energies

Article

Recycling of Coal Fly Ash as an Example of an Efficient Circular Economy: A Stakeholder Approach

Oksana Marinina [1,*], Marina Nevskaya [1], Izabela Jonek-Kowalska [2], Radosław Wolniak [2] and Mikhail Marinin [1]

[1] Faculty of Economics, Saint Petersburg Mining University, 199106 Saint Petersburg, Russia; nevskaya_ma04@spmi.ru (M.N.); Marinin_MA@pers.spmi.ru (M.M.)
[2] Department of Economics and Informatics, Silesian Technical University, 41-800 Zabrze, Poland; Izabela.Jonek-Kowalska@polsl.pl (I.J.-K.); radek_wol@o2.pl (R.W.)
* Correspondence: Marinina_OA@pers.spmi.ru; Tel.: +7-911-295-96-67

Abstract: The scale of waste formation from coal-fired generation is significant and tends to grow steadily in the context of the global use of coal for power production. This paper covers the problems and current opportunities for recycling coal fly ash waste from coal generation from the position of a stakeholder approach, namely, identification of the main participants and determination of the effects for economic agents in coal fly ash recycling projects. Based on the method of economic modeling and the empirical assessment of project efficiency, this paper presents alternative patterns of stakeholder interaction in the process of implementing coal fly ash recycling projects, estimates the effects of using coal fly ash, and identifies conflicting interests between stakeholders. It is shown that the reason behind the low interest of the Russian private sector in the processing of coal fly ash is the lack of stimulating market mechanisms for manufacturers and consumers of ash products, the high risks of implementing recycling projects based on clean coal technologies, and low environmental payments for commercial companies.

Keywords: coal fly ash; coal combustion products; coal-fired power plants; circular economy recycling efficiency; stakeholder interaction; environmental and social benefits

Citation: Marinina, O.; Nevskaya, M.; Jonek-Kowalska, I.; Wolniak, R.; Marinin, M. Recycling of Coal Fly Ash as an Example of an Efficient Circular Economy: A Stakeholder Approach. *Energies* **2021**, *14*, 3597. https://doi.org/10.3390/en14123597

Academic Editors: Idiano D'Adamo and Sergio Ulgiati

Received: 24 April 2021
Accepted: 13 June 2021
Published: 17 June 2021

1. Introduction

The relevance of coal fly ash (CFA) recycling is explained by the scale of global coal-fired generation and the trends of consequent waste formation. Coal fly ash (CFA) produced after coal is burned in a power plant to generate electricity. These materials, known as coal combustion products (CCPs), can be used as products or raw materials (primarily in the construction industry for the latter). The solids included in CCPs are fly ash, bottom ash, and boiler slag [1,2]. Fly ash is a very fine powder-like particle, ranging in color from tan to black. It is usually collected by electrostatic precipitators that prevent it from being released through the smokestacks of the power plant. Coal fly ash is mixed with water and transported in the form of pulp to an ash dump. Coal fly ash is the main solid waste in coal-fired power plants, and the volume of this ash can reach 90 wt % of the total ash volume [1,2].

Globally, coal remains the dominant fuel for power production. The share of coal-fired generation in the world energy balance is currently 36.4% [3,4]. According to most forecasts, by 2040 the share of coal-fired generation will have decreased to 20–25% [3]; however, in terms of electric output, it may remain at the current level, given the use of coal in a number of countries in the Asia-Pacific region (e.g., Vietnam and China), along with Russia [5,6].

In Russia, the situation with CFA recycling is not in line with the global trends in the field of waste management, which based on the application of the 5R principle (reducing waste, reusing, and recycling into secondary resources) [7–10]. The problem of numerous ash dumps with accumulated and annually generated industrial waste, occupying more than 28 thousand hectares of the country's land, affects both the environmental and economic security of Russia. As of the beginning of 2017, the amount of accumulated coal fly ash in Russia exceeded 1.5 billion tons. When taking into account annual CFA formation in the range of 22–23 million tons, by 2045, this figure may exceed 2 billion tons. The processing of ash waste in the Russian Federation amounts to less than 10% of what is produced, which is significantly below the level obtained in economically developed countries [11–14].

The experiences of other countries, such as the USA, Germany, China, and Poland, proves that the level of coal fly ash processing can be increased up to 70–80% due to the state policy of transforming a linear model of economy into a circular one with the purpose of involving a wide range of stakeholders, arousing the interest of economic agents in waste processing, increasing product life cycles, and forming value chains.

The purpose of this study is to estimate stakeholder results in CFA recycling projects. To achieve this goal, a combined heat and power (CHP) plant of a mining company is selected for analysis, where the plant plans to implement a CFA disposal project. The study focuses on the following tasks:

- The first task is the development of alternative scenarios of stakeholder interaction in the process of implementing CFA recycling projects;
- the second task is estimating the effects of CFA use and identifying conflicting interests between stakeholders;
- the choice of the research topic is due to the lack of scientific research on the problem of assessing the benefits of the stakeholders of recycling projects. Most scientific works [15,16] are devoted to the technical part of the problem of waste processing and use. A significant part of the research [17–19] covers the issues of environmental damage from pollution of the territories of sludge collectors, harm to public health. As such, in this paper, an attempt is made to consider an example of a circular economy business model and identify the possible effects for stakeholders.

1.1. Relevance of Coal Fly Ash Recycling

On the one hand, when accumulated in the form of dumps, CFA represents an environmental hazard, where CFA dumps exert a negative impact on human health, ground and surface water, the atmosphere, plants, and animals, as well as inducing the alienation of lands that are almost irrevocably withdrawn from productive use. On the other hand, coal fly ash is a valuable secondary source for raw materials [20–22], e.g., the combustion of one ton of coal from the Donetsk Basin releases about two grams of beryllium (a strong allergen and carcinogen) into the atmosphere, where the content of which in the air near the CHP plant exceeds the maximum permissible concentration (MPC) by 2–3 times. At the same time, beryllium is in high demand in the aircraft missile, space, and nuclear industries [23].

The concentrations of arsenic and mercury in the air of some boiler houses and CHP plants are 100–500 times higher than the permissible levels. The level of background radiation near large coal-fired CHP plants is often higher than that near nuclear power plants, i.e., 45–80 μR/h (the normal level is 10–14 μR/h) [24]. Coal contains radionuclides, such as uranium, radium, thorium, and radon, along with radioisotopes of polonium, lead, and potassium. The annual death risks near coal-fired CHP plants are almost 1000 times higher than those near nuclear power plants. The contribution of radionuclides into these risks is at least 15% [22].

At the same time, the experience of scientific research and achieved practical results, both in Russia and worldwide, shows that the ash and slag from CHP plants, in case of their effective utilization, serves as a significant source of raw material for various sectors of the economy [25].

Coal ash can cost significantly more than coal itself since it contains a variety of valuable elements, including gold, vanadium, cadmium, and indium. Kuzbass ash contains scandium (50 g/t), yttrium (160 g/t), zirconium (2300 g/t), lanthanum (165 g/t), cerium

(236 g/t), and other rare earth metals. One gram of scandium on the world market costs more than 4–6 USD/g. The ash of Kuzbass coal typically contains 0.1–0.3 g/t of gold, and even up to 0.4 g/t (45–50 USD/g) [26].

One ton of captured ash residue can contain tens of kilograms of germanium, e.g., scandium can be obtained from the coal ash of the Borodino coal mine in Russia [23]. Coals from some deposits in the east of Russia (Primorsky Krai, Sakhalin, Buryatia) are rich in germanium. Rare earth metals (REM), which are well known for their unique properties, can also be found in coal, but under conventional technologies they are considered harmful contaminants. The extraction of rare earth metals from coal and ash would allow the enhancement of environmental sustainability for coal generation, and, at the same time, provide the industry with strategic raw materials.

One ton of coal ash from the Kemerovo region can contain up to one kilogram of uranium, and one ton of lignite from the US can contain more than three kilograms of uranium. In the USSR, at the beginning of the atomic project, uranium was mined from coal deposits in Russia, Kazakhstan, and Kyrgyzstan. In the process of coal combustion, about 90% of radionuclides remain in the slag; however, in Russia, more than 37,000 t of uranium and thorium has been emitted into the atmosphere with the production of fly ash [23].

The world-wide scale of coal-fired power generation and the trends of waste formation indicate the need for a comprehensive solution to this problem. Globally, coal remains the dominant fuel for power production. The share of coal-fired generation in the world energy balance is currently 36.4% [3,6].

The IEA predicts insignificant dynamics regarding a decrease in coal consumption. As such, the problem of recycling coal fly ash remains relevant for many countries of the world (Figure 1.) [3].

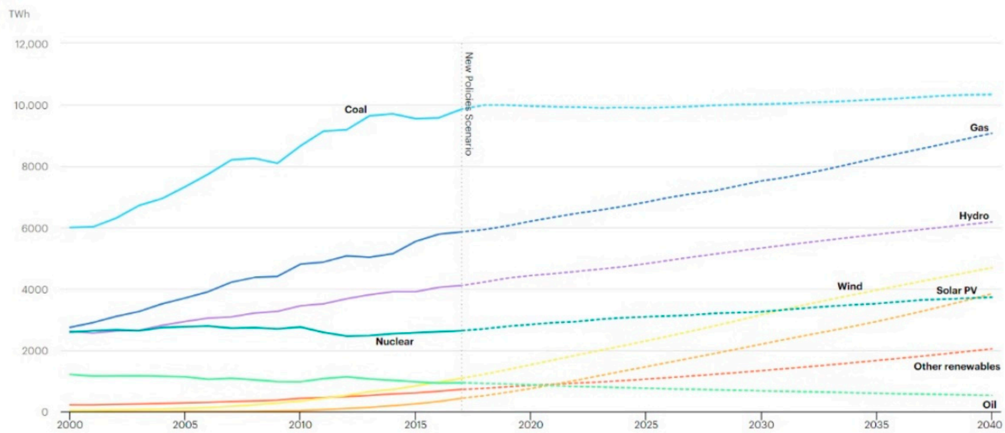

Figure 1. Forecasts regarding coal-fired generation [3].

Gas and coal technologies remain the cheapest in terms of power plant construction and operation. According to [27], the levelized cost of electricity (LCOE) for a coal power plant is 67–91 USD/MWh. For a combined cycle plant operating on natural gas, it is 64–91 USD/MWh. For a brown coal power plant, the cost is 75–88 USD/MWh. As for renewable energy technologies with low emissions, the LCOE for wind farms was found to be 85–121 USD/MWh. For solar photovoltaic power stations, the cost was found to be 118–172 USD/MWh. This means that modern coal generation, which is highly efficient and environmentally friendly, is 1.3 times cheaper than wind power and 1.9 times cheaper than solar generation [28]. As such, there is definitely a place for coal in systemically developing "clean energy", as clean coal generation has significant competitive advantages over renewable energy technologies in terms of the costs of electricity and heat generation [27–29].

For a long time, European countries have been declaring their desire to abandon the use of fossil fuels, and primarily coal [30]; however, according to 2020 data from the non-governmental organization "Europe Beyond Coal", which monitors progress towards a carbon-free Europe, the situation is not so straightforward. In particular, in Germany, which is one of the leaders in the "energy transition", about 15 coal-fired power plants with a total capacity of almost 20 GW will remain in operation even after 2030. In a number of European countries, there are ongoing discussions on the issue of shutting down coal generation and the possible economic consequences of this decision [31,32].

Globally, there is a huge degree of ash utilization. The leaders in this field are UK and Germany (almost 100%), Japan (96%), and France (90.5%), where ash waste is almost completely processed due to government policies that stimulate waste recycling [33]. For EU-15, this represents about 65 million tons, and EU-25 represents about 95 million tons. A large amount of CFA in Europe is used for cement production, where about 1.936 million tons of CFA is used annually [34]. In the USA, the problem of coal fly ash processing has been brought under legislative control since 2000 [35,36]. Eight years later, CFA recycling in the country has reached 70% of that which is produced [37,38]. China recycles more than 80% of waste from CHP plants. The transportation of ash to the consumer is carried out free of charge. In Poland, the enactment of laws regulating the process of waste management, including coal fly ash materials, has made it possible to increase the level of their reuse by 3.5 times in the course of 20 years, reaching up to 80% of that produced. Polish legislators have significantly increased the cost of land allocated for ash dumps, which has made them economically unprofitable for CHP plants [11,39,40].

In Russia and Africa, the rates of recycling are 10% [9,38]. The problem of numerous ash dumps with accumulated and annually generated industrial waste, occupying more than 28 thousand hectares of Russian land, affects both the environmental and economic security of Russia [12]. According to various expert estimates, investments in the construction of one ash dump, meeting all the applicable requirements, range from 2–4 billion RUB, and sometimes even up 10 billion RUB, while the cost of storing a single ton of CFA constitutes up to 5–7% of heat and electricity production costs [9].

The processing of coal fly ash in the Russian Federation amounts to less than 10% of that produced, which is significantly below the levels obtained in economically developed countries; however, since the 1970s, more than 25 normative documents (government standards) have been developed in order to regulate the use of coal fly ash in construction and the production of building materials [41]. Despite the reform of the waste management system and the transition to new principles of state environmental regulation, Russia still lags far behind EU countries in the transition to a new circular economy structure in this regard [42].

1.2. The Modern Concept of the Circular Economy and Stakeholder Theory

The growing public interest in the problem of sustainable development, both in the broad sense (at the macro level) and in the narrow sense (company or territory of presence), led to the rapid development of the stakeholder concept in the 1980s. This strong external factor forces companies, firstly, to reconsider the goals of activities, public relations, and, secondly, to transform the developed strategies for greater sustainability.

Stakeholders are potential beneficiaries who at the same time also run risks as per a company activities. Stakeholders include owners, buyers, suppliers, workers, the local community, various social groups, and the state. Depending on the specifics of the company's activities, stakeholders are classified into different groups according to the degree of their interest. The first category is of the highest interest, where, without them, the company cannot function in the future (investors, personnel, customers, and suppliers). The second category does not have a significant impact on the activities of the company (media, communities) [43].

Key provisions of the modern stakeholder theory include the following [43,44]:

- Companies interact with a large number of groups and individuals (stakeholders);

- stakeholders can be inside or outside the company and they influence the adoption of decisions;
- stakeholder theory studies the nature of the interaction of individuals: management of the interaction and its effects;
- the interests of all stakeholders potentially have the right to be considered and satisfied;
- stakeholder theory can be used in management when making management decisions.

The identification of stakeholder interests shows that a stakeholder is the owner of "some" resources for the company and consumes "some" of results of it. Different interpretations of resource theory can explain the nature of interests. Stakeholder behavior determine the methods of exerting influence in order to maximize the satisfaction of their interests. The possibility of implementing a certain strategy is directly related to the nature of resource relations.

Coordinate all interests and actions between stakeholders is impossible. As such, it is necessary to choose the most important ones and decide whose interests are really worth considering. Thus, the key issues are identifying stakeholders and determining their importance [43].

The focus of stakeholder theory is value engineering. Problems of defining and measuring the social and economic values created by the company do not have a satisfactory solution. The existence of a wide and unlimited range of stakeholders, whose interests must be taken into account, complicates the decision [45]. The relationships between stakeholders and the company are complex, versatile, and predominantly non-financial in nature, but they are focused on a resource basis [46].

The following questions are to be reviewed: Which components of the economic, environmental and social spheres should be measured? How should one determine the results? How should one choose weights and take into account the industry specifics of companies? Finally, how should the activities of companies be reflected in the indicators of corporate sustainability?

The modern concept of the circular economy stands on ideas formulated in various fields of scientific knowledge [47]. Its emergence is attributed to the period of the 1960s and 1970s, when the priority of reorganizing the processes of material movement over the improvement of production technology was recognized. K. E. Boulding gave a report on the need to limit the consumption of natural resources and create an economy similar to closed-loop ecological cycles [48].

In the 1980s, within the ecological paradigm, the concept of natural biological regulation (based on the theory of resource cycles) became widespread [49]. By the early 1990s, the notion of "industrial metabolism" was proposed as a set of human-controlled physical processes that transform raw materials, energy, and labor resources into finished products and waste that enter the environment in a more or less stable state (i.e., without causing harm to it). The theory of resource cycles and the concept of industrial metabolism laid the foundation for industrial ecology as a new subject area of scientific knowledge and practical activity.

Institutional arrangements of the circular economy are considered in the business models of the "functional economy", which implies the creation of maximum use value for a long time with minimum consumption (or preservation of their physical reserves) of resources and energy [50].

Sustainable development based on the circular economy has a direct economic and technological justification, in the core of which lies the "5 R" principles:

- reduction of energy and material consumption (reduce);
- replacement of non-renewable resources with renewable ones (replacement);
- recovery of required components from recycled waste (recovery);
- recycling of waste (recycling);
- reuse of products.

In terms of an economy, recycling allows things of value to be obtained from waste and provides new business opportunities for innovative companies which have a positive impact on society and the environment [10].

A circular economy is a combination of business models that loop, slow down, and narrow product and material flows, ultimately allowing the preservation of natural resources [39]. The extension of a product life cycle, which is inherent to a circular economy, involves the formation of value chains [40] in the process of the production, consumption, transfer for further processing, and consumption of material resources and products, which leads to certain economic, social, and environmental effects.

For example, according to TNO estimates (Netherlands Organization for Applied Scientific Research), the overall annual effect of the circular economy in the Netherlands amounts to EUR 7.3 billion and 54,000 additional workplaces. In the UK, according to the WRAP report [42], development of circular economy will create 500,000 workplaces in the country, and the economic benefits will reach EUR 12 billion. Due to the development of a circular economy in Sweden, CO_2 emissions have been reduced by 70% [51,52]. Currently, cement production is considered to be responsible for approximately 7.4% of the global carbon dioxide emission (2.9 Gtons in 2016). Furthermore, CO_2 emissions can be reduced by concrete carbonation with coal fly ash [53].

European initiatives to transform linear economic models into a circular ones include sets of documents to involve a wide range of stakeholders: EU directives on waste management (COM (2019) 904), green employment (COM (2014) 446), and other environmental initiatives (COM (2014) 440) are considered, along with EU roadmaps for resource preservation (COM (2011) 571) and the Europe Resource Efficiency Platform (EREP) [54]. The set of initiatives defines an action plan that covers the entire economic cycle, from the production and consumption of products to the waste disposal and the market for secondary raw materials, and also involves changes to legal regulation of waste management.

According to [55,56], the effects that companies gain from the introduction of circular business models lies in increasing innovativeness and additional competitive advantages, the emergence of new sources of profit, increasing customer loyalty, and strengthening relationships with partners throughout the entire value chain.

In particular, the economic effect of CFA recycling is expressed by the reduced consumption of raw materials and energy resources, formation of new sectors of circular economy based on CFA recycling, and increase in the number of workplaces, and, as a consequence, decreases social tension in these regions [57,58].

In Russia, despite the widespread acceptance of circular economy ideas in the scientific community, they are still insufficiently embraced in business and government contexts. The main factors behind this situation are the inert nature of the existing economy model based on raw materials export [59], low tariffs for waste disposal and absence of agents interested in reducing waste generation [48], technological inferiority, low investment attractiveness, imperfect legislation [54], competition with producers using natural resources, low interest of large businesses in recycling their own waste, and absence of a real mechanism for attracting small businesses [60]. Thus, a significant part of the problem associated with the transition to circular economy in Russia lies in the field of institutional regulation, providing engagement and motivation for economic agents.

The use of the stakeholder approach is based on the following premises [61]: The extension of a product life cycle and the formation of value chains often requires involvement with additional participants (interested parties) to the process; the effects of value chain formation, particularly in recycling projects, cannot always be monetized and taken into account in commercial estimates; the stakeholder approach allows the estimation of various effects or "losses" from the perspective of not only direct participants of the project, but also of a larger number of stakeholders (the public, municipalities, company employees, etc.) [62].

2. Materials and Methods

The research methodology of this work includes the following steps:

1. The first step is the substantiation and commercial evaluation of economic efficiency for different scenarios of CFA recycling project based on existing methodological guidelines;
2. the second step is the identification of key stakeholders of the project.

The solution to the tasks posed in the paper is based on the application of several theoretical and methodological approaches, i.e., a current version of the sustainable development concept and a stakeholder theory of external (environmental and social) effects. The research design involves the collection, processing, and verification of the obtained results (Table 1).

Table 1. Research design. Source: designed by the authors.

Data Collection	Data Analysis	Credibility of Research
– Data from the comprehensive plan for increasing utilization of solid fuel combustion products at coal CHP plants and boiler houses; – Case study: mining company with a CHP plant in operation that has accumulated CFA waste.	– The analysis of state effects of CFA recycling; – evaluation of commercial effects of CFA recycling (case study); – analysis of stakeholder effects (environmental and social); – graphic design of diagrams for recycling production chains; – institutional, economic, and legal analysis.	Opponent method: – regulation documents and standards in the field of industrial waste processing; – reports of Russian and international agencies (OECD, IEA, and CEWEP); – research papers on the topic of CFA recycling.

2.1. Evaluation of Commercial Effects of CFA Recycling

The study presents an aggregated estimation of commercial efficiency indicators for a project utilizing coal-water slurry technology (CWS) for CFA disposal.

Coal water slurry is a liquid fuel obtained by mixing crushed coal, water, and a plasticizer. It is used at heat generating facilities, mainly as an alternative to natural gas, heavy oil, and coal. CWS allows for a significant reduction in the costs of heat and electricity production. Conceptually, it is a part of "clean coal" technology [63].

To substantiate the project of recycling CFA waste from the boiler houses of the heat and water supply department of "A" mining company, based on commercial evaluation, four groups of data were applied:

- revenue from implementing the project of CWS production and use at the CHP plant;
- current production costs of the output for domestic consumption;
- investment costs for the purchase of basic equipment for CWS production, reconstruction costs for the department of heat and water supply;
- sources and terms of financing (use of equity capital and (or) attraction of loans).

The sources of income in the project of recycling CFA from the boiler houses of the heat and water supply department of "A" mining company are the following:

(1) cost savings for the purchase of raw materials for the needs of the boiler house of the heat and water supply department of "A" due to the use of a new type of CWS fuel produced from the coal fly ash of the enterprise;
(2) savings on operational costs due to reduction of expenses that are associated with the maintenance and operation of fixed assets and other property intended for environmental purposes, as well as a reduction of environmental payments.

The methodology for assessing the efficiency of the project of waste disposal through its processing and use as a fuel for the "A" CHP plant was based on the evaluation of the net present value. Increases in cash flow due to the reduction of payments for environmental pollution and the reduction of costs for disposal, maintenance, and accumulation of coal fly ash were considered miscellaneous income.

2.2. Analysis of Stakeholder Effects, Limitations, and Expectations

The section includes the analysis of the stakeholder effects and graphic design of the diagram for a recycling production chain. This section of the study demonstrates steps where additional stakeholders could be involved in order to increase the interest of commercial companies in the processes of CFA recycling. The diagrams show direct and inverse connections between participants in order to identify contradictory interests between stakeholders, imperfections of legislative regulation, and possibly unaccounted costs and effects in the recycling process. The opponent method is used to compare the experiences of European countries that have achieved high results in waste recycling with the results of Russian experience analysis. The analysis should either confirm or refute the suggested recommendations for improving the recycling process in Russia.

3. Results

3.1. Evaluation of Commercial Effects of CFA Recycling

A company specializing in ore extraction and processing possesses a boiler house for domestic use and produces 239,896.26 t of CFA, where the annual amount of waste formation from coal combustion is 7008.0 tons.

The company sets an objective of efficient CFA recycling.

The options for secondary CFA use include the following:

- coal water slurry (CWS) production [63] with the purpose of partial substitution of the conventional fuel (coal) with the alternative in the department of heat and water supply;
- use of CFA for quarry reclamation;
- use of CFA as a man-made soil for road construction.

At the initial stage, the company will have to assess CFA properties and quality, which will require geotechnical surveys. CFA geotechnical surveys include topographic surveys, reconnaissance surveys, well drilling, ash sampling, laboratory examination of samples, and office work.

The next step involves technical and economic substantiation (TES) of each separate direction of use, with due consideration of the following:

- technological feasibility of project implementation (availability of the necessary equipment in the market);
- marketing conditions for selling CFA products or need (demand) for domestic consumption (use) of CFA products;
- strategic alternatives of the company based on the assessment of economic efficiency of the projects, taking into account the risks of the conflict of interests between interested parties, changes in the requirements of environmental legislation, etc.

3.2. The Effects of CFA Recycling for the Company Include the Following: Cost Savings on the Purchase of Raw Materials

Calculations prove that the use of a CWS unit cannot rely solely on the accumulated coal fly ash waste to maintain usage of the production capacity for the boiler house. The data in the table are aggregated and do not take waste differentiation by volume into account based on energy intensity indicators by zones.

Analysis of structure indicators of CWS volumes in dependence to specific consumption shows that under a specific CWS consumption of 2.56 Gcal/t, the accumulated waste will last for 2.7 years of boiler house operation without using any purchased fuel. Under a specific CWS consumption of 3.27 Gcal/t, the accumulated waste will last for 3.5 years (Table 2).

Table 2. Structure indicator of CWS volumes in dependence to specific consumption rates. Source: designed by authors using [64].

Indicators	CWS Consumption (t)	Share in the Structure of Accumulated Coal Fly Ash Waste (%)	Limiting Condition of CWS Use with Regard to the Amount of Accumulated Waste
Specific CWS consumption of 2.56 Gcal/t	87,670.31	36.6	Useful life of waste is 2.7 years
Specific CWS consumption of 3.27 Gcal/t	68,634.86	28.6	Useful life of waste is 3.5 years
Average energy output of the heat and water supply department in 2014–2018 (Gcal)	224,436		
Amount of accumulated waste (t)	239,896.26		

Taking into account the limitations with regard to the amounts of accumulated waste, the options of combining primary fuel in the form of coal and CWS from coal fly ash are worth considering.

Cost savings resulting from the implementation of the complex and partial substitution of conventional fuel (coal) with CWS are based on the differences between their costs and amounted to USD 120,400 here (Table 3).

Table 3. Technical and economic indicators of the project. Source: designed by authors using [64].

Indicators	Measurement Units	Coal	Coal + CWS Project
1. Coal amount	t	57,762.0	53,083.68
2. Heat output, coal	Gcal	224,436.0	206,496.0
3. Coal price	USD	41.25	41.25
4. Coal cost (p.1 × p.3)	Thousand USD	2382.6	2189.7
5. CWS amount	t	-	7008
6. Heat output, CWS	Gcal	-	17,940.48
7. CWS price	USD/t	-	10.35
8. CWS cost (p.5 × p.7)	Thousand USD	-	72.5
9.Cost savings ($p.4_{coal} - (\times p.4_{coal+CWS} + p.8_{coal+CWS})$)	Thousand USD	-	120.4

Economic indicators of the CWS production project are characterized by high efficiency due to a considerable difference in the prices of CWS (10.35 USD/t) and purchased coal (41.25 USD/t) from coal deposits.

3.3. The Effects of CFA Recycling for the Company Include the Following: Savings on Operational Costs Due to the Reduction of Maintenance Expenses

Operational costs associated with the maintenance of coal fly ash accumulation process at the central boiler house reach 64,296.2 USD/year, with coal fly ash removal being responsible for the major share, i.e., 59.81% (Table 4).

Table 4. Operational costs of CFA disposal and infrastructure maintenance. Source: designed by authors using [64,65].

Cost Elements	Annual Costs (USD) [64]	Cost Structure (%)
Rent payments for the land allocated for coal fly ash collection system	583.6	0.91
Maintenance coal fly ash collection system	25,254.0	39.28
Costs of water for coal fly ash removal	38,458.6	59.81
Total	64,296.2	100

Annual decreases in the amounts of CFA at the waste dump reduce the semi-variable costs of maintenance (transportation, storage, etc.); however, complete reduction of these costs is not possible unless the level of zero-waste production is reached.

Environmental payments for waste disposal within the established limits amount to USD 587.3. This is a very small amount, which provides no incentive for companies to implement environmental measures.

3.4. Analysis of Stakeholder Effects, Limitations, Expectations

Analysis of the state effects model of CFA recycling and the effects of commercial companies, exemplified by company "A", allow the development of diagrams for recycling production chains and the identification of the interests and expectations of stakeholders (Figures 2–4 and Table 5).

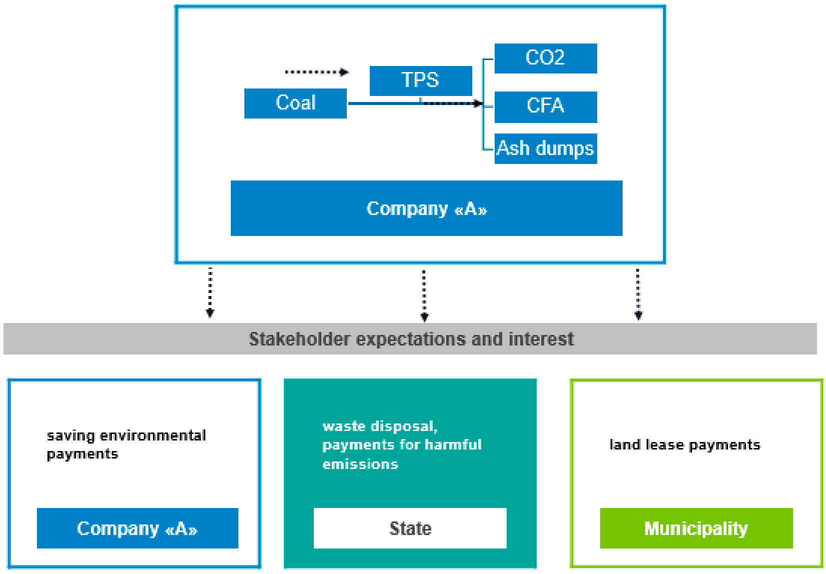

Figure 2. Diagram of the waste formation process, company payments to the state, and municipal budgets. Source: designed by authors.

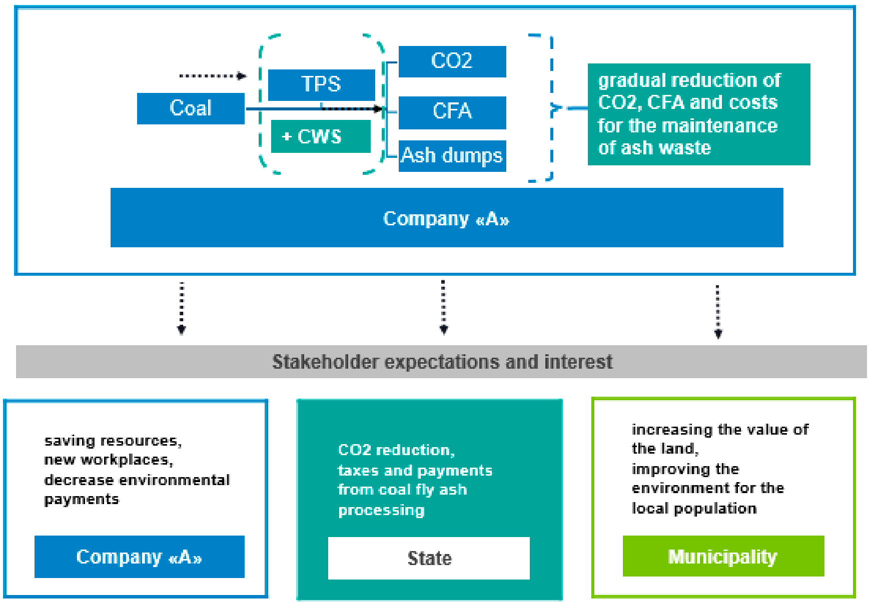

Figure 3. Recycling scenario within the scope of the CFA production company. Source: designed by authors.

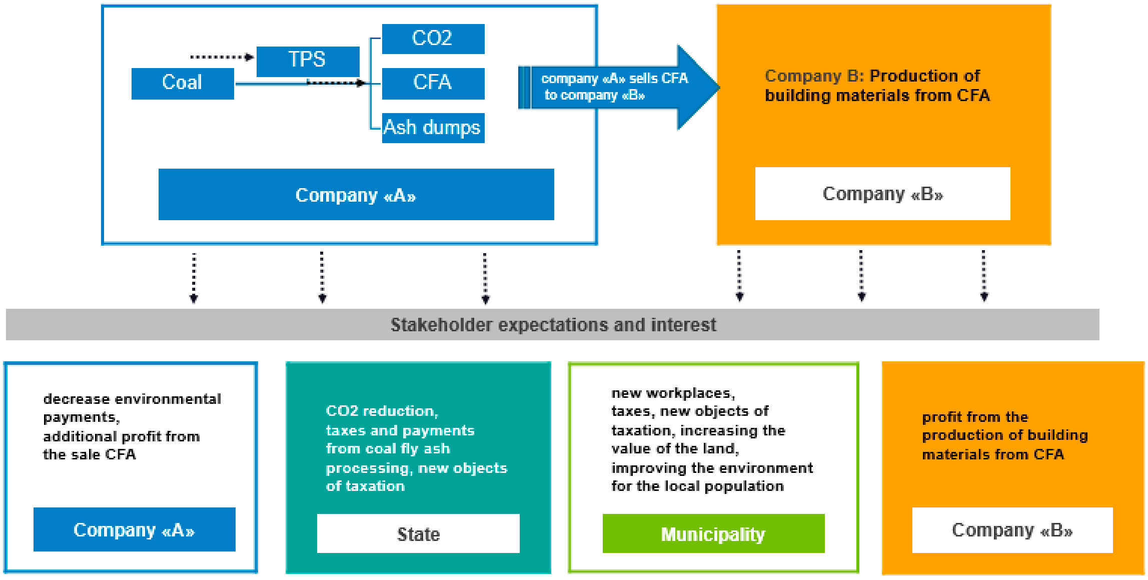

Figure 4. Recycling scenario outside the scope of the CFA producing company. Source: designed by authors.

Table 5. Limitations regarding stakeholder expectations for CFA recycling. Source: designed by authors.

Key Stakeholders	Recycling Scenarios		
	Base Scenario	**Recycling within the Scope of the Company (Suggested Scenario of the Case Study)**	**Recycling Outside the Scope of the Company**
Company	-	Resource preservation; ability to participate in state environmental programs; project of CFA disposal	Reduced payments for emissions of harmful substances and waste disposal; additional income from the sale of raw materials
Municipality	Rent payments for land allocated for CFA	Reclaimed lands; additional tax revenues of the local budget	New leaseholders and taxpayers; infrastructure of the territory
Population	-	Additional workplaces	Additional workplaces
State	Environmental payments for emissions of harmful substances and waste disposal	Meet obligations for the reduction of CO_2 emissions; additional tax revenues (corporate and personal income tax) for the federal budget	Meet obligations for the reduction of CO_2 emissions; new taxpayers and additional budget revenues; budget fund savings (grants, subventions, and subsidies)
Medium- and small-sized businesses	none	none	Profit; participation in the programs of territorial development; new technologies

4. Discussion

The resource potential of CFA may change with the alteration of external factors as it largely depends on the technology, demand, availability of alternative resources, and environmental policy. Various structures may be interested in CFA use or disposal, including commercial organizations, municipalities, and public communities and individual citizens. As such, there is a need for the elucidation of methods to accommodate and formalize these different interests. The use of CFA may involve certain commercial and environmental risks.

The considered examples of recycling projects prove the efficiency of using CFA for the state, municipal districts and commercial organizations. A comprehensive plan to increase the disposal of solid fuel combustion products at coal-fired CHP plants and boiler houses in Russia can become one of the starting points for the formation of national circular economy and advancement towards sustainable development goals. Considering the aforementioned effects, it should be noted that the influence of this plan is complex in its nature, affecting the economy as a whole, as well as the state of the environment and consumption processes.

The introduction of highly efficient coal dust power plants is a significant measure to reduce CO_2 emissions. In Japan, USA, Germany, Denmark, and other countries, governments, power plants, coal suppliers and equipment manufacturers have joined forces to finance research, design equipment, and develop monitoring systems in the area of clean technologies. All these efforts have made it possible for new power plants to reach efficiency percentages of 43–47%. An important advantage of these highly efficient power plants is that for each unit of generated electricity, they produce less CO_2, which will subsequently be captured. Another advantage is that in future supercritical and ultra-supercritical power plants, the losses of efficiency and resources will decrease, as well as the costs of CO_2 capture [52,66].

The economic effects from the application of each scenario can be defined as the difference between the "monetized" expectations and the costs of their implementation.

In terms of creating value chains, the recycling scenario outside the scope of the company can be considered the most promising. A weak point in this chain can be the negotiation of prices on waste as a raw material. Another problem of implementing recycling projects outside the scope of the company can be competition with the existing construction business and the production of building materials from natural resources which are available almost in every region. A weak point in the scenario with the organization of recycling within the scope of an operating company can be passivity of corporate management, since for a large entity such project may be insufficiently profitable and appealing (i.e., it is easier to pay for the waste than to engage in the implementation of new projects). In such cases, as always, the main role is assigned to the state, its policies, and interests. There is always the question of current relevance of the problem and the interest in resolving it.

In the case of CFA recycling, stakeholder interests have a significant impact on the choice of business model within the company and on the overall trend towards the circular economy.

The business models of a stakeholder-based coal fly ash recycling project follow the principles of the circular economy. They identify social, economic, and environmental benefits. The models can be applied at the early stages of project justification in combination with such techniques as the analysis of the expected monetary value (EMV) or net present value (NPV) and damage prevention techniques. These models can serve to justify management decisions based on a qualitative assessment of value for the owner, the state and other stakeholders. They also can be used by the government to develop statutory documents for tax adjusting and mechanisms to stimulate waste recycling processes.

4.1. Solving the Problem of CFA Recycling

The solution to the problem of *CFA* disposal and recycling, according to the considered models (Figures 2–4), is only possible at the state level. The state can apply fairly simple, low cost, and proven measures to develop the *CFA* market. Taking into account the Russian specifics, we can offer some recommendations (Table 6).

State regulations (Table 6) can reduce risks for entrepreneurs, stimulate the market for ash and slag waste producers and consumers, and are beneficial for the state itself as the main stakeholder in the *CFA* recycling process.

Scientists from a financial university [67] have calculated the efficiency of recycling if the state implements all measures to stimulate the *CFA* market. Successful implementation of a comprehensive plan is expected to result in positive economic and environmental effects for the energy, construction, road, and metallurgical industries. Primarily, the economic efficiency of a CHP plant operating on solid (coal) fuels will be increased, while the negative impact on the environment will be reduced.

According to preliminary estimates, the direct effects of the implementation of the comprehensive plan will produced the following results by 2035 [67,68]:

- cost savings on tariffs, i.e., USD 774.24 million (elimination of the need for additional costs of ash dump expansion (from 2020 to 2035) and associated expenses);
- revenues of energy companies from CFA sales, i.e., up to USD 64.47 million annually;
- The economic effect for the budgetary system of the Russian Federation can reach up to USD 120.16 million at the regional level and up to USD 154.72 million at the federal level.

In a case where the measures from the draft of the comprehensive plan are implemented, by 2035, the direct effect for coal-fired generation can be expected to exceed USD 1.29 billion (in 2019 prices). The budgetary effect over the same period may amount to over USD 412.58 million, USD 282.36 million of which will be paid to regional budgets. The income will primarily be provided by additional financial flows from the sales of CFA by coal-fired CHP plants and increasing marginality of products for the construction industry [67–71].

Table 6. Stakeholder risks and reasons for insufficient recycling of CFA. Recommendations for government agencies for the development of the CFA market. Source: designed by authors using [67,69,72].

Stakeholder Limitations (Risks)	Reasons	Recommendations That Can Be Made by the State
Limitations for CFA producer, including a lack of demand for products of CFA processing	Absence of state standards, regulatory and technical documents on the use of CFA in various sectors of economy	The basis for priority use of CFA, available in the region of construction works, should be laid already at the design stage of the facility; control over the implementation of these standards can be carried out through the state environmental project expertise; ability to provide support, including tax incentives for companies that process CFA, implement industrial technologies to expand CFA use, and consumer organizations that use CFA in the production of building materials, agriculture, residential, industrial and road construction.
Absence of incentives for CFA product consumers	Lack of trust in CFA properties among the consumers	Implementation of environmental education programs for the population and potential consumers of CFA
	Risks of long-term contracts	Development of a standardized long-term contract for CFA implementation; sales incentives for CFA products; preferential loans.
	Absence of technological processes of CFA use in production among consumers	Inclusion of CFA use in the list of critical technologies of the Russian Federation to gain access to subsidies and grant support
Risk of CHP plant modernization in order to reduce ash emissions or improve the quality of ash for its further use	CFA is not a by-product (CFA is regarded as waste) and all operations, associated with the production, storage, transportation, and sales of coal fly ash cannot be registered as separate activities	Development of CFA certification for the purpose of their subsequent inclusion into economic circulation
	High costs of CHP plant modernization	Budget loans for investment projects to improve the system of CFA handling; ability to consider the costs of land reclamation using CFA in the calculation of the corporate income tax; ability to reduce environmental payments; system of incentives for railroad transportation of CFA.

For commercial companies, there are still some limitations associated with legislative regulations of CFA use in Russia (Table 6).

4.2. Examples of effective CFA Recycling

Environmental and economic efficiency of CFA recycling is obvious for the state, as evidenced by the examples of effective CFA use in the EU, USA, China.

In Poland, coal fly ash is also recycled to reduce the ecological impact and benefit for the increase of circular economy. For example, fly ash from coal combustion can be used as a matrix for molding sand and as a reinforcing phase for cast composites and aluminium alloys (ALFA composites) [62].

Another example of the methods used to utilize coal fly ash in Poland is the treatment with various methods for subsequent use. The methods used in Poland in this respect include [73] the following:

- dry processing of coal fly ash with or without seasoning;
- wet treatment of coal fly ash with or without seasoning;
- heat treatment.

Granules in the fraction of 6–50 mm and 2–6 mm, representing over 40% of processed ash and slag, after appropriate seasoning may be used as fillers in the construction industry. Sand from a 0.1–2 mm fraction is a problematic fraction as it makes up about 30% and is most often disposed of in landfills as well as residues making up about 20% of processed ash and slag.

The waste after being processed in the aforementioned processes may also be used, under certain conditions [74]:

- in the production of construction materials: cement components, additives for concrete, bituminous masses, and ceramic tiles;
- in geotechnics, road surface foundations, and soil stabilization.

In the case of use of coal fly ash in agriculture it is possible to use it to achieve the effect of minimizing costs associated with soil ameliorants purchase. Coal fly ash can serve as substitute soil ameliorant. It is important because the cost of ameliorants is about 10% up to 90% of the all costs associated with treating a farm [75]. Coal fly ash is estimated as one of the cheapest and widely available waste materials. This material is suitable for the purpose of the reclamation of degraded soil [76].

Chinese researchers have reported that fly ash used in the process of cement and concrete production can reduce the cost of cement and concrete up to 30%. In the construction industry, fly ash can be used with equal opportunity as compared to a cement binder [2]. In the construction industry, the use of a fly ash brick can provide stronger construction with better durability and better protection from salinity and efflorescence. This is possible with meaningful savings in the cost of construction. The additives from fly ash can give cost savings in the brick production industry [77].

Besides the mentioned uses of fly ash, we can also spot with various other possibilities, as for example [77]:

- fly ash-based geopolymer;
- fly ash manufacturing synthetic aggregate;
- fly ash as an adsorbent;
- fly ash for synthesizing zeolites;
- fly ash as a catalyst;
- the extraction of raw minerals from fly ash.

For the primary means of the disposal of coal fly ash in Poland, we can also include the following [78]:

- backfilling of opencast workings;
- backfilling of underground workings;
- fertilization of agricultural land;
- road construction;
- construction, i.e., cement additives, solid bricks, grid bricks, hollow bricks, hollow blocks, fertilizers, composts, self-levelling mixtures, embankments, sealings, ballasts, and concretes.

In other countries we can spot many other examples of the usage of coal fly ash in production. For example, in Belgium, they use it in the process of ceramic manufacturing [79]. The very high content of silica in the filter dust benefits possible usage of coal fly ash for the production of glass ceramics [80]. There are some examples of utilizing those substances for this purpose. High temperatures can generate high-density crystalline products. Those products can be used as building materials and also could bind hazardous inorganic materials, which can make products environmentally safer [81]. The other example of coal fly ash utilization is possibility of use in the cement industry, which is a very promising technology. This industry already recycles many waste streams as potential alternative raw materials. The coal fly ash can be used by the cement industry as an alternative raw material.

Another example from Belgium is the usage of coal fly ash as a pozzolanic addition to cement [82]. Supplementary cement materials are type of an inorganic material that can contribute to hardened concrete. This usage can benefit from adding comprehensive strength, microstructure and flow of concrete and mortar. The coal fly ash is used in the concrete production process in China. Zeng has found the optimum substitution level in concert production as ash substitution level to be 30% and the slag substitution level to be 20% [83]. According his research the strength of concrete mixed with certain amount of coal fly ash was not diminished. In some situation it can increase the characteristic of concrete to a certain extend. Berndt pointed out that we can spot the benefits of partial cement replacement with recycled coal fly ash. This is not only economically beneficial, but is also a very important factor towards the promotion of sustainable concrete production [83].

Table 7 shows examples of the use of coal fly ash in the thermal treatment of waste in selected European Union countries. In this case, in many countries, we can spot the real recycling of these materials, unfortunately, in others, despite the possibility of their practical use, they are only used in landfill [84].

Table 7. Handling of slag and ash for the thermal treatment of waste in selected EU countries. Source: [74,85,86].

Country	Amount of CFA (t/Year)	Degree of Exploitation (%)	Method of Use
Austria	559,400.0	100.0	Stored in landfills
Belgium	500,000.0	100.0	Building materials
Czech Republic	165,000.0	100.0	Stored in landfills
Denmark	564,300.0	98.0	Road construction
Finland	280,000.0	100.0	Stored in landfills Construction Asphalt production
France	2,700,000.0	30.0	Building materials
Germany	6,340,000.0	90.0	Road construction Stored in landfills
Hungary	77,000.0	10.0	Stored in landfills
Holland	1,100,000.0	75.0	Road construction
Ireland	36,000.0	100.0	Stored in landfills Engineering materials Daily cover
Norway	252,000.0	50.0	Stored in landfills
Portugal	232,000.0	60.0	Stored in landfills Road construction Backfilling
Spain	293,700.0	0	Stored in landfills
Sweden	700,000.0	100.0	Road construction Stored in landfills
Great Brittan	625,000.0	40.0	Stored in landfills Road construction
Italy	827,300.0	20.0	Stored in landfills Road construction

In China, the amount of fly ash production totals to about 1,350,000 tons yearly. The methods of utilizations used include the use of fly ash as cement and concrete additives, raw material for alumina extraction, production of inorganic fiber and production of geopolymer [87].

In India, the amount of fly ash production amounts to about 600,000 tons. Utilization now is about 78%. Fly ashes in India are used in construction industry, in manufacturing industry as a part of Portland pozzolana cement, construction of dams, roads or stabilization of slopes. Also, we can spot the usage of fly ash in agriculture [88].

In USA the amount of coal ash production is 129,700 tons per year. It is mainly used to produce concrete, in cement production. In USA we can spot use fly ash in synthetic gypsum production process in panel construction. Also, there are some agricultural applications to improve soil conditions, and structural fills [89].

In Japan, the yearly volume of coal ash production is 127,000 tones. They use coal fly ash as a ground material or agriculture material. For example, they produce concrete, cement, granulated material, or plastic materials from fly ash [90]. In Australia, the volume of production is 32,000 tones yearly. They use fly ash material to produce cement and concrete in the construction and agriculture industries [91].

The increase of coal fly ash usage can be achieved using two ways. First, it is possible to use economic incentives [74]. The emergence of technologies that will allow to obtain materials with parameters not worse, and sometimes, better than traditional ones, is the main factor encouraging companies to use coal fly ash in their production processes [80]. Environmental pressure can also be important. When fines are imposed to organizations that do not process coal fly ash and the costs of landfilling increase, there is pressure to process to a greater extent than before [78,79].

4.3. Limitations

The paper does not address specific features of implementing CFA recycling projects in large energy companies. The calculations of the case study are focused on a small-capacity CHP plant, operating within the scope of the mining company. To take into account a wider range of effects, risks and opportunities for implementing recycling projects, in the future, it will be necessary to compare the results of different cases.

The paper provides a quick look at the relevant effects in related industries. Potential multiplicative effects should be evaluated for the construction and agriculture fields, as well as manufacturers of high-technology clean coal equipment for CHP plants.

Environmental risks require additional assessment in order to characterize the damage from air and water pollution, as well as the withdrawal of land resources for coal fly ash collection systems.

In our study, it is noted that one of the promising areas for the use of fly ash can be the construction industry, but the work does not consider the properties of ash, including the possibilities and limitations of its use in accordance with environmental and regulatory requirements for the construction industry, as is described in more detail in another work [17].

This work provides some examples of the negative environmental impact of fly ash on the environment in the area of its location; however, no assessment of the impact of dusting and pollution by toxic micro-admixtures of soil and groundwater with fly ash is given as this has been studied in other works [19,34,53,92].

5. Conclusions

The paper presents an assessment of a CFA utilization project at a mining company operating a CHP plant. The risks and opportunities of this project have been examined to determine the interests of the owner in the CFA recycling project. The efficiency of using ash for the production of coal-water slurry fuel is proven, which allows the company to preserve energy resources (coal) and reduce environmental payments. It is revealed that the main reason behind the low interest of companies in CFA recycling is insignificantly low environmental payments. It is more profitable for a company to pay the environmental fee than to implement expensive CFA disposal projects. As such, one of scenarios in this case can be the option of selling CFA to another organization, for example, a construction company, for the production of building materials.

In case of implementing clean coal technology projects or the use of CFA in the production of building materials, commercial companies face a number of limitations, like a lack of demand for coal fly ash processing products and risks when modernizing CHP plants in order to reduce ash emissions or to improve ash quality for further use. These limitations and the absence of incentives discourage such activity, despite the high efficiency of recycling projects for the company itself and for the state. In order to resolve the issue of matching individual benefits received by a single stakeholder or their group with the optimum result for the society as a whole, government agencies should develop and make alterations and amendments to the regulatory documents, which will increase the attractiveness of recycling projects. The main expectations on the part of the state include high interest of business in the implementation of high-technology equipment, commitment to the goals of sustainable development, circular economy and the concept of zero waste. The main expectations on the part of commercial companies are changes in legislation that will increase the attractiveness of waste-free production and recycling projects.

Author Contributions: Conceptualization, O.M. and M.N.; methodology, O.M. and M.N.; validation, I.J.-K., R.W. and M.M.; formal analysis, O.M.; I.J.-K. and R.W.; investigation, O.M., I.J.-K. and R.W.; resources, M.M.; data curation, M.M.; writing—original draft preparation, O.M., M.N., I.J.-K. and R.W.; writing—review and editing, I.J.-K. and R.W.; visualization, M.M.; funding acquisition, O.M., M.N. and M.M. All authors have read and agreed to the published version of the manuscript.

Funding: The study was carried out at the expense of a subsidy for the fulfillment of the state task in the field of scientific activity for 2021 No. FSRW-2020-0014.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Murko, V.I., Mastikhina, V.P., Fedyaev, V.I., Karpenok, V.I., Ainetdinov H.L. Pilot project of using coal-water fuel in a boiler house based on coal preparation waste. Heat supply news. 03 (139), 2012 https://www.rosteplo.ru/Tech_stat/stat_shablon.php?id=2959 (accessed on 6 April 2021) Plant for the production of building materials with the possibility of processing man-made materials, 2013 https://sibacc.ru/upload/iblock/ed2/ed25471a0af59974bb621d3c0186bbe7.pdf (accessed on 6 April 2021). Effects from implementing the comprehensive plan, 2020 http://www.fa.ru/org/faculty/fm/coik/Documents/Эффекты%20от%20реализации%20комплексного%20плана%20утилизации%20ПСТТ-ЗШО%20-%20Финансовый%20университе0_23.07.pdf (accessed on 6 April 2021).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Standard Guide for Characterization of Coal Fly Ash and Clean Coal Combustion Fly Ash For Potential Uses. ASTM D5759-12(2020). Available online: https://webstore.ansi.org/standards/astm/astmd5759122020 (accessed on 12 May 2021).
2. Sun, S. Usage of ash from Coal Incineration in Wuhai, China. Master's Thesis, Royal Institute of Technology, Stockholm, Sweden, 2007. Available online: https://www.diva-portal.org/smash/get/diva2:411987/FULLTEXT01.pdf (accessed on 11 May 2021).
3. IEA. *Power Generation in the New Policies Scenario, 2000–2040*; IEA: Paris, France; Available online: https://www.iea.org/data-and-statistics/charts/power-generation-in-the-new-policies-scenario-2000-2040 (accessed on 6 April 2021).
4. Danilov, A.S.; Pashkevich, M.A.; Petrova, T.A. Environmental integrated monitoring system at reclamation of large open-cast coal mine. Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects. In Proceedings of the 11th Conference of the Russian-German Raw Materials, St. Petersburg, Russia, 7 November 2019; pp. 189–194.
5. Khokhlov, A.; Melnikov, Y. Coal Generation: New Challenges and Opportunities. Available online: https://energy.skolkovo.ru/downloads/documents/SEneC/Research/SKOLKOVO_EneC_Coal_generation_2019.01.01_Rus.pdf (accessed on 6 April 2021).
6. Statistical Review of World Energy 2020 | 69th ed. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf (accessed on 6 April 2021).
7. Mazzanti, M.; Zoboli, R. Waste generation, waste disposal and policy effectiveness. *Resour. Conserv. Recycl.* **2008**, *52*, 1221–1234. [CrossRef]

8. Achilias, D.S. Material Recycling—Trends and Perspectives. In *Tech*; Books on Demand: Norderstedt, Germany, 2012; p. 406. [CrossRef]
9. Telizhenko, O.M. Concept of integrated waste management as recoverable resources in product cycle. *J. Environ. Sci. Eng.* **2012**, *1*, 312–323.
10. Di Maio, F.; Rem, P.M. A Robust Indicator for Promoting Circular Economy through Recycling. *J. Environ. Prot.* **2015**, *6*. [CrossRef]
11. Litovkin, S.V. Investigation coal fly ash waste for use as a of recyclable waste. *Int. J. Appl. Fundam. Res.* **2015**, *9*, 23–27.
12. Kozhukhovsky, I.S.; Velichko, E.G.; Tselykovsky, Y.K.; Tskhovrebov, E.S. Organizational, economic and legal aspects of the creation and development of industrial and technical complexes for the processing of coal fly ash waste into construction and other products. *MGSU Bull.* **2019**, *6*, 756–773. [CrossRef]
13. Chubarikov, E.V. Using international experience to address problems of waste- management of production and consumption in the Perm region. Bulletin of the South Ural state University. *Econ. Manag.* **2010**, *7*, 41–48.
14. Zelikovsky, Y.K. *Disposal of Coal Fly Ash Waste of Coal TPP*; VTI Publ.: Moscow, Russia, 2014; p. 63.
15. Ghafari, E.; Ghahari, S.; Feys, D.; Khayat, K.; Baig, A.; Ferron, R. Admixture compatibility with natural supplementary cementitious materials. *Cem. Concr. Compos.* **2020**, *112*, 103683. [CrossRef]
16. Lim, S.; Lee, W.; Choo, H.; Lee, C. Utilization of high carbon fly ash and copper slag in electrically conductive controlled low strength material. *Constr. Build. Mater.* **2017**, *157*, 42–50. [CrossRef]
17. Peng, X.; Tonglin, Z. Comprehensive Utilization of High Alumina Coal Fly Ash Under the Recyclable Economy Model. *Ind. Chem.* **2018**, *4*, 128. [CrossRef]
18. Sanjuán M, Á.; Suárez-Navarro, J.A.; Argiz, C.; Mora, P. Assessment of natural radioactivity and radiation hazards owing to coal fly ash and natural pozzolan Portland cements. *J. Radioanal. Nucl. Chem.* **2020**, *325*, 381–390. [CrossRef]
19. Krylov, D.A. The negative impact of elements of impurities from coal TES on the environment and health. *Gorn. Inf. Anal. Byullete.* **2017**, *12*, 77–87. [CrossRef]
20. Salomatov, V.V. *Environmental Technologies at Thermal and Nuclear Power Plants: Monograph*; Publishing House of NSTU: Novosibirsk, Russia, 2006; p. 853.
21. Tshovrebov, E.S.; Ali, E.A.; Cerenova, M.P.; Yur'ev, K.V. *Ensuring of Ecological Safety in Design of Real Estate Items and During Construction Works*; RGGMU Publ.: Saint Petersburg, Russia, 2013; p. 358.
22. Pashkevich, M.A.; Bech, J.; Matveeva, V.A.; Alekseenko, A.V. Biogeochemical assessment of soils and plants in industrial, residential and recreational areas of Saint Petersburg. *J. Min. Inst.* **2020**, *24*, 125–130. [CrossRef]
23. Verzhanskiy, A.P. Coal-fired generation greening. Excerpts from the roundtable report On the Program of coal-fired generation in the Russia n Federation. *Ugol' Russ. Coal J.* **2017**, *9*, 11–16.
24. Zhao, B.; Chen, G.; Xiong, Z.; Qin, L.; Chen, W.; Han, J. A Model for Predicting Arsenic Volatilization during Coal Combustion Based on the Ash Fusion Temperature and Coal Characteristic. *Energies* **2021**, *14*, 334. [CrossRef]
25. Fedorova, N.V.; Mokhov, V.A.; Babushkin, A.Y. The analysis of foreign experience of using of the thermal power plants coal fly ash waste and the capabilities of multi-agent simulation of the recycling processes (Review). *Ecol. Ind. Prod.* **2015**, *3*, 2–7.
26. Skursky, M.D. Forecast of Rare-Earth-Rare-Metal-Oil and Gas-Coal deposits in Kuzbass. Fuel and Energy Complex and Resources of Kuzbass. Available online: https://library.kuzstu.ru/method/vv_scursky/prognos.htm (accessed on 6 April 2021).
27. Yanovskiy, A.B. Coal: A battle for the future. *Coal* **2020**, *8*, 9–14. [CrossRef]
28. Reshneva, E.; Ponomarenko, T.V. Challenges and opportunities of integration of the energy capacity of the republic of moldova (Rm) in the european energy system. Topical Issues of Rational Use of Natural Resources. In Proceedings of the International Forum-Contest of Young Researchers, St. Petersburg, Russia, 18–20 April 2018; p. 325.
29. Tcvetkov, P.S. The history, present status and future prospects of the Russian fuel peat industry. *MiresPeat* **2017**, *19*, 1–12. [CrossRef]
30. Litvinenko, V. The Role of Hydrocarbons in the Global Energy Agenda: The Focus on Liquefied Natural Gas. *Resources* **2020**, *9*, 59. [CrossRef]
31. Na, C.; Yuan, J.; Zhu, Y.; Xue, L. Economic Decision-Making for Coal Power Flexibility Retrofitting and Compensation in China. *Sustainability* **2018**, *10*, 348. [CrossRef]
32. Sung, B.; Park, S.-D. Who Drives the Transition to a Renewable-Energy Economy? Multi-Actor Perspective on Social Innovation. *Sustainability* **2018**, *10*, 448. [CrossRef]
33. Popp, D. Promoting Innovation for Low-Carbon Technologies. *Policy Propos.* **2019**, *14*, 36. Available online: https://www.hamiltonproject.org/assets/files/Popp_LO_FINAL.pdf (accessed on 6 April 2021).
34. Sanjuan, M.A.; Suarez-Navarro, J.A.; Argiz, C.; Estevez, E. Radiation dose calculation of fine and coarse coal fly ash used for building purposes. *J. Radioanal. Nuclear Chem.* **2021**. [CrossRef]
35. Vasilev, Y.; Cherepovitsyn, A.; Tsvetkova, A.; Komendantova, N. Promoting Public Awareness of Carbon Capture and Storage Technologies in the Russian Federation: A System of Educational Activities. *Energies* **2021**, *14*, 1408. [CrossRef]
36. Popp, D.; Pless, J.; Haščič, I.; Johnstone, N. Innovation and Entrepreneurship in the Energy Sector, Forthcoming. In *The Role of Innovation and Entrepreneurship in Economic Growth*; University of Chicago Press: Chicago, IL, USA, 2020; Available online: https://www.nber.org/books-and-chapters/role-innovation-and-entrepreneurship-economic-growth (accessed on 6 April 2021).
37. Lehmann, P.; Söderholm, P. Can Technology-Specific Deployment Policies Be Cost-Effective? The Case of Renewable Energy Support Schemes. *Environ. Resour. Econ.* **2018**, *71*, 475–505. [CrossRef]

38. Drebenstedt, C. Use of Brown Coal Ash for the Amelioration of Dump Soils. In *Scientific and Practical Studies of Raw Material Issues*; Taylor & Francis: London, UK, 2020; pp. 129–134.
39. OECD. Business Models for the Circular Economy: Opportunities and Challenges forPolicy. 2019. Available online: https://doi.org/10.1787/g2g9dd62-en (accessed on 6 April 2021).
40. Porter, M. *Competitive Advantage: Creating and Sustaining Superior Performance*; Alpina Publisher: Moscow, Russia, 2016; p. 716.
41. Pichugin, E.A. Analytical Review of the Experience of Involving Ash Slag Waste of Thermal Power Plants in Economic Circulation in the Russian Federation. *Probl. Reg. Ecol.* **2019**, *4*. Available online: https://cyberleninka.ru/article/n/analiticheskiy-obzor-nakoplennogo-v-rossiyskoy-federatsii-opyta-vovlecheniya-v-hozyaystvennyy-oborot-zoloshlakovyh-othodov (accessed on 6 April 2021). [CrossRef]
42. WRAP. *Employment and the Circular Economy: Job Creation in a More Resource Efficient Britain*; Green Alliance: London, UK, 2015; Available online: http://www.wrap.org.uk/sites/files/wrap/Employment%20and%20the%20circular%20economy%20summary.pdf (accessed on 6 April 2021).
43. Jonek-Kowalska, I.; Ponomarenko, T.V.; Marinina, O.A. Problems of Interaction with Stakeholders during Implementation of Long-Term Mining Projects. *J. Min. Inst.* **2018**, *232*, 428–437. [CrossRef]
44. Blagov, Y.E. *Corporate Social Responsibility: An Evolution of the Concept*, 2nd ed.; Higher School of Management Publishing House: St. Petersburg, Russia, 2011; p. 272.
45. Narbel, F.; Muff, K. Should the Evolution of Stakeholder Theory Be Discontinued Given Its Limitations? *Theor. Econ. Lett.* **2017**, *7*, 1357–1381. [CrossRef]
46. Antolín-López, R.; Montiel, I.; Delgado-Ceballos, J. Deconstructing Corporate Sustainability: A Comparison of Different Stakeholder Metrics. *J. Clean. Prod.* **2016**, *136*, 5–17. [CrossRef]
47. Ratner, S.V. Circular Economy: Theoretical Foundations and Practical Applications in the Field of Regional Economics and Management. *Innovation* **2018**, *9*, 239. Available online: https://cyberleninka.ru/article/n/tsirkulyarnaya-ekonomika-teoreticheskie-osnovy-i-prakticheskie-prilozheniya-v-oblasti-regionalnoy-ekonomiki-i-upravleniya (accessed on 13 May 2021).
48. Kudryavtseva, O.V.; Mitenkova, E.N.; Solodova, M.A. Circular economy as a tool for sustainable development in Russia. *EVR* **2019**, *3*, 61. Available online: https://cyberleninka.ru/article/n/tsirkulyarnaya-ekonomika-kak-instrument-ustoychivogo-razvitiya-rossii (accessed on 13 May 2021).
49. Sokolov, S.N. Theoretical and methodological foundations of the territorial organization of society. *NVGU Bull.* **2013**, *3*, 1–11. Available online: https://cyberleninka.ru/article/n/teoretiko-metodologicheskie-osnovy-territorialnoy-organizatsii-obschestva (accessed on 13 May 2021).
50. Stahel, W.R. Circular economy. *Nature* **2016**, *531*, 435–438. [CrossRef]
51. Ilinova, A.A.; Romasheva, N.V.; Stroykov, G.A. Prospects and social effects of carbon dioxide sequestration and utilization projects. *J. Min. Inst.* **2020**, *244*, 493–502. [CrossRef]
52. The Circular Economy and Benefits for Society, Interim Report, Club of Rome with Support from MAVA Foundation and Swedish Association of Recycling Industries. Available online: http://www.clubofrome.org/wp-content/uploads/2016/03/The-Circular-Economy-and-Benefits-for-Society.pdf (accessed on 6 April 2021).
53. Sanjuán, M.A.; Andrade, C.; Mora, P.; Zaragoza, A. Carbon Dioxide Uptake by Cement-Based Materials: A Spanish Case Study. *Appl. Sci.* **2020**, *10*, 339. [CrossRef]
54. Pakhomova, N.V.; Richter, K.K.; Vetrova, M.A. Transition to circular economy and closed loop supply chains as driver of sustainable development. *J. Econ. Stud.* **2017**, *33*, 244–268. [CrossRef]
55. Cavaleiro de Ferreira, A.; Fuso-Nerini, F. A Framework for Implementing and Tracking Circular Economy in Cities: The Case of Porto. *Sustainability* **2019**, *11*, 1813. [CrossRef]
56. Firnkorn, J.; Müller, M. Selling Mobility instead of Cars: New Business Strategies of Automakers and the Impact on Private Vehicle Holding. *Bus. Strategy Environ.* **2012**, *21*, 264–280. [CrossRef]
57. Halog, A.; Sandra Anieke, S. A Review of Circular Economy Studies in Developed Countries and Its Potential Adoption in Developing Countries. *Circ. Econ. Sustain.* **2021**, 1–22. [CrossRef]
58. Opportunities for a Circular Economy in The Netherlands 2013. Available online: https://www.tno.nl/media/8551/tno-circular-economy-for-ienm.pdf (accessed on 6 April 2021).
59. Bobylev, S.N.; Solovyeva, S.V. Circular Economy and Its Indicators for Russia. *World New Econ.* **2020**, *2*. Available online: https://cyberleninka.ru/article/n/tsirkulyarnaya-ekonomika-i-ee-indikatory-dlya-rossii (accessed on 6 April 2021). [CrossRef]
60. Nevskaya, M.; Seleznev, S.; Masloboev, V.; Klyuchnikova, E.; Makarov, D. Involving small and medium-sized mining industry businesses in mining waste processing in the Russian Federation. *Miner. Econ.* **2021**, *34*, 81–86. [CrossRef]
61. Cherepovitsyn, A.; Ilinova, A.; Evseeva, O. Stakeholders management of carbon sequestration project in the state-business-society system. *Zap. Gorn. Inst. J. Min. Inst.* **2019**, *240*, 731. [CrossRef]
62. Kharin, A.G. *Extended Concept of Value-Based Management: Theory, Methodology, Practice*; Immanuel Kant Baltic Federal University Publ.: Kaliningrad, Russia, 2014.
63. Modern Fuel for Power Engineering. 2015. Available online: http://vodougol.ru/wp-content/uploads/2015/04/20150410-Carbon-slurry-fuel-katalog-WEB.pdf (accessed on 6 April 2021).

64. Murko, V.I.; Mastikhina, V.P.; Fedyaev, V.I.; Karpenok, V.I.; Ainetdinov, H.L. Pilot project of using coal-water fuel in a boiler house based on coal preparation waste. *Heat Supply News* **2012**, *3*, 139. Available online: https://www.rosteplo.ru/Tech_stat/stat_shablon.php?id=2959 (accessed on 6 April 2021).
65. Plant for the Production of Building Materials with the Possibility of Processing Man-Made Materials. 2013. Available online: https://sibacc.ru/upload/iblock/ed2/ed25471a0af59974bb621d3c0186bbe7.pdf (accessed on 6 April 2021).
66. Vasilev, Y.; Vasileva, P.; Tsvetkova, A. International review of public perception of CCS technologies. *Int. Multidiscip. Sci. Geoconf. SGEM* **2019**, *19*, 415–422.
67. Effects from Implementing the Comprehensive Plan. 2020. Available online: http://www.fa.ru/org/faculty/fm/coik/Documents/Эффекты%20от%20реализации%20комплексного%20плана%20утилизации%20ПСТТ-ЗШО%20-%20Финансовый%20университет_23.07.pdf (accessed on 6 April 2021).
68. Comprehensive Plan to Increase the Utilization of Solid Fuel Combustion Products at Coal and Thermal Power Plants; Ministry of Energy of the Russian Federation: Moscow, Russia. 2020. Available online: https://energy.s-kon.ru/wp-content/uploads/2020/07/document-120669.pdf (accessed on 6 April 2021).
69. A Comprehensive Plan has been Developed to Increase the Volume of Utilization of Solid Fuel Combustion Products at Coal-Fired CHPPs and Boiler Houses; Ministry of Energy of the Russian Federation: Moscow, Russia. 2020. Available online: https://minenergo.gov.ru/node/18342 (accessed on 6 April 2021).
70. Zolotova, I.Y. Benchmarking best practices of coal combustion product utilization. *Innov. Invest.* **2020**, 123–128. Available online: https://cyberleninka.ru/article/n/benchmarking-zarubezhnogo-opyta-utilizatsii-produktov-szhiganiya-tverdogo-topliva-ugolnyh-tes (accessed on 6 April 2021).
71. Zhavoronkova, N.G.; Shpakovsky, Y.G. Energy Strategy 2035: Legal Problems of Innovative Development and Environmental Safety. *Univ. Bull.* **2020**, 31–47. [CrossRef]
72. Round Table Recommendations of the State Duma Committee on Energy on the Subject of "Legislative Regulation of the Use of Coal Fly Ash Waste from Coal-Fired CHP Plants". Available online: http://komitet2-13.km.duma.gov.ru/Rabota/Rekomendacii-po-itogam-meropriyatij/item/19029746/ (accessed on 6 April 2021).
73. Baliński, A. Recycling of waste fly ash formed during combustion of hard coal for use in moulding mixtures manufacture. *Pract. Inst. Odlew.* **2008**, *3*, 5–30.
74. Wielgosiński, G.; Wasiak, D. Wtórne odpady z procesu termicznego przekształcania odpadów. *Nowa Energ.* **2015**, *1*, 46–56.
75. Yunusa, I.A.M.; Loganathan, P.; Nissanka, S.P.; Manoharan, V.; Burchett, M.D.; Skilbeck, C.G.; Eamus, D. Application of Coal Fly Ash in Agriculture: A Strategic Perspective. *Crit. Rev. Environ. Sci. Technol.* **2012**, *42*, 559–600. [CrossRef]
76. Shaheen, S.M.; Hooda, P.S.; Tsadilas, C.D. Opportunities and challenges in the use of coal fly ash for soil improvements e A review. *J. Environ. Manag.* **2014**, *145*, 249–267. [CrossRef] [PubMed]
77. *Low Carbon Living. State of Practice: High Volume Applications of Fly Ash and Barriers to Commercialisation*; CRC: Melbourne, Australia; Available online: http://www.lowcarbonlivingcrc.com.au/sites/all/files/publications_file_attachments/rp1004_fly_ash_and_barriers_to_commercialisation_report.pdf (accessed on 11 May 2021).
78. Czajkowska, A.; Bożejewicz, D. Review of recovery methods of waste from industry and power plant service. *Energy Market* **2019**, *6*, 67–76.
79. Joseph, A.M.; Snellings, R.; Heede, P.V.; Matthys, S. The Use of Municipal SolidWaste Incineration Ash in Various Building Materials: A Belgian Point of View. *Materials* **2018**, *11*, 141. [CrossRef]
80. Lee, T.; Wang, W.; Shih, P.; Lin, K. Enhancement in early strengths of slag-cement mortars by adjusting basicity of the slag prepared from fl y-ash of MSWI. *Cem. Concr. Res.* **2009**, *39*, 651–658. [CrossRef]
81. Tam, V.W.; Le, K.N.; Evangelista, A.C.J.; Butera, A.; Tran, C.N.; Teara, A. Effect of fly ash on concrete: Properties and emission analyses. *Front. Eng. Manag.* **2019**, *6*, 395–405. [CrossRef]
82. Beauchemin, L. *Jaarverslag van de Belgische Cementnijverheid*; Federatie van de Belgische cementnijverheid vzw: Brussels, Belgium, 2015.
83. Zeng, C.; Lyu, D.; Wang, D.; Ju, Y.; Shang, X.; Li, L. Application of Fly Ash Generated by Incineration of Municipal Solid Waste in Concrete. *Adv. Mater. Sci. Eng.* **2020**, 1–7. [CrossRef]
84. Berndt, M.I. Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Constr. Build. Mater.* **2009**, *23*, 2606–2613. [CrossRef]
85. CEWEP Country Reports 2018. Available online: https://www.cewep.eu/country-reports-2018 (accessed on 11 May 2021).
86. CEWEP Country Reports 2016. Available online: https://www.cewep.eu/country-reports-2016 (accessed on 11 May 2021).
87. Tang, Z.; Ma, S.; Ding, J.; Wang, Y.; Zheng, S.; Zhai, G. Current Status and Prospect of Fly Ash Utilization in China. In Proceedings of the World of Coal Ash (WOCA) Conference, Lexington, KY, USA, 22–25 April 2013; Available online: https://www.researchgate.net/profile/Jian-Ding-14/publication/285851228_Current_status_and_prospect_of_fly_ash_Utilization_in_China/links/5869ca8c08ae6eb871b9666c/Current-status-and-prospect-of-fly-ash-Utilization-in-China.pdf?_sg%5B0%5D=Tb8dlHQcoAjYGR_jfKCR56uzBzYx9ljtRhEcOyL7JS7SvtTml28mzEBs7g-Rb_yTb-ul2M9vtABmToYcNTQAkA.U0biY-bOuVGTH92Z0dbStvvsPIx3kB2hX9PBcsKqmimVQgqp47L5OumYlzmqz5yZv0cFVjIsSYnMfzLi2v_-DQ&_sg%5B1%5D=1fKLelh_YfNO_EuO5bjt_ji_hodek-hovRyjk6AqYhmzmOOqFsD-qq7zlKOZjcwO1QGuLHAVvUvpeGPIxxuThFsfTK9hmQsOHTefQ3JKYegC.U0biY-bOuVGTH92Z0dbStvvsPIx3kB2hX9PBcsKqmimVQgqp47L5OumYlzmqz5yZv0cFVjIsSYnMfzLi2v_-DQ&_iepl= (accessed on 11 May 2021).

88. Yousuf, A.; Manzoor, S.O.; Youssouf, M.; Malik, Z.A.; Khawaja, K.S. Fly Ash: Production and Utilization in India—An Overview. *J. Mater. Environ. Sci.* **2020**, *11*, 911–921.
89. Coal Ash Recycling Rate Declines Amid Shifting Production and Use Patterns. Available online: https://www.prnewswire.com/news-releases/coal-ash-recycling-rate-declines-amid-shifting-production-and-use-patterns-300961238.html (accessed on 11 May 2021).
90. Sato, K.; Fujiakawa, T. Effective use of coal ash as ground materials in Japan. *Jpn. Geotech. Soc. Spec. Publ.* **2017**, *5*, 65–70. [CrossRef]
91. Ash Development Association of Australia. Available online: https://www.adaa.asn.au (accessed on 11 May 2021).
92. Blissett, R. Coal fly Ash and the Circular Economy. Ph.D. Thesis, University of Birmingham, Birmingham, UK, 2015; p. 266. Available online: https://core.ac.uk/download/pdf/33528279.pdf (accessed on 6 April 2021).