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Review

# A Review of the Energy Potential of Residual Biomass for Coincineration in Kazakhstan

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**Abstract:** Although it has access to hydrocarbon reserves, Kazakhstan has developed a strategy for the transition to a low-carbon economy, which should include the use of renewable energy sources. In this framework, the use of biomass from waste could have the potential to reduce emissions from traditionally fueled energy generation, as well as adding value to the generated waste, which also improves waste management according to the principles of a circular economy. The analysis of the resources and energy potential from residual biomass in Kazakhstan presents an annual production of $37.26 \times 10^6$ tons of residual biomass, which could be capable of producing an energy potential of 466.74 PJ/year, little more than half to the total production from all the installed power plants in the country. Agricultural, animal and municipal solid waste are available to produce energy in Kazakhstan based on combustion technologies; however, animal waste and agricultural are the main potential sources with 61.02% and 38.34% of the theoretical total biomass potential energy analyses, respectively. Considering that 80% of Kazakhstan's electricity generation comes from coal-fired plants, energy from agriculture could be co-fired for the gradual replacement of coal with biomass in operational power plants, without substantially increasing costs or infrastructure investments, thereby making the transition to a low-carbon economy and renewable energy sources in the country easier.

**Keywords:** energy potential; Kazakhstan; renewable energy; residual biomass

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## 1. Introduction

The ecological situation in the world is gradually deteriorating. The development of new technologies, the economic growth of countries, the increase in the extraction of the main raw materials and the overpopulation of the countries of the planet all lead to the deterioration of the ecological situation [1]. The main environmental problems of our planet look like this: climate change, overpopulation, a decrease in the protective ozone layer, a decrease in biological diversity, a shortage of fresh water, deforestation, manufactured disasters, and pollution of nature with heavy metals and toxic substances, as well as pandemics [2]. The question of the development of alternative energy sources is acute. Not only in the limitation of natural resources, but also in greenhouse gas emissions and global warming due to the burning of a huge amount of fuel, scientists around the world are striving to introduce the use of renewable energy sources in the near future [3].

A big environmental problem for Kazakhstan is air pollution. Kazakhstan ranks 20th among 221 countries in terms of carbon dioxide emissions and 10th in per capita emissions. Greenhouse gas (GHG) emissions according to the latest inventory amounted to 351 million tons of $CO_2$ equivalent (carbon dioxide) [4]. Kazakhstan is stepping up measures to implement its obligations as part of the global fight against climate change. At the same time, efforts are focused on increasing the resilience and decarbonization of the economy. In the implementation of the Paris Agreement of the Republic of Kazakhstan by 2030, the government is targeting a reduction in GHG emissions by 15%. To achieve this goal, Kazakhstan has updated its Nationally Determined Emission Reduction Contribution and developed an associated Roadmap for 2022–2025 [5]. The government is also taking practical measures to achieve the goal announced by the President of the Republic of Kazakhstan, in December 2020 as part of the UN Summit on Climate Ambition to achieve carbon neutrality by 2060 for Kazakhstan. The Doctrine of achieving carbon neutrality of the Republic of Kazakhstan by 2060 is being developed, which was presented in November 2021 in Glasgow at the UN Climate Change Conference. The document provides for measures to improve the energy efficiency of the economy of the Republic of Kazakhstan, electrification and large-scale use of renewable energy sources [5].

Kazakhstan has taken a number of structural measures to improve the investment environment in order to attract foreign capital and advanced technologies to the alternative energy development industry.

Kazakhstan is one of only a few countries with a huge hydrocarbon reserve. This reserve has a significant impact on the formation and condition of the world energy market, with deposits of ~33.6 million tons of coal (3.8% of the world's reserves), 30 million barrels of oil (1.8% of the world's reserves) and 1.5 trillion $m^3$ of natural gas (0.8% of the world's reserves) [6]. As a consequence, up to 85% of the total electricity production in Kazakhstan is produced by burning fossil fuels, mainly local coal, with specifically ~80% of the energy supply coming from the production of electricity by 63 coal-fired plants, including the main coal sources from the Kazakh, Ekibastuz, Karaganda and Turgai basins [7,8].

Coal in Kazakhstan possesses several advantages, including low sulfur content, high yields of volatiles on a dry ash-less mass [9,10] and low price, because the coal mining is carried out mainly in an open way. However, it is characterized as low grade because of the high ash content in its composition. As a consequence, the use of such fuel in thermal power engineering leads to problems in stabilizing the flame and burning in general, in the slagging of convective heating surfaces (furnace screens) and in air pollution by fly ash, carbon and nitrogen oxides ($CO_x$, $NO_x$), sulfur ($SO_x$), hydrocarbons ($C_nH_m$) and other combustion products.

Although the availability of many traditional fuels can result in a threat to the country's energy security in the future, Kazakhstan was the first of the Central Asian states to develop a strategy for a transition to a low-carbon economy that should include renewable energy sources. At a conference on climate change in Copenhagen in December 2009, within the framework of implementing the Kyoto agreements, Kazakhstan accepted voluntary commitments to reduce GHGs by 25% by 2050, compared to the level in 1992 [11]. As a result, in subsequent years, serious structural and technological changes have been made in Kazakhstan's energy power sector, accompanied by unprecedented investments in the development of renewable energy technologies and effective energy-saving policies [12].

In this sense, renewable energy sources can provide a solution to the global energy problem, characterized by environmental issues related to climate change, the need to reduce GHG emissions, reduce inventories and the exhaustibility of non-renewable fuel and energy resources [13]. In fact, in the Republic of Kazakhstan, the total reduction of GHG emissions from energy using renewable energy sources ranges from 500 thousand tons to 2.5 million tons [14]. Consequently, in recent years, the use of renewable energy sources in this country has become a priority area for the development of energy conservation, which is to reduce the energy intensity of the republic's economy. This is primarily due to the fact that such production does not require high material costs, because it is based on the use of energy sources that are continuously renewed due to the natural course of natural processes. In addition, the development of renewable energy in the country is conditioned by the significant potential of these sources, which makes this sector a promising and investment-attractive area for the development of the energy sector in Kazakhstan [15].

In addition to the environmental benefits of using renewable energy sources, there are significant economic benefits. In particular, the use of renewable energy sources for the generation and supply of electricity to existing grid systems can be economically justified in the energy-deficient regions of Kazakhstan [16]. Simultaneously, renewable energy can become a key factor in the development of the remote regions of the country. Therefore, one of the priority directions is the development of the electric power industry, and the solution to the environmental problems of Kazakhstan is the use of renewable energy resources, since it contributes to the solution of strategic tasks for the creation of an environmentally balanced and sustainable development. To achieve this, the following types of renewable energy sources are the most promising for the territory of Kazakhstan [17]:

- Hydropower energy. In terms of hydropower resources, Kazakhstan is third in the Commonwealth of Independent States behind Russia and Tajikistan, with a hydro potential estimated at 170 billion kWh per year, technically possible for sale—62 billion. Therefore, the technical potential for the use of small hydropower plants is ~108 billion kWh [18].
- Wind energy. The most significant of all renewable energy sources is the wind energy potential, with a total area of ~50,000 $m^2$ with average annual wind speed over 6 m/s, resulting in a wind potential 10–20 times greater than the volumes of energy consumption in Kazakhstan. The Dzungarian Corridor is the most significant area for the development of wind energy (17,000 kWh/$m^2$) [19], although other promising areas are the Dzungar Gates, Shelek Corridor and the Almaty, Erejmentau and Kordai regions.
- Solar energy. Despite the fact that Kazakhstan is located in northern latitudes, the potential for solar radiation on the territory of the republic is quite significant, so the potential generation of solar energy is estimated at 2.5 billion kWh per year. Simultaneously, solar energy can be used to generate not only electricity but also heat, which allows for the possibility of the point-in-time introduction of solar installations, including areas remote from the central electricity and heat supply [20].
- Energy from biomass. In relation to the use of biomass as an energy source, biomass co-firing has the potential to reduce emissions from traditionally-fueled energy generation, without substantially increasing costs or infrastructure investments. On this basis, by substituting coal with biomass, it could be possible to achieve a 93% decrease in net $CO_2$ emissions per unit of heating value and an 84% decrease in this emission by using a combined heating power process, where natural gas is replaced with biomass [21]. In addition, it has an advantage over other sources of renewable energy, as it can be stored and is readily available all year round from various sources [22]. Additionally, strong points include a rich resource base, while weak points include underdeveloped infrastructure [23]. Finally, the use of biomass from waste can lead to a substantial reduction in the overall quantities of waste requiring final disposal, which can then be better managed for safe disposal in a controlled manner while meeting pollution control standards.

The use of biomass for the generation of heat and electric energy allows the reduction of GHG emissions to 1.03–1.1 kg $CO_2$-eq/kg of fuel equivalent [24]. Kusuma et al. in a recent review, found that 20–30% of fossil fuels can be replaced with biofuels without significant capital investments; moreover, this can be further enhanced through pre-processing of biomass and process optimization [25]. Experiences of cofiring of biomass with coal have been carried out successfully in the two last decades. In 2005, Baxter identified over 100 successful field demonstrations in 16 countries, using many types of biomasses in combination with various types of coals and boilers [26]. In fact, nowadays numerous full-scale plants with biomass or cofiring with biomass and other fossil fuels are operating nowadays [27].

Therefore, biomass from waste with coal could be a good option for the transition to a low-carbon future in Kazakhstan, as well as having waste management objectives aligned with the two governing principles of a circular economy, i.e., to maximize the service provided by the materials embedded in products, and minimize the loss of service with time [28], reducing the negative environmental impacts of waste. For biomass-based power production, an accurate estimation of biomass and establishing biomass from the waste supply chain is a preliminary exercise. While the spatial distribution and potential of solar and wind energy has already been demonstrated [29,30], to date there has not been any analysis of bioenergy feedstocks for potential use in energy generation in Kazakhstan. Thus, this study presents a preliminary review of the energy potential from residual biomass in Kazakhstan, to analyses of the potential of biomass in this market for its use for electric power generation to satisfy the growth of electricity consumption while reducing the use of fossil fuels and the negative impact of the fuel and energy complex on the environment. This type of assessment is needed by policymakers in local governments in their efforts to establish medium- and long-term planning for the development of biomass and biogas resources, and by planners to arrange for the development and implementation of projects.

## 2. Energy Situation in Kazakhstan

### *2.1. General Data for Study Area*

Kazakhstan is a country in Central Asia bordered on the northwest and north by Russia, on the east by China and on the south by Kyrgyzstan, Uzbekistan, Turkmenistan and the Aral Sea. The Caspian Sea borders Kazakhstan to the southwest. It covers a total area of almost 2,724,900 km$^2$, making it the largest country in Central Asia and the ninth largest in the world [31], with an estimated population of ~19 million in 2021 [32]. The climate of Kazakhstan is continental [33], characterized by intensely cold winters with January air temperatures ranging from 18.5 °C in the north of the country to −1.8 °C in the south, and hot summers with July air temperatures ranging from 19.4 °C in the north to 28.4 °C in the south [34].

The energy sector plays a major role in Kazakhstan's economic development. Reliable and efficient operation of industry and a stable supply of electricity and heat to consumers are the basis for the development of the country's economy and an integral factor in ensuring civilized living conditions for the population. In fact, to date, the development of industry is by increasing production, which leads to an increase in electricity consumption. Figure 1 shows the primary non-renewable and renewable energy production and consumption in this country in 2021.

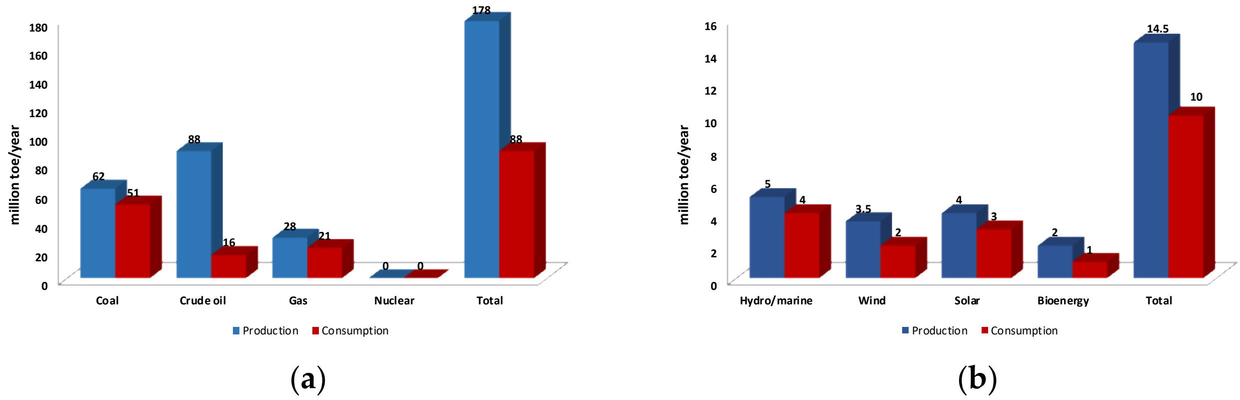


**Figure 1.** Primary crude (**a**) and renewable (**b**) energy production and consumption in Kazakhstan in 2021. Data for figure from [14,35].

It can be seen that consumption is about 50% of the total production and fossil fuels are the most important resources, with 178 million tons/year, representing 92.5% of the total resources and 89.3% of the total consumption. In production, crude oil is the most important, representing 45.7% of the total resources, followed by coal and natural gas that represents 32.2 and 14.5% of the resources, respectively. In relation to the consumption, coal is the most important (52.4%) followed by natural gas (21.4%) and crude oil (16.3%). At the moment, nuclear energy is not used in Kazakhstan, despite the fact that the reserves of uranium in the country are estimated at 900,000 tons (Figure 1a) [14].

In contrast, renewable energy resources have a smaller presence; nowadays, hydropower is the most significant renewable energy resource, representing 35% of the total resources and 44% of the total consumption [35]. This is followed by solar and wind, which represents 28%, with 25% and 22% of consumption, respectively. Only 14% of the energy production is from bioenergy and its consumption is 11% (Figure 1b).

### 2.2. Electrical Energy in Kazakhstan

Nowadays, the electric power industry is the basic branch of the economy of Kazakhstan and plays an important role in the political, economic and social spheres in the country. Figure 2 shows the evolution of electricity generation and demand during the last nine years. Prior to 2012, Kazakhstan was a net exporter of electricity, and later became a net importer, consuming more than it produces until 2013, when the growth of electricity production again allowed the country to export electricity [36]. According to the Kazakhstan operator of the electricity and capacity market, electricity production has increased since 2013 to reach 114.8 billion kWh in 2021, representing an increase of 21%, in addition to a major increase registered during 2021, 1% compared to the 2020 total production (113.5 billion kWh of electricity) [36]. Taking into account the predictions of the Ministry of Energy, this growth is expected to continue in future to produce 150 billion kWh of electricity by 2030.

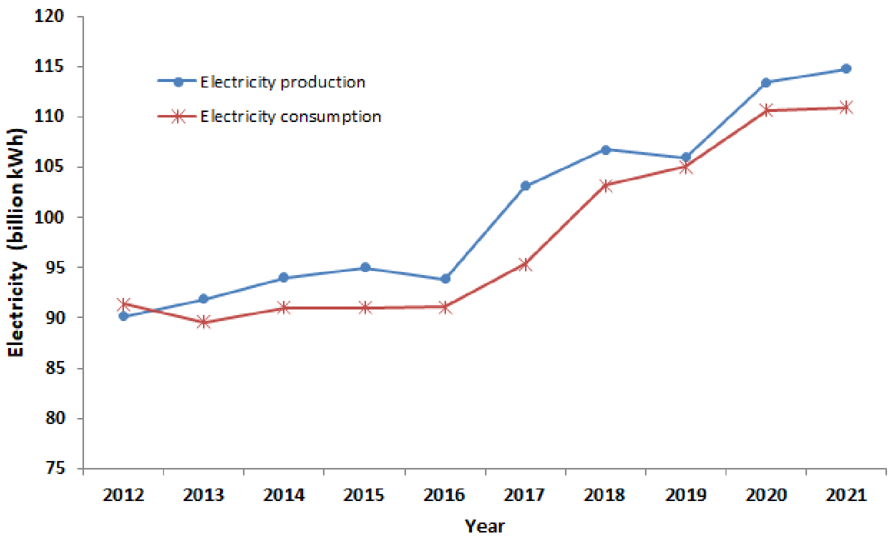


**Figure 2.** Evolution of electricity generation and demand in Kazakhstan. Data for figure from [36].

Although 80% of the country's electricity generation comes from 63 coal-fired plants located in the northern coal-producing regions, Kazakhstan also has five hydroelectric power stations, which give the country an overall installed generating capacity of 19.9 GW [37]. Kazakhstan's hydroelectric facilities are located primarily along the Irtysh River, which flows from China across northeast Kazakhstan. In terms of output, the leading position is held by condensing power plants, accounting for about half of the energy generated by power plants, followed by combined heat and power plants (36.5%), hydroelectric (12.3%) and gas turbine power plants (2.3%) [36].

Finally, and in relation to electrical energy consumption by sector in Kazakhstan, the industry and household sectors account for the major values, with 68.1% and 9.3%, respectively, followed by the service sector (8%), transport (5.6%) and agriculture (1.2%) [36] (Figure 3).

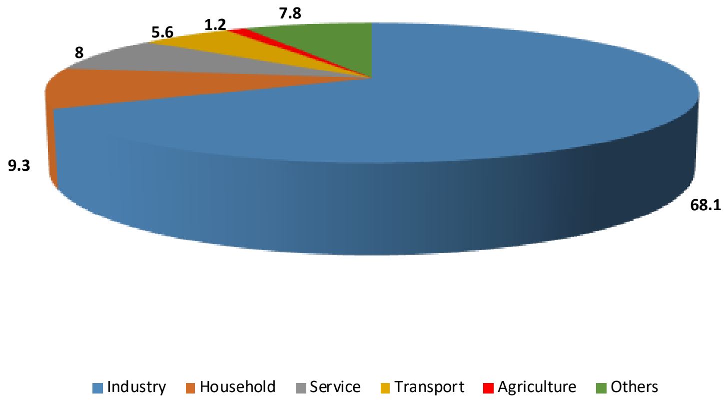


**Figure 3.** Electricity consumption by sectors in Kazakhstan. Data for figure from [36].

## 3. Residual Biomass Resources in Kazakhstan

Biomass is found abundantly in nature and it can be conveniently generated in most non-urban settings [38–40]. It is usually classified into the following three types:

- Natural biomass. This type is produced in natural ecosystems, without human intervention to enhance or modify it. It includes, fundamentally, waste produce during forest cleaning labor and plantation remains, fire wood and branches and coniferous and broad-leaved forests.
- Residual biomass. This biomass is defined as resources of residues generated during human activities that use organic matter. It includes residues, co-products and waste that could potentially become available, in quantity, at relatively low cost or even negative cost where there is currently a requirement to pay for disposal that could be used to produce energy. Dry residual biomass comes from agricultural activities, forestry, food industries and wood, among others; wet residual biomass is biodegradable waste produced in wastewater treatment, industrial process and livestock waste.
- Energy crops. These are usually grown specifically for fuel and are characterized by their high yield per hectare, very little or no fertilizer input requirements after the initial establishment phase, high resistance to drought and diseases, vigor, precocity of growth, regrowth capacity and adaptation to marginal lands, and, finally, much shorter rotation than traditional forestry.

Inadequate disposal of residual biomass can cause soil contamination, compromise the quality of water resources and promote environmental disturbances among species. As a consequence, the residual biomass before its final disposal needs to undergo an appropriate treatment process to reduce its potential environmental risk. Residual biomass from agricultural, animal and solid waste has been considered for energy production in Kazakhstan, to be incorporated into existing fuel storage and handling systems and be co-fired. Energy valorization from residual biomass would also be a key component in waste management into valuable products in a circular economy. The results are summarized in the subsections presented below.

### *3.1. Agricultural Residues*

Agricultural residues are formed directly during harvesting and the subsequent processing and sorting of agricultural crops. In Kazakhstan, crop production occupies a leading place in the structure of the agriculture of the country, accounting for 56% of all production [41]. Cereals account for 70% of all acreage [42]. Furthermore, Kazakhstan accounts for 21% of the acreage of grain crops in the Commonwealth of Independent States. As a consequence, millions of tons of agricultural waste are produced in Kazakhstan every year. Despite some of this waste being used as litter for farm animals, fertilizers or animal feed, it is principally burnt directly on the fields or in inefficient burners (with less than 10% efficiency) in small villages [43], resulting in a significant impact on the greenhouse effect in terms of gas emissions and air pollution [44]. In fact, during crop harvest, the elimination of waste is frequently carried out by farmers by burning it in the fields, crushing and mixing it with the soil or abandoning it in the field, because of the difficulty and high cost of removing [45]. The elimination of waste by burning during crop harvest makes possible the reincorporation of part of the necessary nutrients for the crop [46], however, open burning results in emissions to air of high concentrations of pollutants in the form of particles, $CO_x$, hydrocarbons, $NO_x$, $SO_2$, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), polychlorated compounds, dioxins and furans, that have a deleterious effect on air quality and human health [45,47]. On the other hand, the alternative of burying the straw in the soil generates between 2.5 and 4.5 times more methane than burning it [48]. Finally, the abandoned crop waste in the field sometimes may flow into the drainage during the rainy season, causing an obstruction of the drainage, but also providing a suitable place for the propagation of the bacteria [49].

Agricultural residues depend upon a wide range of local conditions and the primary factors influencing the amount of crop residue are the type and variety of crops planted and their yields [44]. In Kazakhstan, four globally important crops in terms of production quantities are wheat, barley, maize and rice, with their harvested area covering 35 million ha [50]. The annual collectible dry biomass ($C_B$) production is calculated according to Equation (1), where $C_P$ is the annual production of crops, $R_F$ is the residue factor, defined as the ratio of a field weight of residue per mass unit of crop yield [51], $W_F$ is the dry weight factor, which is used to take into account the high percentage of water in crops and depends on the type of crop and the amount of water in its environment [52–54] and $A_F$ is the availability factor, which is evaluated considering various constraints and excluding the fraction that is already used for energy production [52–54].

$$C_B = C_P \times R_F \times W_F \times A_F \tag{1}$$

Table 1 summarizes the annual production of crops, as well as the calculated collectible dry biomass, in this study. It shows that despite an annual production of crops of $23.41 \times 10^6$ tons/year, the total annual collectible dry biomass calculated is $15.10 \times 10^6$ tons/year, of which 63.31% is from wheat, followed by barley, maize and rice with 16.89%, 16.69% and 3.11%, respectively. The comparison between the annual collectible dry biomass ($C_B$) and the annual production of crops ($C_p$) shows how the type of crop and its residues and availability factors affect the collectible biomass. For example, wheat represents 53.40% of annual production but 63.31% of annual collectible dry biomass; however, in the case of maize, although it represents 30.75% of annual production, finally, the contribution in collectible dry biomass is reduced to 16.69%.

**Table 1.** Calculated collectible dry biomass ($C_B$) from crop residues available in Kazakhstan.

| **Crops** | **$C_P$ [41,42]** | | **$R_F$ [51]** | **$A_F$ [51]** | **$W_F$ [52–54]** | **$C_B$** | |
|---|---|---|---|---|---|---|---|
| | **$10^6$ ton/Year** | **%** | | | | **$10^6$ ton/Year** | **%** |
| Wheat | 12.50 | 53.40 | 0.85 | 1.00 | 0.90 | 9.56 | 63.31 |
| Rice | 0.51 | 2.17 | 1.43 | 0.80 | 0.80 | 0.47 | 3.11 |
| Maize | 7.20 | 30.75 | 1.10 | 0.60 | 0.53 | 2.52 | 16.69 |
| Barley | 3.20 | 13.67 | 1.90 | 0.70 | 0.60 | 2.55 | 16.89 |
| Total | 23.41 | 100.00 | | | | 15.10 | 100.00 |

### 3.2. Animal Waste

The amount of farm animal waste varies depending on the type of animal, feeding methods, size of animal body, type of breeding and population density for each location and keeping time at day or night [55]. Nevertheless, the modernization of the confined animals breeding systems is intensifying the generation of waste, which causes environmental problems due to the concentration and scale of the activity.

The most important branches of livestock breeding in Kazakhstan in 2021 are summarized in Table 2 and include sheep and goats, cattle, poultry and horse breeding [56].

Poultry breeding is the main branch of livestock production (55.26%), as many regions of Kazakhstan have favorable natural conditions for the development of poultry farming. The next branch of livestock production is sheep and goat, which is especially developed in East Kazakhstan, Akmola, South Kazakhstan and several other areas, where pastures of different seasons are successfully combined, representing 31.21% of the animals considered in this study.

**Table 2.** Livestock breeding and potential waste production.

| Livestock | Population | | Dry Matter ($D_i$) (kg/Head and Day) [56] | Collection Efficiency ($\eta_i$) (%) [56] | Animal Waste Production (AW) | | |
|---|---|---|---|---|---|---|---|
| | Number (Million) [40] | Percentage (%) | | | Dry Matter (ton/d) | Dry Matter ($10^6$ ton/Year) | Percentage (%) |
| Cattle | 8.20 | 9.47 | 3.5 | 80 | 22,960.00 | 8.38 | 50.00 |
| Sheep and goats | 27.00 | 31.21 | 0.45 | 60 | 7290.00 | 2.66 | 15.87 |
| Horses | 3.50 | 4.04 | 4.9 | 60 | 10,290.00 | 3.76 | 22.43 |
| Poultry | 47.80 | 55.26 | 0.15 | 75 | 5377.50 | 1.96 | 11.70 |
| Total | 53.40 | 100.00 | | | 45,917.50 | 16.76 | 100.00 |

Taking into account branches of livestock breeding, the potential mass of animal waste ($AW_i$), in tons of dry matter/day, for each animal species $I$ has been calculated using Equation (2). In this expression, $N_i$ is the population of animals of species $I$, $D_i$ is the dry dung output per day for animal species $I$ and $\eta_i$ is the collection efficiency of $i$ animal dung and depends on the dimensions and duration of stock farming per year of manure used for every type of animal. The values of $D_i$ and $\eta_i$ are included in Table 2 from [57].

$$AW_i = N_i \times D_i \times \eta_i \quad (2)$$

From the overview given in Table 2, it can be concluded that the potential dry waste production from animals included in this study is estimated to be 45,917.50 ton/d. Although poultry are the main branch of livestock production, cattle could have the greatest potential to be used as a source of clean energy, producing 50% of this waste, with horses in second place with 22.43% of the total production. According to official statistics, the uncontrolled handling and storage of animal waste in Kazakhstan produces 22.1 million tons of liquid waste annually [58], contributing to air pollution with harmful substances to humans, plants and animals, as well as a loss of organic matter [57–60]. The livestock sector is a significant contributor to global human-induced GHG emissions. Thus, Food and Agriculture Organization (FAO) has reported a total of 8.1 Gton $CO_2$-eq in 2010 (using 298 and 34 as global warming potential for $N_2O$ and $CH_4$ respectively) from livestock supply chains [61]. In these emissions, methane ($CH_4$), nitrous oxide ($N_2O$) and carbon dioxide ($CO_2$) account for about 50, 24 and 26 percent of the total, respectively.

### 3.3. Municipal Solid Waste

Municipal solid waste (MSW) is defined as waste consisting of everyday items, such as product packaging, grass clippings, furniture, clothing, bottles and cans, food scraps, newspapers and other fractions. This waste comes from homes, institutions, such as schools and hospitals, and commercial sources, such as restaurants and small businesses. In production terms, generally, the more urbanized the area is, the higher the amount of waste generation per capita; therefore, a positive correlation exists between increased welfare and the generation of municipal waste [58,59].

According to the Ministry of Energy of the Republic of Kazakhstan, at the end of 2021, the population of Kazakhstan was 19,169,550 people [32], which produced 5.5 million tons of MSW [53], resulting in a production rate of 0.84 kg/(person and day). An overview of the typical composition of MSW in the country shows that organic waste is the main component, representing 40% of the waste produced. A major percentage of combustible waste is also produced, representing ~54% of the total waste produced (paper and cardboard, plastic and textiles) [62].

The typical composition of MSW in Kazakhstan's cities is shown in Table 3 [63], where organic waste, composed by food and landscaping wastes, is the main component, representing 46% of the waste produced. Five percent of the material is denoted as 'other' and mainly includes construction and demolition debris and hazardous waste.

**Table 3.** Typical composition of municipal solid wastes in Kazakhstan cities, %. Data for table from [62].

| Waste Composition | Percentage (%) |
| --- | --- |
| Paper | 15 |
| Food wastes | 25 |
| Landscaping wastes | 21 |
| Plastic | 16 |
| Metals | 7 |
| Textiles | 4 |
| Glass | 7 |
| Other | 5 |

According to the Ministry of Energy of the Republic of Kazakhstan [64], in 2021, 9% of MSW was recycled, resulting in a disposal rate of 91% of MSW produced [65]. Consequently, more than 1000 hectares of land are occupied by this waste in the country, 98% of which is unsuitable and represents a potential hazard [65]. As a result, analysis of the existing state of accumulation of MSW in Kazakhstan shows that municipal waste management is one of the country's most significant environmental problems, so it is necessary to improve the waste management system and the application of advanced methods based on circular economy principles. This is further supported by the fact that it is planned by 2030 to increase the share of recycling to 40% [65].

### *3.4. Potential Inventories of Residual Biomass*

The residual biomass inventory from the different categories of biomass production included in this study has shown that Kazakhstan currently has a sustainable annual production of $37.26 \times 10^6$ tons of residual biomass, which is capable of producing energy.

The highest residual biomass production came from animal residues, closed followed by agricultural waste; in fact, both residues contribute 85.51% of the country's biomass production. Finally, although urban waste represents only 14.49% of total production ($5.5 \times 10^6$ ton/year), the foreseeable increase in population and the rate of generation of waste in the country could suggest an increase of this fraction in coming years; in fact, the annual increase of population in the last year was 1.55% [32].

## 4. Theoretical Energy Potential from Biomass

The information presented in the previous section showed that the high potential biomass production in the Republic of Kazakhstan is based on agricultural residues, animal waste and municipal solid waste. This could be used to produce bioenergy, reducing fossil fuel consumption and improving the environment as a safe method of waste disposal. Despite thermo-chemical and bio-chemical technologies which are being used to convert biomass into energy and the possibilities of biofuel production from biomass, taking into account the extensive network of existing coal-fired power plants in the country, for this study, theoretical energy potential has been quantified for co-combustion process. The selection of conversion technologies for biomass depends upon the form in which the energy is required, like combustion to produce heat, mechanical, or electrical energy. The results are summarized in the subsections below.

### *4.1. Potential Energy from Agricultural Crop Residues*

The potential energy content of the collectible dry residue ($P_c$) is calculated using Equation (3), according to Klass [54]. In this expression, $C_B$ is the amount of residue calculated in the previous section and summarized in Table 1, $O_c$ is its organic content expressed per unit and *LHV* is the lower heating value of the organic material. $O_c$ (%) which values for each crop has been established according to Phyllis2 [66].

$$P_C = C_B \times O_C \times LHV \quad (3)$$

Taking into account Equation (3), Table 4 shows the calculated potential energy from agricultural crop residue. From this table, it can be observed that the amount of theoretical potential energy obtained from 15.10 million tons/year of dry biomass rises to 174.23 PJ/year. The greatest capacity to produce energy corresponds to wheat residues because of its higher production and organic content; in fact, wheat residues make up 63.31% of agricultural waste, from which 55.88% of potential energy can be obtained. It is followed by maize and barley residues, which potential energy has been calculated in 39.49 and 31.38 PJ/year, representing 22.67 and 18.01% of the energy potential from crops.

**Table 4.** Energy potential of different crop residues available in Kazakhstan.

| Crops | $C_B$ | | Organic Content | Lower Heating Value | $P_C$ | |
|---|---|---|---|---|---|---|
| | $10^6$ ton/Year | % | $O_C$ [54] | (GJ/Dry ton) [66] | PJ/Year | % |
| Wheat | 9.56 | 63.31 | 67 | 15.20 | 97.36 | 55.88 |
| Rice | 0.47 | 3.11 | 78 | 16.38 | 6.00 | 3.44 |
| Maize | 2.52 | 16.69 | 90 | 17.41 | 39.49 | 22.67 |
| Barley | 2.55 | 16.89 | 76 | 16.19 | 31.38 | 18.01 |
| Total | 15.10 | 100.00 | | | 174.23 | 100.00 |

### *4.2. Theoretical Energy from Animal Waste*

In this study, the energy potential of livestock can be calculated using Equation (4) [54], where $AW_i$ is the dry matter produced for each type of animal per day, calculated in the previous section and summarised in Table 2, and $LHV_i$ is the lower heating value of *i*th animal dung.

$$E_j = 365 \sum_{i=1}^{n} AW_i \times LHV_i \quad (4)$$

Table 5 shows the theoretical calculated energy potential from livestock. It can be observed that the theoretical total potential rises to 284.82 PJ of energy per year, of which more than half could be produced by cattle, followed by poultry and horses with 14.75 and 14.5% of the potential harvestable energy.

**Table 5.** Energy potential from livestock.

| Livestock | Dry Matter (ton/d) | LHV (GJ/ton) [51] | Potential Harvestable Energy | |
|---|---|---|---|---|
| | | | PJ/Year | % |
| Cattle | 22,960.00 | 19.6 | 164.26 | 57.67 |
| Sheep and goats | 7290.00 | 14.0 | 37.25 | 13.08 |
| Horses | 10,290.00 | 11.0 | 41.31 | 14.5 |
| Poultry | 5377.50 | 21.4 | 42.00 | 14.75 |
| Total | 45,917.50 | | 284.82 | 100.00 |

### *4.3. Theoretical Energy from Municipal Waste*

Currently, energy from MSW can be recovered in two main ways: thermo-chemical conversion and bio-chemical conversion by anaerobic digestion of the biodegradable fraction of waste. Both conversion processes can also be combined to optimize the energy output. In the case of thermo-chemical conversion, the conversion technology for waste to energy in Europe is by burning unprocessed waste to generate steam (or hot water) for local heating and electric power generation. However, more recently, the number of solutions has been growing, for example mechanical processing of waste to upgrade it to solid recovered fuel (SRF) for use by itself or as a coal supplement. As a consequence, and with the objective of determining the greatest exploitation of the energy content in waste, in this study, the production of SRF, to be used in the cofiring process with coal, has been considered to determine the theoretical energy from municipal waste. According the theoretical efficiency of municipal waste treatment plants defined by Fernández-González et al. [67], production of SRF accounts 23.36% of the waste treated (Figure 4). For this study, a flowchart including the recuperation of organic matter to be biostabilized has been considered, based on the rates retrieval from reference treatment plants operating in Spain, as well as similar studies and relevant businesses in the sector [67]. The potential energy produced has been calculated according to Equation (5) ($E_C$).

$$E_C = G \times R_f \times LHV_{RF} \quad (5)$$

In this expression:

$G$—Tons of waste treated annually at the facilities (ton/year). The value taken for the area of study was $5.5 \times 10^6$ ton/year.

$R_f$—Percentage of SRF after treatment (%) quantified in 23.36% according to the flow charts of Figure 4.

$LHV_{RF}$—Lower heating value of the rejected material (MJ/t). The value taken is 8000 MJ/t for incineration [68].

Considering the mass balance of the flowchart of the process (Figure 3), and taking into account $5.5 \times 10^6$ t/year of municipal solid waste production, the potential energy from SRF produced from the rejected fraction, to be co-incinerated, has been quantified in 10.28 PJ/year.

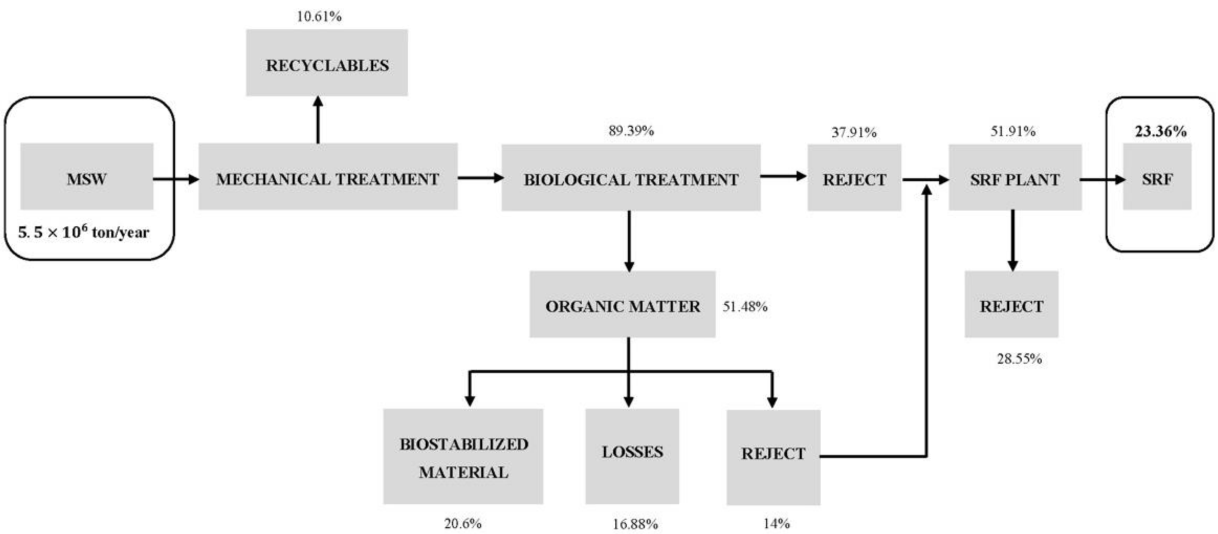


**Figure 4.** Flowchart of the process showing the mass balance (in % of the initial $5.5 \times 10^6$ ton/year) [68].

### 4.4. Theoretical Potential Energy from Biomass

Table 6 summarizes the total theoretical potential energy that could be obtained from biomass waste in Kazakhstan in co-incineration process, considering biomass from agricultural crops, animal waste and municipal solids. It is possible to conclude that the total theoretical energy production from biomass is calculated as near to 469.33 PJ/year; this value is 52.70% of the total production in all the currently installed power plants in Kazakhstan (890.57 PJ/year). Table 6 highlights the energy potential of waste generated from the animal wastes, which is 60.69% of the total potential energy.

**Table 6.** Theoretical potential energy from biomass residues in Kazakhstan.

| Type of Biomass | Theoretical Potential Energy (PJ/Year) | Percentage of Total Energy (%) |
|---|---|---|
| Agricultural crop residues | 174.23 | 37.12 |
| Animal wastes | 284.82 | 60.69 |
| Municipal solid waste | 10.28 | 2.19 |
| Total | 469.33 | 100 |

As a result, co-firing biomass (agricultural crop residues, animal waste and municipal solid waste) with coal could be an option in Kazakhstan because the biomass could be incorporated into existing fuel storage and handling systems with relatively minor modifications, meaning that the generating capacity already exists to produce dispatch able and renewable power [69,70]. In addition, if the biomass is properly sourced it can be a carbon-neutral feedstock and even result in negative emissions if $CO_2$ in the flue gas from biomass combustion is captured and stored [71].

Koshim [72] analyzed the spatial distribution and bioenergy generation potential of different feedstocks using an ArcGIS platform and demonstrated a significant opportunity for a range of bioenergy technologies. The authors concluded that biomass cofiring is an attractive option for reducing carbon emissions as it can use existing power plant infrastructure.

## 5. Conclusions

In Kazakhstan, growing concerns are arising regarding the sustainability demands of the reduction of GHGs, so the development of clean technologies for obtaining renewable resources is necessary. In the case of the energy from residual biomass, it adds value to the generated waste, which would also improve waste management according to circular economy principles.

Our analysis of the resources and energy potential from residual biomass in Kazakhstan concludes that an annual production of $37.26 \times 10^6$ tons of residual biomass could be capable of producing energy which has been estimated as 469.33 PJ/year, little more than half to the total production from all the installed power plants in the country. Although there are diverse sources from which to obtain waste biomass, including agricultural, animal and municipal solid waste, according to the quantity of biomass waste calculated and its energy content, animal wastes and agricultural are the main biomass sources in Kazakhstan (60.69% and 37.12% of theoretical potential energy, respectively).

At present, different technologies could be applied to convert biomass into energy; thermo-chemical and bio-chemical. The selection of the conversion technologies for biomass depends upon the form in which the energy is required, like combustion to produce heat, mechanical, or electrical energy. Taking into account that 80% of the country's electricity generation comes from 63 coal-fired plants, agricultural biomass could be incorporated into existing fuel storage and handling systems and be co-fired with coal to reduce $CO_2$ emissions, making the transition to a low-carbon economy and renewable energy sources in Kazakhstan easier.

Implementation of environmentally friendly energy technologies related to converting agricultural waste into energy can enable the energy sector to be a less energy-intensive, more sustainable and climate-friendly market. However, it is important to create effective policies and incentive mechanisms to ensure that investors view the biomass conversion sector as an attractive and competitive business area.

The following are recommendations for improving the sector conditions:

– Creation of additional investments focused on the use of biomass and agricultural waste and biogas technologies, since recent investments have been mainly focused on the use of wind, solar and water energy.
– Creation of specialized programs for sustainable agriculture with the aim of making the transition to clean energy and minimizing waste, which will motivate farmers to

convert their heating and energy systems to the use of agricultural waste and biomass instead of fossil fuels.

– Defining a clear relationship between energy policy, strategy, an action plan in the field of renewable energy and other sectors, especially with the agricultural sectors, and the sector energy efficiency and overall targets for the green economy.

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