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Research on Efficient Energy Conversion and Intelligentization of Nuclear Waste Reutilization under the Background of New-Quality Productive Forces

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Abstract: This paper focuses on the context of new productive forces, conducting an in-depth study on the efficient energy conversion and intelligent management of nuclear waste recycling. By exploring the application prospects of the nuclear waste industry, it analyzes the principles, current status, and the opportunities and challenges of nuclear waste energy technology under the "dual carbon" goal. The research constructs a comprehensive evaluation system including the coefficient of variation method, multiple regression, and mediation effect models, and employs LSTM and Random Forest models for long-term benefit evaluation. Empirical results show that the application degree of new productive forces, R&D investment, and infrastructure perfection have significant positive impacts on efficient energy conversion, with technical indicators contributing the most to long-term benefits. Case studies demonstrate that closed-loop fuel cycles and intelligent management are key to enhancing economic feasibility and safety. This study provides new ideas and methodological support for the development of nuclear waste treatment and the energy field.

Keywords: New Productive Forces; Nuclear Waste Recycling; Energy-Efficient Conversion; Intelligent Management; LSTM Model

1. Introduction

1.1 Research Background

Global energy demand continues to grow alongside increasing environmental pressures, making the search for sustainable and efficient energy solutions an urgent task. Nuclear energy, as a low-carbon energy source, is seeing its share increase annually, but the concomitant issue of nuclear waste treatment has become a key challenge constraining its development. Historical major nuclear accidents reveal the profound hazards of nuclear contamination [1], and even during normal operations, the global annual production of about 12,000 tons of spent fuel presents a worldwide treatment challenge. The "dual carbon" goal proposed by China provides an opportunity for nuclear energy development but also sets higher requirements for the harmless and resource-based treatment of nuclear waste [2]. In this context, new productive forces, characterized by innovation-driven development, technological leadership, and green low-carbon principles, provide a novel theoretical perspective and practical path for tackling the challenges of nuclear waste treatment and realizing its efficient energy utilization and intelligent management [3,4].

1.2 Research Purpose and Methods

This study aims to construct an efficient energy conversion and intelligent management system based on nuclear waste reuse. Specific objectives include: 1. To reveal the key role of nuclear waste reuse in efficient energy conversion; 2. To explore innovative technological pathways for efficient energy conversion; 3. To construct an intelligent energy system; 4. To evaluate the comprehensive benefits of this system. A combination of theoretical analysis and empirical research is adopted, comprehensively applying the coefficient of variation method, multiple regression, and mediation effect models, and employs LSTM and Random Forest models for quantitative analysis and evaluation [5].

1.3 Research Significance and Innovations

This study has profound theoretical and practical significance. Theoretically, it applies the theory of new productive forces to the field of nuclear waste treatment, expanding its application boundaries. Practically, it holds significant value for environmental protection (reducing radioactive risks), energy security (improving resource utilization), economic development (creating new growth points), and the sustainable development of the nuclear industry [1,3,6].

The innovations of this study are mainly reflected in three aspects: First, technological integration innovation, deeply integrating advanced separation technologies, IoT, big data, and artificial intelligence [4,6]. Second, system construction innovation, proposing and constructing an integrated intelligent system for nuclear waste reuse and energy conversion. Third, research perspective innovation, examining and promoting deep changes in the nuclear waste field from the novel perspective of new productive forces [3].

2. Principles of Nuclear Waste Energy Technology and Guidance by New Productive Forces

2.1 Characteristics and Energy Potential of Nuclear Waste

Nuclear waste can be categorized into high-level (HLW), intermediate-level (ILW), and low-level (LLW) waste based on radioactivity levels. HLW is rich in long-lived, highly radioactive nuclides such as Uranium-238 and Plutonium-239, containing enormous decay energy. Using advanced reactor technologies like fast neutron reactors (fast reactors) and molten salt reactors, or transmutation methods, this energy can be converted into electricity or heat. The energy release offers advantages of long duration and high stability, providing potential support for building a continuous energy supply system [4].

2.2 Review of Existing Energy Conversion Technologies

Current mainstream technologies include Fast Neutron Reactors (Fast Reactors) and Accelerator-Driven Subcritical Systems (ADS). Fast reactors can efficiently utilize uranium, plutonium, and other elements in nuclear waste to achieve fuel breeding and energy output; for example, Russia's BN-800 fast reactor has significantly increased fuel utilization. ADS, on the other hand, uses high-energy proton beams from an accelerator to drive a subcritical core, focusing on transmuting long-lived nuclides to reduce long-term radioactive risk, as seen in the EU's MYRRHA project. While promising, these technologies still face challenges related to materials, control, and cost [4,7].

2.3 Theory of New Productive Forces and the Revolutionary Breakthrough of Nuclear Waste Energy

New productive forces represent a new form of productivity with technological innovation at its core and characterized by high efficiency and sustainability. Applying Carlota Perez's "Techno-Economic Paradigm" theory to nuclear waste energy reveals revolutionary breakthroughs: In terms of technological innovation, advanced separation technologies are deeply integrated with information technology, and intelligent transmutation technologies continue to develop [4, 6]. In terms of industrial transformation, it promotes the shift of the nuclear energy industry from "single electricity generation" to "full-industry-chain resource cycling." In terms of economic and social impact, by improving resource utilization and reducing environmental risks, it provides a new path for energy economic transformation and social sustainable development, achieving a fundamental leap beyond the traditional "solidification and deep burial" disposal paradigm [3, 4].

3. Research Model Construction

3.1 Comprehensive Evaluation Indicator System and Weight Determination

To quantitatively assess the level of efficient energy conversion and intelligence, this study constructed a comprehensive evaluation indicator system covering four dimensions: treatment cost, energy conversion efficiency, resource utilization degree, and intelligence level. The coefficient of variation method was used to objectively determine the weight of each indicator. The calculation results are shown in Table 1.

Table 1. Comprehensive Evaluation Indicator Weights

Indicator Name	Weight
Direct Processing Cost	0.623
Indirect Processing Cost	0.242
Energy Conversion Rate (%)	0.036
Element Recovery Rate (%)	0.014
Intelligent Control Coverage (%)	0.022

Number of IoT Devices	0.099

The weight distribution in Table 1 indicates that processing costs dominate the current evaluation system, while the number of IoT devices, representing the foundation of intelligence, also holds considerable importance.

3.2 Core Variable Relationship Testing Model

To explore the impact of various factors on the level of efficient energy conversion and intelligence (Y), this study established a multiple linear regression model. The core explanatory variable is the application degree of new productive forces (X), with control variables including policy support intensity, R&D investment level, and infrastructure perfection.

The basic form of the model is:

$$Y = \beta_0 + \beta_1 X + \beta_2 Policy + \beta_3 Research + \beta_4 Infrastructure + \varepsilon$$

Furthermore, to test whether new productive forces indirectly affect the energy efficiency level by enhancing management innovation (M), a mediation effect model was introduced, tested using the three-step method proposed by Wen Zhonglin et al. [8].

3.3 Long-Term Benefit Evaluation Model

To evaluate the long-term benefits of nuclear waste energy, this study integrated LSTM and Random Forest models [5]. The LSTM model excels at processing time-series data and was used to capture long-term dependencies and delay effects in energy output. The Random Forest model was used to assess the importance of various feature variables. The entropy method was used to objectively assign weights to three types of benefit indicators---economic (NPV), environmental (emission reduction), and technical (conversion rate)-to construct a comprehensive benefit evaluation index.

4. Empirical Analysis and Results

4.1 Data Sources and Processing

This study used Monte Carlo simulation to generate data related to nuclear waste processing, including initial nuclear waste content, processing efficiency, and energy conversion rates considering time decay, to simulate uncertainty and randomness in real scenarios. The data passed tests for distribution rationality, ensuring the reliability of subsequent analyses.

4.2 Model Results and Key Findings

4.2.1 Multiple regression results

Regression analysis showed that the application degree of new productive forces (β=0.0036, $p<0.01$), R&D investment level (β=0.0012, $p<0.01$), and infrastructure perfection (β=0.0815, $p<0.01$) had significant positive effects on the energy efficiency level. Among them, infrastructure perfection had the most prominent marginal effect. The impact of policy support intensity was not statistically significant in this model.

4.2.2 Long-term benefit evaluation results

- Model Performance: The LSTM model performed excellently in predicting long-term benefits (RMSE=0.124, MAE=0.098), outperforming the Random Forest model (RMSE=0.158, MAE=0.121) [5].
- Feature importance: SHAP analysis of the Random Forest revealed that "Processing Efficiency" was the most critical feature affecting long-term benefits, with a contribution of 38%.
- Delay effect: The LSTM-CPD model detected a benefit delay cycle of approximately 9 months in nuclear waste processing (Cohen's d=1.23), suggesting that project planning needs to reserve a technology digestion period.
- Benefit composition: The entropy weight method showed that technical indicators (weight 0.45) contributed the most to the comprehensive benefits, highlighting the core position of technological innovation.

4.3 Discussion and Innovation

Connection to New Productive Forces: The empirical results confirm the core position of new productive forces. Technological innovation (evidenced by the high weight of technical indicators and the significance of R&D investment) is the fundamental driving force for the development of nuclear waste energy [3,4].

Mechanism of Delay Effect: The identified benefit delay cycle provides a scientific basis for optimizing project management and rationally allocating resources.

Advantages of Multi-method Integration: The integrated framework of "LSTM + Random Forest + Entropy Method" balances time-series prediction, feature interpretation, and comprehensive evaluation, providing an effective methodology for assessing such complex systems [5,8].

5. Case Study and Intelligent Application Analysis

5.1 Cost-Benefit Analysis of La Hague Reprocessing Plant, France

The La Hague plant in France uses the advanced PUREX process, with an annual processing capacity of 1,700 tons, achieving the recovery of high-value elements such as uranium (recovery rate 99.9%) and plutonium (recovery rate 99.8%). Although its unit processing cost is relatively high (about 12,000 euros/ton), the reuse of fuel reduces the power generation cost for Électricité de France by about 20%. Compared to the open fuel cycle, its closed-loop model, despite higher initial investment, saves about 30% in long-term fuel procurement costs and reduces HLW volume by 70%, demonstrating significant economic and environmental benefits [9].

5.2 Application Prospects of Intelligent Management

The UK's nuclear waste traceability system integrates IoT sensors and blockchain technology, enabling real-time monitoring and tamper-proof data management of the entire process from nuclear waste generation to disposal, significantly improving regulatory efficiency and public trust [6,10]. The future trend of intelligent management lies in AI-driven decision-making and data security ensured by quantum encryption communication. However, its promotion still faces challenges such as high initial investment, inconsistent technical standards, and cybersecurity risks [4,6].

6. Conclusion and Outlook

6.1 Summary of Research Findings

In the macro context of new productive forces, this study systematically explored the pathways for efficient energy conversion and intelligent management based on nuclear waste reuse. Through the construction of comprehensive evaluation models and empirical analysis, the following core conclusions are drawn:

New productive forces, through technological innovation and factor optimization, have a significant driving effect on improving the efficiency of nuclear waste energy.

The nuclear waste energy process has a significant benefit delay effect, and technical performance is the key determinant of long-term benefits.

Closed-loop fuel cycles and intelligent management are effective strategies for enhancing the economic feasibility and safety transparency of nuclear waste treatment.

The multi-method integrated model framework provides a reliable analytical tool for evaluating complex energy systems.

6.2 Research Limitations and Future Outlook

The simulated data in this study may deviate from actual situations, and the model complexity is relatively high. Future research can deepen in the following aspects: First, introduce more actual operational data to validate and optimize the models; second, explore more efficient algorithms to reduce computational costs; third, incorporate more dimensions such as social benefits and policy dynamics into the evaluation system, promoting the high-quality and sustainable development of the nuclear waste reuse industry under the guidance of new productive forces.

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