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Research on Intensive Utilization Model of Fly Ash Resources under the Constraint of Energy Conservation and Emission Reduction

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Abstract. Fly ash is a by-product generated by coal-fired power plants. Its production volume is constantly increasing while the comprehensive utilization rate is relatively low, which has become one of the main obstacles hindering the green development of the power industry. Under the dual requirements of energy conservation and emission reduction, a model for the intensive utilization of fly ash resources is established. It is proposed that the intensive utilization of fly ash resources should follow the principles of "reduction, resource utilization, and harmless treatment", reducing the production of fly ash at the source, achieving resource conversion during the process, and improving efficiency at the end, thereby achieving overall control. The model is evaluated from three aspects: technical suitability, economic feasibility, and environmental risk. It emphasizes the gradient matching between large-scale consumption and high-value utilization to increase overall benefits. Large-scale consumption in the building materials sector is the prerequisite for intensive utilization, breakthroughs in high-value technologies are the driving force for increasing added value and expanding the utilization scope, and full life cycle environmental risk control is an important condition for ensuring the sustainable development of intensive utilization. This paper hopes to provide decision-making basis for coal-fired power plants and regional solid waste operators, transforming fly ash from an "environmental burden" into a "resource asset".

Keywords. Fly ash, resource utilization, intensive model, energy conservation and emission reduction, environmental hazards

1. Introduction

China is a major coal consuming country, with over 100 million tons of fly ash produced annually by coal-fired power plants. According to data, as of the end of 2000, the amount of fly ash accumulation in China was approximately 1.25 billion tons. According to the general scope of fly ash accumulation, it would require at least 500000 to 625000 acres of farmland to meet the demand. Due to the continuous increase in electricity demand, the amount of fly ash has been consistently increasing. If fly ash is piled up outdoors, it will occupy a lot of valuable land resources, and the dust emitted will drift with the wind. Its harmful substances will penetrate into the soil, causing long-term damage to the surrounding environment.

At the same time, the establishment of the national strategic goal of "dual carbon" has also raised new heights for the treatment of fly ash. The

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resource utilization of fly ash is an environmental requirement for reducing solid waste and an effective path for carbon reduction. Someone has found that if fly ash is used as a cement admixture or concrete admixture, it will reduce the demand for cement clinker, and about 0.8 to 1 ton of CO2 emissions can be saved per ton of fly ash. How to break through the technical bottleneck and market barriers of comprehensive use of fly ash, and transform from "inefficient digestion" to "centralized utilization", has become an urgent key issue.

Most of the existing research is about the application technology of fly ash in a certain aspect, and there is no overall study on the intensive utilization of fly ash. This article attempts to establish an intensive utilization model of fly ash that includes technology, economy, and environment, in order to provide an analytical tool and decision-making basis for the resource management of fly ash.

2. The Practical Challenges in the Resource Utilization of Fly Ash

2.1 Production-Extraction Discrepancy and Imbalance in Utilization Pattern

The first major challenge currently faced in the resource utilization of fly ash is the structural imbalance between the production and emission scale and the absorption capacity. Take the Ningdong Energy Chemical Base as an example. In 2019, the total weight of general industrial solid waste generated in this area reached 19.42 million tons, accounting for 34% of the total industrial solid waste in Ningxia Hui Autonomous Region at that time. However, its comprehensive utilization rate remained stable at approximately 31.7%. While in places like Daqing City, before this, records showed that the overall utilization rate of fly ash in the entire city was only 27.24% in 1998, which was much lower than the national average of 40%.

From the perspective of utilization methods, the utilization of fly ash exhibits significant path dependence. Road construction and building materials account for a large proportion of the utilization volume, with road construction alone accounting for 62.2%. This single utilization method makes the absorption of fly ash completely dependent on the speed of local infrastructure construction. When the construction market in a certain area becomes saturated or investment decreases, it will lead to a narrowing of the channels for absorbing fly ash.

2.2 Insufficient utilization of hierarchy and value mining

Another dilemma in the resource utilization of fly ash is the mismatch between "quantity" and "quality". A large amount of fly ash is used for low-end landfill, low-grade building materials, etc. The cementitious activity, micro aggregate effect, and chemical composition value in fly ash have not been fully utilized. The situation of low-level utilization is due to both technical and market reasons.

Technically speaking, there are various types of coal used in coal-fired power plants in China, and there are significant differences in coal quality. In addition, the different types of coal mills cause significant changes in the particle size, loss on ignition, and chemical composition of fly ash, which cannot meet the requirements for raw material stability in high-end utilization. In terms of the market, fly ash belongs to low value bulk materials, and its economic transportation range is relatively small. Cross regional circulation will be limited by high logistics costs. The operation of the first special train for the transportation of fly ash resources from Ningdong Base occurred under such circumstances.

2.3 Discrepancy between Policy-driven Actions and Market Responses

The country has introduced a large number of preferential policies for the comprehensive utilization of fly ash, such as tax reduction, tax exemption, low-interest loans and free supply of fly ash. However, many problems have arisen during the actual implementation process. The policies have not been well implemented and there are insufficient incentive measures. Some local governments do not attach great importance to the comprehensive

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utilization of fly ash. There is also a lack of good communication and collaboration among various departments, making it difficult to achieve the goal of extensive utilization of fly ash.

What is more worthy of attention is that the current policy framework overly emphasizes "encouraging utilization" while neglecting "limiting emissions". Although some places have begun to implement a gradient charging system for solid waste disposal, the charging standards are not high, and they do not adequately consider the environmental external costs caused by the treatment of fly ash, thus leaving the ash-disposal enterprises without much motivation to fundamentally reduce emissions and actively seek resource utilization.

3. Construction of The Intensive Utilization Model

The model of intensively utilizing fly ash resources proposed in this article is based on the theory of circular economy and full life cycle management. The term "intensification" has three meanings: Firstly, the resource utilization rate is the highest, that is, every piece of fly ash should be utilized to maximize the economic benefits and environmental benefits; Secondly, the system coordination is the best, ensuring the mutual coordination among all the links from the emission of fly ash residue, transportation and transmission, processing and processing, to the final application; Thirdly, the risk prevention ability is the strongest, meaning that potential environmental risks can be measured and controlled at any time throughout the entire process, and they can be limited within an acceptable range.

The model architecture is composed of three core subsystems:

First, the source reduction subsystem. From the perspective of circular economy reduction, intensive utilization should start from the source of fly ash production. There are mainly three aspects: First, optimize coal blending, that is, mix different types of coal; second, strengthen coal washing to remove harmful substances before combustion; third, improve combustion technology to increase combustion efficiency and reduce the content of unburned carbon. Source reduction is not merely a reduction in quantity, but a purification in quality. Through the purification process during combustion, a more stable and more active fly ash is obtained, thereby creating conditions for subsequent high-value utilization.

Second, the process diversion subsystem. According to the grade of the fly ash, it is utilized in a graded manner, achieving the principle of "using high-quality ash for high-quality applications and low-quality ash for general applications". The method of stepwise utilization is adopted. The first grade of fly ash (with fine particle size, low loss on ignition, and high activity index meeting the high-standard indicators) is used as a blending material for high-performance concrete and a mixed material for high-grade cement; the second grade of fly ash is used to manufacture general building materials and road construction materials; the low-quality fly ash is used as backfill material and soil conditioner. This ensures neither "wasting good resources" nor "overusing poor resources".

Third, the terminal value-added subsystem: In addition to absorbing traditional building materials, it explores new high-value utilization methods. It extracts valuable elements such as aluminum and silicon from building materials to produce alloy materials; produces new green materials like geopolymer; and uses them as environmental functional materials for waste gas and wastewater treatment, etc. Terminal value-added means breaking through the old routine of traditional building material absorption and creating a multi-level and multi-channel utilization situation.

Based on the four aspects of technical feasibility, utilization volume, economic benefits, and environmental protection outcomes, after conducting a comparative evaluation of the main methods for resource utilization of fly ash, the following hierarchical characteristics will emerge:

The first level is the major basic utilization destinations, such as cement admixtures, concrete additives, and road construction projects, etc. These destinations have a high level of technical maturity, consume a large amount of waste (often exceeding 60% of the total utilization volume), and the cost of individual utilization is relatively low. The added value of each utilization link may not be particularly prominent, but due to the large-scale utilization, it forms a stable pressure buffering device.

The second level is what is called the "mid-range value-enhancing approach", such as the production of fired bricks, aerated concrete blocks, and 陶粒 (pottery clay particles). These approaches have certain quality requirements for fly ash. The products have some added value and can partially replace traditional clay bricks and other materials， featuring energy conservation and waste utilization.

The third level is high value-added innovative technology, such as converting fly ash into aluminum oxide or aluminum silicon alloy, as well as manufacturing molecular sieves, adsorbent materials, etc. This technology requires high technological content and significant investment, but each ton of fly ash can create several times or even ten times more value. The new process of "aluminum silicon co utilization" developed by Mengtai Group can directly produce aluminum silicon alloys from fly ash, which is an important step towards achieving high value-added utilization.

It should be noted that choosing a resource utilization method does not mean simply "abandoning low-level resources and focusing on high-level resources". Efficient management should establish a reasonable gradient between different levels, achieve overall reduction through extensive absorption, obtain overall benefits through intermediate improvements, and promote technological innovation and promotion through high-level breakthroughs. These three aspects are not mutually exclusive, but complementary to each other. Task: Rewrite the following paragraphs into more natural expressions while maintaining accuracy in facts, terminology, and length (± 10%), and reducing traces of artificial intelligence. The evaluation of the benefits of centralized utilization mode requires the establishment of a quantifiable accounting system. According to the boundary of the thermal power plant system, it includes "fly ash generation pretreatment transportation utilization as a substitute". The baseline scenario is "fly ash landfill disposal+traditional raw material production", while the project is "fly ash resource utilization+raw material substitution to achieve cost savings".

Emission reduction calculation follows the following formula:

$$ERy=BEy-PEy-LEy \quad (1)$$

Among them, ERy represents the carbon emission reduction in the y-th year, BEy is the baseline emission volume, PEy is the project emission volume, and LEy is the leakage emission volume. The main reason for this is the newly generated emissions during transportation.

Taking the substitution of cement clinker with fly ash as an example, the baseline emissions consist of two parts: the first is the methane emissions from the landfill of fly ash; the second is the total emissions generated during the production of cement clinker due to the decomposition of limestone and fuel combustion. The project emissions mainly involve the following aspects: the emission situation caused by the energy consumed in the pre-treatment process of fly ash; the emission status caused by transportation issues, etc. Studies have shown that for a thermal power plant with an installed capacity of 500×10^4kW, approximately 58.74 million tons of fly ash are transported to the cement plant annually, which can reduce approximately 489 million tons of carbon dioxide emissions in a year. Attention should be paid to the impact of harmful substances such as heavy metals in fly ash on the environment. Fly ash contains heavy metal components such as lead, chromium, cadmium, mercury, and arsenic. When it is recycled and reused, these substances may be released into the environment through leaching, volatilization, etc. Environmental risk control is a strict requirement for the intensive utilization model.

Risk management should cover three aspects. The first is source monitoring, which involves establishing a system capable of quickly detecting harmful components in fly ash, thus preventing fly ash with excessive harmful components from being put into the utilization process. The second is process control, where improved process parameters or solidification stabilization methods are adopted to reduce the migration ability of harmful elements. The third is terminal evaluation, where the long-term environmental impact of the finished fly ash is tracked and risk assessment is carried out. According to the research results, carbon fixation behavior can improve the migration characteristics of heavy metals in fly ash and reduce its environmental hazard.

4. Guarantee Mechanism for Model Application

The implementation of centralized mode requires technical support from multiple aspects. The first level is the breakthrough of key core technologies, mainly including online detection and classification technology for coal ash quality, low-cost activation technology, and harmful element control technology. The second level is the technical connection of the industrial chain, which matches corresponding technologies for each link of "coal ash production sorting processing utilization". The third level is standard formulation, including classification standards for coal ash products, application technical regulations, and environmental safety assessment standards. The policy design adheres to the principle of "positive promotion combined with reverse restraint". Positively, for enterprises that fully utilize fly ash, tax reduction policies are implemented, green credit is provided, land allocation is given priority, and other preferential conditions are offered; the utilization of fly ash is included in the category of green building materials for recognition, thereby expanding its market prospects. On the contrary, the intensity of collecting fees for the disposal of fly ash landfill is increased to prompt the external costs of it to be transformed internally, and the comprehensive utilization rate of fly ash should be regarded as one of the considerations for power generation enterprises to meet environmental protection standards.

The utilization of fly ash for resource recovery has faced the issue of being well-received but not widely adopted in the market. The main approaches include: taking the lead in using solid waste as raw material to produce building materials in government procurement services and key projects; establishing a quality certification and brand system for fly ash to ensure that downstream users do not worry about quality issues; and signing long-term cooperation agreements between the ash-discharging party and the ash-using party to achieve stable connection between the supply and demand sides.

5. Conclusion

This article, after a comprehensive analysis of the current predicaments in the utilization of fly ash resources, has established a model for intensive utilization under the constraints of energy conservation and emission reduction. The general idea of this model can be summarized as: "Start from the small scale - control the quantity and quality of fly ash generation at the source; start from layered treatment - separate and reuse according to the grade; aim for value addition - seek high prices on the basis of extensive digestion; take green as the bottom line - prevent environmental risks throughout the process." Intensive utilization is not the sum of various technical routes, but the superposition of spatial, temporal and functional layers of utilization approaches at different levels. Bulk consumption of building materials is the basic foundation, breakthrough of high-value technology is the key point, and strict control of environmental risks is the red line that cannot be crossed. All three elements are indispensable to achieve a win-win situation of economic benefits, social benefits and environmental benefits in the utilization of fly ash resources.

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