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RESEARCH ARTICLE

Enhancing energy efficiency in power looms: utilizing regression machine learning for electrokinetic energy assessment

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ABSTRACT

This study focuses on optimizing electro-kinetic energy utilization in textile weaving units, addressing power interruptions, reducing electrical costs, and harnessing latent kinetic energy during the weaving process. Power looms, vital to textile production, often incur inefficiencies and increased operational costs due to underutilized kinetic energy. To address these challenges, three innovative electrokinetic energy harvesting approaches are proposed: the Modified Series-Parallel Piezo Matrix, bi-directional linear generation, and uni-directional non-linear power extraction methods. The research further incorporates the Super Lift and Ultra Lift DC-DC power conversion techniques to enhance energy efficiency. The Modified Series-Parallel Piezo Array integrates Piezoelectric elements to capture and convert discarded kinetic energy efficiently. The bi-directional linear generation method captures mechanical energy from both forward and backward movements in weaving, minimizing energy wastage. The uni-directional non-linear power extraction method optimizes energy recovery by targeting specific weaving cycle phases. Machine learning algorithms, including Gaussian Process Regression, Linear Regression, Neural Network, and Support Vector Machine, enable precise energy estimation for meticulous modeling and optimization. Rigorous validation through MATLAB simulations aims to bolster energy efficiency, trim operational costs, and promote sustainable energy practices in the textile industry, contributing to a more environmentally friendly and sustainable future for the sector.

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KEYWORDS
Textile unit; GHG; electro-kinetic energy; DC-DC power conversion; machine learning

1. Introduction

Power looms are indispensable machines in the textile industry, facilitating efficient and high-volume fabric production. However, their operation heavily relies on electrical energy, resulting in a substantial demand for electricity in weaving units (Saravanan & Albert, 2023). Weavers face challenges such as power breakdowns and escalating costs of electrical energy show in Figure 1, which directly impact their productivity and operational efficiency. To overcome these challenges, the concept of electro-kinetic energy optimization has emerged as a promising solution. This article explores the significance of electro-kinetic energy in weaving power looms and its role in addressing the demand for electricity. Efficient operation of weaving power looms requires a significant amount of electricity (Saravanan & Albert, 2023; Saravanan & Ramaswamy, 2023). The demand arises from various aspects of the weaving process, including the operation of the loom itself, auxiliary equipment such as fans and air conditioning systems, and lighting. The power requirements can vary based on factors such as the type of power loom, complexity of the fabric being woven, and production scale (Saravanan & Albert, 2023). Power breakdowns pose a significant challenge for power loom weavers as they disrupt the weaving process, leading to downtime and reduced productivity. Additionally, the rising costs of electrical energy add to the burden, especially for weavers operating at low-level and medium-level capacities (Saravanan & Albert, 2023). Therefore, optimizing electricity usage and reducing dependence on the grid have become imperative goals. Electro-kinetic energy, derived from mechanical movements and vibrations, offers a promising solution to address the electricity demand in weaving power looms. By harnessing and optimizing electro-kinetic energy, power loom weavers can reduce their reliance on traditional energy sources and mitigate the challenges associated with power breakdowns and escalating energy costs. One of the primary applications of electro-kinetic energy in weaving power looms is the utilization of piezoelectric materials. These Energy materials exhibit a unique property of generating an electric charge in response to mechanical stress or vibrations. By incorporating piezoelectric materials into the loom structure or fabric itself, the mechanical movements and vibrations during the weaving process can be converted into electrical energy. Several strategies have been proposed to optimize electro-kinetic energy in weaving power looms. These include the implementation of series-parallel piezo arrays, where multiple piezoelectric elements are arranged in a specific configuration to maximize energy harvesting efficiency. Another approach is the use of bi-directional linear generation, which capitalizes on the reciprocating motion of the loom to generate electricity in both forward and

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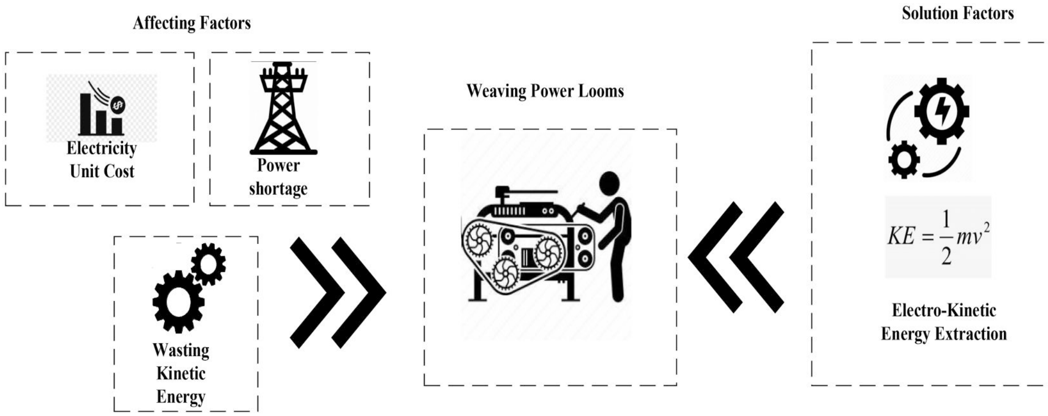

Figure 1. Influence of factors on power loom-based weaving units and corresponding solutions.

backward directions (Saravanan & Albert, 2023). Additionally, uni-directional non-linear power extraction techniques can be employed to capture and convert specific vibrations into electrical energy (Saravanan & Albert, 2023). To maximize the benefits of electro-kinetic energy optimization, machine learning algorithms are being integrated into the energy estimation and management processes. Regression machine learning algorithms enable accurate modeling and estimation of energy production and consumption based on the outcome parameters of the electro-kinetic energy harvesting strategies. This data-driven approach facilitates fine-tuning of the energy optimization techniques, ensuring optimal utilization of available electro-kinetic energy. Implementing electro-kinetic energy optimization in weaving power looms offers several advantages. Firstly, it enhances the sustainability of the textile industry by reducing reliance on traditional energy sources and minimizing carbon emissions. This aligns with the industry's growing emphasis on environmentally friendly practices. Secondly, it helps power loom weavers reduce their dependence on the electrical grid, making them more resilient to power breakdowns and fluctuations in energy prices. Additionally, electro-kinetic energy optimization contributes to cost savings by reducing energy consumption and optimizing resource allocation. In conclusion, the demand for electricity in weaving power looms poses challenges for weavers. However, by harnessing electro-kinetic energy and implementing optimization strategies, power loom weavers can enhance sustainability, reduce dependence on the grid, and achieve cost savings. The integration of machine learning algorithms further enhances energy estimation and management, leading to improved efficiency and productivity in the weaving process (Saravanan & Albert, 2023; Saravanan & Ramaswamy, 2022; 2022; 2023; 2023).

2. Background analysis

2.1. Study about importance of industrial energy optimization and how its applied industrial units

Energy optimization involves every cycle of electrical energy, including generation, transmission, distribution, and energy storage technologies (Zhou et al., 2023). Various industrial energy harvesting methodologies and advanced power electronics interfaces such as AC-DC, DC-DC, and AC-AC power conversion, along with battery energy storage methods, are applied (Sun et al., 2021). Large-scale industries often have multi-energy systems to reduce total energy costs and stabilize energy consumption. Many of these industries utilize captive power plant units and hybrid energy sources. However, these methods are influenced by certain uncertain factors. In paper 13, enthalpies of inlet and steam extraction from a real ethylene plant were collected. The data was processed using kernel super vector clustering machine learning algorithms to group similar factors with specific relationships. The authors then mathematically derived methods for industrial total energy cost reduction through deterministic optimization and robust optimization techniques. However, it should be noted that industrial energy optimization does not always provide 100% accurate predictions due to unpredictable factors affecting energy sources (Saravanan & Albert, 2023; Shen et al., 2020). Figure 2 illustrates the industrial energy flow and its affecting factors. Overall, the aim of energy optimization is to improve efficiency and reduce costs in the industrial sector. By utilizing advanced technologies and optimization strategies, industries can better manage their energy consumption and contribute to a more sustainable future.

According to the observation of Figure 2, each stage of energy flow is influenced by various factors such as energy sources, effects of power electronics interface circuit elements, load variations, and battery management systems. To optimize energy, large-scale industries often integrate all energy units into a closed-loop system, which helps maintain overall system stability. This closed-loop system balances each stage of electrical energy transaction and computes required actions based on certain source factors, thereby reducing energy breakdown and related issues.In Paper 17, two different models of artificial intelligence systems were developed: ANFIS (Adaptive Neuro-Fuzzy Inference System) and ANN (Artificial Neural Network) models, specifically focusing on renewable energy sources. The paper demonstrates that the ANN model performs better in predicting renewable energy availability compared to the ANFIS model. The study collected data from three different renewable energy sources using various datasets. The data was processed and stored in a cloud server, and the machine learning-based ANN and

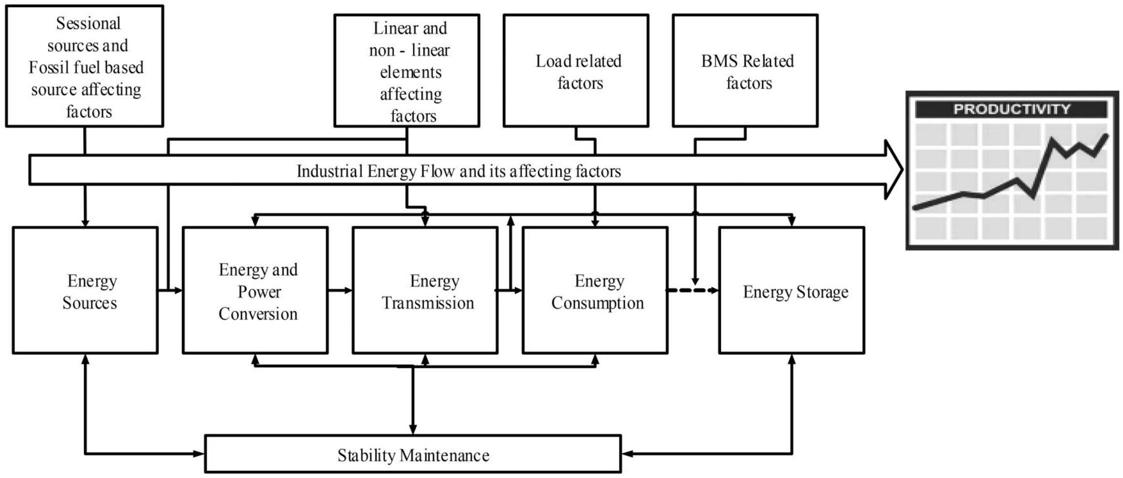

Figure 2. Optimizing industrial energy flow: exploring influencing factors and strategies for improvement.

ANFIS models were designed. These models provided two values: the root mean square error (RMSE) and the correlation coefficient (R2). The paper presents a total of four models using different combinations of datasets. Finally, the RMSE and R2 values of the four models based on ANN and ANFIS were compared. The observation suggests that the ANN-based machine learning model is more effective for predicting renewable energy-based electrical energy generation. The dataset used in the study includes generated voltage and current across each renewable power source, as well as time series data of energy generation and harvester dimensions (Ahamad et al., 2019). Overall, this research emphasizes the importance of utilizing artificial intelligence models, such as ANN, for predicting renewable energy availability and optimizing electrical energy generation from renewable sources. These models can contribute to more efficient and sustainable energy management in industrial systems. Paper 12 focuses on the energy optimization methods in the steel industry and explores the primary and secondary energy technologies employed in this sector. Primary energy technologies encompass power generation, heating, cooling, transportation, and storage, which are necessary for initiating the steel production process. On the other hand, secondary energy technologies involve recovering waste energy from steel production processes. The paper discusses the application of thermal generators and thermal photovoltaic systems for generating electrical energy from waste heat in steel industries. These technologies aim to optimize the utilization of waste heat energy (Punnachaiya et al., 2010; Wang et al., 2020). By implementing waste heat recovery systems and utilizing thermal generators and thermal photovoltaic systems, steel industries can improve energy efficiency and reduce their environmental impact. The research presented in Paper 12 provides insights and strategies for optimizing energy consumption and reducing waste heat in the steel production process.

The implementation of secondary energy technologies can effectively reduce the demand for primary energy sources (Wang et al., 2020). Among different countries, China has demonstrated the highest potential for achieving significant energy savings through the utilization of secondary energy technologies compared to countries like India, Europe, and Russia (Wang et al., 2020). Paper 7 introduces the concept of an Industrial Park-Integrated Energy System (IP-IES). This system integrates various energy sources such as coal, wind, and photovoltaic power within an industrial park. The objective of the IP-IES is to reduce the unit cost of power generation and optimize power generation based on the plant's capacity. The energy optimization process in this paper employs Particle-Swarm algorithms. It is important to note that Paper 7 primarily focuses on outdoor energy generation units, utilizing semi-renewable energy sources, and complemented by a backup unit powered by coal in a captive power plant. However, the use of coal-based power generation contributes to greenhouse gas emissions, leading to environmental concerns and energy stability challenges (Sun et al., 2021). Artificial intelligence and renewable power sources play crucial roles in achieving industrial energy optimization. Paper 11 explores the utilization of waste kinetic energy from transportation networks through the implementation of kinetic energy harvesters and regenerative braking units. The paper proposes three sub-areas for kinetic energy harvesting: road-side electro-kinetic energy harvesting, track-side kinetic energy harvesting, and vehicle-side energy harvesting. These measures aim to reduce energy demands in specific areas (Li et al., 2020). In the textile industry, combined heat and power generation, as well as combined cooling, heating, and power generation strategies, are commonly employed. Since most textile industry sub-units primarily require heat energy, co-generation and tri-generation methods are utilized for industrial energy harvesting (Manual on Energy Conservation in Textile Cluster. PDF, XXXX). However, our project focuses on a different aspect, specifically the optimization of kinetic energy production in weaving units for increased electro-kinetic energy extraction in industrial indoor environments.

2.2. Study about importance of electro-kinetic energy optimization from industrial units

Electro-kinetic energy extraction is a crucial aspect of industrial secondary energy saving technologies. Initially, the extraction of electro-kinetic energy was achieved outdoors through the use of wind plants or micro wind turbine units. However, it is important to note that wind energy-based electro-kinetic energy extraction may not be applicable in every geographical location. The effectiveness of wind energy conservation depends heavily on wind density, as shown in Figure 3, which depicts the variations in wind density per day under different weather conditions. Furthermore, wind energy harvesting requires a significant amount of agricultural land and can generate substantial noise during the energy generation process (Li et al., 2020).

MEMS-based electro-kinetic energy optimization processes, such as Piezo-array, linear, and non-linear systems, are indeed present in the field. However, these systems are mostly applied in outdoor industrial settings for secondary energy-saving purposes. In recent times, the aforementioned electro-kinetic energy extraction methods have also been utilized in low and medium power applications.The efficiency of electro-kinetic energy extraction is influenced by several factors, with the amount of kinetic energy being a key factor. The amount of kinetic energy available for extraction determines the overall effectiveness and efficiency of the system. Other factors that impact the efficiency include the nature of the material used in the system, the power electronics interface, and other design considerations.To optimize the efficiency of electro-kinetic energy extraction, it is important to maximize the amount of kinetic energy that can be harnessed. This can be achieved through various means such as increasing the movement or vibrations of the system, selecting materials with high energy conversion capabilities, and designing efficient power electronics interfaces to capture and convert the kinetic energy effectively.By focusing on optimizing the amount of kinetic energy and considering factors such as material selection and power electronics interface design, the efficiency of electro-kinetic energy extraction systems can be improved, resulting in more effective energy harvesting and utilization.

$$E\% = \frac{Pout}{Pin} \ X \ 100 \tag{1}$$

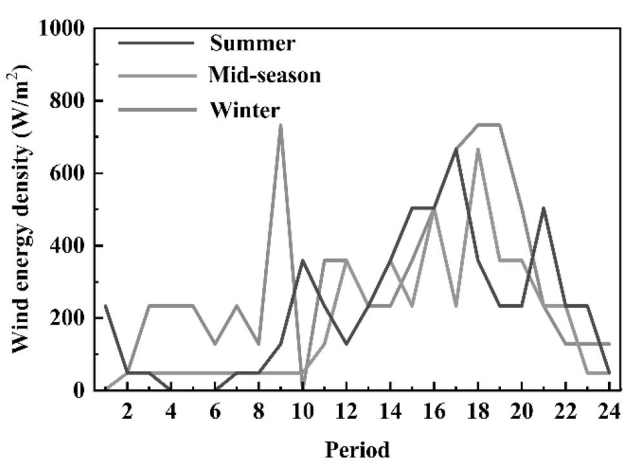

Figure 3. Per day wind density with different weather conditions.

Pout-is electrical output

$$Pout = Vp{*}Ip \tag{2}$$

Pin-is Mechanical input

$$Pout = F{*}v \tag{3}$$

Were,

Vp-Total Voltage generated from EKE Harvester output terminal

Ip-Output current of EKE Harvester output terminal

F-External mechanical force

v-Speed of moving object

Increasing the amount of mechanical force and speed applied to a moving object will result in maximum electro-kinetic energy generation from harvester units. Another factor that affects electro-kinetic energy is the nature of the material or structure used in power generation units.In our project, we are focusing on three kinetic energy optimization processes, and we have initiated the use of piezo-cell-based electro-kinetic energy extraction. Piezo cells are commonly used in wireless applications and smartwatches because they produce relatively low output voltages, ranging from a minimum of 0.7 V to a maximum of 3 V AC. The output voltage depends on the material composition of the piezo cell. Typically, piezo cells are made of LZT (Lead Zirconate Titanate) or PVDF (Polyvinylidene Fluoride). To achieve a higher amount of electro-kinetic energy extraction, piezo cells can be arranged in series and parallel connections, forming a piezo-array. However, commercially available piezo plates such as Pavegen (5 W), Drum Harvester (3 W), and BATio3 (7mW) can be expensive (Aabid et al., 2021; Safaei et al., 2019). Therefore, for our project, we have designed a piezo array manually. In this design, a series connection of piezo cells produces a good voltage, while a parallel connection generates a good current. However, the series connection has a poor current output, and the parallel connection has a poor voltage output. To overcome this limitation, we have implemented a series-parallel structure for our piezo array. The configuration of the series-parallel piezo array is illustrated in Figure 4 (Abidin et al., 2020),. This design ensures the production of proper output voltage and current for our project.

According to the literature cited in papers 6–16, the best way to increase electro-kinetic energy extraction is through a series-parallel configuration of piezo cells. This configuration allows for optimized power generation by effectively combining multiple piezo cells (Aabid et al., 2021; Abidin et al., 2020; Ahamad et al., 2019; Farrok et al., 2020; Li et al., 2020; Narciso & Martins, 2020; Nguyen & Hoang, 2020; Safaei et al., 2019; Shen et al., 2020; Sun et al., 2021;

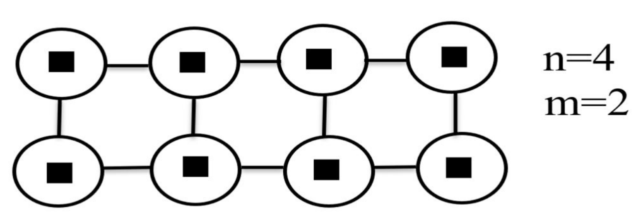

Figure 4. Piezo array series-parallel configuration.

Wang et al., 2020). In addition to the piezo array-based electro-kinetic energy extraction, another approach is the utilization of linear electro-kinetic energy extraction based on MEMS (Micro Electro-Mechanical Systems) technology. Linear kinetic energy extraction is considered superior to piezo array-based extraction because it follows an inverted model of electro-mechanical generation. In this method, the field movement is linear, as depicted in Figure 5 (Sun et al., 2021).

Paper 7 provides comprehensive details about linear generation from sea wave areas. It includes a typical power diagram of a linear generator-based kinetic energy extraction system, as depicted in Figure 6 (Farrok et al., 2020). This diagram illustrates the process of extracting electro-kinetic energy from sea waves using a linear generator. Additionally, the paper also discusses the utilization of piezoelectric-based and normal electro-mechanical generator-based methods for electro-kinetic energy extraction from wave energy sources (Farrok et al., 2020; Luo & Ye, 2016). These different approaches allow for the conversion of wave energy into usable electrical energy using piezoelectric materials or conventional electro-mechanical generator.

The final source in our project is non-linear power generation, which involves the utilization of flywheel energy storage technologies for electro-kinetic energy extraction. This method relies on flywheel systems to store and deliver energy based on the power demand. There are two cases in flywheel energy storage technologies. In the first case, when the power demand is low, the flywheel system stores energy in the form of mechanical energy. In the second case, when the power demand is high, the Flywheel Energy Storage System (FESS) delivers electrical energy to the same pipeline (Ahamad et al., 2019; Nguyen & Hoang, 2020). These configurations showcase various designs and setups of flywheel systems used for energy storage and delivery in non-linear power generation applications.

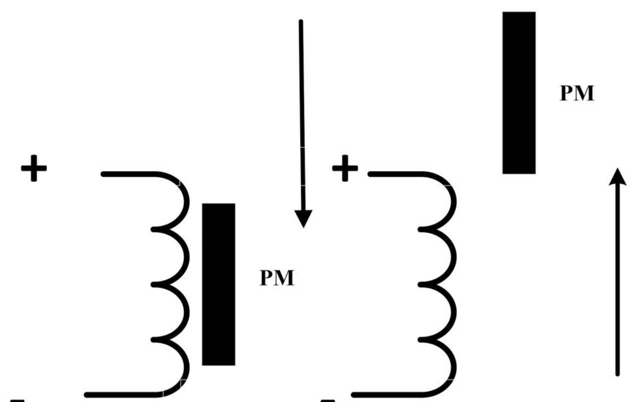

Figure 5. Representation of linear generation.

Typically, Singleton flywheel energy storage systems are employed for low and medium-level power applications. On the other hand, high-power applications require FESS with a higher amount of kinetic energy storage. In such cases, FESS with two-stage or multi-stage interconnections are utilized. This setup involves multiple stages of flywheel energy storage interconnected to meet the higher power demands and efficiently store and deliver the kinetic energy.

In Paper 15, the focus is on FESS-based electro-kinetic energy extraction from crane applications. The study proposes three modes of FESS operation. Mode one involves extracting energy from the external power grid, where the power is supplied solely by the FESS to the cranes. Mode two combines power from both the power grid and the FESS to provide power to the cranes during their upward movement. Mode three occurs when the crane moves from top to bottom, allowing the kinetic energy to be transferred to the FESS. In this mode, the power grid dependency is completely ignored, and the energy is solely fed into the FESS. In our project, we aim to utilize these three kinetic energy extraction strategies in various weaving applications. The goal is to enhance the extraction strength of kinetic energy in all levels of industrial units, thereby reducing the reliance on other semi-renewable power sources and fossil fuel-based power generation. Another significant factor in electro-kinetic energy extraction is electrical power conversion, which involves converting between AC and DC, as well as various power electronics interfaces such as AC-DC, DC-AC, AC-AC, and DC-DC. Advanced power electronics interfaces enable smooth handling of electrical power conversion in conjunction with the load or energy storage system.

2.3. Study about power electronics interfaces for electro kinetic energy extraction

Electro-kinetic energy extraction-based power electronics interfaces commonly employ two-level or multi-level power

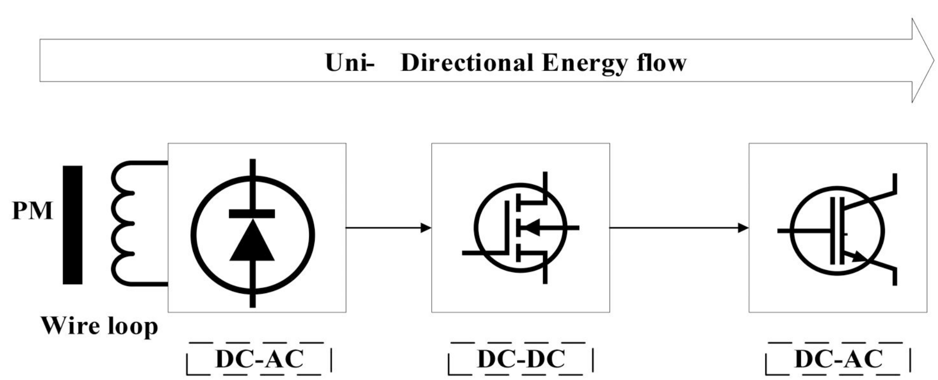

Figure 6. Linear generation based electro-kinetic energy extraction.

conversion techniques. As of the current state of technology, piezo electric-based electro-kinetic energy extraction systems typically use a two-level power conversion approach. In the first stage, the AC output from the piezo electric generator is converted to DC using a diode bridge rectifier or a resonant rectifier. Once the AC power is rectified to a constant DC power, it is then further converted to variable DC power for energy storage, as described in the literature. For effective power conversion, a piezo electric-based EKE system with a parallel or series synchronous switch is considered superior.

The synchronized switch on harvester inductor-based power electronics interface may not be suitable for variable loads. Therefore, for DC-DC power conversion, a second-level power conversion is required to convert constant voltage to variable voltage. Various DC-DC power converters have been explored in recent studies (Szarka et al., 2011). In papers 3, 5, and 6, different DC-DC converter topologies were analyzed for kinetic energy extraction, including boost converter, double stage boost converter, and flyback converter. Among these, the flyback converter was found to be better for second-level power conversion in literature 15. However, the flyback converter has a lower output voltage gain compared to the zeta and super lift Luo converters. The zeta converter provides good feedback stability, while the super lift Luo converter offers high voltage gain and low ripple content in the output voltage (Anung et al., 2023; Gurumoorthy & Balaraman, 2023; Luo & Ye, 2016; Szarka et al., 2011). On the other hand, the ultra lift Luo converter provides higher output voltage gain compared to the super lift Luo converter.In our project, for the first model based on piezo array kinetic energy extraction, the second-level power conversion will employ the super lift Luo converter (Beulin & Pradeep, 2018; Raghavendra et al., 2019). For the other kinetic energy extraction models, such as open wheel unidirectional nonlinear and linear power generation, the second-level energy conversion will integrate the ultra lift Luo converter (Beulin & Pradeep, 2018; Raghavendra et al., 2019). These choices were made because the second and third models are electromagnetic models and can extract more power from the input source. The piezo array model has a nonstable output voltage due to the non-continuous mechanical input, resulting in very low output power (Saravanan & Ramaswamy, 2022; 2023; 2023).

2.4. Machine learning importance in electro-kinetic energy extraction strategies

Machine-learning algorithms play a crucial role in electrical energy optimization. They are utilized for various tasks such as energy demand prediction, determining the amount of energy needed for industrial and commercial electric load demands, and battery management. In paper 17, a performance analysis was conducted using two machine learning algorithms on three different energy sources. The study concluded that artificial neural network (ANN) based machine learning algorithms provided accurate results. On the other hand, in paper 18, wind speed prediction for wind power generation was explored using different regression and classification algorithms along with wind speed and wind turbine data. Figure 7 provides a visual representation of machine learning's application in wind power generation.

In the mentioned paper, LASSO, MAE, SVR, RF, and Boost regression algorithms were applied for wind speed-based wind power generation. The results showed that the LASSO algorithm performed the worst, while the random forest (RF) algorithm yielded the highest R2 value of 0.99, making it more suitable for wind energy conservation even with data from locations where the model was not trained (Demolli et al., 2019). In paper 20, various machine learning and metaheuristic models were explored for PV-based energy generation. The study emphasized the importance of using optimized algorithms in machine learning to improve the accuracy of output predictions. Multiple PV-related datasets were used, considering different time periods (Akhter et al., 2019). Based on the comprehensive studies in papers 17 and 20, supervised machine learning models were found to be well-suited for energy stability prediction. In your project, it would be beneficial to assess the energy stability of the three electro-kinetic energy extraction models. This analysis will provide insights into the energy availability, integration of the electro-kinetic energy model with other renewable power sources and smart grid systems, as well as battery management processes.

3. Summary of survey

The Summary of background analysis given following Table 1.

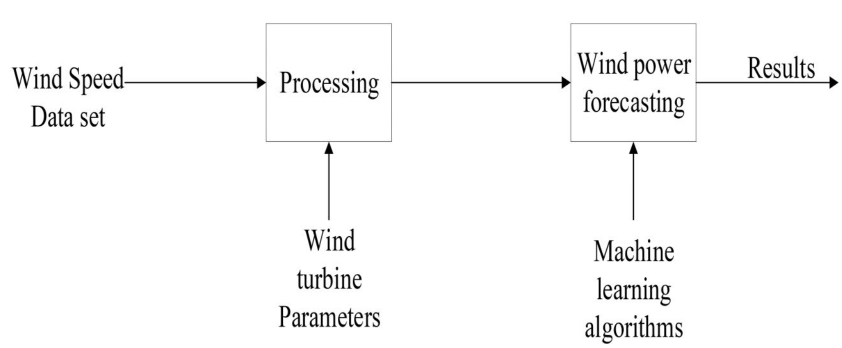

Figure 7. Machine learning based wind energy generation.

Table 1. Summary of background analysis.

Reference	Focus	Summary
Zhou et al. (2023), Zhang et al. (2023), Sun et al. (2021), Saravanan and Ramaswamy (2023), Saravanan and Albert (2023)	Industrial Energy Harvesting Topologies	Refers to capturing and harnessing ambient energy from various sources within the industrial environment. Topologies include solar energy harvesting, vibration-based energy harvesting, thermoelectric energy harvesting, and electromagnetic energy harvesting. Choice of method depends on specific industrial application and available ambient energy sources.
Zhou et al. (2023), Zhang et al. (2023), Sun et al. (2021), Saravanan and Ramaswamy (2023)	Optimizing Renewable Power Sources-based Power Generation	Integrating renewable power sources like solar, wind, and hydroelectric energy into the global energy transition. Advanced control strategies and smart grid technologies employed for optimization. AI algorithms, real-time weather forecasting, and demand prediction manage renewable power sources for matching energy supply with demand. Battery storage solutions ensure stable and reliable power supply.
Aabid et al. (2021), Nguyen and Hoang (2020), Farrok et al. (2020), Abidin et al., (2020), Li et al. (2020), Ahamad et al. (2019), Safaei et al. (2019), Sarker et al. (2019), Zeng and Khaligh (2012), Saravanan and Ramaswamy (2022), Saravanan and Ramaswamy (2023) Saravanan and Ramaswamy (2022), Saravanan and Albert (2023)	Importance of Electro-Kinetic Energy and its Impact on Strengthening Renewable Power Sources	Focuses on harnessing electrical energy from mechanical motion or vibrations. Electro-kinetic energy extraction enhances the strength and efficiency of renewable power sources. Offers a complementary solution to conventional energy harvesting methods. Researchers derived three different electro-kinetic energy extraction strategies for specific industrial settings and energy requirements.
Ramady et al. (2023), Al-Baidhani and Kazimierczuk (2023), Gurumoorthy and Balaraman (2023), Raghavendra et al. (2019), Beulin and Pradeep (2018), Luo and Ye (2016), Zeng and Khaligh (2012), Saravanan and Ramaswamy (2022), Saravanan and Ramaswamy (2023)	Power Conversion Models with Advanced DC-DC Power Conversion Strategies	Critical role in energy optimization and renewable energy systems. Advanced DC-DC power conversion strategies enable efficient energy transfer and management. Facilitates seamless power conversion between different voltage levels. Integrates with renewable energy sources, storage systems, and loads for higher energy efficiency and reduced losses.
Narciso and Martins (2020), Puri et al. (2019), Demolli et al. (2019), Akhter et al. (2019)	Machine Learning Strategies and their Vital Role in Energy Optimization	ML algorithms powerful tools for optimizing energy consumption and enhancing efficiency. Predictive maintenance, load forecasting, and energy consumption optimization. Hybrid ML models offer greater accuracy and flexibility in predicting energy demand and optimizing usage. Implementing ML strategies results in significant energy savings, reduced operational costs, and enhanced energy stability.
Punnachaiya et al. (2010), Manual on Energy Conservation in Textile Cluster. PDF, Saravanan and Albert (2023)	Existing Industrial Energy Harvesting Methods and their Limitations (Specific to Textile Industry)	**In the context of the textile industry's electrical energy needs, pollution is a significant concern due to reliance on conventional energy sources like coal, oil, or natural gas. These sources emit pollutants and greenhouse gases during combustion, contributing to air pollution and climate change. Additionally, the production and transportation of electricity further exacerbate environmental impacts.** **While renewable energy sources offer cleaner alternatives, they come with limitations. Solar energy production can be inconsistent due to weather conditions, and wind energy generation depends on variable wind patterns. Hydroelectric power is constrained by geographical limitations and environmental concerns related to dam construction. Integrating renewable energy into textile manufacturing requires substantial upfront investments and may pose challenges for industries operating on tight budgets or in regions with limited access to renewable resources.** **Despite these limitations, exploring alternative energy sources and implementing energy-efficient technologies is crucial for reducing environmental impact. Strategies like electro-kinetic energy extraction can help mitigate pollution and promote sustainability in the textile industry.**

As per Table 1 observation electro-kinetic energy optimization theoretical frame work model given below flow chart Figure 8.

The theoretical framework model consists of four sub-units. The first sub-unit focuses on the measurement and calculation of kinetic energy sources generated from weaving applications. This area will provide detailed information about the weaving unit operations and how mechanical and kinetic energy are wasted during the thread interlacing process. The second sub-unit involves the design of the electro-kinetic energy extraction model and its integration with the kinetic energy sources from weaving applications. This section will outline the specific design details and configurations of the electro-kinetic energy extraction system. The third sub-unit deals with power electronics interfaces. It will explore how the captured electro-kinetic energy is converted from variable DC to DC using the super lift Luo converter. This converter plays a crucial role in efficiently converting and managing the energy harvested from the weaving applications. The final sub-unit focuses on energy estimation. It will provide information about the output voltage, current, and power approximation of the electro-kinetic energy models. This estimation is important for understanding the performance of the system and will guide further design considerations such as power conversion, energy storage models, and grid integration strategies. By considering these four sub-units, the theoretical framework provides a comprehensive understanding of the measurement, extraction, conversion, and estimation aspects of electro-kinetic energy in weaving applications.

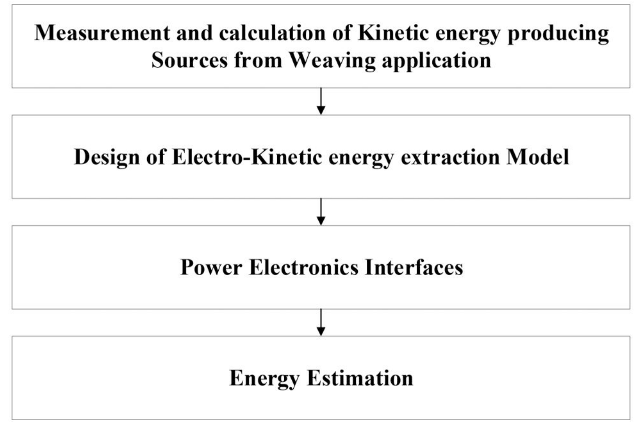

Figure 8. Theoretical frame work of electro-kinetic energy optimization.

4. Theoreitical frame work

4.1. Measurement and calculation of kinetic energy producing sources from weaving applications

In the weaving application, power looms and hand looms are commonly used for the thread interlacing process. Power looms have become increasingly important in weaving due to their higher productivity compared to hand looms. A small-scale weaving unit typically requires up to 6 units of electrical energy to operate the weaving process. Currently, this electrical energy is mostly extracted from external power grids or industrial captive power units. However, both methods have certain technical and non-technical barriers.To optimize industrial energy usage, engineers suggest the implementation of hybrid renewable power sources for industrial energy generation. However, the dependency on hybrid power sources introduces new challenges, and industrial power demand still relies on external power grid sources. The unit cost of electrical energy from the external power grid is higher, and there are additional losses during transmission and distribution.In this project, the focus is on enhancing the indoor electro-kinetic energy extraction in industrial settings to reduce the reliance on captive power units and external power grids. Power loom weaving processes consist of various kinetic energy producing parts, such as horizontal and vertical open-loop mechanisms, uni-directional open wheel mechanical energy transfer systems, and bi-directional yarn filling processes. The power loom architecture varies based on clothing design and business requirements, resulting in different mechanisms for producing kinetic energy in different power loom types.The general principle of a power loom can be categorized into two types: bottom closed loop design printing units and top closed loop design printing units. The power loom based on a top closed loop design printing unit is known as a Jacquard machine and is commonly used for silk saree weaving processes. On the other hand, the power loom based on a bottom closed loop design printing unit is called an auto loom, which is used for weaving plain cloths.For a visual representation of the different types of power looms, refer to Figure 9 and Figure 10.

The weaving process of power loom is show in Figure 11.

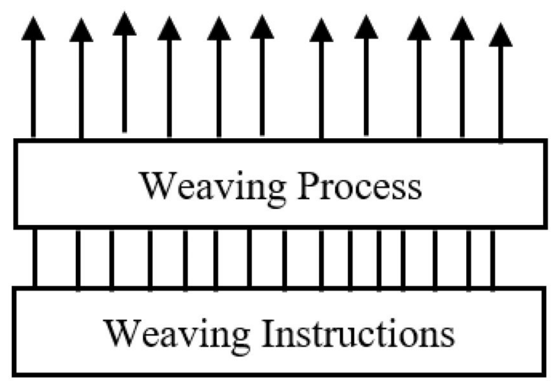

Figure 9. Bottom closed loop power loom architecture.

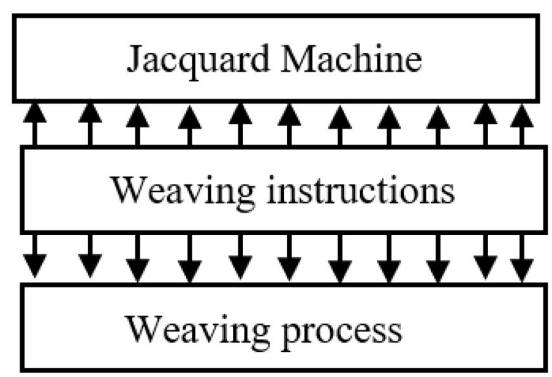

Figure 10. Top closed loop power loom architecture.

In the weaving process, horizontal and vertical yarns are interlaced to create fabric. The main parts involved in the weaving process include the warp beam, filling carrier, and cloth roll. The overall weaving process is powered by single-phase or three-phase electric drives.Initially, the electric break switch is turned on, which activates the power contactor to supply power to the electric drives. The electric drives then convert electrical energy into mechanical energy, which is transferred to a lengthy open wheel unidirectional pipeline. This open wheel pipeline is connected to the yarn interlacing mechanism, as shown in Figure 12. The mechanical energy is transferred to various units of the power loom, including the front wheeling power loom (cloth roll), back-end warp beam, top Jacquard machine, and movable X-Y read. The movable read moves horizontally back and

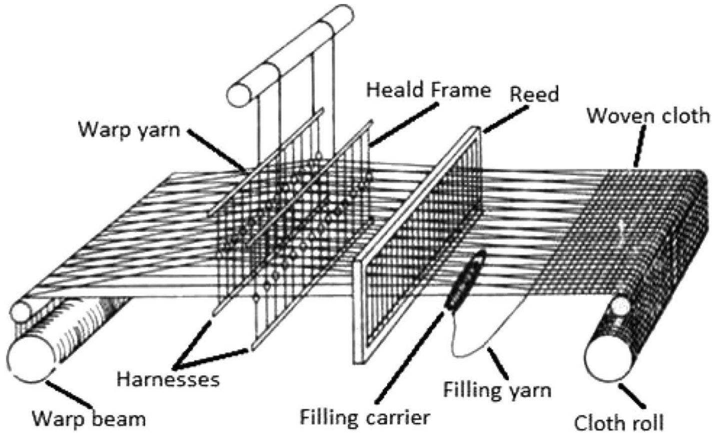

Figure 11. Typical diagram of weaving process.

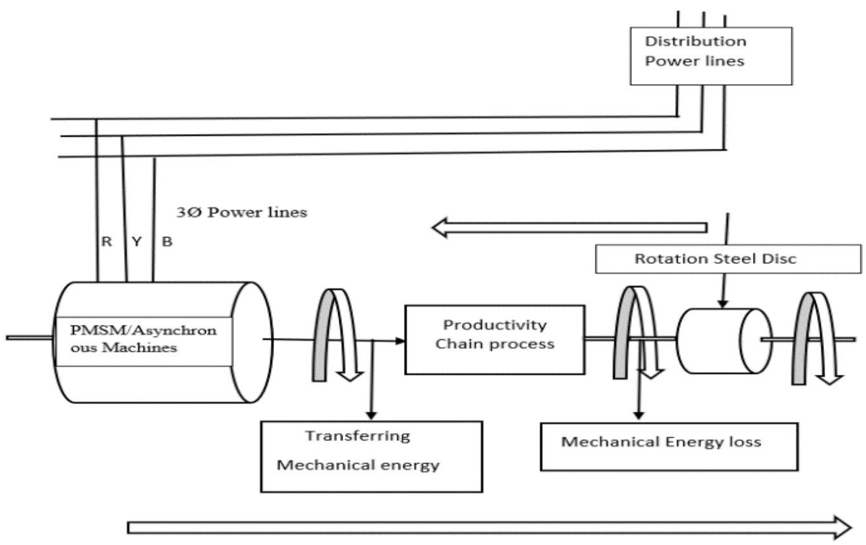

Figure 12. Energy transaction model of weaving process.

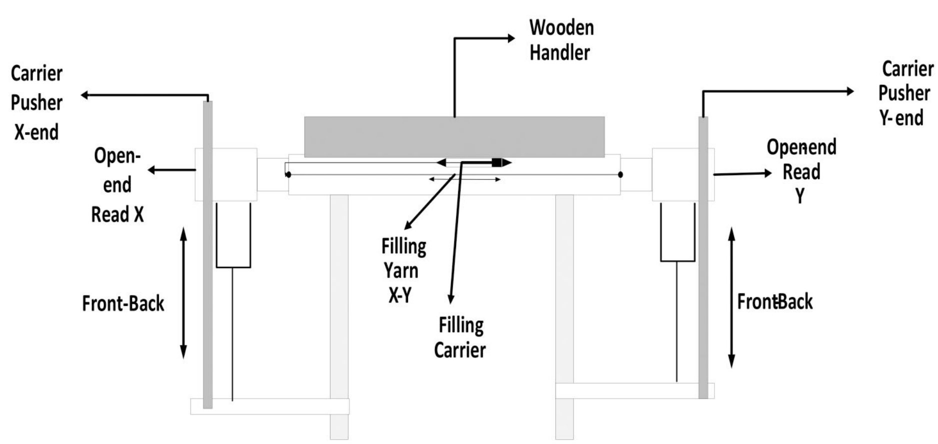

Figure 13. Movable X-Y open-end read with shuttle model.

forth, and the X-Y read facilitates the bi-directional yarn filling process. Figure 12 illustrates the energy transaction model of the weaving application, depicting the mechanical energy transfer in the weaving process (Energy Transaction Model of Weaving Process).

In the Jacquard-based power loom design printing process, the power loom is a top-closed design. However, the kinetic energy for the process is obtained from the Movable X-Y open-end read, as shown in Figure 13. The Movable X-Y End read supports the bi-directional yarn filing process. The Movable X-Y Open-End Read is constructed using a combination of wood and steel materials. The mass of a single open-end read is approximately 70 kg, and it operates at a speed of 0.3 N.

In the Movable Open-End Read subunit, the bi-directional yarn filing process is facilitated by the Carrier Pusher and Yarn Filing Carrier. The Carrier Pusher operates in a clock swing model, where one end of the carrier pusher moves while the other end is equipped with a vacuum system, as depicted in Figure 14. This arrangement allows the open-end carrier pusher to generate a specific amount of kinetic energy.A single power loom typically consists of two open-end reads, resulting in a bi-directional carrier pusher system in the weaving process. Table 2 provides an overview of the number of kinetic energy-producing utilities in the top closed-loop power loom design.

In the bottom closed loop power loom design, the kinetic energy is obtained from the Open-End Head Frame. This component is responsible for supporting the bi-directional yarn filing process. The Open-End Head Frame is constructed using a combination of aluminum and wooden plates. Typically, there are three aluminum plates incorporated into the open-end head frame configuration, as depicted in Figure 15.

The Open-End Head Frame in the bottom closed loop power loom design moves vertically, resulting in a specific amount of kinetic energy being generated. The weight of a single wooden pillar is 1 kg, and its speed is 0.3 N.

4.2. Design of electro-kinetic energy extraction models

The electro-kinetic energy extraction models in this project are classified into three types: matrix type based on piezo plates, open-wheel unidirectional non-linear energy extraction, and linear energy extraction. The selection of the electro-kinetic energy model for the power loom is based on the size of the kinetic energy producer and the force of the moving object.In the case of the bottom closed loop power loom with an open-head frame, approximately 9 piezo plates are required for a single open-end head frame. Each piezo plate contains 8 piezo discs (4×2). A single piezo cell can produce 3 V AC, resulting in a total voltage of 24 V for the 4×2 piezo plate configuration. However, the actual voltage output may vary depending on the configuration and the amount of kinetic energy involved.The wooden pillar in the power loom weighs approximately 1 kg, and its speed is 0.3 N. This translates to an output voltage of approximately 5.6 V or 8 V, with an output current of less than 1 Amp. Due to the parallel or series connection of the piezo discs, the current obtained is in the microampere range, with a series-parallel connection yielding approximately 0.1 mA.The matrix-type piezo array is applied to the open-head frame and the yarn filing X-Y open-end read. The open-end X-Y read has a larger area compared to the wooden pillar, and it is made of steel, resulting in a higher mass. A single open-end read weighs 50 kg, and its speed is 0.3 N. The integration of piezo plates with the open-head frame and the open-end X-Y read is depicted in Figures 16 and 17.

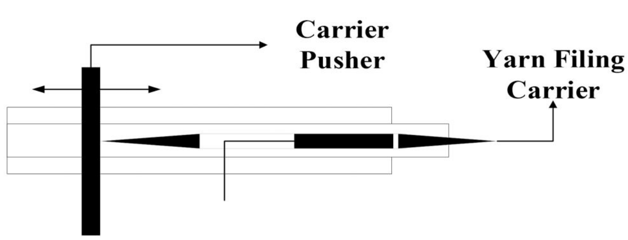

Figure 14. Yarn filing carrier pusher model.

The second model of electro-kinetic energy extraction is the open-wheel uni-directional non-linear power extraction. In most power looms, electric drives are used to operate the entire weaving process. These drives can be three-phase squirrel cage induction motors or single-phase capacitance motors. The electric drive shaft is connected to a lengthy open-wheel pipeline, with the productivity chain process unit integrated in between.At the end of the open-wheel pipeline, there is a rotational steel disc. This disc does not play a direct role in the weaving process but is used when the power loom design printing unit is not functioning correctly. Weavers manually rotate the steel disc to observe any errors in the design and make corrections. This process requires step-by-step electrical input to the drives, which is achieved using an electric brake switch.The open-wheel uni-directional non-linear power extraction model is similar to

Table 2. Kinetic energy producing utilities from bottom and top closed loop power loom.

Power loom types	Applicable sub categories	Kinetic energy producing source	Electro-kinetic energy extraction model
Top Closed Loop Power loom	Normal Loom, Under-Pick, Drop Box, Pick and Pick	Movable X-Y Open-end read Bi-Directional Yarn filing Carrier Pusher Open- wheel pipe line	Piezo Electric plates integration Linear Generation Uni-directional Non-linear energy extraction
Bottom Closed Loop Power loom Types	Auto Loom Auto Loom, Rapier loom	Open-end Head frame Open- wheel pipe line	Multi array piezo plates integration Uni-directional Non-linear energy extraction

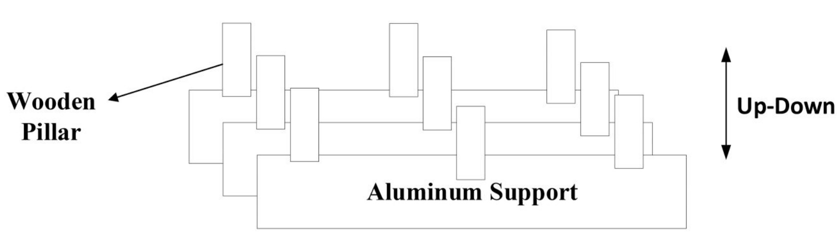

Figure 15. Open-end head frame model.

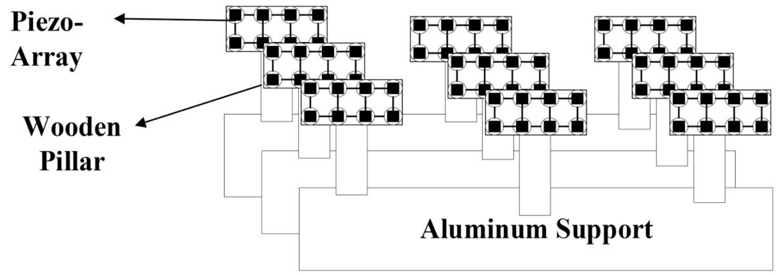

Figure 16. Piezo array integration with open head frame.

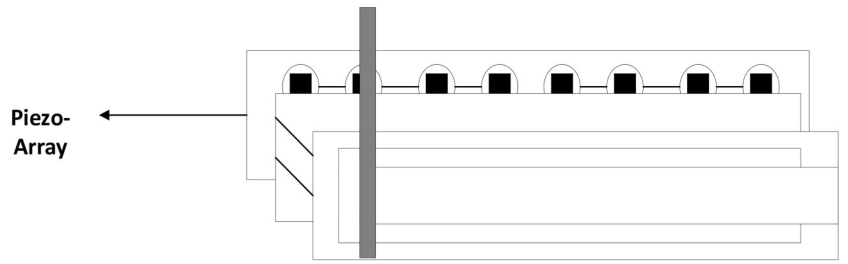

Figure 17. Piezo array integration with open end X-Y read.

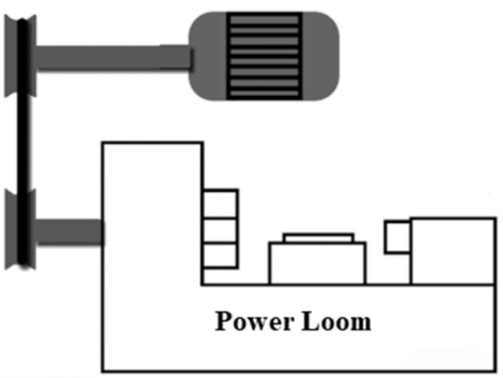

Figure 18. Single electric drives with single power loom.

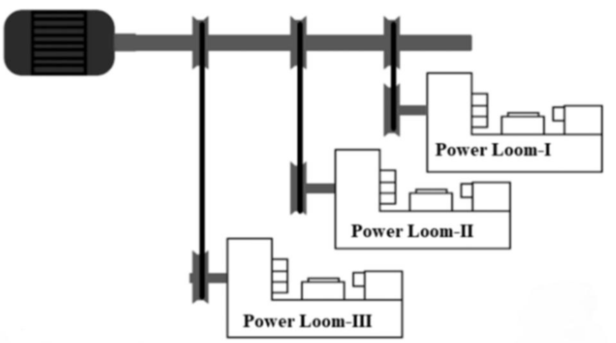

Figure 19. Single electric drives with multiple power looms.

flywheel energy storage technologies, but it involves uni-directional mechanical energy transfer. The open-wheel lengthy pipeline is designed for uni-directional mechanical energy transfer, resulting in uni-directional electrical energy extraction. At the end of the lengthy pipeline, an AC or DC generator is installed. The size of the generator should be smaller than the power loom electric drives to ensure that the electric drives do not draw excessive voltage from the input supply. The theoretical output voltage of the generator is typically taken as 12 V DC or 12 V AC, but it may vary depending on the electric drives used and how they are connected to the power loom. In small-scale power loom industries, only one electric drive is connected to one power loom. In medium or large-scale industries, a single electric drive can be connected to multiple power loom shafts. These configurations are illustrated in Figures 18 and 19.

The open-wheel uni-directional non-linear power extraction model can be applied to both bottom and top closed loop power loom types. Figure 20 illustrates the integration of the open-wheel uni-directional non-linear energy extraction model with the power loom weaving process. This model allows for the extraction of mechanical energy from the power loom's open-wheel pipeline and converts it into electrical energy using a generator. The mechanical energy transaction model demonstrates how the open-wheel uni-directional non-linear power extraction contributes to the overall energy optimization of the power loom.

The final electro-kinetic energy extraction model is the linear power generation model. Unlike the open-wheel uni-directional non-linear power extraction, the linear power generation model follows the principle of linear motion, where the field moves linearly while the current-carrying coil remains static. This model is specifically applicable to top closed loop power loom types.In the linear power generation model, the output is typically taken as 3 V AC theoretically. It integrates with various components of the power loom, such as the bi-directional yarn filing carrier pusher, open-end X-Y read, and open-end head frame. Figure 21 illustrates the integration of the linear power generation model with the yarn filing carrier pusher in the power loom setup. By incorporating the linear power generation model, the power loom can harness additional electrical energy from the linear motion components, contributing to the overall energy optimization and efficiency of the weaving process show in Figures 22 and 23.

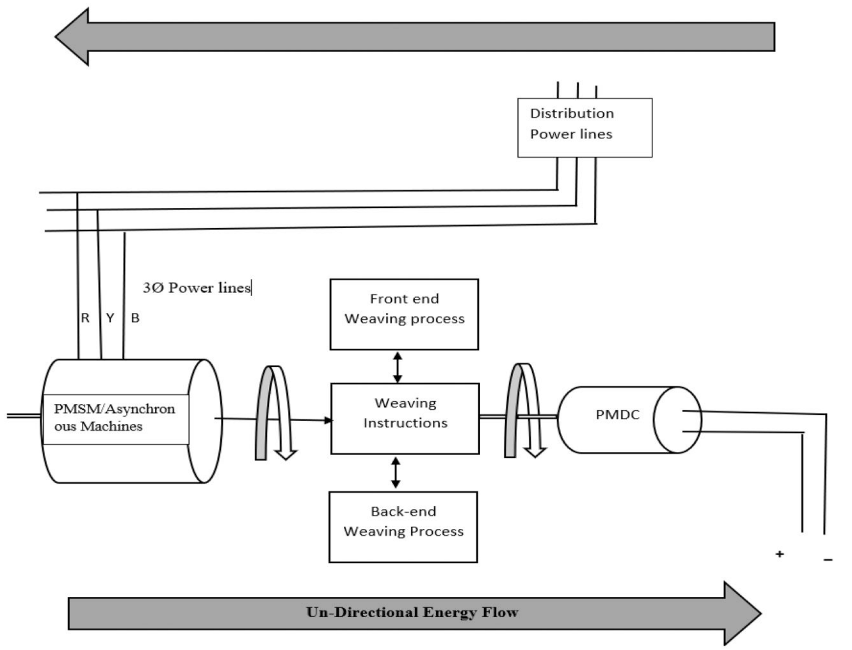

Figure 20. Open wheel uni-directional non-linear energy extraction with power loom weaving process.

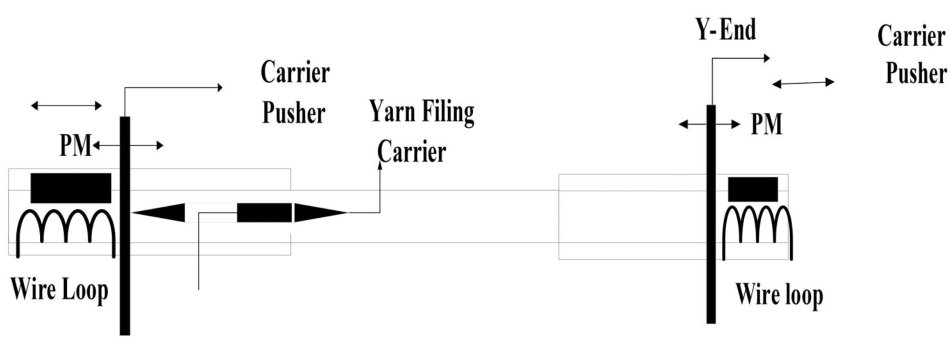

Figure 21. Bi-Directional linear power generation with yarn filing carrier pusher.

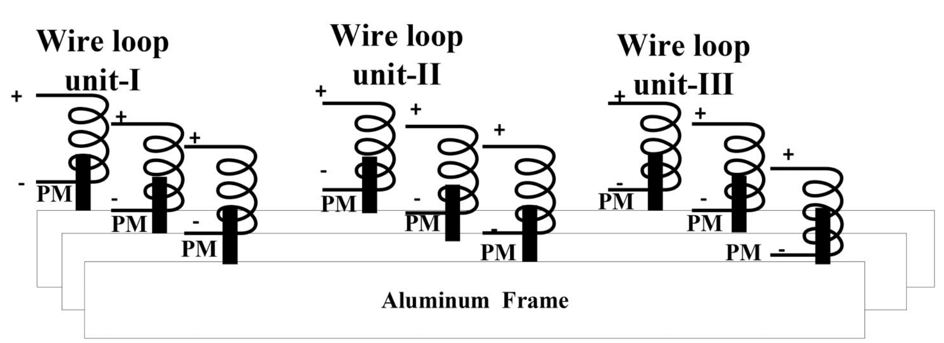

Figure 22. Linear power generation with open end head frame.

4.3. Power electronics interfaces

In this project, three electro-kinetic energy extraction models are present, and each model requires a dedicated power electronics interface design. Let's discuss the power electronics interface for the piezo array as an example.The output voltage of the piezo array is AC, so the first step is to forward the AC voltage to an energy storing capacitor. The capacitor then supplies the voltage to a half-wave rectifier, which converts the AC voltage to DC voltage. However, since the output current of the piezo array is poor, directly applying the DC voltage to the load or second-level power conversion would not yield sufficient power. Therefore, the DC voltage is stored in a battery unit.To enable the second-level power conversion, a Super lift Luo converter is used. This converter converts the constant DC voltage from the battery unit to variable DC voltage. In mode one, when the power switch turns on, the inductor and capacitor charge diode 1 forward bias, while diode 2 is in reverse bias. Capacitor 2 is closed with the load. In mode two, when the switch turns off, the inductor current flows to Capacitor 1,

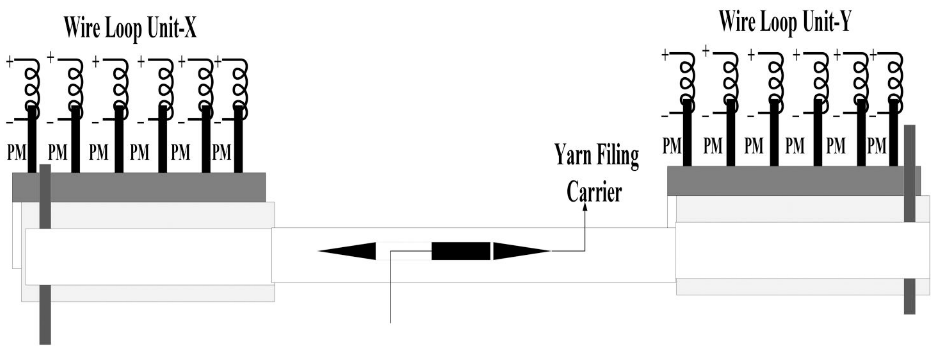

Figure 23. Linear power generation with open end X-Y read.

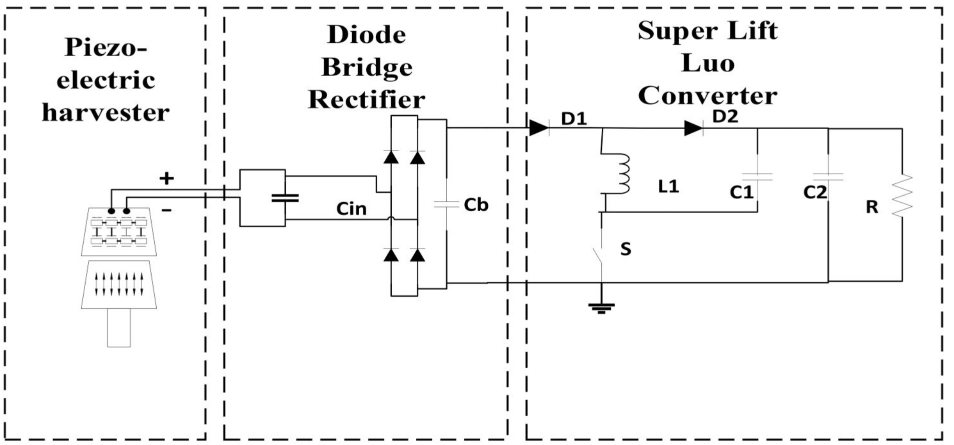

Figure 24. Power electronics interface integrated with (4X2 piezo array) single wooden pilar.

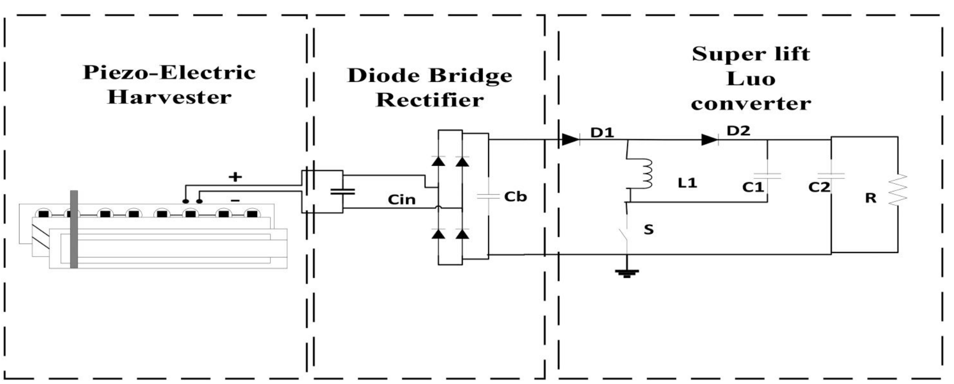

Figure 25. Power electronics interface integrated with (2X[4X2 piezo array]) X-open end read.

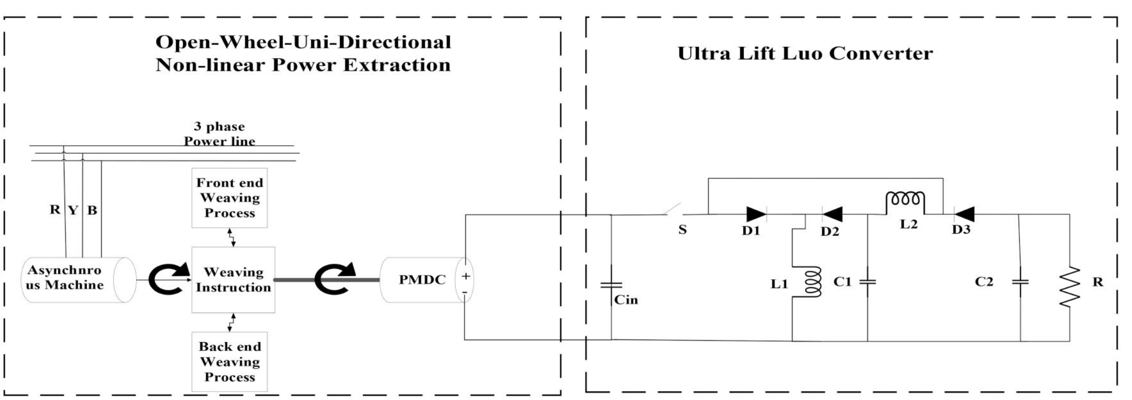

Figure 26. Power electronics interface integrated with open wheel -unidirectional non-linear power generation.

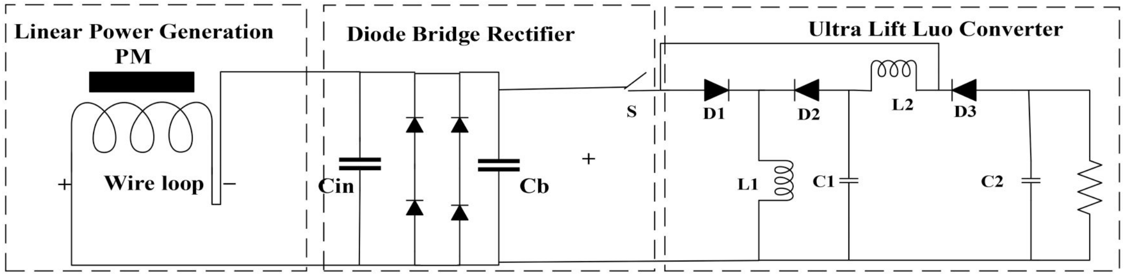

Figure 27. Power electronics interface integrated with linear power generation.

Table 3. Electrical output parameters calculation for electro-kinetic energy extraction models.

Electro-kinetic energy (EKE) models	Approximate electrical out put parameters values
Single 4 × 2 Piezo Array	$V = 20$ V AC $I = 0.08$ A AC P = 1.6W $E = 1.6 \times 3600$ $E = 5760$ Watts-hrs
Single Open wheel Uni-directional Non-Linear Power Extraction Model	$V = 12$ V DC $I = 1.5$ A DC $p = 18$ W E = 18 × 3600 $E = 64800$ Watts-hrs
Single Linear Power Extraction Model	$V = 3$ V AC $I = 0.011$ A AC $p = 12$ W E = 0.033 × 3600 $E = 118.8$ Watts-hrs

Table 4. Energy estimation of top and bottom closed loop power looms.

Appliable EKE models	Quantity of EKE presence	Energy estimation
Top Closed Loop Based Power Loom		
Open end X-Y Read (Piezo Array Integration)	Single Open end Read Integrated 2 4 × 2 Piezo Array Totally two Reads so total Quantity of EKE is 4	E = 4 × 5760 $E = 23040$ Watts-hrs
Open End -Unidirectional Non-linear Power Extraction	Only One Pipe line end So Quantity of EKE is	E = 1 × 64800 $E = 64800$ Watts-hrs
Bi-Directional Yarn Filing process (Linear Power Extraction Integration)	Two Carrier Pusher so Quantity of EKE is 2	E = 2 × 118.8 $E = 237.6$ Watts-hrs
Instead of Piezo array Open end X-Y read with Linear Power Extraction Model (Linear Power Extraction Integration)	Single end Read will integrate 6 EKE Model Totally Two Read Present so Quantity of EKE 12	E = 12 × 43200 $E = 1425.6$ Watts-hrs
Bottom Closed Loop Based Power Loom		
Open Head Frame (Piezo Array Integration)	Single Aluminum Frame Contain 3 Wooden Pilar, Totally 3 Frame Contain, so EKE Model Quantity is 9	E = 9 × 5760 $E = 51840$ Watts-hrs
Open End -Unidirectional Non-linear Power Extraction	Only One Pipe line end So Quantity of EKE is	E = 1 × 64800 $E = 64800$ Watts-hrs
Instead of Piezo array Open end Head Frame with Linear Power Extraction Model (Linear Power Extraction Integration)	Single Aluminum Frame Contain 3 Wooden Pilar, Totally 3 Frame Contain, so EKE Model Quantity is 9	E = 9 × 118.8 $E = 1069.2$ Watts-hrs

charging capacitor 2. The circuit is closed with Inductor 1 and capacitor 1 with the load.Figure 24 illustrates the integration of the power electronics interface with a (4 × 2 Piezo array) single wooden pillar, and Figure 25 shows the integration with a (2X(4 × 2 Piezo array)) X-open end read. Similar integration applies to the open-end Y-read as well.These power electronics interfaces play a crucial role in efficiently converting and managing the electrical energy harvested from the electro-kinetic energy extraction models, ensuring proper power delivery to the load or synchronization with the power grid.

In the case of the piezo array model, the output power is relatively low due to the non-stable power output resulting from the push-pull flow of the input kinetic energy. To efficiently convert this low-power output, a second-level power conversion is employed using a super lift Luo converter. The super lift Luo converter is specifically designed to handle low-power inputs and provides stable voltage output. The output of the super lift Luo converter can then be used for various applications or further power conditioning.On the other hand, for the open-wheel unidirectional non-linear energy extraction model, which directly integrates an electric generator, a different power electronics interface is used. In this case, an ultra lift Luo converter is employed. The ultra lift Luo converter is suitable for higher power applications and can efficiently handle the output from the electric generator. Since the output of the PMDC generator is already in pure DC form, there is no need for a diode bridge rectifier in the interface.Figure 26 illustrates the integration of the power electronics interface with the open-wheel unidirectional non-linear power extraction model. In mode one, the power switch is turned on, and diodes 2 and 3 are in reverse bias. Inductor 1 and 2, as well as Capacitor 1, will charge, and the load is closed with Capacitor 2. In mode 2, diode 1 is in reverse bias, and inductor 1 and 2, along with Capacitor 1, discharge while Capacitor 2 charges and the load is closed with the power supply.Similarly, for the linear power generation model, the AC power generated is converted to constant DC power, and the constant DC power is then forwarded to the second-level power conversion. In this case, an ultra lift Luo converter is again utilized for efficient power conversion.Figure 27 demonstrates the integration of the power electronics interface with the linear power extraction model.These power electronics interfaces, employing the super lift Luo converter and ultra lift Luo converter, play a vital role in effectively converting and managing the electrical energy output from the respective electro-kinetic energy extraction models, ensuring stable and suitable power for further utilization.

The Voltage gain of super lift Luo converter and ultra lift Luo converter show in Eqs. (1–2).

Voltage gain of Super lift Luo converter

$$\frac{Vo}{Vin} = \frac{(2-K)}{(1-K)} \tag{1}$$

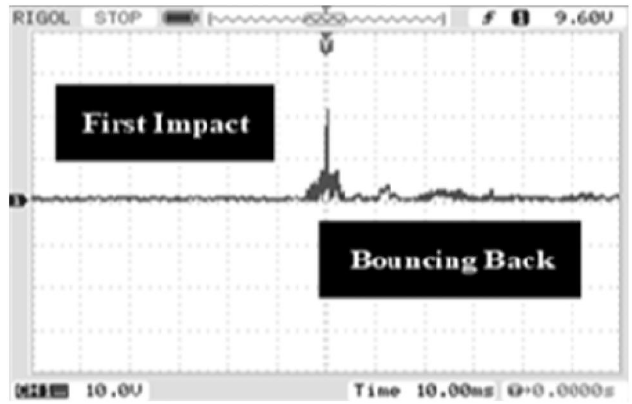

Figure 30. Output voltage due to single wooden pilar force.

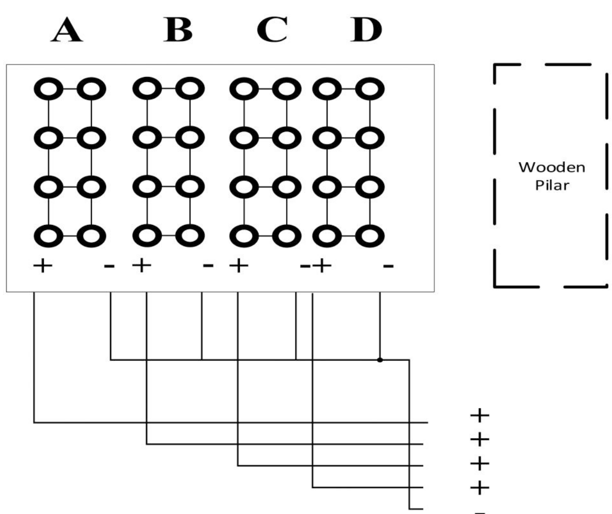

Figure 28. T-model matrix piezo array model for open end head frame.

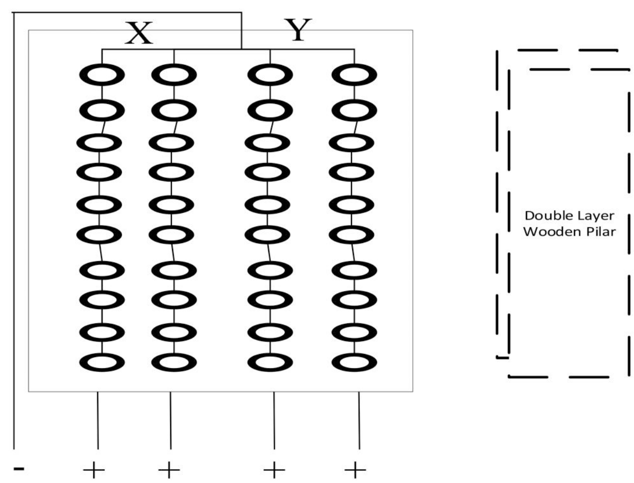

Figure 31. Rectangular matrix piezo array model for open-end X-Y read.

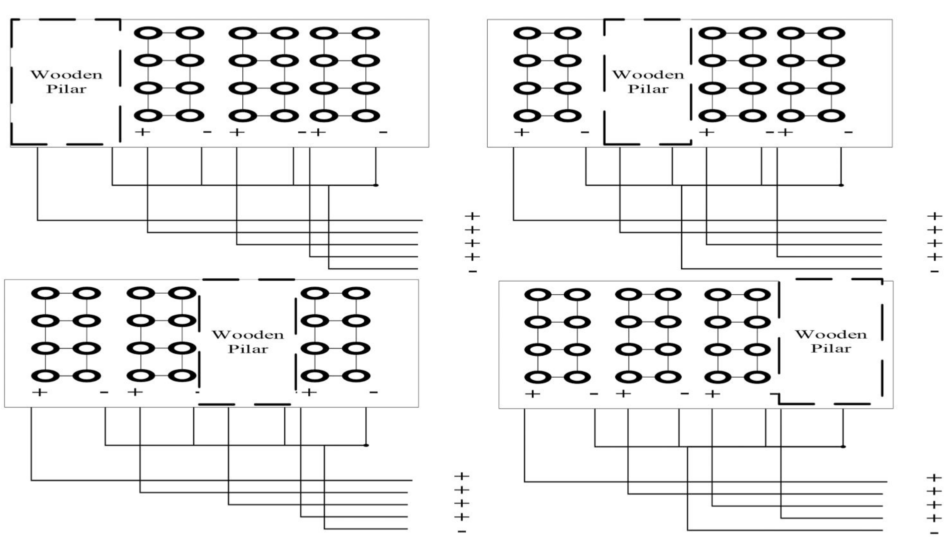

Figure 29. Testing notations of T- model matrix piezo array foe open-end head frame.

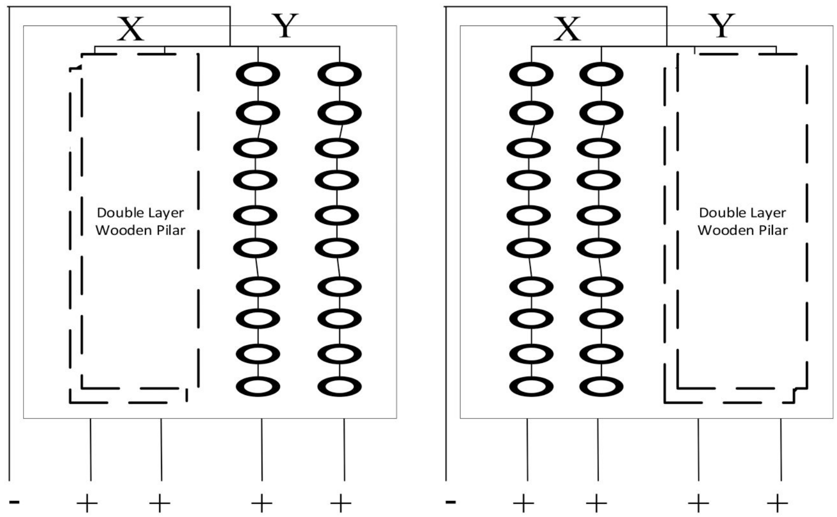

Figure 32. Open-end X-Y read based electro-kinetic energy extraction testing frame.

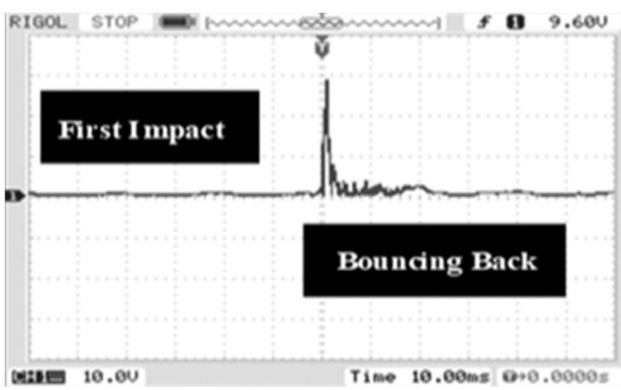

Figure 33. Output voltage due to double layer wooden pilar force.

Voltage gain of Ultra lift Luo converter

$$\frac{Vo}{Vin} = \frac{K(2-K)}{(1-K)2} \tag{2}$$

4.4. Energy estimation

Energy estimation in power loom applications depends on factors such as the running time of the loom and the specific electro-kinetic energy extraction model employed. Small-scale weaving industries typically run for 12 h, while medium and large-scale industries operate on a 24/7 shift basis.For top closed power looms, two electro-kinetic energy extraction models are considered: the matrix piezo array model integrated with the open-end read and the open-wheel uni-directional non-linear power extraction model. In the matrix piezo array model, the open-end read is integrated with $2(4 \times 2)$ piezo arrays, and the read moves continuously at a speed of 0.3 N. The open-wheel uni-directional non-linear power extraction model replaces the rotational steel disc at the end of the open-wheel pipe with a PMDC generator.For bottom closed power looms, the applicable models are the open-end head frame integrated with the piezo array model or the PM-based linear power extraction model. The open-end head frame may also be integrated with the open-wheel uni-directional non-linear power extraction model.The electrical output parameters and energy estimation calculations for these electro-kinetic energy extraction models can be found in Tables 3 and 4 of your reference material. These tables provide power equations and outline the outputs of each model for energy estimation in weaving applications.

5. Experimental source details analysis

The experimental setup comprises three sub-models, each meticulously designed with unique configurations and power electronics interfaces to harness kinetic energy efficiently. These sub-models are equipped with a Matrix Piezo Array, a versatile energy extraction unit known for its ability to convert mechanical vibrations into electrical energy. In addition to the Matrix Piezo Array, the setup includes common components like the Open-wheel uni-directional non-linear power generation unit and PM-based Linear generation, making it a comprehensive and adaptable system.For the Matrix Piezo Array models, two different setups are employed: an open-end head frame and an open-end X-Y read. The Open-end Head frame is constructed using a combination of Aluminum support and Wooden pillars, forming a sturdy structure to support the energy extraction process. The unique feature of this setup lies in the continuous up-and-down movement of the Wooden pillars during the thread interlacing process, which generates periodic force on the Matrix Piezo Array. Each open-end head frame integrates a T-Model Matrix Piezo Array (4×2), and the presence of nine wooden pillars optimizes the energy extraction efficiency (Figure 28). To test the T-Model Matrix Piezo Array's performance, a single wooden pillar applies force at multiple positions on the Matrix array (Figure 29). These tests involve careful measurements of electrical parameters using a Digital Oscilloscope. The output voltage generated by the Matrix Piezo Array due to the force applied by a single wooden pillar is recorded and displayed in Figure 30. This data aids researchers in analyzing the energy output characteristics and optimizing the energy

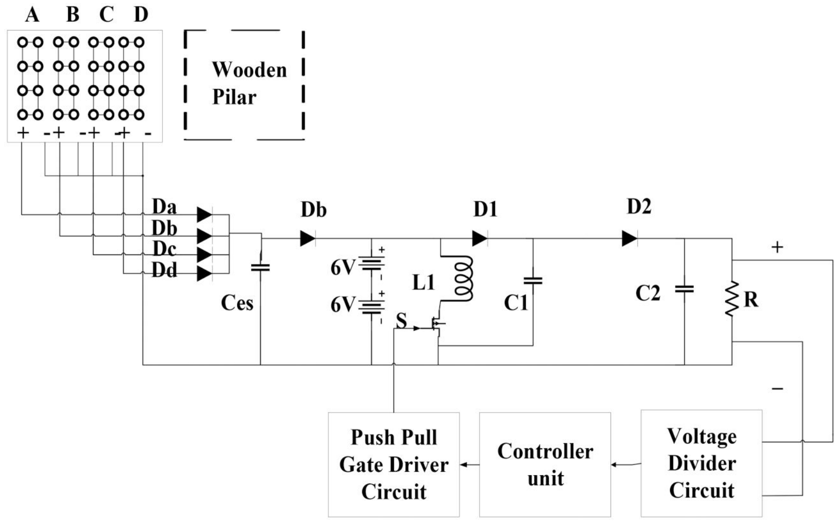

Figure 34. Open-end head frame based electro-kinetic energy extraction with second level DC-DC power conversion.

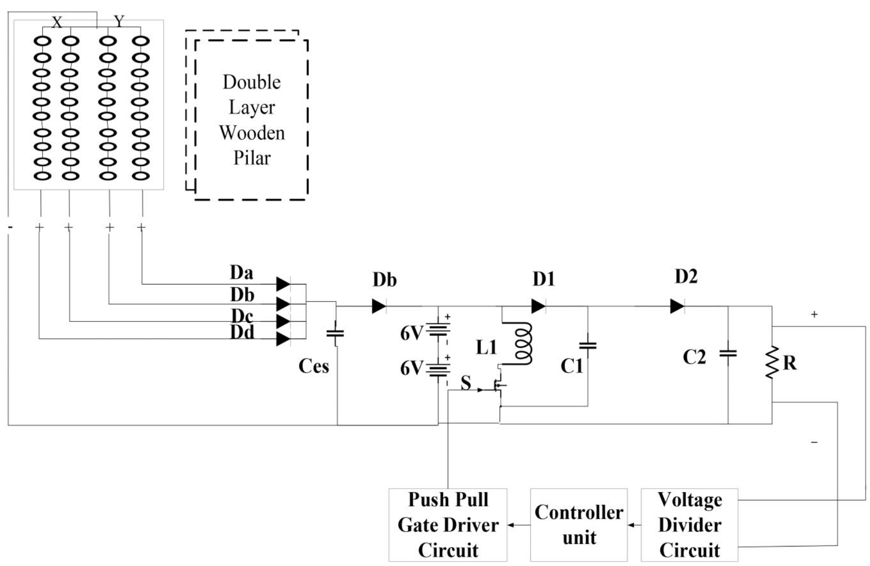

Figure 35. Open-end X-Y read based electro-kinetic energy extraction with second level DC-DC power conversion.

extraction process.The second sub-model, Open-end X-Y Reads, employs a different construction using Steel and Wooden plates, contributing to its relatively heavy mass. The setup is equipped with 24 mm piezo cells arranged in a 10×2 configuration on an area of 90 cm within the Read (Figure 31). The Matrix Piezo Array in this setup captures the force generated by double-layer Wooden pillars during the energy extraction process. This design enhances the energy harvesting capability of the Open-end X-Y Read.Testing the Open-end X-Y Read-based Electro-kinetic energy extraction involves subjecting it to the force from double-layer Wooden pillars (Figure 32). The resulting output voltage, measured and displayed in Figure 33, gives insights into the efficiency of energy extraction and helps optimize the Read's design for maximum energy output.Both the Open-end Head Frame and Open-end X-Y Read electro-kinetic energy extraction models are integrated with a second-level DC-DC power conversion to manage the harvested energy effectively. The Super Lift Luo converter is the key component used for this purpose (Figures 34 and 35). This converter efficiently steps up the voltage output from the Matrix Piezo Array to a suitable level for further power processing and energy storage. It operates based on principles of inductance and switching, ensuring optimal energy transfer and utilization.The heart of the energy extraction process lies in the push-pull operation of each wooden pillar on the Matrix piezo plates, generating an average power output ranging from 0.21 to 0.27 watts. This extracted energy is directed to an Energy Storing Capacitor, where it is accumulated. Once the capacitor reaches its full charge capacity, the excess energy is discharged and stored in the Battery, enabling continuous and reliable energy supply for various applications.Figure 36 illustrates the voltage across the Battery. Monitoring this voltage level is crucial to ensure the efficient charging and discharging of the Battery, determining its energy storage capacity and readiness for use.Figure 37 shows the Pulse-Width Modulation (PWM) pulse for the MOSFET, a power switch. The PWM signal governs the switch's on and off times, regulating the energy transfer between the Energy

Figure 36. Voltage across battery during open-end X-Y read and head frame.

Figure 37. PWM signal for super lift luo converter power switch.

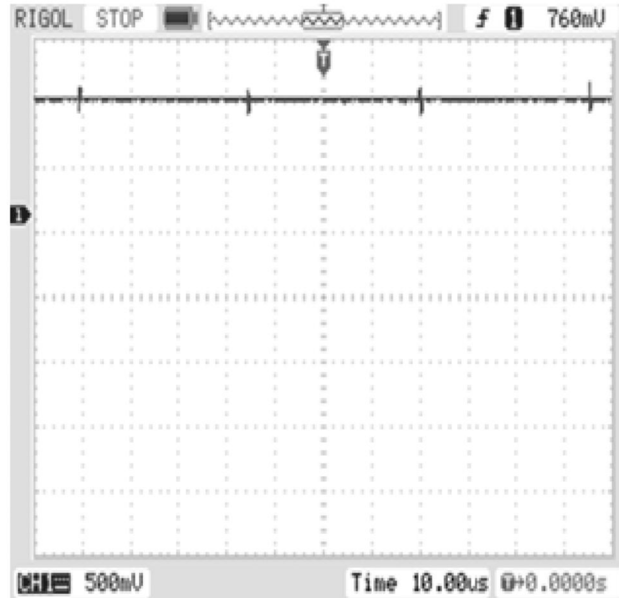

Figure 38. Output voltage of super lift luo converter.

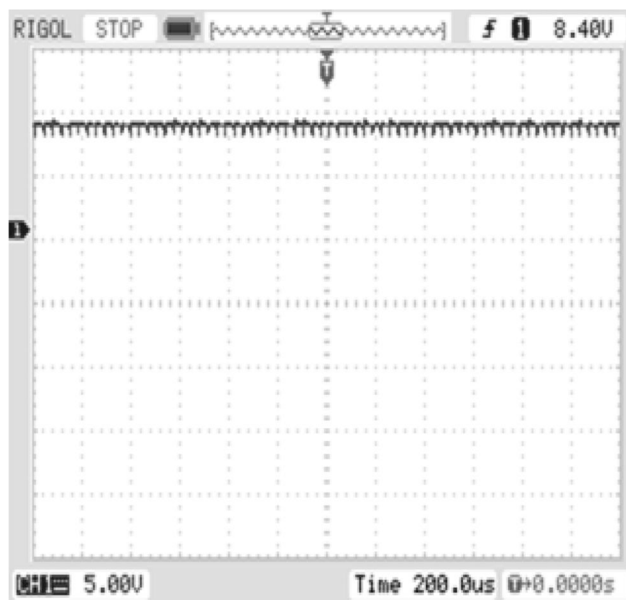

Figure 39. Output current of super lift luo converter.

Storing Capacitor and the Battery during the discharge process. This controlled energy transfer optimizes energy conversion and minimizes losses. Figure 38 depicts the output voltage of the Super Lift Luo converter. This voltage level plays a significant role in evaluating the converter's efficiency and its impact on the overall energy extraction process.Lastly, Figure 39 provides details about the output current of the Super Lift Luo converter. Understanding the converter's output current characteristics helps optimize its design and operation for enhanced energy utilization.

The experimental setup for Uni/Bi-Directional Linear generation involves testing wire loops with Permanent magnets shows Figure 40, and this generation method is applicable only to linearly moving objects. The Bottom closed loop-based power loom is equipped with an open-end Head frame featuring Wooden pillar zig-zag movements, while the Top closed loop power loom incorporates an Open-end X-Y Read with front and back moments, as well as a yarn filing process. To facilitate the generation process, an X-Y carrier pusher is utilized, which generates Bi-directional linear moments. On the other hand, the non-linear generation is applicable to both top and bottom closed loop-based power looms, The Open end wheel uni-directional non-linear power extraction applicable both types of power looms shows Figure 41. Figures 40 and 41 depict the power generation characteristics from these power looms. Figure 42 displays the voltage waveform during the PM Push and Pull for linear power extraction, with an average output voltage of approximately 2.8 V AC. In contrast, Figure 43 illustrates the voltage output achieved during the non-linear power extraction process, which yields an approximate voltage of 11.6 V DC. For both linear and non-linear electro-kinetic energy extraction

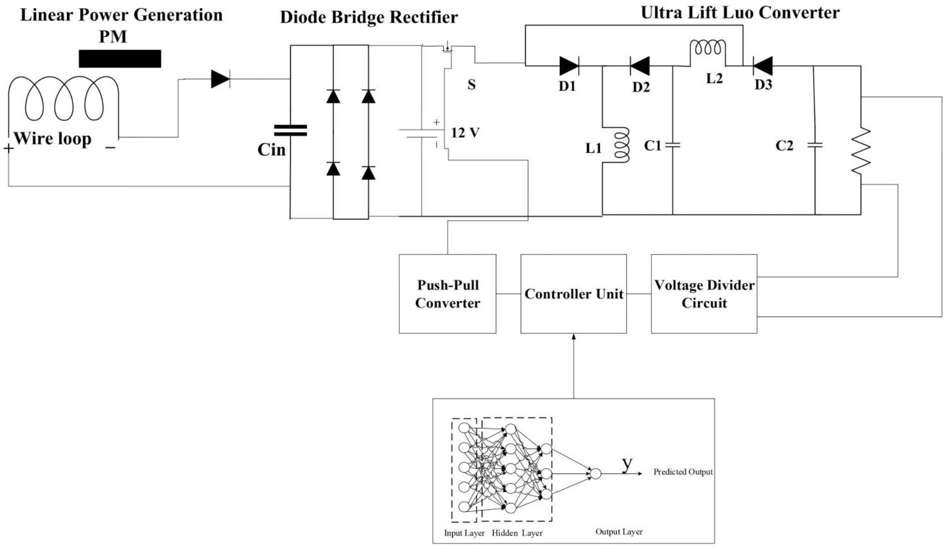

Figure 40. Uni/bi-directional linear power extraction.

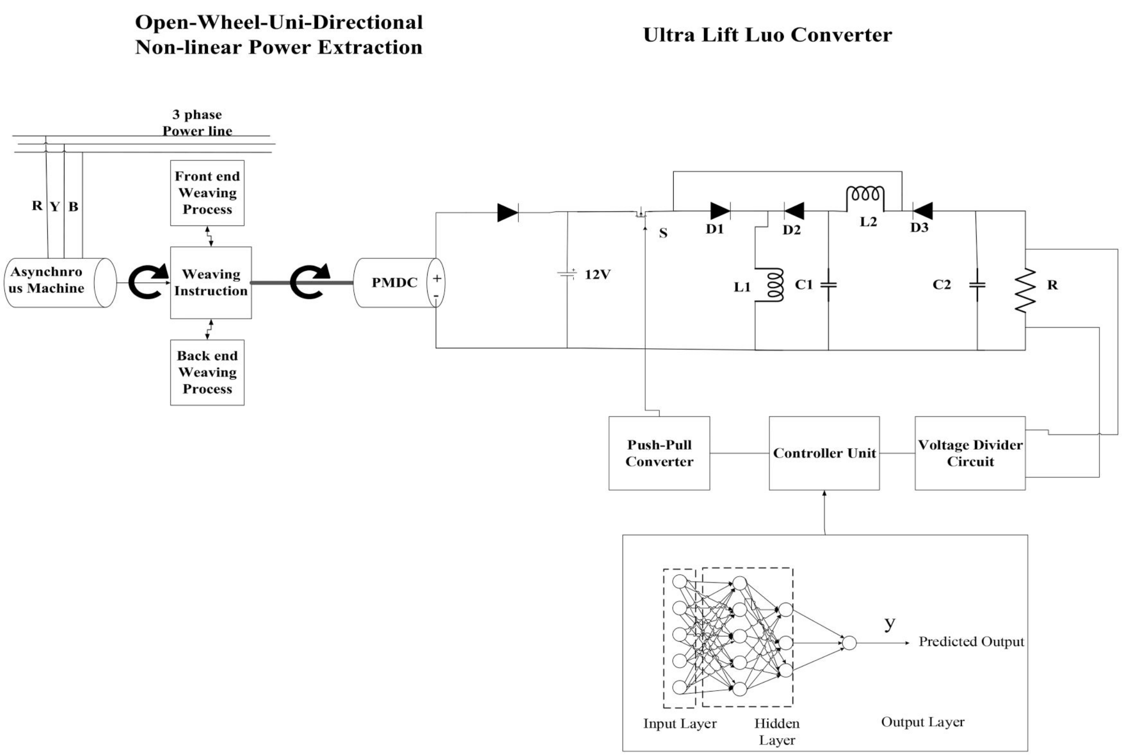

Figure 41. Open end wheel uni-directional non-linear power extraction.

models, a second-level power conversion is implemented using the Ultra Lift Luo converter. The output voltage of the Ultra Lift Luo converter is shown in Figure 44, while Figure 45 displays the corresponding output current. The Ultra Lift Luo converter's controller unit employs Feedforward Artificial Neural Network algorithms to optimize the output voltage. Finally, Figure 46 provides insights into the Pulse-Width Modulation (PWM) signal for the power MOSFET, which is crucial for regulating the energy transfer between the Energy Storing Capacitor and the Battery during the discharge process. This controlled and optimized energy transfer process helps maximize energy conversion efficiency and minimize losses during power conversion.

The Experimental Design details of Open-end head frame, Open end X-Y read, Linear generation and Non-linear electro-kinetic energy extraction details given following tables, Tables 5 and 6 shows Second level power conversion of each electro-kinetic energy extraction, Figure 47 shows Experimental setup of Electro-kinetic energy extraction.

6. Energy estimation by using ML algorthims

The energy estimation of various electro-kinetic energy extraction models, namely Open-end Head Frame, Open-end X-Y Read, Uni/Bi-Directional Linear Generation, and Open-end

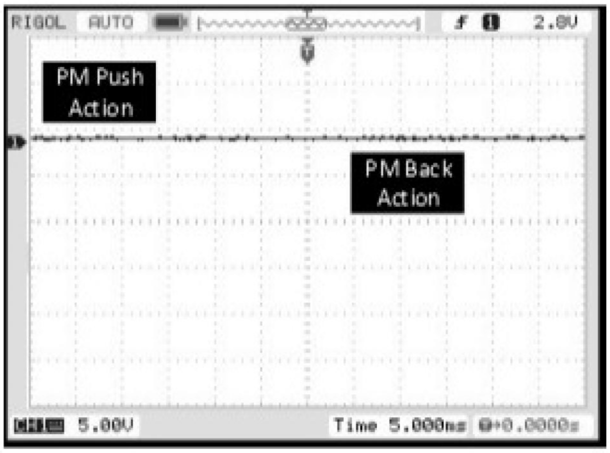

Figure 42. Uni/bi-directional linear power extraction model output voltage voltage.

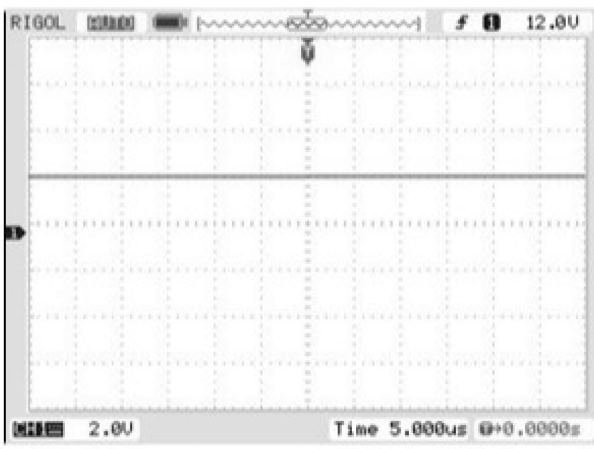

Figure 43. Open end uni-directional non-linear power extraction output voltage.

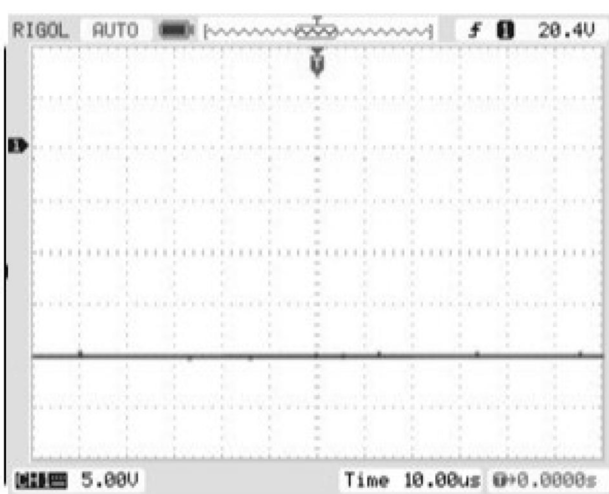

Figure 44. Output voltage of ultra lift luo converter.

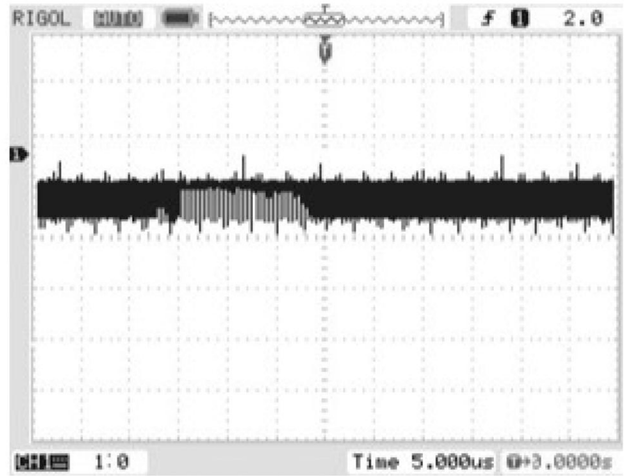

Figure 45. Output current of ultra lift luo converter.

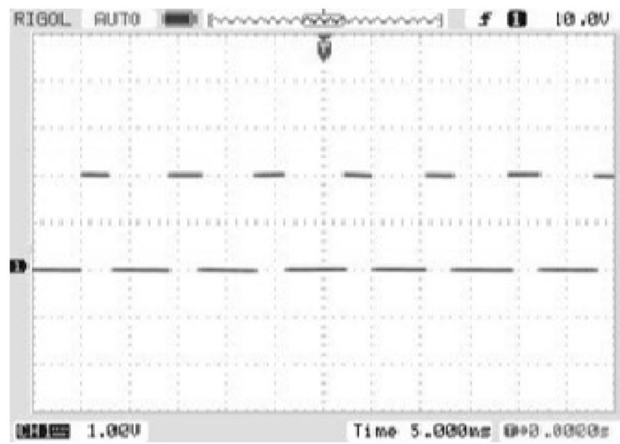

Figure 46. PWM pulse for ultra lift luo converter power switch.

Wheel Uni-Directional Non-linear Power Extraction, was conducted based on captured output power observations. Data sets were meticulously prepared for each model, and a diverse set of regression machine learning algorithms, including linear regression models, regression trees, support vector machines, Gaussian Process Regression models, and Neural Network models, were applied to the datasets. To assess the performance of each model, the Root Mean Square Error (RMSE) was utilized, enabling the selection of the most appropriate predictive model. These predictive models provide valuable approximations of the expected energy generation behavior of the experimental energy sources, whether they exhibit linear or non-linear characteristics. Table 7 summarizes the electro-kinetic energy predictive models, while Figure 48 showcases the Open-end Head Frame Based Electro-Kinetic Energy Prediction model. In Figure 49, the Open-end X-Y Read Based Electro-Kinetic Energy Predictive model is presented, and Figure 50 depicts the Uni/Bi-Directional Linear Generation Energy Predictive model. Lastly, Figure 51 illustrates the Open-end Wheel Uni-Directional Non-linear Energy Predictive model. Based on thorough testing and analysis, the energy estimations derived from each energy predictive model are effectively presented in Table 8. This comprehensive evaluation, leveraging a variety of machine learning algorithms, provides crucial insights into the expected energy output of different electro-kinetic energy extraction systems. These predictive models contribute to a deeper understanding of energy generation behavior and hold great potential for practical applications and further research.

Table 5. Experimental design details of electro kinetic energy extraction sources.

Particulars	Open end head frame model	Open end X-Y read model	Uni/bi-directional linear generation	Open end wheel uni-directional non-linear power extraction
Energy Extraction Tool	4X(4 × 2) Matrix Piezo	2(10 × 2) Matrix Piezo	PM with Winding loop	Micro PMDC gen
Force Model	Single layer T wooden Pilar	Double layer Rectangular wooden Pilar	Push-Pull Actions	Rotational Actions
Bi-Directional Utilization	Not-Applicable	Not-Applicable	Applicable	Applicable
Raw Kinetic Energy level	Non-Continuous	Non-Continuous	Non-Continuous	Continuous
Average Output Voltage	21 V	28V	2.8 V	11.6 V
Average Output Current	0.011 A	0.011 A	0.01 A	1 A
Average Output Power of Single model	0.231	0.308	0.0308	11 .6 V
Second level power Conversion	Super lift Luo converter	Super lift Luo converter	Ultra lift Luo Converter	Ultra lift Luo Converter

Table 6. Second level power conversion source details.

Particulars	Super lift luo converter		Ultra lift luo converter	
Integrated Models	Open end Head Frame, Open end X-Y Read		Uni/Bi Directional Linear Generation, Open end wheel Pipeline Non-Linear Power Extraction	
	Theoretical	Practical	Theoretical	Practical
Input Voltage Vin	12V	12V	12V	12V
Expected Voltage Vo	100V	100 V	−200V	−200V
Inductor	L1 = 6.5 mH	L1 = 14.5 mH	L1 = 1 H,L2 = 100mH	L1 = 80mH,L2 = 80mH
Capacitor	C1 = 1495μF	C1 = 2200μF	C1 = 0.667 μF,C2 = 6.67 μF	C1 = C2 = 33 μF
Resistive Load	100 ohms	100 ohms	150 ohms	150 ohms
Duty Cycle	0.65	0.5	0.94	0.5
Switching Frequency	20000Hz	20000Hz	20000Hz	20000Hz
Controller	PIC Micro Controller		PIC Micro Controller	
Optimization Algorithms	Not applied		ANN Feedforward Algorithms Trained and Applied	

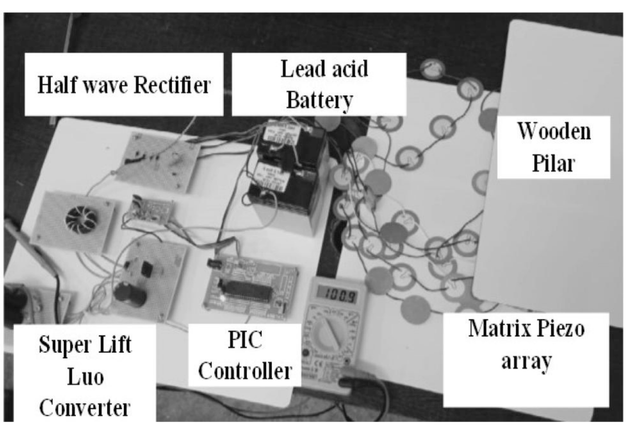

Figure 47. Experimental setup of electro-kinetic energy extraction.

The following charts (Figures 52–56) provide a comprehensive overview of our research, showcasing theoretical, experimental, and machine learning-based results. These charts also assess the feasibility of an electrokinetic energy-based weaving machine running efficiently without external power sources.

7. Future scope and summary of reserach

The electro-kinetic energy-based power loom sector holds immense potential for the future of sustainable energy utilization in the textile industry, as shown in Figure 57. With continuous advancements in energy conversion technology, the sector is expected to witness higher energy conversion efficiencies from various electro-kinetic devices, thereby generating more power from the same input. Integration of artificial intelligence (AI) and automation will optimize energy usage by predicting demand and adjusting consumption and generation in real-time, minimizing wastage. Furthermore, advancements in energy storage solutions, such as battery technology and supercapacitors, will ensure reliable energy supply and effective management systems, enhancing the sector's stability and scalability. As novel electro-kinetic devices emerge, tailored for power loom applications, the efficiency, scalability, and adaptability of the technology will improve further. The sector's growth will be reinforced by the integration with green energy grids, enabling power looms to contribute excess energy and promote circular economies. Support from governments and regulatory bodies, in the form of economic incentives and favourable policies, will accelerate the adoption of electro-kinetic energy-based power looms and bolster the industry's market penetration. With a strong focus on sustainability, these power looms will align with consumer values, positioning textile manufacturers as environmentally-conscious businesses. As the world undergoes a global energy transition towards renewable sources, the electro-kinetic energy-based power loom sector will play a pivotal role in reducing the textile industry's carbon footprint and advancing sustainability goals. Collaborations between various stakeholders will drive innovation, resulting in groundbreaking solutions to energy challenges. In conclusion, the future of the electro-

Table 7. Summary of electro-kinetic energy extraction predictive models.

Energy predictive model	Regression machine learning category	Sub-division of ML algorithms	RMSE	MAE	Test result
Open Head Frame based Energy Model	Gaussian Process Regression	Mateen 5/2	0.0037	0.0030	0.21
Open end X-Y Read based Energy Predictive Model	Gaussian Process Regression	Rational Quadratic	0.0031	0.0023	0.25
Uni/Bi-Directional Linear Generation based Energy Predictive model	Linear Regression	Linear, Interactions Linear, Stepwise Linear	0.0035	0.0029	0.0319
Open end wheel Uni-Directional Non-Linear Power Extraction based energy Predictive model	Super Vector Machine	Cubic SVM	0.039	0.034	11.6

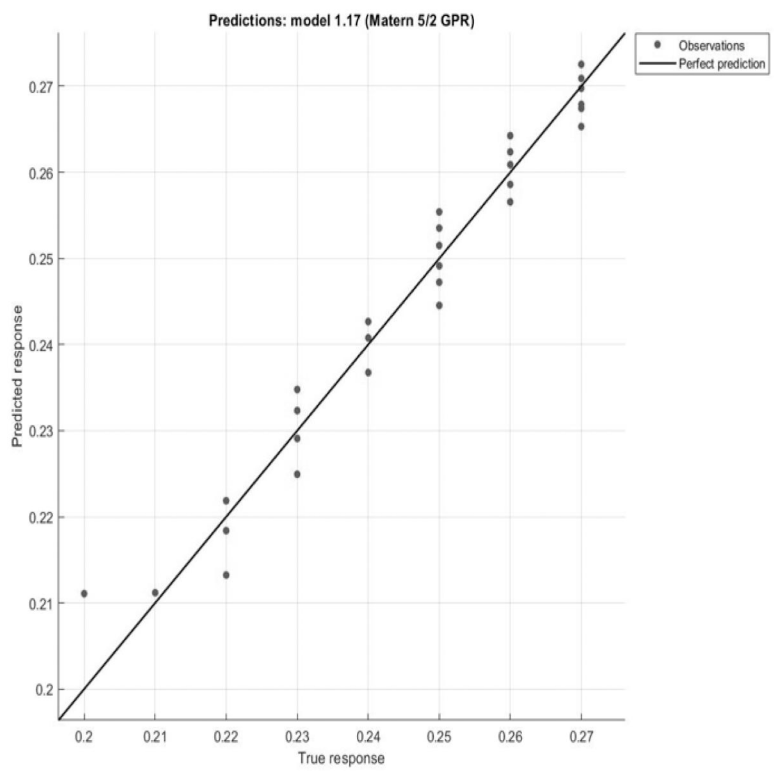

Figure 48. Energy predictive model-I.

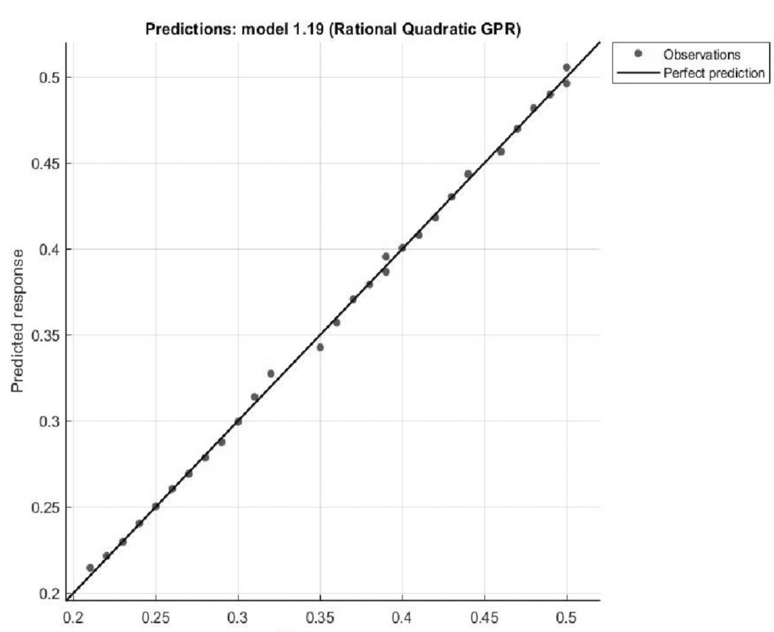

Figure 49. Energy predictive model-II.

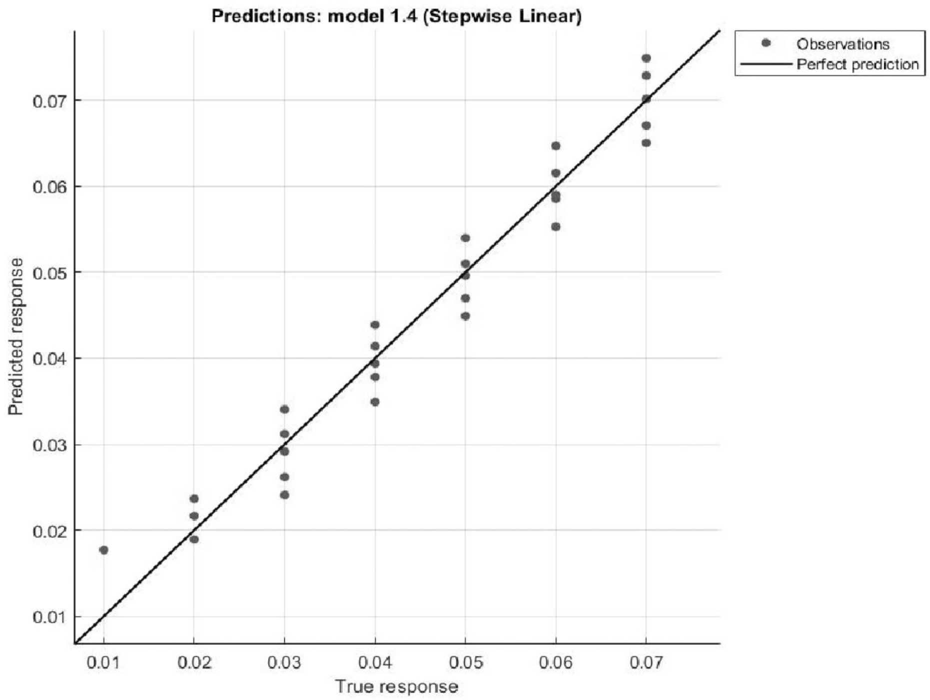

Figure 50. Energy predictive model-III.

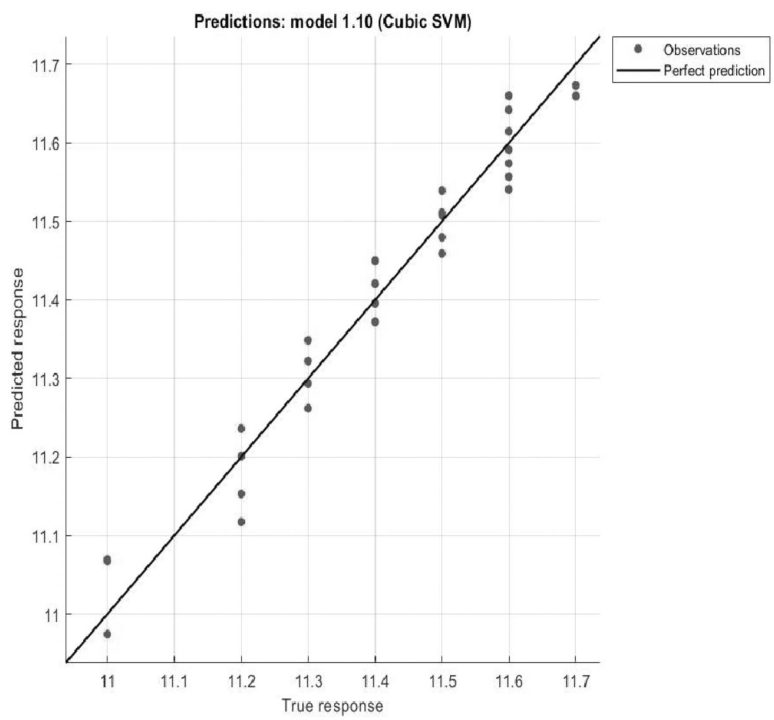

Figure 51. Energy predictive model-IV.

kinetic energy-based power loom sector is promising, poised to revolutionize energy consumption in the textile industry, and contribute to a greener and more sustainable global future.

The summary of our project details, comparing the existing power source-based power loom sector with the electro-kinetic energy-based power loom sector, is presented in Table 9.

In the comparative analysis, the ‘Electro-Kinetic Energy Based Power Loom Sector’ is highlighted as the best option compared to other power loom sectors in several aspects. It offers more efficient energy conversion processes, potentially lower long-term maintenance costs, and aligns with modern sustainable trends. Additionally, it provides a higher level of energy conversion efficiency compared to traditional methods and exhibits No greenhouse gas emissions during the

Table 8. Details of energy estimation based upon energy predictive models.

Appliable EKE models	Quantity of EKE presence	Predicted result based energy estimation
Top Closed Loop Based Power Loom		
Open end X-Y Read (Piezo Array Integration)	Single Open end Read Integrated 2 4 $\times$ 2 Piezo Array Totally two Reads so total Quantity of EKE is 4	Test Result $= 0.25 \times 4 = 1$ $\mathrm{E} = 1 \times 3600$ $E = 3600$ Watts-hrs
Open End -Unidirectional Non-linear Power Extraction	Only One Pipe line end So Quantity of EKE is	Test Result $= 11.6 \times 1 = 11.6$ $\mathrm{E} = 11.6 \times 3600$ $E = 41760$ Watts-hrs
Bi-Directional Yarn Filing process (Linear Power Extraction Integration)	Two Carrier Pusher so Quantity of EKE is 2	Test Result $= 0.0319 \times 2 = 0.063$ $\mathrm{E} = 0.063 \times 3600$ $E = 229.68$ Watts-hrs
Instead of Piezo array Open end X-Y read with Linear Power Extraction Model (Linear Power Extraction Integration)	Single end Read will integrate 6 EKE Model Totally Two Read Present so Quantity of EKE 12	Test Result $= 0.0319 \times 12 = 0.38$ $\mathrm{E} = 0.38 \times 3600$ $E = 1378$ Watts-hrs
Bottom Closed Loop Based Power Loom		
Open Head Frame (Piezo Array Integration)	Single Aluminum Frame Contain 3 Wooden Pilar, Totally 3 Frame Contain, so EKE Model Quantity is 9	Test Result $= 0.21 \times 9 = 1.89$ $E = 1.89 \times 3600$ $E = 6804$ Watts-hrs
Open End -Unidirectional Non-linear Power Extraction	Only One Pipe line end So Quantity of EKE is	Test Result $= 11.6 \times 1 = 11.6$ $\mathrm{E} = 11.6 \times 3600$ $E = 41760$ Watts-hrs
Instead of Piezo array Open end Head Frame with Linear Power Extraction Model (Linear Power Extraction Integration)	Single Aluminum Frame Contain 3 Wooden Pilar, Totally 3 Frame Contain, so EKE Model Quantity is 9	Test Result $= 0.0319 \times 9 = 0.28$ $\mathrm{E} = 0.28 \times 3600$ $E = 1033$ Watts-hrs

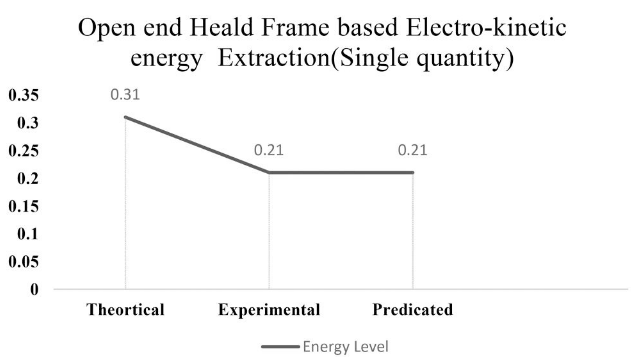

Figure 52. Open end heald frame based EKE stability analysis.

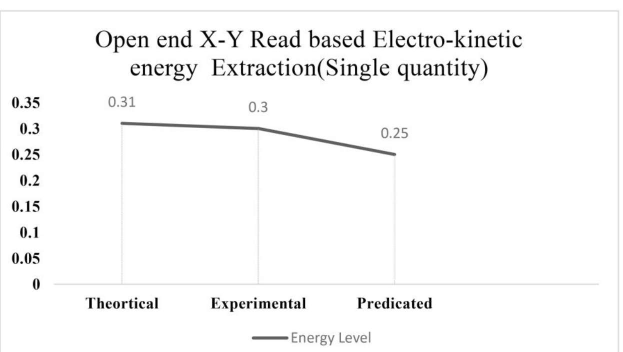

Figure 53. Open end X-Y read based EKE stability analysis.

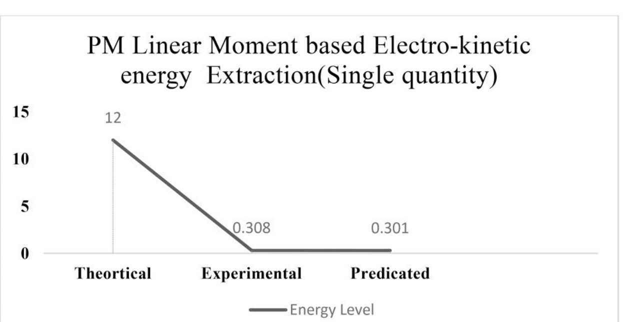

Figure 54. Linear generation based EKE stability analysis.

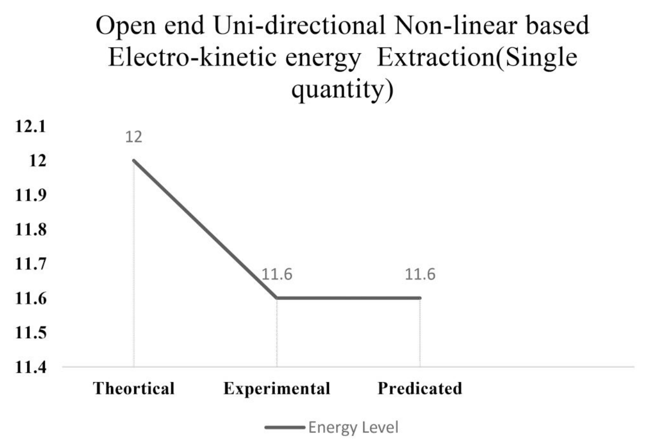

Figure 55. Non-linear generation based EKE stability analysis.

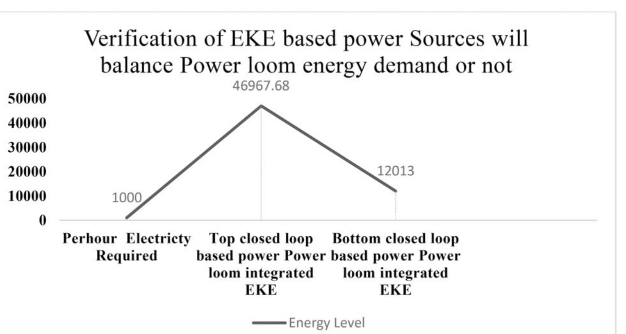

Figure 56. Assessing the electro-kinetic energy-based power sources' capacity to offset power loom energy demand.

energy conversion process, making it the most environmentally friendly option.

8. Discussion and conclusion

In summary, the incorporation of electro-kinetic energy-based power looms, utilizing open-end head frames, open-end X-Y read technology, and employing both linear and non-linear energy generation, represents a significant advancement in energy solutions for the textile industry.

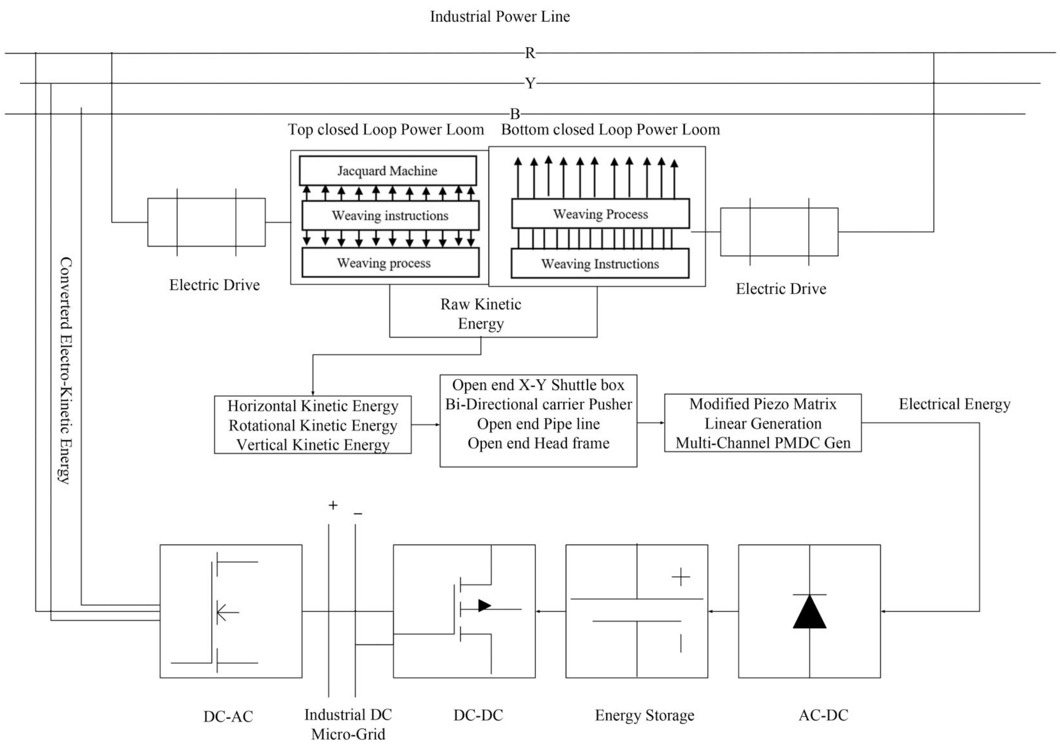

Figure 57. Outline of electro-kinetic energy-based power loom sector.

Table 9. Comparative analysis of existing power source-based power loom sector and electro-kinetic energy-based power loom sector.

Aspect	Oscillating power source (solar and wind) based power loom sector	Electro-kinetic energy based power loom sector	Captive power source based power loom sector	Industrial cogeneration based power loom sector
Advantages	- Utilizes renewable energy sources. - Reduces the carbon footprint. - Mature and established technology. - May be suitable for remote locations with ample sunlight or wind resources.	- More efficient energy conversion process. (Best) - Potentially lower long-term maintenance costs. - Aligns with modern sustainable trends. - Environmentally friendly with appropriate energy sources.	- Independent power generation capability. - May offer cost savings in areas with unstable grids. - Flexibility in fuel choice, including renewable options. - Potential for financial incentives and environmental certifications.	- Simultaneous electricity and heat production. - Lower greenhouse gas emissions. - Energy-efficient and cost-effective solution for industries. - Enhances energy security and reduces reliance on external energy sources.
Energy Optimization	- Implementing tracking systems for solar panels to maximize sunlight exposure throughout the day. - Using predictive algorithms to forecast energy demand and adjust power generation accordingly. - Integrating smart grids to balance energy supply and demand effectively. - Leveraging energy storage systems to optimize energy utilization and reduce energy wastage.	- Optimizing the design of electro-kinetic generators for better energy conversion efficiency. - Employing energy management systems to regulate power usage and reduce wastage. - Exploring advanced materials and technologies for more efficient energy extraction. - Maximizing the direct conversion of mechanical energy into electrical energy.	- Implementing efficient power generation and distribution systems. - Incorporating energy-saving measures in the power generation process. - Conducting regular energy audits to identify areas for improvement.	- Utilizing waste heat for additional energy production. - Implementing energy-efficient practices in industrial processes. - Maximizing the utilization of waste heat for industrial processes.
Efficiency	- High energy conversion efficiency with proper system design.	- Higher efficiency compared to traditional energy conversion methods.	- High efficiency in power generation and utilization.	- Efficient simultaneous electricity and heat generation.
Greenhouse Gas Emissions	–	- No any greenhouse gas emissions during energy conversion process.	–	–

Their superior energy conversion efficiency, supported by advanced control systems and energy recovery mechanisms, not only optimizes energy usage but also reduces waste. Furthermore, by harnessing renewable energy sources and decreasing greenhouse gas emissions, these power looms promote sustainable practices, contributing to environmental preservation. Moreover, their capacity to ensure energy security and independence enhances operational stability, particularly in remote areas. Continuous research and development efforts are anticipated to further improve their efficiency and scalability, playing a crucial role in achieving a sustainable and eco-friendly future for textile manufacturing.

Disclosure statement

The author declares no conflicts of interest regarding the publication of this article.

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