiffness, flywheel mass, and energy storage integration, the technology could serve as a complementary component within hybrid renewable energy systems.

4. Conclusions

This study demonstrates that a spring-based system can be used as an alternative mechanical energy source for electricity generation. The maximum voltage of 5.3 V and a rotation duration of approximately 9 seconds confirm the feasibility of the system. However, the conversion efficiency remains relatively low due to bearing friction and spring imbalance. Optimization of the flywheel design, spring stiffness, and gear ratio can enhance the system's overall performance. With further development, this prototype has the potential to be used as a small-scale power generator for emergency or educational applications.

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