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Valorizacija otpadne poljoprivredne biomase kao goriva za održivu proizvodnju energije kosagorevanjem

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Apstrakt: Otpadna poljoprivredna biomasa, kao što su ostaci od useva, predstavlja značajan autohtoni obnovljivi izvor energije u Srbiji. Kao takvi, poljoprivredni ostaci se mogu koristiti u cilju proizvodnje energije. Direktno kosagorevanje biomase sa ugljem/lignitom nudi održivu opciju za uklanjanje ove vrste otpada i istovremeno korišćenje njegovog energetskog potencijala, smanjenje štetnih emisija i ekonomičnu revitalizaciju postojećih termoelektrana na ugalj. Međutim, postoje ozbiljna pitanja u vezi sa upravljanjem ovim otpadom i samim procesom kosagorevanja, koja tek treba da budu rešena. Glavni cilj ovog rada je da predstavi prednosti i izazove kosagorevanja otpadne poljoprivredne biomase, kao perspektivne tehnologije za valorizaciju biomase i dekarbonizaciju u energetici, sa fokusom na energetski potencijal poljoprivrednih ostataka i karakteristike biomase kao alternativnog goriva, njenu pripremu i efikasno korišćenje u elektroenergetskom sektoru.

Ključne reči: poljoprivredni ostaci, upravljanje otpadnom biomasom, kosagorevanje, elektrane, emisija.

Valorization of Waste Agricultural Biomass as a Fuel for Sustainable Power Production by Co-Firing

Abstract: Waste agricultural biomass, like the crop residue, is an abundant indigenous renewable energy source in Serbia. As such, the agricultural residue might be utilized for sustainable power production. Direct co-combustion of biomass with coal/lignite offers a viable option to remove this kind of waste and, in the same time, to use its energy potential, mitigate harmful emissions and retrofit existing coal-fired power plants cost-effectively. However, there are serious issues regarding the waste management and the co-firing process itself, yet to be solved. The main aim of this paper is to present benefits and challenges of co-firing the waste agricultural biomass, as a promising technology for biomass valorization and decarbonization in energy, focusing the agricultural residues energy potential, as well as characteristics, preparation and efficient utilization of the biomass as an alternative fuel in power sector.

Keywords: crop residue, biomass waste management, co-firing, power plants, emission.

1. Introduction

Due to the ever-increasing emission of CO_2, global warming, as a consequence of the greenhouse effect, is threatening the world eco-system. In order to tackle the climate change and its negative impacts, the Paris Agreement was adopted in 2016, setting a long-term goal to limit global temperature increase to less than 2°C above pre-industrial levels, pursuing efforts to limit it to 1.5°C (United Nations, 2016).

Agriculture is the second-largest source of greenhouse gases (GHG), 19.9%, after the energy sector, generating a huge amount of solid waste (Lamb et al., 2021; Kamusoko et al., 2021). Agriculture residue generated globally is equivalent to 50 billion tons of oil, while burning the crop residue causses environmental and health problems (UNEP, 2022). Proper management of different kinds of waste agricultural biomass enable diverse applications (Kamusoko et al., 2021; Tripathi et al., 2019; Marković and Tomašević, 2022). Agricultural biomass to energy conversion has significant potential to reduce the use of fossil fuels and GHG emission, contributing to the green energy (Varjani et al., 2022). The use of agricultural waste for energy generation is of great importance (Tripathi et al., 2019). Effective management of agricultural waste should address emission problems and energy security, focusing sustainable utilization of renewables (RES) and reducing the coal use in power plants (Babu et al., 2022).

Criteria for biomass and bioenergy sustainability can be classified as environmental, socio-economic and cross-cutting criteria, such as the land use, thus requiring complex approach (Adams, 2013). Bioenergy may help to climate change mitigation, secure energy supply and economic development, while biomass combustion provides over 90% percent of global contribution to bioenergy (van Loo and Kooppejan, 2010). Generally, biomass is considered a carbon neutral fuel, if its use in energy is managed in a sustainable way (Almena et al, 2022). Co-firing biomass and coal for power production can effectively reduce CO_2 emission, but also emissions of other pollutants, such as NO_x, SO_2, CO, and particulate matter (Liu et al., 2022; Jiang et al., 2022; Zhang et al., 2020). Co-firing crop residues with coals is a cost-effective option for power sector decarbonization and utilization of biomass as RES (Roni et al., 2017; van Loo and Kooppejan, 2010). This kind of waste valorization technology enables also local social benefits (Souza et al, 2017). It plays important role in achieving European renewable targets for power production, while the crop residue is abundant indigenous resource in many countries, such as Serbia.

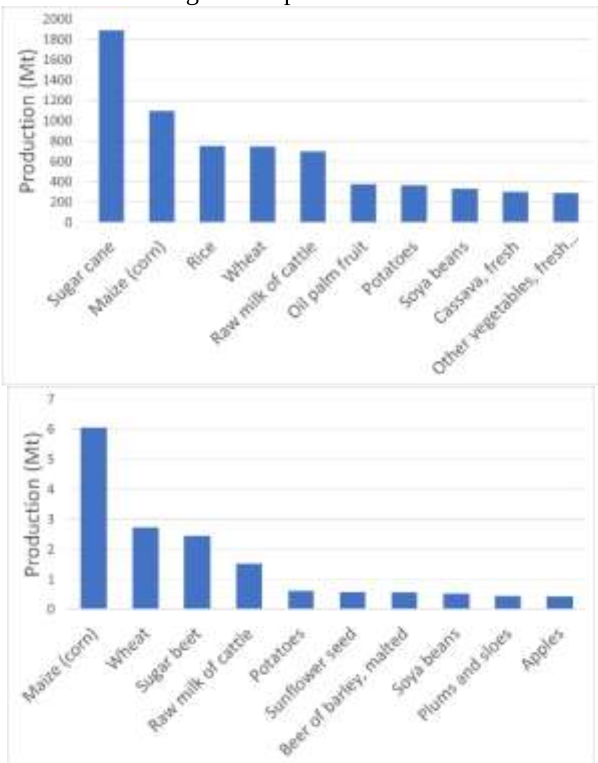
There are three main configurations for the biomass/coal co-firing in power plants: direct, indirect and parallel co-firing (Loo and Kooppejan, 2010; Liu, 2023). Direct co-firing is the most common co-combustion technology for power generation, because of the lowest costs to retrofit the existing coal-fired power plants (Basu et al., 2011), but imposes serious problems, like slagging, fouling and corrosion, connected with characteristics and diversity of biomass fuels (Belošević, 2010). In order to make the most of the co-combustion process, choosing appropriate technology, operating conditions (such as biomass/coal mixing ratio) and pretreatment of the biomass waste fuel are crucial to the task (Liu, 2023). Better understanding of the co-firing process and making an appropriate co-firing strategy are supported by numerical parametric studies (Belošević, 2010; Gao et al, 2016; Milićević et al, 2020; Milićević et al, 2021).

2. Waste agricultural biomass – energy potential in Serbia

The Republic of Serbia has a significant biomass potential, regarding both the availability and the biological diversity. Among all of RES in Serbia (hydro, biomass, wind, solar and geothermal energy sources), biomass has the biggest potential, especially important in agricultural sector (UNDP Serbia, 2019). The estimated technically viable potential of RES in the Republic of Serbia is 5.65 Mtoe per year (million toe; toe-equivalent to tons of oil), the majority of which is made up of biomass, which amounts approximately to 3.45 Mtoe per year (out of these 2.3 Mtoe is unused), contributing with 61% to the total RES potential (Energy portal, 2021). Agricultural biomass is 48% and 44% is wood biomass. The estimated potential of agricultural biomass (field crops residues, residues from wine and other fruit growing and food processing) is 1.67 Mtoe per year.

Agriculture represents one of the key sectors of economy and accounts for about 10% of GDP in the Republic of Serbia. Residues from agriculture can be classified into three groups: residues originating from growing field crops, fruit and livestock breeding. The farms mostly grow crops, such as wheat, corn and soybean and produces abundant amounts of residue (Škrbić et al, 2020). The agricultural biomass is most commonly found in northern Serbia. Farming in Serbia covers 1.7 Mha, with corn covering 0.9 Mha and wheat 0.64 Mha. Cereal annual production is about 2.9 Mt of wheat and 1 Mt of corn (excluding silage corn), generating about 3.7 Mt of straw (The Ministry of Environmental Protection, 2022). Thus, the most important biomass potential in Serbia is the crop residue. From the total amount of the crop residues, around 25% is estimated to be available for energy production (Milićević, 2018).

Figure 1: Most produced food commodities in the world (a) and in Serbia (b), average in the period 2012-2022

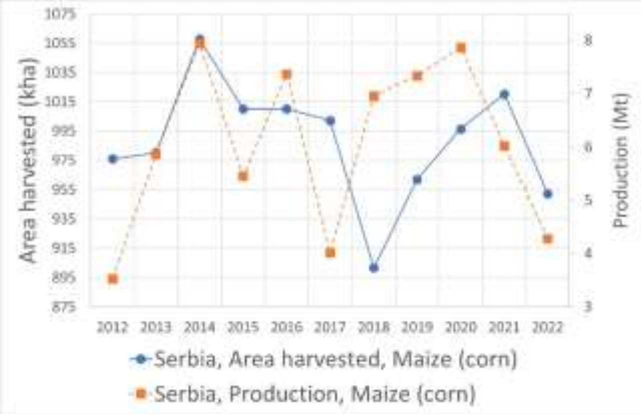


(a) (b)

Source: (FAOSTAT, Retrieved April 11, 2024)

Average amounts of the most produced agricultural (food) commodities in the world and in the Republic of Serbia, respectively, in the ten years period 2012-2022, are shown in Figure 1, retrieved from The United Nation Food and Agriculture Organization database (FAOSTAT). The crops are among the most abundant ones, both in the world and in Serbia, while the maize (corn), wheat, sugar beet, sunflower seed and soya beans are the most important crops in Serbia; among them the residues from production of maize, wheat and soya are used in energy production most often (like in the form of corn and wheat straw). The FAOSTAT domain 'Crops and livestock products' provides data on production and yield quantities of most produced and selected commodities in selected country during the chosen period of time, as shown in Figures 2-4 for production and yield of maize (corn), wheat and soya beans in Serbia. Both the production and area harvested show the oscillating character, depending on various factors, such as environmental, economic and social ones. Thus, there is a drop in production of these crops in 2020-2022, or 2021-2022 period, probably due to the well-known world health crisis.

Figure 2: Production of maize (corn) in Serbia for the period from 2012 to 2022
(total amount and area harvested)

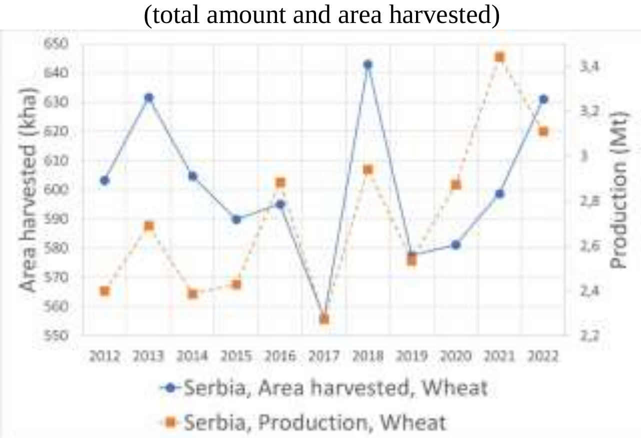


Source: (FAOSTAT, Retrieved April 11, 2024)

Annual production of maize, wheat and soya beans in 2020 (maximal production in the 10 years period) were around 8 Mt, 3.5 Mt and 0.75 Mt (FAOSTAT, (FAOSTAT, April 11, 2024, Figs. 2-4). In general, there is an increasing character of the area harvested and the production of maize and soya in the period. Increased production of these commodities suggests an increase in the amount of the crop residue/waste biomass generated. The FAOSTAT domain 'Emissions from Crops' provides available data on emissions of greenhouse gases from (uncontrolled) burning of crop residues, as shown in Figure 5 for Serbia in the ten years period. There was an obvious increase in the emissions of both N_2O and CH_4 from 2018 on. If only a part of the crop residues generated would be co-fired in an eco-friendly way in utility boilers to produce energy, this environmental issue may be alleviated.

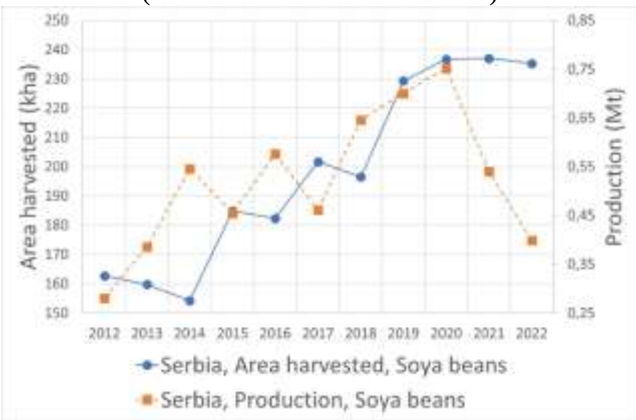
Thus, this abundant waste from agricultural production (crop residue) should be managed in a sustainable way, i.e. to enable mitigation of the harmful environmental impact with respect to both the waste removal and the GHG and other pollutants emission. As suggested, the valorization of the agricultural waste by utilizing it for energy production as a fuel may meet these requirements. Management of agricultural and other kinds of waste is planned through the planning documents, among which the 'Waste management program of the republic of Serbia for the period 2022-2031 is of paramount importance (The Ministry of Environmental Protection, 2022).

Figure 3: Production of wheat in Serbia for the period from 2012 to 2022
(total amount and area harvested)



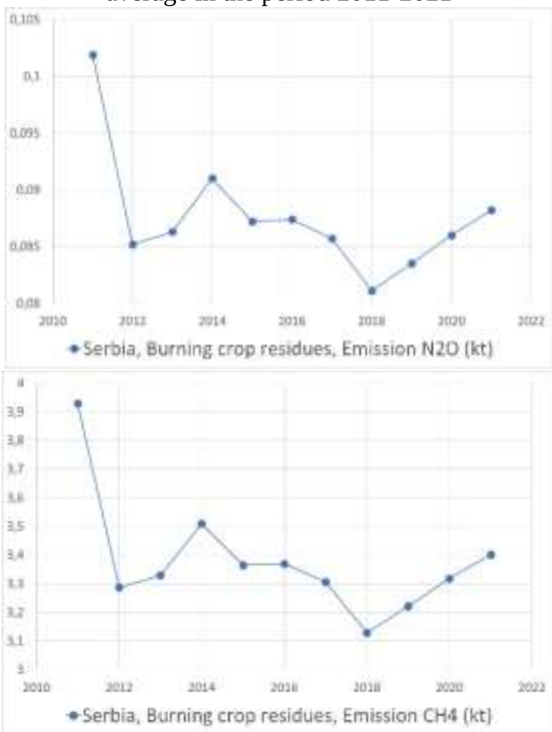
Source: (FAOSTAT, Retrieved April 11, 2024)

Figure 4: Production of soya beans in Serbia for the period from 2012 to 2022
(total amount and area harvested)



Source: (FAOSTAT, Retrieved April 11, 2024)

Figure 5: Emission of N_2O (a) and CH_4 (b) due to the burning of crop residues in Serbia,
average in the period 2011-2021



(a) (b)

Source: (FAOSTAT, Retrieved April 11, 2024)

3. Characteristics of the crop residue as an alternative fuel

The GHG emission during the biomass combustion is thought to be zero; there is no net increase in CO_2 because the biomass is considered to consume the same amount of CO_2 from the atmosphere during growth as it is released during combustion; so, released CO_2 is returned into the natural carbon loop. In addition, the alkaline ash from biomass captures some of CO_2 and SO_2 released by combustion (Vassilev et al, 2015; Demirbas, 2005).

Characteristics of a great variety of biomass fuels affect the whole process of biomass utilization (fuel supply, combustion system and emission). Due to differences in physical properties and chemical composition, combustion properties are considerably different for various biomass types and also when compared to coal. Numerous issues regarding the properties and combustion of agricultural residues are discussed (Werther et al., 2000). Biomass particles are large and non-spherical by shape, which influence heat and mass transfer and is challenging for the fuel conversion efficiency. The biomass particle density is lower than for coal particle by a factor of 4-7. The biomass has low friability, but generally it is not necessary to reduce biomass particles to the same size as coals (Baxter, 2005). Biomass has lower heating value than most coals, generally due to the higher moisture and, in part, oxygen content. Biomass is higher in volatiles than even the low rank coals and usually consists of 70–80% volatile matter versus 10–50% for coals; thus, biomass particles quickly burn off and the time of complete combustion is short in comparison with coal particle of similar size. For particle sizes and heating rates such as in pulverized coal co-firing biomass yields up to 90–95% of its dry, inorganic-free mass during devolatilization, compared with 55–60% for most coals (Baxter, 2005). With respect to ‘typical’ coal, biomass has less carbon, more oxygen, low sulphur and more silica and potassium. The content of chlorine for certain biomass fuels can exceed the levels for coal. The compositions of biomass fuels are extremely variable, especially with respect to inorganic constituents, such as chlorine, alkali elements (like potassium) and alkaline earth metals, which are critical to the problems of ash formations, fouling and slagging. Characteristics of the solid biomass fuels and their most important effects can be found as summarized in details elsewhere (van Loo and Kooppejan, 2010).

Table 1: Properties of biomass fuels compared with coal

Fuel	**LHV (MJ/kg) daf**	**Volatile matter (mass %) daf**	**Ash (mass%) dry**	**Ultimate analysis (mass %) daf**				
				C	**H**	**O**	**N**	**S**
Straw	18.2	81.3	6.6	49.0	6.0	44.0	0.8	0.2
Wood	18.7	83.0	1.8	50.5	6.1	43.0	0.3	0.1
Bark	16.2	76.0	7.0	50.5	5.8	43.2	0.4	0.1
Peat	19.0	74.2	2.7	52.6	5.8	40.6	0.9	0.1
Typical bituminous coal	31.8	34.7	8.3	82.4	5.1	10.3	1.4	0.8

Source: (Dai et al, 2008)

Table 2: Properties of domestic wheat straw and Serbian lignite (Kostolac, Drmno)

Fuel	**LHV (MJ/kg) daf**	**Ash (mass %) dry**	**Ultimate analysis (mass %) daf**				
			C	**H**	**O**	**N**	**S**
Wheat straw	17.8	6.6	48.8	6.5	44.0	0.7	0.0
Lignite	24.7	39.7	66.4	6.3	22.8	2.6	1.9

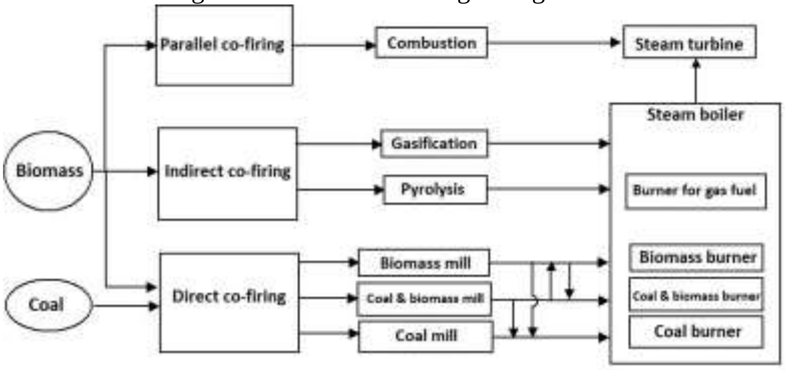
Source: (Janić, 2000; Authors)

A comparison of coal and biomass properties and combustion is given in (Dai et al, 2008). Properties of different biomass fuels compared with ‘typical’ bituminous coal are summarized in Table 1 (where ‘LHV’ means ‘lower heating value’, while ‘daf’ and ‘dry’ mean ‘dry ash-free’ basis and ‘dry basis’, respectively). When compare the crop residue like domestic wheat straw with the low rank coal, such as Serbian lignite, there are to some extent different relations between the fuels, Table 2. Thus, it is necessary to take into account carefully the composition for each of the case-study fuels. Properties of different domestic biomass fuels are summarized in literature (Radovanović, 1994; Brkić et al, 2018).

4. The biomass/coal co-firing technology for power production

Demonstration of the co-firing of the biomass (cereal straw) with coal started in 1995 in 150 MW_e pulverized coal-fired boiler, at Unit 1, Sdustrup power plant, near Aarhus in Jutland, Denmark (van Loo and Kooppejan, 2010). There are three main configurations for the biomass/coal co-firing in power plants: direct, indirect and parallel co-firing. In direct co-firing at least two fuels are co-combusted in the same boiler, in indirect co-firing the solid fuel is gasified and then burns together with the gaseous fuel, while in parallel co-combustion the fuels are combusted in separate boilers, while the produced steam is fed to the same turbines (van Loo and Kooppejan, 2010; Liu, 2023). The co-firing configurations and technological schemes for each of them are shown in Figure 6.

Figure 6: Different co-firing configurations

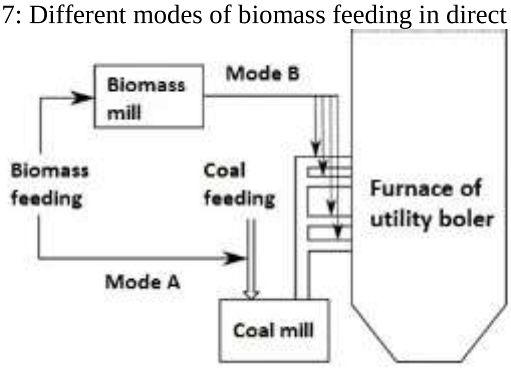


Source: Authors

Great variety of the biomass fuels requires appropriate transport, handling and preparation (pretreatment) processes and systems. The processes may include preliminary size reduction, bulk handling, storage and transportation, washing/cleaning, drying and secondary size reduction prior to firing into the power plant. In the case of direct co-firing, reduction of the biomass particle maximal size to less than about 4-5 mm is required. In order to transport the fuel from the storage to combustion system, the feeding system is needed, affecting the performance and availability of the combustion system, so it must be adjusted to it carefully (van Loo and Kooppejan, 2010).

In nowadays' biomass conversion technologies, such as biomass/coal co-firing, torrefaction pretreatment method has attracted considerable attention. Torrefaction is a thermal process to upgrade the properties of biomass, in particular to increase the particle energy density and grindability, then approaching the properties of coal. During torrefaction, components with low energy density and strong hydrophilicity, such as hemicellulose and cellulose, are removed from the particle. Torrefaction of waste, such as the biomass agricultural waste, is currently of special interest because its properties (low energy density and grindability, high moisture content, irregular shape, hydrophilicity) can be reduced considerably (Głód at el, 2023). Release of chlorine, sulphur and potassium in torrefaction can alleviate ash-related problems during co-firing (Niu et al, 2019). Biomass torrefaction is most often performed at a relatively low temperature range: 200-300 ^{O}C. Torrefaction technology can be divided into dry and wet torrefaction and the dry torrefaction can be divided into inert and oxidative torrefaction, while regarding economy and practicality, oxidative torrefaction is considered more advantages. The biomass after torrefaction pretreatment is more suitable for combustion and co-firing (Yang et al, 2024).

Figure 7: Different modes of biomass feeding in direct co-firing



Source: Authors

For direct co-firing of biomass and coal, two methods of the fuel injection have been developed, Figure 7: Mode A, where the biomass and coal are blended in the fuel handling system and the blended fuel is then fed into the furnace and Mode B, in which there are separate fuel handling and separate burners for the biomass and coal, thus avoiding influence of the conventional coal delivery system. Generally speaking, for smaller amounts of biomass, the coal and biomass are milled together and both enter the same burner (Mode A) and for larger amounts of biomass, the biomass is milled separately and enters the furnace in a dedicated burner (Mode B), while other burners operate on coal (Belošević, 2010).

In order to optimize the co-firing process of pulverized coal (lignite) and the crop residues, such as the wheat straw, a number of operation parameters have to be properly managed, such as (Milićević, 2018):

- thermal share of the biomass in the coal/biomass mixture during co-combustion,
- quality of biomass and coal used in the co-firing,
- grinding fineness (size) of particles,
- injection mode of the biomass into the furnace,
- biomass, coal and air distributions over the burners and burner tiers, etc.

However, the biomass co-firing imposes serious risks and limitations. The fraction of biomass that can be fed into the pulverized coal-fired boiler is an important limit. A separate feeding system with dedicated biomass burners are required for higher biomass percentages. The thermal input from biomass can be in the range of 5–15% or possibly up to 20%, depending on the biomass feeding method (Sondreal et al, 2001). The addition of biomass to coal increases risks of fouling and slagging. High concentrations of potassium, chlorine and silica in herbaceous biomass (like most agricultural crops) represent a special concern for ash deposition and corrosion in power boilers and furnaces (Sondreal et al, 2001). High concentrations of potassium and chlorine in most agricultural residues is the main cause for problems with the ash deposits formation, fouling and slagging. Potassium facilitates formation of low melting-point eutectics and thus promote the ash sintering, while also silica reacts with potassium to form this kind of eutectics. Chlorine is responsible for formation of potassium chloride and ash deposits on low-temperature heating surfaces. The higher chlorine content in agricultural biomass causes also corrosion problems. In majority of cases the biomass co-firing ratio is less than or around 10% on the heat input basis, but for firing 20% of straw, corrosion rate is increased by 100-200%. Deposits from biomass are denser and more difficult to remove when compared to deposits from coal (Sami et al, 2001).

Comprehensive overview of the biomass/coal co-firing technology is available (Zhang and Meloni, 2020; Agbor et al, 2014). Some prospects of the waste biomass valorization as RES in Serbia and the co-firing in power plants in the Balkans region are also provided (Dodić et al, 2010; Hodžić et al, 2016).

5. Conclusions

Agricultural waste biomass, such as the crop residue, is an abundant indigenous RES in Serbia and might be utilized for sustainable power production by direct co-firing with coal (lignite), which is a sustainable way to remove this kind of waste, use its energy potential, mitigate harmful emissions and retrofit existing coal-fired power plants cost-effectively. Co-firing of the crop residues is presented as a promising technology for the biomass valorization and decarbonization in power sector, focusing the crop residue energy potential, fuel characteristics, fuel preparation and technology of co-firing with coal.

However, despite the progress already made, biomass and coal co-firing still faces many challenges. There are serious issues regarding the waste management and the co-firing process itself yet to be solved, such as increasing the biomass share in the co-firing as much as possible without disturbing the utility boiler operation and widen the domain of the biomass fuels used in the co-firing process.

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