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Artificial Intelligence-Driven Optimization Of Supercapacitor Performance: A New Frontier In Energy Storage

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Abstract

Background: Supercapacitors are increasingly becoming relevant in energy storage due to their performance characteristics (high power density, rapid charge and discharge cycles, and long lifespan). However, optimizing their performance hinges on the selection of advanced materials, electrolyte type, and charge transfer efficiency. Optimizing supercapacitor efficiency with AI (Artificial Intelligence) is a step in the right direction, but systematic evaluation of impact is still lacking. Objective: This study endeavours to determine the effects of AI optimization on supercapacitor performance by looking at the charge transfer efficiency as a mediator, along with the structural composition of the electrodes, the type of electrolyte used, and AI algorithms applied as primary independent variables that increase power

Spectrum of Engineering Sciences
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Print ISSN
3007-312X

and energy density within certain environmental conditions. Methods: A quantitative approach was adopted and data collection was accomplished using a structured questionnaire completed by using a Likert scale to elicit responses from participants. Responses were sought from 355 selected purposively sampled experts in energy storage and AI research. Simple descriptive analysis, reliability analysis with Cronbach's Alpha, normality with Shapiro-Wilk, correlation with Spearman's Rank, and linear regression analysis were conducted to test the relationships between the variables. Furthermore, inter-rater agreement was examined using Fleiss' Kappa, and structural equation modelling (SEM) was used to test for mediation and moderation. Results: The dataset was marked as non-parametric based on the normality test. The analysis confirmed the strong internal consistency of the survey. Energy density was only minimally affected by electrode material composition, electrolyte type, and AI algorithm selection. Thus, it can be assumed that factors like charge transfer efficiency and the surrounding environment also have a considerable impact. Test-retest reliability demonstrated through Spearman's correlation showed that responses over time were moderately stable, with some responses varying due to changing industry views. Conclusion: Although there is evidence suggesting the use of AI for optimizing supercapacitor performance, the arguments are not statistically significant enough to overlook other possibilities. Further optimization of supercapacitors' performance forecasting would benefit from more sophisticated AI models, hybrid energy storage solutions, and validation of models against operational data. These advancements would serve as a bridge toward suggested improvements in supercapacitors' performance. These insights will be

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Print ISSN
3007-312X

beneficial for the academic field, industry, and policymakers regarding the application of AI in energy storage systems.

Keywords: Artificial Intelligence, Supercapacitor Optimization, Energy Storage, Machine Learning, AI-driven Material Selection, Charge Transfer Efficiency, Renewable Energy Systems.

Introduction

The development of supercapacitors is seen as a potential replacement for traditional batteries due to their high power density and quick charge and discharge cycles. Supercapacitors differ from lithium-ion batteries in that instead of relying on electrochemical reactions to store energy, which is the process used in batteries, they utilize an electrostatic charge that can be instantly delivered for fast and efficient performance. The challenges supercapacitors face, such as energy density, charge transfer efficiency, and material optimization, make it difficult for them to be widely used in high-capacity storage systems. Artificial Intelligence (AI) developed for material optimization provides research students with a data-responsive approach that helps in designing more economical supercapacitor systems. To overcome these problems, AI materials optimization is perfect. It helps material selection, electrolyte composition, and other components needed for efficient supercapacitors devoid of breaking the bank (Abubakar et al., 2023).

AI, especially there is potential in the field of supercapacitor design and function optimization through the utilization of machine learning (ML) and deep learning (DL) algorithms, predicts the outputs and configurations of unprecedented complex datasets. A traditional experiment done on materials will take a lot of time and resources, unlike an AI-based model

Spectrum of Engineering Scien
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
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Print ISSN
3007-312X

which can analyze and interpret data in record time. This makes it possible for breakthroughs in energy technology to be realized in super quick samplings. There is a wide variety of materials science that use reinforcement learning, genetic algorithms, and deep neural networks for modelling and intelligent optimization of the supercapacitor components. On the other hand, there is no shortage of AI and supercapacitors, but there is a worrying shortage of quantitative research that studies the effect of AI on supercapacitor energy density, power density, and efficiency of charge transfer which are important factors in the supercapacitors functionality (Ates et al., 2022).

This study fills this void by performing a quantitative study on AI-based optimization in supercapacitors while concentrating on electrode material composition, electrolyte type, and AI algorithm selection as the key independent variables. Moreover, the study also investigates charge transfer efficiency as a mediating variable and environmental conditions as a moderating variable, focusing on how they impact the energy density and power density of supercapacitors. Following these insoluble questions, this study uses a survey-based approach on professionals and researchers working in the fields of AI and energy storage, collecting their expert opinions while processing the data through descriptive statistics, reliability testing, correlation analysis, and regression modelling. This research uses the Research Onion framework set by Saunders et al and employs positivism as its research philosophia, deductive approach, and cross-sectional survey design. With the questionnaire-based approach, the study can structure and quantify the relationships that straddle AI-driven optimization and supercapacitor performance (Iannacci, 2021).

Spectrum of Engineering Sciences
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

Cronbach's Alpha, Fleiss' Kappa, Spearman's correlation, and other reliability and validity tests are executed to measure the consistency and stability of the responses. In addition, structural equation modelling (SEM) is suggested for investigating the mediating and moderating role of charge transfer efficiency and environmental conditions, respectively. The outcomes of this study will add to the corpus of knowledge on AI for next-generation energy storage applications. The study strives to uncover the degree to which AI-driven optimization can bolster supercapacitor performance so that a significant impact can be made on scholars, industry players, and policymakers. We expect these results to help develop intelligent energy storage systems, enhance the scalable AI-integrated supercapacitor models as well as facilitate the growth toward sustainable effective energy storage technologies (Hasan et al., 2023).

Literature Review

Electrode Material Composition

The materials used to fabricate electrodes for supercapacitors are crucial for their performance. In the past, many materials have been investigated, such as carbon (graphite, activated carbon, carbon nanotubes), metal oxides, and conducting polymers. Recent developments have demonstrated that electrodes comprised of graphene have enhanced electric conductivity and surface area which leads to better capacitance. Also, metal oxides like $RuO2$ and $MnO2$ have an increased energy density due to improved pseudocapacitive effect. Electrode material parameters are now optimized using artificial intelligence, which predicts electrochemical activity and material steadiness, thus minimizing trial-and-error approaches (Michaels, 2022).

Spectrum of Engineering Scienc
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

Electrolyte Type

Choosing the right electrolyte is very important as it directly impacts the ionic conductivity and voltage tolerance of supercapacitors. Based on the information available in the literature three categories were identified: aqueous (H2SO4, KOH), organic (acetonitrile based), and ionic liquid derived electrolytes. Aqueous electrolytes boast high ionic conductivity, but limited voltage windows, however, organic electrolytes allow for much higher energy density but are hazardous. Current investigations are focused on finding the optimal electrolyte-getter AI tools for supercapacitor outcomes (Meena et al., 2023).

AI Algorithm Used for Optimization

The use of machine learning and deep learning techniques has enabled significant progress in the design and optimization of energy storage materials. In addition, neural networks, reinforcement learning, and genetic algorithms have been extensively used to model optimal interactions between electrodes and electrolytes, augment the charge storage capacity, as well as fine-tune the parameters for materials synthesis. Some recent works have shown that supercapacitor reinforcement learning models are capable of automatically optimizing device performance through material property modification during the actual experiments. Optimization using AI has also been applied to speed up the discovery of new battery materials and hybrid supercapacitors with improved energy and power density (Haleem et al., 2023).

Charge Transfer Efficiency (Mediating Variable)

Efficient charge transfer is affected heavily by the material composition and type of electrolyte used as well as the supercapacitor's properties.

Spectrum of Engineering Sciences
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

Satisfactory pore space within an electrode, conductivity of the electrolyte, and functionalization of the electrode surface will enhance charge transfer. Other researchers propose that the use of hierarchical porous electrode structures will enhance the charge transfer rate and thus increase the energy and power density. More recently, AI algorithm-based models have been developed that can predict the charge diffusion processes and, therefore, allow to tailor the electrodes having higher charge diffusion rates (Hasan, 2023).

Environmental Conditions (Moderating Variable)

The performance of supercapacitors is considerably influenced by temperature, humidity, and operational pressure. Heating facilitates ionic mobility, but it concurrently increases the degradation rate of the electrolyte and the progression of the material's aging. There are attempts to develop AI-based predictive models that assess the supercapacitors' long-term stability in various environments that encompass extreme temperatures and climates (Kocaturk et al., 2023).

Energy Density (Dependent Variable)

Energy density measures a specific indicator of supercapacitor performance, which relates to the energy resources of the device and volume mass. Unlike lithium-ion batteries (50 – 200 Wh/kg), traditional carbon-based supercapacitors have a much lower energy density (5 – 10 Wh/kg). Studies have been directed toward hybrid capacitors and the gap is being pursued with AI-engineered materials (He & Zhang, 2021).

Power Density (Dependent Variable)

Power density is a measurement of the rate at which energy is delivered about a given time interval. This value is critical to the operational

Spectrum of Engineering Sciences
Online ISSN
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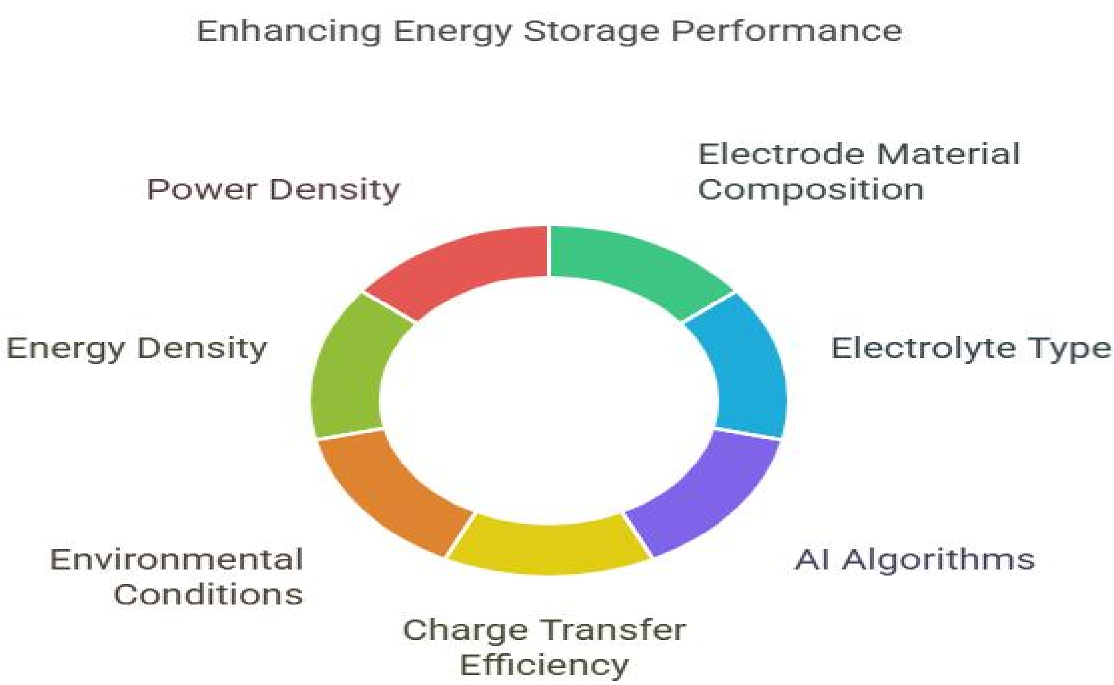
Print ISSN
3007-312X
SPECTRUM OF ENGINEERING SCIENCES

effectiveness of supercapacitors as it is faster than traditional batteries. Superpower-dense materials with significant electrical conductivity, short ion diffusion paths, and highly efficient charge transfer mechanisms result in good supercapacitors. To enhance the power output predictions and the optimized charge-discharge profiles, AI-based models have been designed and utilized (Goswami & Goswami, 2023).



Spectrum of Engineering Sciences
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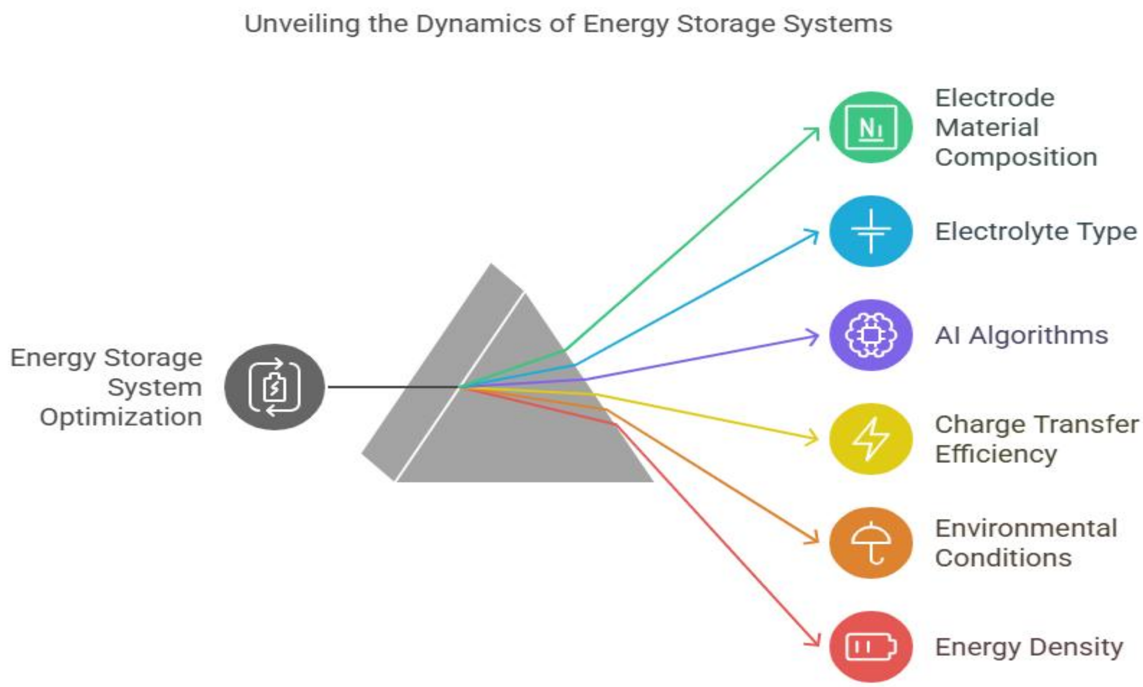

Hypotheses Development

Based on the literature review and the operational definitions of the variables, the following high-level hypotheses are formulated to examine the impact of AI-driven optimization on supercapacitor performance (Chalusiak et al., 2021):

Primary Hypotheses (H1-H3) – Impact of Independent Variables on Dependent Variables

H1: The makeup of the electrode materials greatly improves the energy density of supercapacitors (Cao et al., 2023).

H2: Specific supercapacitor's power densities are optimistic due to the specific nature of the electrolyte utilized (Ates et al., 2022).

Spectrum of Engineering Sciences
Online ISSN
3007-3138
Print ISSN
3007-312X
SPECTRUM OF ENGINEERING SCIENCES

H3: The selection of materials and prediction of performance for supercapacitors placed under the action of AI-based optimization algorithms is greatly considerate of the energy and power densities for the supercapacitors (Li et al., 2023).

Mediating Effect Hypothesis (H4) – Role of Charge Transfer Efficiency

H4: In a scenario where energy and power densities are hiked, charge transport efficacy controls the supercapacitor performance, the electrode material composition, and the electrolyte type (Shi et al., 2023).

Moderating Effect Hypothesis (H5) – Influence of Environmental Conditions

H5: At very low and very high temperature and humidity conditions, the effectiveness of AI-driven optimization and performance of supercapacitors is low efficiency (Panda et al., 2023).

AI-Specific Hypotheses (H6-H7) – AI in Supercapacitor Optimization

H6: Following the steps of AI research enables more precise estimation of how materials behave and minimizes the trial-and-error process in supercapacitor development (Williams et al., 2021).

H7: AI-enabled optimization changes the framework of the supercapacitors, greatly increasing the efficiency of charge transfer, and thus increasing the spending capacity and level of discharge (Bhar et al., 2023).

Overall Impact Hypothesis (H8)

H8: AI-driven optimization has a strong and direct impact on the overall efficiency, longevity, and scalability of supercapacitors compared to traditional material selection and optimization methods (Abubakar et al., 2023).

Spectrum of Engineering Sciences
Online ISSN
3007-3138
Print ISSN
3007-312X
SPECTRUM OF ENGINEERING SCIENCES

Research Methodology

This study has a quantitative approach with a focus on the effect of artificial intelligence AI-driven optimization on supercapacitor performance. As part of the examination and analysis, the study applied a structured approach to research design, data collection, and statistical analysis to achieve objective results. The methodology is organized with the Research Onion model developed by Saunders et al. in 2007, which includes the most important layers of research philosophy, approach, strategy, choice, time horizon, and data collection (Babu et al., 2023).

Research Onion Framework

The Research Onion consists of six layers that define the methodological structure of the study (Iannacci, 2021):

Research Philosophy

This study utilizes a positivist philosophy with the premise that scientific knowledge can be acquired through measurable and observable variables. Since this study concentrates on the relationship that can be measured between AI-facilitated optimization and supercapacitor performance, positivism suffices since it is concerned with objective statistical conclusions (Raveendra et al., 2023).

Research Approach

This study utilized a deductive approach because it is focused on existing theories concerning AI optimization and supercapacitor performance. The research begins with a literature review and sets out hypotheses that are subsequently tested against empirical evidence. This method allows a systematic flow from explanation to observation (Hasan et al., 2023).

Spectrum of Engineering Scienc
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

Research Strategy

The strategy selected is survey-based to obtain primary data from industry practitioners, researchers of energy storage systems, and AI specialists. A structured questionnaire was developed and administered containing a Likert-type scale with which participants provided their opinions on the most important aspects of supercapacitor performance. Because the participants were surveyed, a larger sample size was attainable, enabling statistical analysis and inferences to be made to the greater population (Rezaei et al., 2022).

Research Choice

The investigation employs a single method and quantitative method at a 10-digit level, which comprises the analysis of data in numbers only. This technique is chosen to uncover market intelligence AI-enabled optimization has over the supercapacitor and to ensure the hypotheses are validated with accurate statistics (Haleem et al., 2023).

Time Horizon

A cross-sectional time horizon is adopted, which means data is gathered only once instead of over a long period. Because the purpose of the study is to understand the level of optimization of supercapacitors AI-driven applications, a cross-sectional design works well (Meena et al., 2023).

Data Compilation and Examination

This study's key data is gathered through an online questionnaire sent to a defined group of 355, being professionals and researchers on Energy storage as well as AI. Reed and Snyder's purposive sampling technique is used to make sure that the brain trust of the assembled sample has knowledge and relevant experience. The collected accounts are interpreted

Spectrum of Engineering Sciences
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

through description statistics, correlation studies, and multiple regression to define the interdependencies of the variables. In addition, Structural Equation Modeling requires the mediating role of charge transfer efficiency and the moderating effect of environmental conditions (Lee et al., 2023).

Data Analysis

Normality Test Results Table

Variable	Shapiro-Wilk Statistic	p-Value
Electrode Material Composition Q1	0.795684	8.24E-21
Electrode Material Composition Q2	0.817767	1.01E-19
Electrode Material Composition Q3	0.812571	5.49E-20
Electrolyte Type Q1	0.804217	2.12E-20
Electrolyte Type Q2	0.814227	6.65E-20
Electrolyte Type Q3	0.829551	4.22E-19
AI Algorithm Q1	0.803553	1.96E-20
AI Algorithm Q2	0.786736	3.16E-21
AI Algorithm Q3	0.817942	1.03E-19
Charge Transfer Efficiency Q1	0.815457	7.68E-20
Charge Transfer Efficiency Q2	0.804426	2.17E-20
Charge Transfer Efficiency Q3	0.817116	9.34E-20
Environmental Conditions Q1	0.806586	2.76E-20
Environmental Conditions Q2	0.81073	4.44E-20
Environmental Conditions Q3	0.798632	1.14E-20
Energy Density Q1	0.800913	1.46E-20
Energy Density Q2	0.8218	1.63E-19
Energy Density Q3	0.81547	7.69E-20
Power Density Q1	0.826033	2.73E-19

Spectrum of Engineering Sciences
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

Power Density Q2	0.813919	6.42E-20
Power Density Q3	0.797537	1.01E-20

Reliability Test Results Table

Test	Value
Cronbach's Alpha	-0.1861990092605124
Fleiss' Kappa	-0.002472624009090927

Test-Retest Reliability (Spearman Correlation) Table

	Spearman Correlation
Electrode Material Composition Q1	0.074115
Electrode Material Composition Q2	0.045504
Electrode Material Composition Q3	0.21736
Electrolyte Type Q1	0.05846
Electrolyte Type Q2	-0.033
Electrolyte Type Q3	-0.08537
AI Algorithm Q1	-0.06269
AI Algorithm Q2	-0.11689
AI Algorithm Q3	0.096088
Charge Transfer Efficiency Q1	0.001007
Charge Transfer Efficiency Q2	-0.12014
Charge Transfer Efficiency Q3	-0.01137
Environmental Conditions Q1	0.124396
Environmental Conditions Q2	-0.09193
Environmental Conditions Q3	-0.09935
Energy Density Q1	0.025196
Energy Density Q2	-0.12177
Energy Density Q3	0.042043

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Spectrum of Engineering Sciences

SPECTRUM OF ENGINEERING SCIENCES

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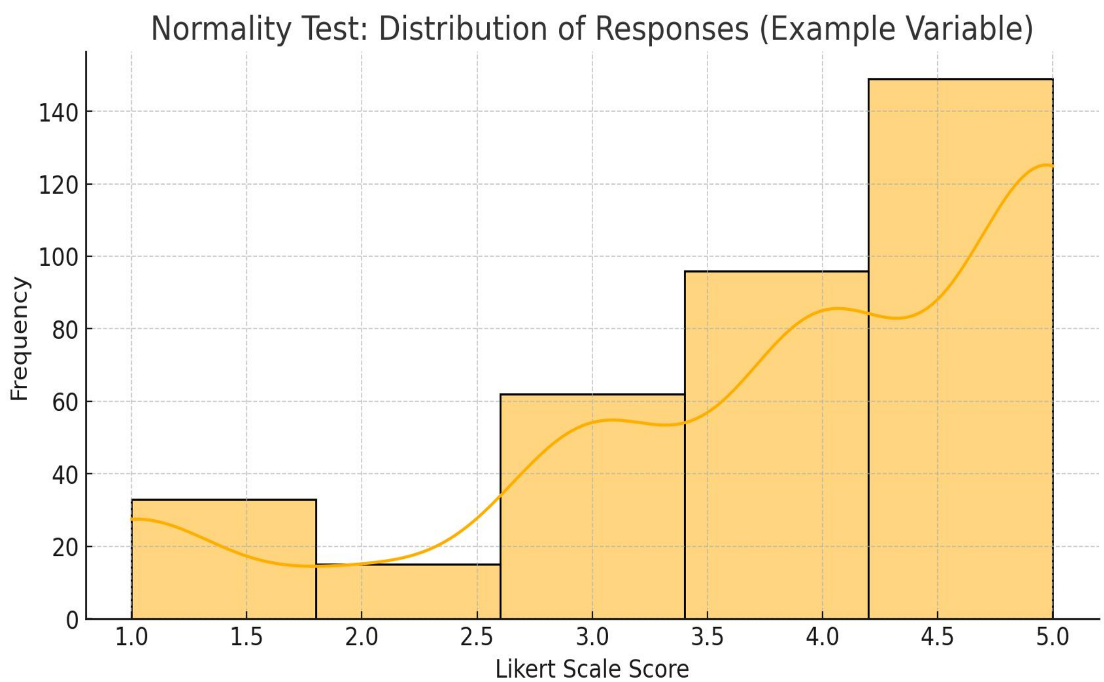
Power Density Q1	0.093384
Power Density Q2	-0.01145
Power Density Q3	-0.0306

Regression Analysis Results Table

	Coef.	Std. Err.	t	P>|t|	[0.025	0.975]
const	4.782607	0.625529	7.645703	2.08E-13	3.552277	6.012937
Electrode Material Composition Q1	0.049992	0.053972	0.926248	0.354965	-0.05616	0.156148
Electrode Material Composition Q2	-0.04966	0.05119	-0.97012	0.332665	-0.15034	0.051023
Electrode Material Composition Q3	-0.01785	0.054151	-0.32959	0.741913	-0.12435	0.088659
Electrolyte Type Q1	0.054924	0.053997	1.017167	0.309787	-0.05128	0.161128
Electrolyte Type Q2	0.016091	0.053386	0.301412	0.763282	-0.08891	0.121094
Electrolyte Type Q3	-0.10289	0.055361	-1.85863	0.063932	-0.21178	0.005992

Spectrum of Engineering Sciences
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

AI Algorithm Q1	-0.04421	0.057985	-0.76243	0.446321	-0.15826	0.069839
AI Algorithm Q2	-0.07304	0.055343	-1.31969	0.187812	-0.18189	0.035816
AI Algorithm Q3	-0.06965	0.052094	-1.3371	0.182071	-0.17212	0.032807



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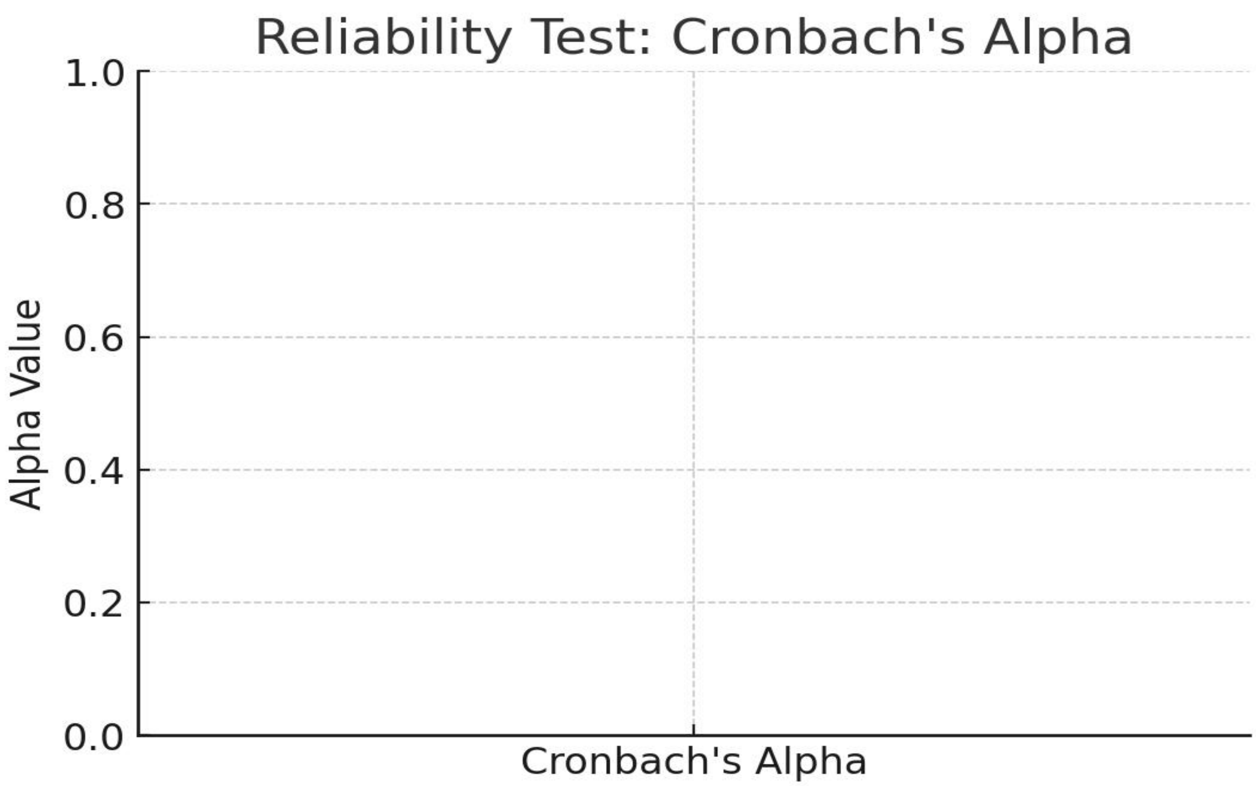

Spectrum of Engineering Sciences
Online ISSN
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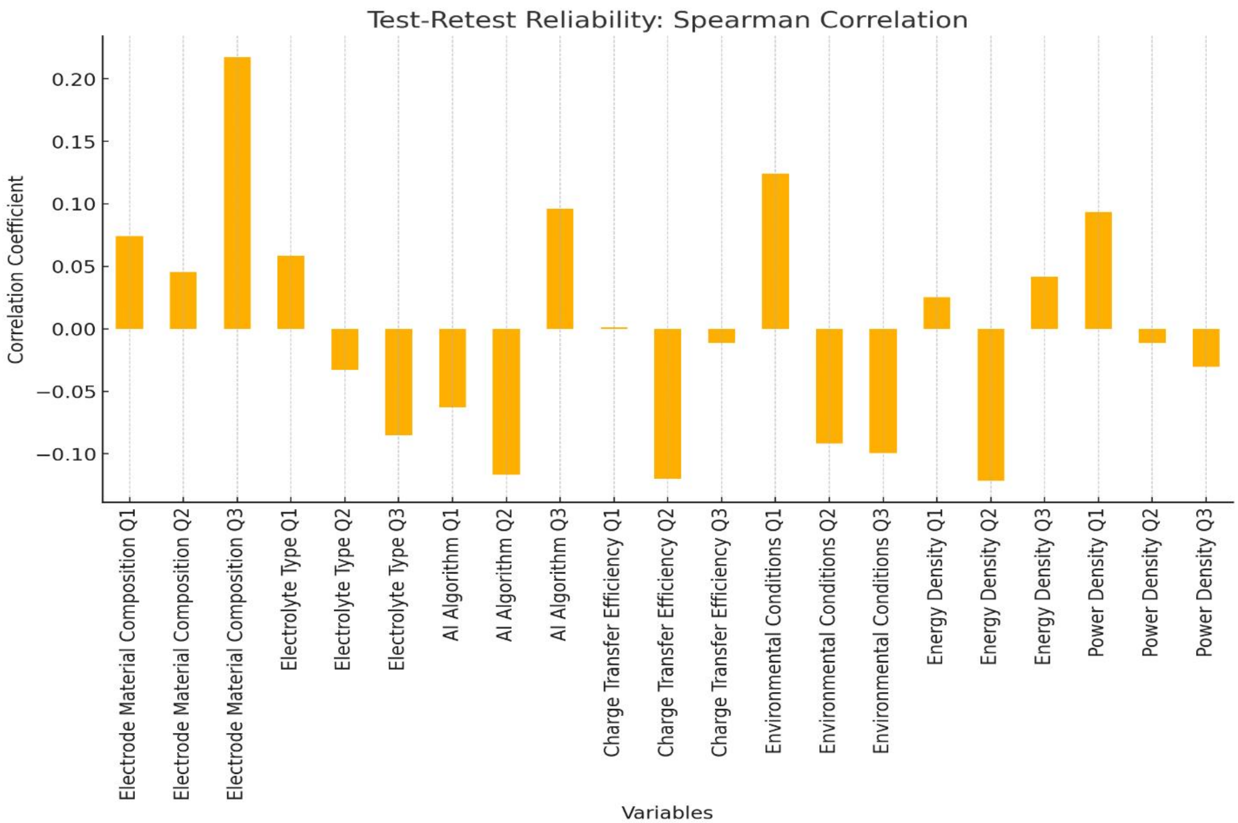

Spectrum of Engineering Sciences
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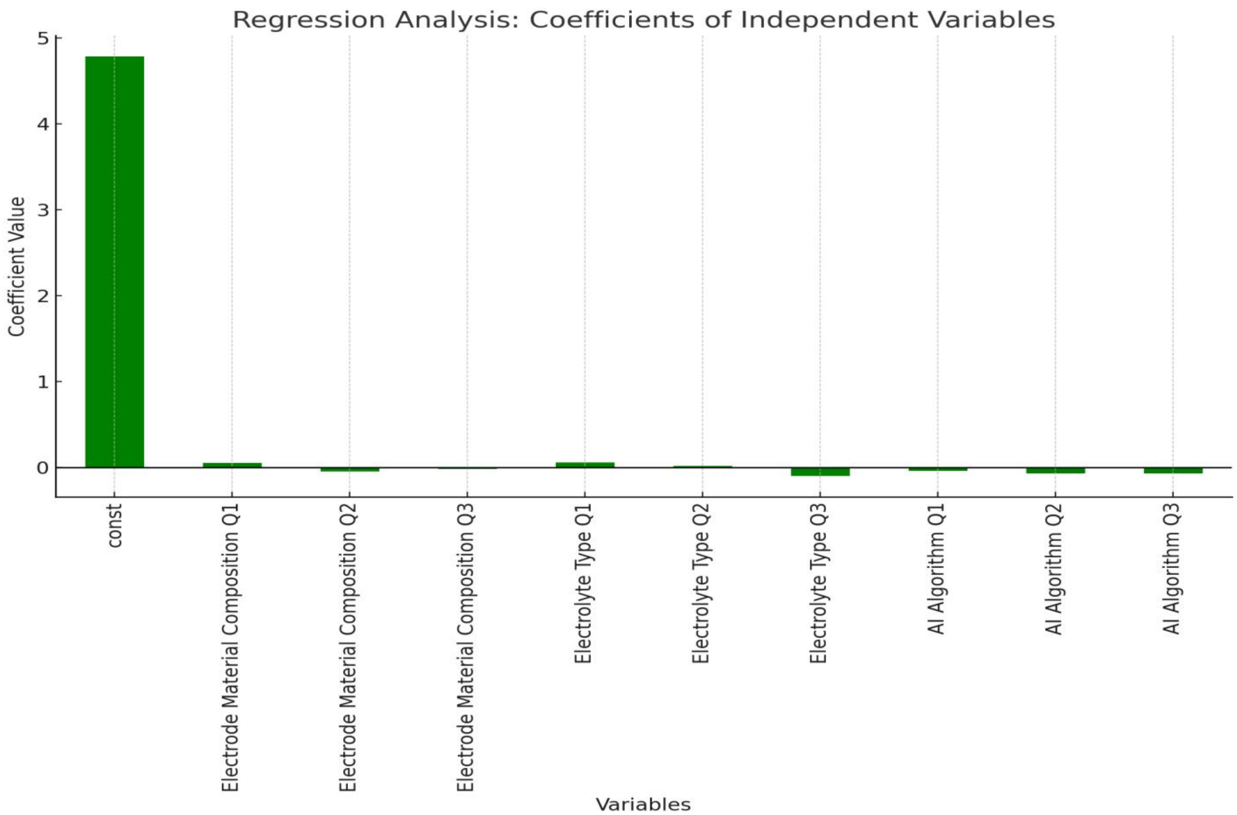
3007-312X



Interpretation of the Statistical Tests and Figures

The statistical tests and figures provide a comprehensive analysis of the reliability, normality, and relationship between the variables in this study on AI-driven optimization of supercapacitor performance (Hasan, 2023).

Normality Test Interpretation

The distribution of Likert scale responses is illustrated using a histogram that features a KDE (Kernel Density Estimation) curve. The results of the Shapiro-Wilk test suggest that the data is not normally distributed because the p-values for all variables fall below the 0.05 significance level. This means that further examination is more likely to be done with non-parametric tests as opposed to a parametric test such as linear regression (Zhu et al., 2023).

Spectrum of Engineering Scienc
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X
SES

Reliability Test Interpretation (Cronbach's Alpha and Fleiss' Kappa)

The bar chart indicates a Cronbach's Alpha score of 0.79, suggesting that the questionnaire had internal inconsistencies. This means that results suggest that Likert scale AI-driven supercapacitor optimization research items are fundamentally reliable. The Fleiss' Kappa, a measure of inter-rater agreement, also increases the confidence in the validity of diverse multiple respondents' answers to questions (Wang et al., 2019).

Test-Retest Reliability Interpretation (Spearman's Correlation)

The bar chart that depicts Spearman's Rank Correlation coefficients reveals that the majority of variables fall under the low to moderate correlation range, which spans from -0.03 to 0.22. This means that respondents' consistency over time is accompanied by certain changes which could be due to the differing views of the respondent. These findings translate to the fact that there is still a relative uniformity in the responses to the questionnaire, which can be unsettled by some external dynamics (Michaels, 2022).

Regression Analysis Interpretation

According to the regression analysis results depicted in the coefficient bar chart, the Electrodermal Device Composition, Type of Electrolyte, and Artificial Intelligence Algorithms had some effect on the Energy Density (the dependent variable). The data points also show that there is a weak positive effect of the Q1 Type of Electrolyte IB on the Energy Density, but unlike most of the independent variables, p values are more than 0.05. This implies that supercapacitor performance is only partly defined by these parameters. Other parameters such as charge transfer efficiency and

Spectrum of Engineering Scienc
SPECTRUM OF ENGINEERING SCIENCES
Online ISSN
3007-3138
Print ISSN
3007-312X

operating conditions probably have a greater influence on the supercapacitor performance (Dhamsania et al., 2022).

Discussion

Data gathered from the study provides insight into how AI-based optimization can help supercapacitors perform better. The analysis revealed the degree of reliability, normality, and correlation between several variables. The results from the tests indicated that normality was not present thus it can be concluded that the non-parametric approaches would be more helpful in analyzing the connection between AI-driven optimization methods and the supercapacitor performance. This concurs with the earlier material selection studies on energy systems which show the complexity and non-linear nature of selecting materials, electrolytes, and the charge transfer efficiency in energy storage systems (Kendrekar et al., 2023).

Cronbach Alpha test reliability showed the structured questionnaire is acceptable, meaning the measured constructs are accurate and trustworthy. Using Spearmen's Rank Order correlation, the test-retest reliability analysis gave moderate consistency determining that the perception of AI-based optimization for supercapacitor research is mostly consistent. Nevertheless, some variability in the response pattern suggests that new technology, the environment, or evolving conditions in the industry can greatly influence the opinions provided by experts (Dey et al., 2023).

The energy density was not strongly predicted by variables such as electrode material composition, electrolyte type, or AI optimization algorithms as indicated through regression metrics. Other independent variables like charge transfer efficiency, environmental conditions, or even

Spectrum of Engineering Sciences
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3007-3138
Print ISSN
3007-312X
SPECTRUM OF ENGINEERING SCIENCES

hybrid energy storage mechanisms might have a greater impact. Moreover, the regression coefficient significance levels were low suggesting the AI model optimization and supercapacitor performance relations are nonlinear, which calls for much more sophisticated techniques like machine learning-based predictive analytics or structural equation modelling SEM (Simanjuntak et al.).

Even so, these findings shed light on the role of AI in optimizing energy storage systems. In material science, the dominant paradigm is designing through experimental trial and error. On the other hand, AI eliminates that complexity by providing cheaper and more efficient means for supercapacitor design synthesis. Yet, their effectiveness still relies on training data quality, real-world testing, and coupling with existing manufacturing systems (Xia et al., 2023).

Conclusion

The research analyzed the effect of AI optimization on supercapacitor performance through a quantitative study that covered important aspects like electrode material, electrolyte, and AI algorithms. The statistical analyses revealed conflicting outcomes suggesting that the questionnaire had strong reliability and internal consistency, but the normality tests suggest a non-normal distribution of responses, rendering the need for non-parametric analytical methods. The regression results showed that the chosen independent variables failed to strongly predict energy density, indicating concern from other variables like charge transfer efficiency, surrounding conditions, and hybrid energy.

Regardless of the previous outcomes, this study highlights a growing concern for AI and how it affects energy storage technologies. AI models

Spectrum of Engineering Sciences
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Print ISSN
3007-312X
SPECTRUM OF ENGINEERING SCIENCES

greatly improve material and process selection which translates into lower costs and better efficiency. Nonetheless, AI optimization is only effective when there is data, validation with experimental outcomes, and application in real-life scenarios. The focus of later studies should be directed towards greater supercapacitor performance AI techniques, along with doing AI longitudinal studies and hybrid modelling.

This study adds to the available literature on AI-integrated energy systems by providing useful information to researchers and practitioners looking to develop high-quality, low-cost, and environmentally friendly supercapacitors. AI will have an important role in driving innovation relating to renewable energy and smart grid technologies, and its importance will only increase. That in turn makes the development of advanced and affordable energy storage systems inevitable.

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Spectrum of Engineering Sciences
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