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Considering Waste Generation in the Energy Sector during the Transition to a Circular Economy

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Abstract: The need to reduce the negative environmental impact of energetics with the growing energy demand in the world is the core objective of the industry for the upcoming decades. The global agenda in the field of environmental protection increases the requirements for evaluation of the energy investment projects, in particular for their environmental efficiency. Currently, much attention is paid to assessing the impact of the project on atmospheric air, water bodies and land resources, including the formation of industrial waste during the operational stage. The formation of production and consumption waste at other stages of the project life cycle is not considered either when generating cash flows or when conducting the assessment pf environmental efficiency. It might significantly reduce the reliability of assessment results. The purpose of this study is to develop a system of integrated accounting for all types of waste generated and the environmental costs incurred for handling them during the environmental and economic assessment of energy projects. The paper discusses modern waste management practices at energy enterprises, waste generation at various stages of investment projects implementation, and provides recommendations on waste accounting when assessing their environmental and economic efficiency.

Keywords: waste management; energy sector; traditional energy; renewable energy; circular economy; investment project; efficiency assessment

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1. Introduction

Economic growth caused by technological progress and the growth of total production leads to an increase in the level of social welfare—growth of household incomes and consumption of material goods and services, improvement of education quality, accessibility of affordable healthcare [1]. The long-term economic growth rates are largely determined by the energy sector and its ability to meet the growing demand for primary energy [2,3]. If the energy sector is unable to provide the required level of energy consumption, the pace of economic development slows down.

In this regard, such factors as the availability and cheapness of energy resources, developed energy infrastructure, and the use of the latest energy technologies are beginning to play a system-forming role in the national economy. However, the increase in energy consumption also leads to an increase in the anthropogenic impact on the environment [4,5].

The energy industry is one of the largest environmental pollutants. According to data for 2021, 36.3 Gt of CO_2 emissions accounted for the energy sector, while in 2000, this figure was 24.3 Gt of CO_2 [6]. The largest part of emissions of greenhouse gases and other pollutants (NO_x, SO_2, PM, etc.) falls on traditional energy, in which fossil fuels (coal, oil and natural gas) are used as fuel for energy production [7,8]. The energy sector also has a negative impact on water resources, land resources and biodiversity of territories located in the immediate vicinity of the energy facility.

Despite the high level of anthropogenic impact on the environment, energy does not belong to the largest producers of industrial waste in comparison with other sectors of the economy. In 2020, on the territory of the EU, only 3.1% of all production waste was accounted for by the electricity, gas, and steam supply sector—air conditioning, which includes the energy sector. In Russia, this value in 2021 was less than 0.3% [9,10] (Table 1). The insignificant share of the energy industry in the structure of waste generation in Russia is due to the high volume of waste generation at the enterprises of the extractive industry—more than 91%. A more detailed structure of production waste generation in the EU and Russia is shown in Figure 1.

Table 1. Production waste generation in electricity, gas, steam, and air conditioning supply industry in EU and Russia from 2016 to 2020 (made by authors using data from [9,10]).

Year	2016	2018	2020 (2021) [1]
Total production waste generation, thousand tons			
Russia	5,350,102	7,167,738	8,282,729
EU	1,759,210	1,804,540	1,611,610
Production waste generation in gas, steam, and air conditioning supply industry, thousand tons			
Russia	20,509	20,105	18,696
EU	76,800	78,370	49,970
The share of the sector in the total volume of waste generation, %			
Russia	0.38%	0.28%	0.23%
EU	4.37%	4.34%	3.10%

[1] Data for Russia is presented for 2021 due to its availability.

The volume of production waste generation in the analyzed sector in the EU is higher than in Russia, which might be due to the specifics of waste generation accounting and environmental reporting at Russian and European energy enterprises. For instance, waste sent by Russian enterprises for disposal, decontamination, or recycling within the framework of reporting is reflected only in those organizations where these wastes are sent. These wastes are not reflected on the ecological "balance sheet" of the waste-producing enterprise.

The classification of waste according to the degree of negative impact on the environment in Russia and the EU also has a number of fundamental differences. In Russia, the waste classification includes five hazard classes: Class I—extremely hazardous waste, Class II—highly hazardous waste, Class III—moderately hazardous waste, Class IV—low–hazard waste, and Class V—practically non-hazardous waste [11]. In the EU, waste is divided into two main classes: non-hazardous waste and hazardous waste. Hazardous waste is classified into classes depending on the nature of the hazard (for example, carcinogenic type of waste), then they are classified according to the degree of danger (for example, carcinogenic waste can be of three hazard classes: 1A, 1B and 2) [12].

The formation of production waste and their disposal is an urgent problem of modern energy. For example, the use of fossil fuels, in particular coal, for energy production leads to the formation of a huge amount of ash and slag waste, for the storage of which large territories are alienated [13].

Renewable energy sources (RES), despite a significantly less negative impact on the environment in comparison with traditional energy facilities, form a certain amount of industrial waste, but after the decommissioning of facilities (spent wind turbine blades, faulty solar panels, etc.) [14–17]. Table 2 presents a list of waste generated at traditional (thermal power plants (TPP) operating on coal, fuel oil, and natural gas) and renewable energy facilities (hydro power plant, solar power plant, wind power plant) during the production of electricity, in the general operation of the energy facility and at the stage of its decommissioning.

Table 2. Waste generated on energy enterprises (made by authors using data from [18,19]).

Type of Energy Facility	Waste Generation from Fuel Consumption	Waste Generation during Operation	Decommissioning Waste
Thermal Power Plant (Coal)	- coal combustion slags; - ash-and-slag mixture from coal combustion; - ash and slag mixtures from coal combustion during hydraulic removal of fly ash and fuel slag; - limited radioactive coal ash removed at decommissioning	- waste from pre-boiler water treatment to power steam boilers - (waste of mineral salts, sewage treatment plant sediments, cleaning waste mixtures, etc.); - waste from mechanical/chemical/steam-oxygen purification of equipment (waste from the neutralization of washing water, waste oils, sludge of waste treatment plants, etc.); - waste of cleaning of external heating surfaces of boilers, regenerative air heaters (waste of water purification of regenerative air heaters); - waste from cleaning air ducts of ventilation systems and technical channels of boiler rooms; - other waste generated during equipment cleaning (waste oil, sludge of waste treatment plants, etc.); - waste generated during storage and preparation of solid fuel (waste of preparation (sorting) of coal for crushing, waste during crushing and sorting of coal containing dust); - electronic waste (including spent lamps) (e-waste); - municipal solid waste (MSW).	- electronic waste (generators, turbines, boilers, cables, wiring, transmission towers, inverters, transformers, other power electronics); - construction waste (railway spurs, steel, brick, etc.)
Thermal Power Plant (Fuel oil)	- fuel oil ash and soot from fuel combustion; - limited radioactive sludge removed at decommissioning.	- waste from pre-boiler water treatment to power steam boilers - (waste of mineral salts, sewage treatment plant sediments, cleaning waste mixtures, etc.); - waste from mechanical/chemical/steam-oxygen purification of equipment (waste from the neutralization of washing water, waste oils, sludge of waste treatment plants, etc.); - waste of cleaning of external heating surfaces of boilers, regenerative air heaters (waste of water purification of regenerative air heaters); - waste from cleaning air ducts of ventilation systems and technical channels of boiler rooms; - waste of cleaning of smoke channels, pipes and equipment of thermal power plants during the fuel oil combustion; - other waste generated during equipment cleaning (waste oil, sludge of waste treatment plants, etc.); - electronic waste (including spent lamps); - MSW.	- electronic waste (generators, turbines, boilers, cables, wiring, transmission towers, inverters, transformers, other power electronics); - construction waste (railway spurs, steel, brick, etc.)

Table 2. *Cont.*

Type of Energy Facility	Waste Generation from Fuel Consumption	Waste Generation during Operation	Decommissioning Waste
Thermal Power Plant (Natural gas)	- waste of cleaning of smoke channels, pipes and equipment of thermal power plants during fuel combustion (low-hazard); - limited radioactive sludge removed at decommissioning	- waste from pre-boiler water treatment to power steam boilers - (waste of mineral salts, sewage treatment plant sediments, cleaning waste mixtures, etc.); - waste from mechanical/chemical/steam-oxygen purification of equipment (waste from the neutralization of washing water, waste oils, sludge of waste treatment plants, etc.); - waste of cleaning of external heating surfaces of boilers, regenerative air heaters (waste of water purification of regenerative air heaters); - waste from cleaning air ducts of ventilation systems and technical channels of boiler rooms; - other waste generated during equipment cleaning (waste oil, sludge of waste treatment plants, etc.); - waste generated during the preparation of gaseous fuel (fabric filters, waste from the regeneration of cleaning filters); - electronic waste (including spent lamps); - MSW.	- electronic waste (generators, turbines, boilers, cables, wiring, transmission towers, inverters, transformers, other power electronics); - construction waste (railway spurs, steel, brick, etc.)
Hydro Power Plant	-	- debris from protective grilles; - waste from cleaning lattices, gates of hydraulic structures from biological fouling and corrosion; - electronic waste (including spent lamps); - MSW.	- electronic waste (generators, hydro-turbines, dams, cables, wiring, inverters, transformers); - construction waste (steel, copper, etc.)
Wind Power Plant	-	- electronic waste (including spent lamps); - MSW.	- parts of wind turbines (blades); - electronic waste (generators, poles, blades, cables, wiring, inverters, transformers); - construction waste (steel, copper, etc.)
Solar Photovoltaics	-	- sand, dust, dirt; - electronic waste (including spent lamps); - MSW.	- solar photovoltaic panels; - electronic waste (wiring, inverters, transformers, etc.); - construction waste (steel frames, cables, glass, silicon wafers, etc.).

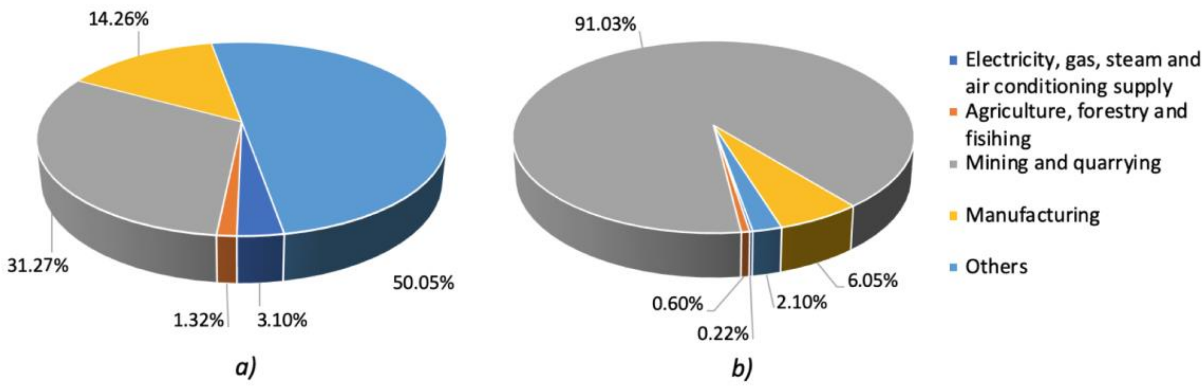

Figure 1. Structure of production waste generation (here and hereafter presented data not including nuclear waste): (**a**) in EU 2020, % (**b**) in Russia 2021, % (made by authors using data from [9,10]).

The largest contribution to the volume of waste generation by the energy sector is made by coal-fired thermal power plants, which is one of the reasons for the refusal to use coal as fuel for energy production. At the considered renewable energy facilities and gas thermal power plants, a small amount of waste generation occurs at the stage of operation of the energy facility and a significant amount at the elimination stage.

One of the ways to reduce the anthropogenic impact of the energy sector on the environment is to carry out its large-scale eco-modernization, the construction of high-tech renewable energy facilities [20], and the introduction of the principles of circular economy—all this implies the development and implementation of major investment projects [21]. In addition, the requirements for environmental performance assessment are being tightened—the impact of the project on atmospheric air, water bodies, and land resources (including waste generation in the process of electricity production) is being analyzed. Energy waste leaves a negative ecological footprint and implies the costs of handling them. Therefore, they should be reflected in the procedure for evaluating the effectiveness of investment projects.

At present, there are no studies in the field of accounting for production waste generation in the process of environmental assessment of energy investment projects and their subsequent implementation. The purpose of this study is to develop a system of integrated accounting of waste generation and incurred environmental costs for handling them during the environmental and economic assessment of investment projects in the energy sector. The article discusses modern waste management practices at energy enterprises (mainly at traditional energy enterprises), waste generation at various stages of investment projects implementation, and provides recommendations on waste accounting when assessing their environmental and economic efficiency.

2. Brief Review of Waste Management Practices on Energy Facilities

Waste management at traditional energy enterprises. The structure and volume of waste generation at traditional energy facilities directly depend on the type of fuel used: when burning coal, a significant amount of ash and slag waste is formed, which may contain toxic elements such as arsenic or mercury; when burning fuel oil, fuel oil ash is generated; when burning natural gas, production waste is practically not generated [22,23]. Regardless of the type of fuel, such types of waste are generated at energy facilities as used oils (hazard class III), cleaning material contaminated with oils (hazard class III), electronic waste (hazard classes I–IV), waste from household activities in organizational premises (hazard class IV–V), etc.

In the scientific literature, most of the work in the field of waste management practices at traditional energy enterprises is devoted to improving the ash and slag waste management system at coal-fired thermal power plants and improving the efficiency of their processing [13,24–26]. There are practically no studies of waste management practices used at gas power facilities.

In total, there are four main directions of waste management at thermal power plants: organization of waste storage, their disposal, processing, and neutralization. Figure 2 shows a typical logistics scheme for waste management at traditional energy enterprises.

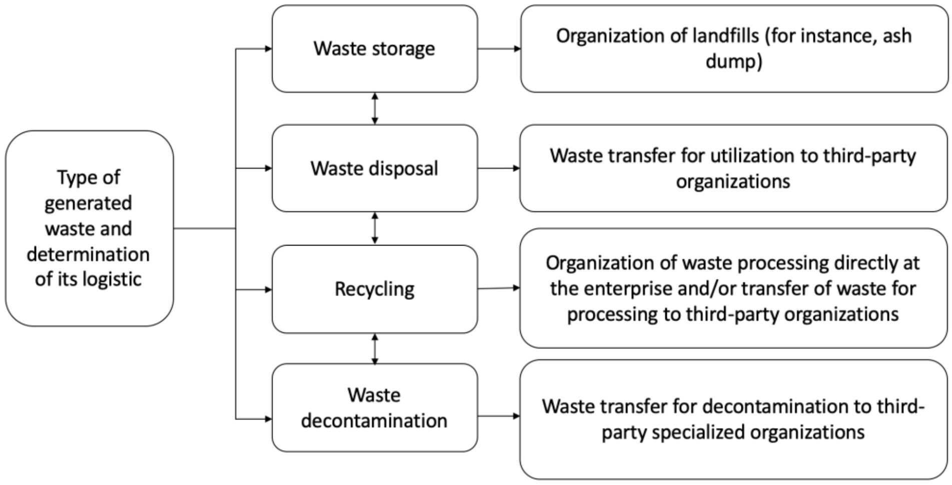

Figure 2. A typical logistics scheme for waste management at traditional energy enterprises (made by authors using data from [27–29].

The chosen method of waste management depends primarily on the type of waste: MSW generated mainly in organizational premises can be transferred for disposal to third-party organizations or processed directly at the enterprise; waste oils and mercury lamps are sent for disposal and/or neutralization to third-party specialized organizations; ash and slag waste at coal-fired thermal power plants either they are sent for storage in ash and slag dumps, or for disposal and further processing.

The generation, storage, and processing of ash and slag waste is one of the central environmental problems of coal power. On the territory of Russia, a common practice of handling ash and slag waste, despite the possibility of their processing for secondary use, is storage in ash and slag dumps: according to the data presented in [13], more than 28 thousand hectares of land have been alienated for ash and slag dumps, and the total amount of accumulated waste can reach 2 billion tons. In the USA and the EU, about 60% of all ash and slag waste is sent for recycling, which brings additional income to electric power companies [29], while in Russia this practice is just beginning to be implemented at energy enterprises.

At gas-fired thermal power plants, the waste management system is even more simplified in comparison with coal-fired thermal power plants due to the absence of production waste generation during fuel combustion—almost all types of generated waste are sent for disposal, storage, or neutralization to third-party organizations, which allows not to take into account their formation in the framework of environmental reporting and, consequently, environmental efficiency assessment.

Thus, the waste management system at traditional energy enterprises has a fairly typical character due to the specifics of waste generation and their low hazard class (the vast majority of waste generated belongs to hazard Class IV–V). In the scientific literature, the topic of improving the accounting of the waste management system at thermal power plants is practically not considered.

Waste management at renewable energy enterprises (hydropower, wind energy, and solar energy). Renewable energy is one of the components of the transition to a closed-cycle economy—obtaining energy from renewable energy sources can significantly reduce the negative impact on the environment, compared with energy based on the use of fossil fuels, and complies with the principles of circular economy [30–33]. In the process of construction and maintenance of renewable energy facilities, MSW, construction waste, electronic waste, etc., are also generated on par with traditional ones, which must be taken into account when assessing the environmental efficiency of an enterprise or when conducting an environmental and economic assessment of investment projects.

A simplified environmental monitoring system operates at hydropower, wind, and solar energy facilities. Accounting and assessment of production waste generation usually is not carried out due to its absence at an operational stage. However, a significant part of waste, including industrial waste, is generated at the stage of shutdown or reconstruction of energy facilities, which is especially important for solar and wind power facilities [14,15,34–37].

For example, most of the photovoltaic modules are sent either for burial at special landfills, or for disposal and neutralization to specialized organizations; a smaller part is sent for recycling [37,38]. According to the forecasts of the International Renewable Energy Agency and the International Energy Agency, up to 1.8 million tons of photovoltaics waste may be generated by 2030, and by 2050 this figure may reach 60 million tons [39].

The spent parts of wind turbines (in particular the blades) are sent for burial to special landfills, for the organization of which significant territories are alienated. The problem of processing and reuse of blades is considered in the works [14,35,36,40]. One of the barriers to their processing is the complex composition of the material from which they are made—the processing of blades is possible but is hampered by the need to use complex specialized and expensive equipment to separate the material into demanded components. Incineration (disposal) of the blades is not possible due to their mild burning and clogging of the cleaning plants.

The main practices of waste management at hydropower enterprises, due to the absence of complex specifics of their formation, include disposal (electronic waste, MSW, construction waste) and neutralization (electronic, construction waste).

Thus, it can be concluded that there are no specific waste management practices at renewable energy enterprises.

3. Results and Discussion

Due to the specifics of the energy facilities' impact on the environment, the insignificant amount of waste generation by most types of energy facilities (with the exception of coal and fuel oil thermal power plants), accounting, and evaluation of waste management costs in the framework of environmental and economic assessment of investment projects is practically not carried out.

According to the data from Table 2, a significant amount of production waste generation at traditional energy enterprises, in particular coal-fired thermal power plants, falls on the production process and on the elimination stage. At renewable energy enterprises, most of the production waste is generated at the stage of their elimination.

At the same time, during the design, construction, and operation of an energy facility, MSW (mainly during administrative activities), electronic waste (used electrical appliances for industrial and non-industrial purposes) and construction waste (during construction and repair work) are generated. The costs of its handling are often not taken into account when forming the cash flows of the project, and the calculation of environmental costs that are included in the calculation of the performance indicators of the investment project. To improve the accuracy of the formation of cash flows of an investment project and the effectiveness of assessing the negative impact on the environment, it is necessary to consider the formation of waste not only at the operational stage, but also at the stages of its development, implementation, and elimination.

Production waste has the largest ecological footprint in comparison with other types of waste (with the exception of electronic waste). In this regard, the assessment and analysis of their generation must necessarily be carried out when assessing the environmental efficiency of an investment project (for instance, calculating the volume of production waste generation per unit of energy produced [25] or forecasting the potential volume of industrial waste generated at the stage of elimination of an energy facility).

The inclusion of other types of waste in the calculation of environmental indicators is impractical due to the specifics of their generation and insignificant environmental impact (with the exception of electronic waste).

The costs of handling all types of waste should be reflected as environmental costs and included in the formation of cash flows. Despite the insignificant environmental impact of MSW, construction waste, etc., an energy facility can incur significant costs for handling them that might affects the commercial effectiveness of the project in the future.

The costs of handling MSW and electronic waste should be included in the investment (costs of developing waste management system, staff training) and operational flows of the investment project (staff salaries, payments to third-party organizations for the collection and disposal of MSW, the costs of processing MSW). Their inclusion in the calculation of environmental performance indicators of the functioning of a traditional or renewable energy facility is optional due to their non-productive nature and, consequently, insignificant environmental impact (hazard classes IV–V).

The largest volume of construction waste that belongs to hazard classes IV–V, is formed at the investment and elimination stages. At the stage of construction/reconstruction of an investment facility (investment phase), the costs of collection, removal and/or transfer of waste to third parties are most often reflected in the cash flows of the project. Their inclusion in the calculation of environmental indicators may be optional on par with MSW. The costs of waste management at the elimination stage during the evaluation of the effectiveness of the investment project are not predicted and are not included in the cash flows of the project, despite the significant amount of their formation and possible problems with their disposal. Forecasting the level of costs for the management of construction and man-made waste during the elimination phase of the project and their inclusion in investment and operational flows contributes to improving the accuracy of calculations of economic and financial indicators of the project. In addition, some of the man-made waste that may be generated during the shutdown of an energy facility should be taken into account when assessing the environmental effectiveness of an investment project.

Figure 3 shows a potential scheme for accounting for waste generation when generating cash flows and conducting an environmental assessment of an investment project in the energy sector.

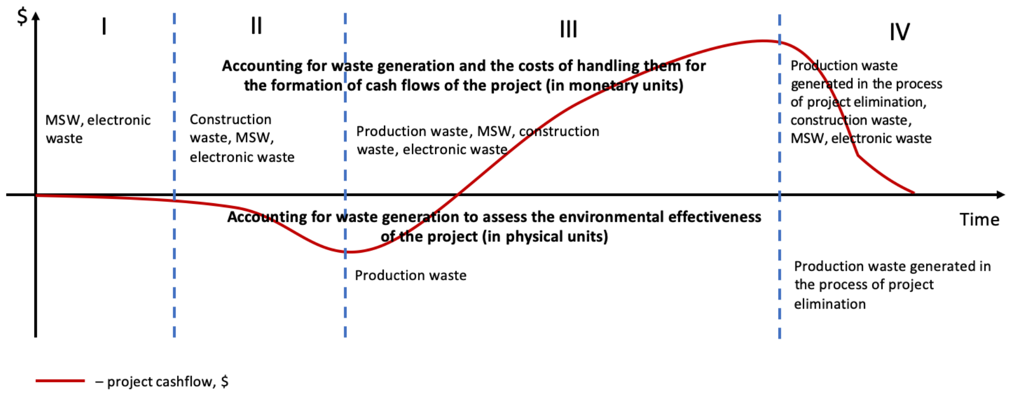

Figure 3. A potential scheme for accounting for waste generation in the formation of cash flows and conducting an environmental assessment of an investment project in the energy sector.

The use of the proposed waste generation accounting system within all stages of project implementation in the energy sector will allow the following:

- To more accurately predict the environmental costs of the project—despite the insignificant amount of waste generation in the I and II phases of project implementation in comparison with the III phase, the organization will still bear the costs of handling them (collection, sorting, disposal, payment for the services of third-party organizations, etc.);

- To increase the accuracy of the formation of cash flows of an investment project by including additional environmental costs in them and the effectiveness of the economic efficiency evaluation;
- To increase the informativeness of the environmental assessment of an investment project by considering waste generation more comprehensively at all stages of its implementation—often, the generation of man-made waste at the stage of elimination of an energy facility (completion of an investment project) is not taken into account, despite their significant volume and, in some cases, a high hazard class;
- To make a more complete accounting of waste generation at energy enterprises—the generation of all types of waste and the costs of handling them will be reflected in the cash flows of the investment project;
- To simplify the calculation of environmental indicators without losing the objectivity of the results obtained, only man-made waste that has a significant negative impact on the environment will be taken into account.

The use of the proposed waste generation accounting system in the development and evaluation of an investment project involves the mandatory introduction of an environmental management system, within which a waste management system is designed.

On the territory of the EU, most of the production and consumption waste is sent for recycling for secondary use, which is one of the components of the transition to the concept of a circular economy. In Russia, the share of waste sent for recycling is critically low. The application of the accounting system will make it possible to predict the formation of various types of waste at all stages of the project implementation and, therefore, can serve as a tool to stimulate the introduction of modern waste management practices, in particular at Russian energy enterprises. Table 3 presents recommended waste management practices at energy enterprises.

Table 3. Recommended waste management practices for energy facilities (made by the authors using data from [26,31,41–46]).

Type of Waste	Recommended Practices
Solid waste	1 Implementation of the system of separate waste collection at all facilities of the energy enterprise. 2 Waste paper, certain types of plastic and glass should be sent for recycling to specialized organizations.
Ash and slag waste	1 Transfer of ash and slag waste to specialized organizations for their further disposal, neutralization, and processing. The use of recycled products is possible in road construction and in the production of building materials. 2 Sale of ash and slag waste to interested organizations in order to obtain additional profit—some types of waste can be used to fill mining workings, reclamation of spent quarries, etc.
Construction waste	1 Collection and transfer of certain types of construction waste for processing into crushed stone with the possibility of subsequent sale. Reuse of metal structures.
Electronic waste	1 Mandatory transfer of waste to third-party organizations that are engaged in their disposal and neutralization, namely disassembly of electronic equipment, extraction of components with resource value and their transfer to recycling and crushing of unassembled devices with further sorting of scrap and obtaining polymetallic concentrate.

The implementation of these practices will help to minimize the total volume of waste generation in order to increase the degree of their valorization for potential profit, and minimize environmental costs, which corresponds to the concept of a circular economy. For instance, the ash and slag waste, depending on its composition and structure, is widely used in the construction sector of the economy, namely in the production of building materials (brick, cement, etc.), in road construction, for the production of various construction fillers, etc. Certain ash and slag wastes could also be used in agriculture as fertilizers. MSW could be used to produce recyclable materials suitable for the production of new products (plastic, paper, etc.), some parts of decommissioned electronic devices can be reused, and from unusable raw materials a special polymetallic concentrate is produced that is used in the production of various goods. In general, most of the waste generated at energy facilities can be recycled and reused in other sectors of the economy.

The need to improve the accounting of waste generation in the energy sector and the concomitant introduction of the principles of circular economy is noted in [28,47]. Rodrigo M. et al. note the predominant role of environmental reporting as a stimulating tool for improving accounting, reducing waste generation while increasing the valorization of industrial waste [27].

The increasing role of accounting and subsequent disposal of electronic waste at traditional energy enterprises is noted in studies [48,49]. At the same time, there are practically no works containing recommendations for including the analysis and considering of waste generation in the framework of the environmental and economic efficiency assessment of energy projects. The vast majority of research focuses on the evaluation of pollution of atmospheric air by energy facilities [25,50,51], water bodies [25,27,52], and the use of land resources [25].

The developed system makes it possible to increase the effectiveness of the environmental assessment procedure and the accuracy of the formation of cash flows at all stages of the energy project implementation. In addition, the introduction of an accounting system contributes to solving the problem of unaccounted costs—often the formation of waste at enterprises in a non-monetized state is transferred to society, and their ecological footprint is practically not taken into account. The proposed concept of waste accounting during the implementation of the investment project allows one to “return” these costs to production and take into account their impact on the environment at least in monetary terms (the environmental costs incurred for waste management at all stages of the project implementation).

4. Materials and Methods

In order to form a comprehensive waste accounting system, the existing waste management practices at traditional and renewable energy enterprises were studied, as well as the specifics of waste generation during the implementation of investment projects. Further, the most promising practices were identified, the classification of the generated production and consumption waste by stages of the life cycle was carried out. The stages and logic of the study are shown in Figure 4.

In order to improve approaches to accounting and assessment of waste generation in the development of investment projects in the energy sector, it is proposed to use the concept of Life Cycle Impact Assessment (LCIA) [53,54], according to which environmental impact assessment should be carried out at all stages of the life cycle of both a single product and an enterprise or investment project. Despite the possibility of comprehensive impact accounting and a standardized assessment procedure, its results can vary significantly depending on the selected functional unit, which is the main disadvantage of the methodology [55,56].

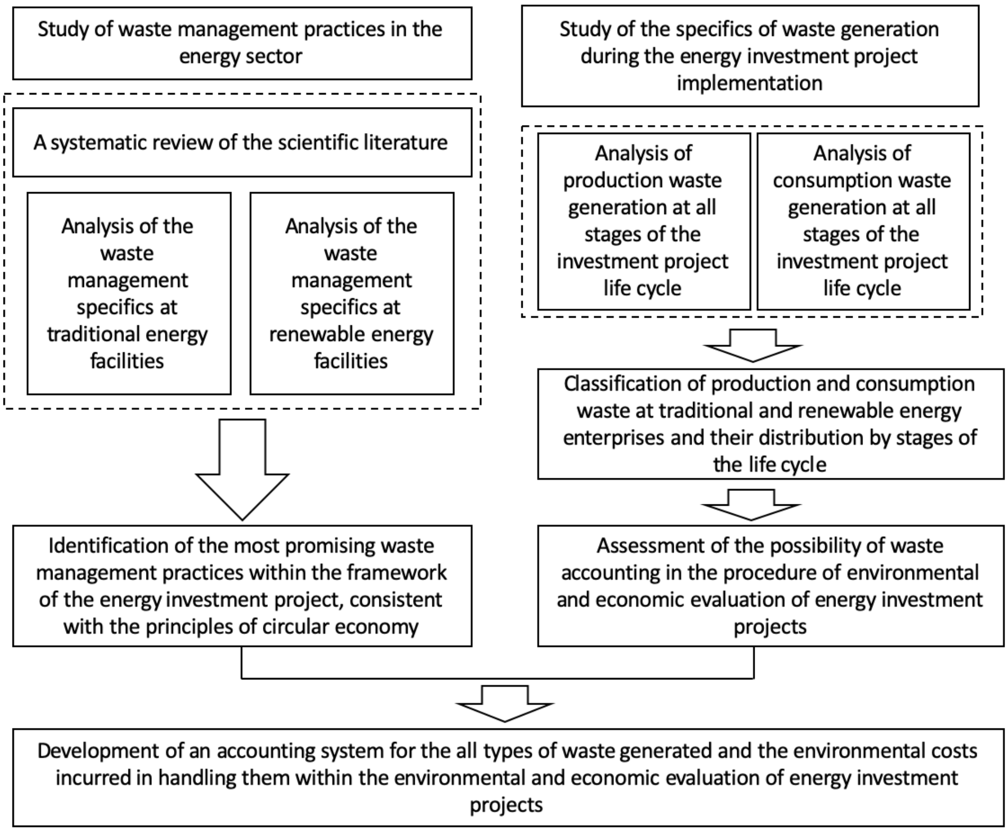

Figure 4. The logic of the research and its stages.

It is proposed to take into account not only production waste, but also consumption waste generated in administrative premises and industrial facilities at various stages of the project life cycle that includes 4 phases:

I. Pre-investment stage: (i) formation of the initial project idea, setting goals and objectives; (ii) conducting marketing and investment analysis; (iii) preparation of a feasibility study of investments; (iv) development of a business plan and a calendar plan of the project.

II. Investment stage: (i) development of the necessary documentation; (ii) conclusion of contracts; (iii) engineering and technical design; (iv) initial investment; (v) construction/implementation of planned activities.

III. Operational stage: (i) production, sale of products and services; (ii) monitoring of current economic and environmental indicators.

IV. Elimination stage: (i) suspension or complete shutdown of production processes; (ii) reformation, sale of assets and development of a new project.

Production and consumption waste generated at all stages of the project life cycle within the framework of the proposed accounting concept based on the results of the first stages, were divided into 4 groups: MSW, electronic waste, construction waste, and production waste, which will be conditionally divided into two groups (waste generated in the process of energy production, and in the process of shutdown of industrial objects). It should be noted that part of the construction waste (plaster, brick, etc.) belongs to MSW and, therefore, will be taken into account in this group. All other waste generated during construction works (scrap, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.) will be accounted for in the construction waste group. The separation of production waste by stages of the investment project is presented in Table 4.

Table 4. Types of waste generated at various stages of the project life cycle in the energy sector (made by the authors).

Investment Project Stage/ Type of Energy Facility	Pre-Investment Stage (I)	Investment Stage (II)	Operational Stage (III)	Elimination Stage (IV)
Thermal Power Plant (Coal)	- MSW (waste paper, plastic, etc.); - electronic waste (spent office equipment, lamps, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, food waste, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- production waste (ash and slag waste, soot, waste from pre-boiler water treatment for powering steam boilers; waste from mechanical/ chemical/steam-oxygen cleaning of equipment, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent industrial electric equipment, spent office equipment, lamps, wires, etc.).
Thermal Power Plant (Fuel oil)	- MSW (waste paper, plastic, etc.); - electronic waste (spent office equipment, lamps, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, food waste, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- production waste (fuel oil ash and soot, waste from pre-boiler water treatment to power steam boilers, waste from mechanical/chemical/steam-oxygen purification of equipment, etc.) - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent industrial electric equipment, spent office equipment, lamps, wires, etc.).
Thermal Power Plant (Natural gas)	- MSW (waste paper, plastic, etc.); - electronic waste (spent office equipment, lamps, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, food waste, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- production waste (waste of cleaning of smoke channels, pipes and equipment - waste from pre-boiler water treatment to power steam boilers - waste from mechanical/chemical/steam-oxygen purification of equipment, waste generated during the preparation of gaseous fuel, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent industrial electric equipment, spent office equipment, lamps, wires, etc.).
Hydropower Power Plant	- MSW (waste paper, plastic, etc.); - electronic waste (spent office equipment, lamps, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, food waste, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- production waste (debris from protective grilles, etc.) - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (hydro-turbines, spent office equipment, lamps, wires, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent industrial electric equipment, spent office equipment, lamps, wires, etc.).

Table 4. *Cont.*

Investment Project Stage/ Type of Energy Facility	Pre-Investment Stage (I)	Investment Stage (II)	Operational Stage (III)	Elimination Stage (IV)
Wind Power Plant	- MSW (waste paper, plastic, etc.); - electronic waste (spent office equipment, lamps, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, food waste, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- municipal solid waste (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- production waste (parts of wind turbines, etc.); - construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent industrial electric equipment, spent office equipment, lamps, wires, etc.).
Solar Photovoltaics	- MSW (waste paper, plastic, etc.); - electronic waste (spent office equipment, lamps, etc.).	- construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, food waste, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- production waste (dirt, dust, sand); - municipal solid waste (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent office equipment, lamps, wires, etc.).	- production waste (parts of solar panels, etc.) - construction waste (construction demolition debris, gypsum waste, bitumen, dust, waterproofing materials, acetone, etc.); - MSW (waste paper, plastic, glass, plaster, etc.); - electronic waste (spent industrial electric equipment, spent office equipment, lamps, wires, etc.).

5. Conclusions

In the course of the study, the specifics of waste generation at energy enterprises were analyzed and the main practices of handling them were studied. Based on the analysis, a waste generation accounting system has been developed for the stages of project implementation in the energy sector, which allows solving a number of tasks:

- The formation of all types of waste and the potential costs of handling them are taken into account, which contributes to a more accurate formation of project cash flows;
- The costs of man-made waste management at the elimination stage or during the reconstruction of an energy facility are laid down, which are usually not taken into account in the process of developing a project and conducting its environmental and economic assessment;
- The problem of unaccounted costs at all stages of the energy project implementation is being solved—responsibility for all types of waste generated and their negative impact on the environment falls entirely on the energy company;
- Improvement of the procedure for environmental and economic efficiency assessment of the energy investment project—for the calculation of environmental indicators, only man-made waste that has the greatest negative impact on the environment will be considered, the formation of other types of waste and the costs of handling them will be reflected in environmental costs that are included in the cash flows of the project—thus, most of the waste is taken into account when assessing the project efficiency.

The waste accounting system by stages of project life cycle might serve as an incentive for the introduction and effective waste management system at energy enterprises and an increase in the share of waste sent for recycling, for the purpose of their secondary use, sale to third-party organizations for additional profit, and a general reduction in environmental costs, which corresponds to the concept of a circular economy.

One of the significant disadvantages of the proposed system is the complexity of predicting the volume of waste generation at each phase of the housing and communal services, taking into account the time factor when forecasting environmental costs for their inclusion in the project cash flows and dependence on environmental legislation (different countries may have different requirements for waste disposal/processing/storage and environmental requirements may be subject to changes according to the passage of time). To solve these problems, it is planned to study the proposed system in more detail and adapt it to existing approaches of environmental and economic assessment (costs-benefits and costs-efficiency).

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