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Possibilities of Cement Industry Decarbonisation Using Biomass

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Abstract – The integration of renewable energy sources in the final energy mix has become a narrative due to current environmental problems, such as global warming, air pollution, dependence on fossil fuels, and others. It is also known that the industry had a significant impact on the emergence, development, and maintenance of these problems. Accordingly, a large number of researchers have contributed to the field of application of renewable energy sources in industry. The diversity of renewable energy sources that can be used in industry is conditioned by the operating temperature, which in most cases reaches values of 1000 °C. One of the renewable energy sources that can achieve these operating temperatures is biomass. This paper provides an overview of the current technologies of biomass application in the cement industry, considers the possibilities of their application in the Republic of Serbia, and analyses the benefits that are achieved by them.

Index Terms – Decarbonisation, Biomass, Cement industry

I INTRODUCTION

Transition from fossil fuels to renewable energy sources (RES) became a necessity due to the current environmental and climate problems [1]. Besides that, the European Commission published the REPowerEU plan in 2022 as an answer to current geopolitical happenings, which strives toward energy security and renewable electricity production to reduce the dependence on imported fossil fuels [2]. These aspirations should be present in all branches of human activities, including industry, which was responsible for 20% of global greenhouse gas (GHG) emissions in 2022 [3]. Guided by the Paris Agreement directions, industrial emissions of developed countries should be equal to zero until 2050, and reduced to 75% by 2030 [4]. Taking into account the high temperature requirements of the industry (working temperatures around 1000°C), among all RES, biomass represents one of the best choices for its decarbonisation. Additionally, there are a lot of recent studies that have shown the potential of biomass from the aspect of industrial decarbonisation [5–9].

It is known that industry has an average share of 27% in final energy consumption in the European Union [10]. Analogously, the industry in the Republic of Serbia has a significant share in final energy consumption and GHG emissions. A review of the GHG emissions by industry sectors in Serbia is shown in Table 1. It is noticeable that the cement industry is the second most GHG-intensive industry sector, right after the steel and iron industry.

Cement is one of the basic materials whose use has increased over time, from 100 million tons in 1950 to 4.1 billion tons in 2023 [11,12]. The cement industry represents one of the most energy-intensive industries, responsible for 10.1% of final electricity consumption in China [13], 15% in Iran [14], and 18.5% in Turkey. From the technological aspect, cement production includes three phases: preparation of raw materials, clinker production, and clinker grinding. The cement production process is illustrated in Figure 1. The process starts with the collection of raw materials (lime, sand, and clay), their grinding, and combining into a homogeneous powder, which is later sent into high-temperature furnaces where the clinker is produced. During this process, the most CO_2 emissions occur, part of them are caused by the fuel combustion (30-40%), while the other part comes from the process of chemical transformation of lime into calcium oxide (60-70%). Finally, the clinker is ground and mixed with gypsum to produce cement [16].

Table 1. Review of the GHG emissions by industry sectors in Serbia

Industry sector	***GHG emissions [Gg CO_2 eq]***
A: Mineral industry	***1371.58***
A1: Cement industry	1167.81
A2: Lime industry	139.54
A3: Glass industry	6.12
A4: Other process uses of carbonates	58.11
A5: Other	0
B: Chemical industry	***300.49***
B1: Ammonia industry	0
B2: Production of nitric acid	0
B3: Petrochemical industry	294.39
B4: Other	0
C: Metal industry	***2660.19***
C1: Steel and iron industry	2623.34
C2: Production of magnesium	36.85
C3: Other	0
D: Electronic industry	***0***
E: Other	***0***

This study analyses the possibility of biomass implementation in the cement industry of Serbia with the goal of its decarbonisation. The Republic of Serbia has 3 cement plants presented in Table 2.

Table 2. Review of cement plants in Serbia

Ref.	**Plant**	**Technology**	**Capacity [t]**
[17]	1	Dry process	1.5×10^6
[18]	2	Dry process	1.35×10^6
[19]	3	Dry process	0.75×10^6

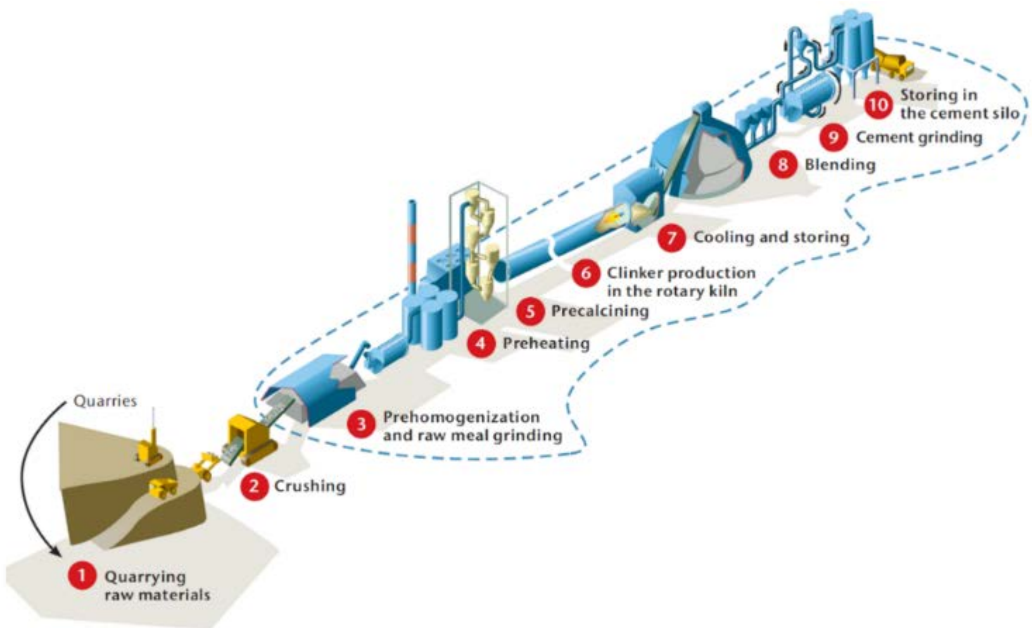

Figure 1. Illustration of the cement production process [16]

II CEMENT INDUSTRY DECARBONISATION POSSIBILITIES

Taking into account that clinker production is responsible for more than 50% of total GHG emissions, its substitution is the crucial step toward cement industry decarbonisation. Cementitious materials, which can replace clinker, can be classified as hydraulic and pozzolanic materials. Hydraulic materials harden in contact with water, while pozzolanic materials harden only in the presence of dissolved calcium hydroxide [20]. Table 3 gives the systematization of cementitious materials.

Table 3. Cementitious materials

Hydraulic materials	Pozzolanic materials
• Blast furnace slag • Burned oil shales	• Fly ash • Silica dust • Calcined clay • Burnt rice husk • Natural pozzolans

Fly ash represents the most common cementitious material [21] produced during the coal combustion process. However, its availability will be reduced due to the current aspirations toward energy transition. Amran et al. [22] showed that the composition of biomass fly ash is competent to replace coal ash. Olatoyan et al. [23] analysed the potential of biomass ash as a cementitious material. They showed that the addition of biomass ash to concrete increases its mechanical characteristics, durability, and usability, while reducing its negative impact on the environment. Additionally, other research came to similar conclusions [24–28]. Table 4 gives a review of studies that analysed the potential of biomass ash as a cementitious material. These studies concluded that:

- Biomass ash is a good alternative for coal fly ash;
- Substitution of clinker with biomass fly ash reduces the negative impact of cement production on the environment;
- One of the studies showed that the addition of biomass ash to concrete reduces the emission factor from 0.772 to 0.338 kg CO_2 per kg of concrete;
- Substitution of clinker with biomass fly ash can simultaneously improve or worsen concrete's mechanical characteristics and functionality depending on the substitution rate;
- Mechanical characteristics of the concrete enhanced with biomass ash can be improved with ash pretreatment (sifting, washing, and grinding);
- Addition of biomass fly ash can delay the setting time of the concrete;
- Cementitious composites enhanced with biomass ash showed worsened characteristics in the first 3 to 7 days of curing, afterwards, they improved significantly due to pozzolanic activities.

Table 5 gives a review of studies that analysed the implementation of alternative fuels in the cement industry. Specifically, biomass such as wood and wood products [29–32], forest residues [29,33,34], agricultural residues [34–38], animal residues [29,38–42], and municipal solid waste [34,38,43–46]. These studies showed significant environmental and economic benefits, however followed by significant challenges. To ensure the performance of biomass as an alternative fuel, it has to be preprocessed and improved by applying conversion technologies. Additionally, the choice of the biomass and the substitution rate has to be carefully defined, taking into account its availability, the energy requirements of the industry, and its physical and chemical characteristics.

Table 4. Review of studies on biomass ash potential as a cementitious material

Reference	***Summary***	***Conclusions***
[23]	This work examines the advantages of replacing coal fly ash with biomass fly ash in cement production.	• The addition of biomass fly ash into concrete enhanced its mechanical properties, durability, and workability. • The addition of biomass fly ash into concrete mitigated its impact on the environment.
[24]	This study analyses wood ash as a cement replacement and as an alkali-activated material.	• Wood ash has larger, more porous, and more irregular particles compared to Portland cement, causing a decrease in the workability of the concrete. • The wood ash-based concrete workability can be enhanced by pre-treatment methods (sieving, washing, and grinding). • With an increase in wood ash share the setting time usually delays. • Cement with a partition of wood ash can show slightly worse or better mechanical properties than Portland cement-based concrete. • The optimum wood ash participation is between 10 and 20 wt%. • Water absorption increased with the levels of wood ash. • The addition of wood ash improves cement shrinkage. • The addition of wood ash increases the chloride permeability of the cement.
[25]	This research analyses geopolymer concrete and compares it with conventional concrete from the aspect of carbon and cost impact.	• Geopolymers based on biomass fly ash showed enhanced mechanical strength, acid resistance, sulphate degradation, and reduced shrinkage. • Geopolymer concrete has significantly decreased environmental impact compared to conventional concrete. The emission factor decreased from 0.772 kg of CO_2 per kg of concrete to 0.338.
[26]	This study evaluates the functional aspects of biomass fly ash as an alternative to coal fly ash in blended cements.	• Biomass fly ash contains significantly lower concentrations of hazardous elements. • The addition of biomass fly ash decreases the hydration heat evolution. • Replacement of 30 wt% of Portland cement with biomass fly ash resulted in minor changes in functional properties.
[48]	This work examines the impact of biomass ashes (from five available agricultural wastes) on the performance of cementitious composites.	• Large, irregularly shaped, highly porous, and rough on surfaces, untreated biomass ash particles significantly degrade the qualities of cementitious composites. • Biomass ash-enriched cementitious composites showed reduced mechanical properties in the first 3 to 7 days of curing, however, with the increased curing time, mechanical properties are significantly improved due to improved pozzolanic activity.
[49]	This research evaluates the influence of biomass feedstock and thermal conversion technology on ash properties.	• Generally, using biomass ash as supplementary cementitious material is a good approach to reduce CO_2 emissions and the volume of landfilled biomass ash. • Biomass ash quality can be influenced either positively or negatively by the thermal conversion technology. Two combinations of fuel/technology were recognized as most promising: i) a combination of wood biomass with low exogenous inclusion and high bark content combusted in a pulverized fuel installation, and ii) paper sludge and wood/bark combusted in a fluidized bed.

Table 5. Review of studies on the potential of biomass as an alternative fuel

Reference	***Summary***	***Conclusions***
[50]	This study analyses the impact of alternative fuels on production cost, environment, operation, and maintenance of Indian cement plants.	• Utilization of alternative fuels brings substantial savings in cement production. • Alternative fuels carry the potential to reduce greenhouse gas emissions. • The main issue with alternative fuel utilization is the jamming of the transfer and alternative fuel feeding chute to the calciner. • Another problem with alternative fuel utilization is economic demand, which could be recovered in 2 to 3 years.
[51]	This research evaluates the utilization of alternative fuels in the cement factory in Ethiopia.	• Caloric values of Prosopis juliflora (P. j.) wood, P. j. leaf, P. j. charcoal, used tires, and optimized fuels ranged between 14.37 and 33 MJ, meeting the minimum international standard of 14 MJ/kg. • Replacing 40% of coal with alternative fuels such as P. j. wood, P. j. leaf, P. j. charcoal, used tires, and optimized fuels can reduce CO_2 emissions by 2%, 9%, 9%, 21%, and 17% respectively. • Additionally, these alternative fuels carry the potential to reduce SO_2 emissions by 75%, 85%, 92%, 95%, and 17% respectively. • The problem with the utilization of alternative fuels is the NO_x emissions, but overall, all alternative fuels except P. j. charcoal and P. j. wood meet the emission standards. Still, P. j. charcoal and P. j. wood can be used as alternative fuels, but the replacement rate should not exceed 35% and 20%, respectively. • The alternative fuel utilization affects the quality of cement negatively, but the quality still meets international standards.

[43]	This paper analyses the status of alternative fuels and their usage in the cement industry.	• Used tires and biomass are the most attractive alternative fuels for the cement industry due to their low operational cost and high substitution rates. • Meat and bone meal, municipal solid waste, and sewage sludge need to be preprocessed before usage in the cement kiln. • Tire-derived fuel substitution rate above 30% is negatively affecting the chemistry of the cement and its hardening process. • Agricultural biomass is the best option from the environmental aspect, but its availability is a barrier toward its utilization. • Meat and bone meal and municipal solid waste are highly available, and have low environmental impact, but are economically expensive to use.
[44]	This paper compares six fuel alternatives using economic and environmental criteria.	• Municipal solid waste also showed a significant decrease in cumulative combustion and indirect GHG emissions reduction compared to reference from 2020 to 2050 (9%) with the most profitable marginal abatement cost in most regions (-54 – -170 CAD/tonne of CO_2e). • Hydrogen and electrification at full deployment offer the largest 2050 GHG emissions reduction of 98% and 89% respectively, compared to 76% and 52% reductions offered by the biomass and hythane, and municipal solid waste and hythane fuel mix. However, marginal abatement costs of hydrogen and electrification are not attractive as those of biomass and municipal solid waste.

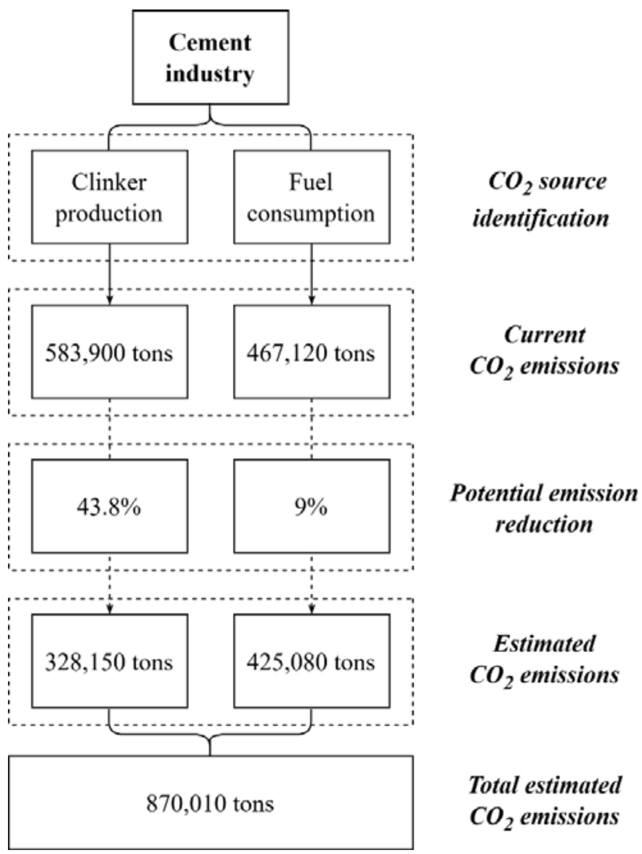

Figure 2. Estimation of CO_2 emission reduction of the cement industry in the Republic of Serbia

III CO_2 Reduction Estimation

As already mentioned, the cement production in the Republic of Serbia emitted around 1,167,810 tons of GHG in CO_2 eq. in 2020. To estimate the CO_2 emission reduction, firstly, it is necessary to define the sources of the emissions. According to Benhelal et al. [52] clinker production, fuel consumption, and transport and electricity consumption are responsible for 50%, 40%, and 10% of CO_2 emissions, respectively. Literature review showed that the potential reduction of CO_2 emissions in the case of clinker production is 43.8% [25] and 9% in the case of using biomass as an alternative fuel. The estimation (Figure 2) showed that by using biomass in the cement industry, the emissions can be reduced by 15.5% (181,010 tons of CO_2 eq).

IV Conclusion

Guided by the temperature requirements of the industry, economical costs, and implementation simplicity, biomass represents one of the best choices among RES for its decarbonisation. A hefty number of studies analyzed the biomass use in the cement industry, which represents the second most GHG-intensive industry sector in Serbia. Those studies showed that biomass can be used in the cement industry in two ways: 1) biomass fly ash can be used as a cementitious material, 2) biomass can be used as an alternative fuel.

Taking into account the quality of the produced cement, which depends on the substitution rate of clinker with biomass ash and on the amount of biomass used as alternative fuel, the CO_2 emission reduction estimation was done. It is concluded that by using biomass in the cement industry, the CO_2 emissions can be reduced from 1,167,810 to 986,800 tons CO_2 eq, which represents a reduction of 15.5%.

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Mogućnosti za dekarbonizaciju cementne industrije primenom biomase

Rezime *- Integracija obnovljivih izvora energije u finalnom energetskom miksu je postao narativ usled aktuelnih ekoloških problema, kao što su globalno zagrevanje, zagađenje vazduha, zavisnost od fosilnih goriva i drugi. Takođe je poznato da je industrija, zbog dosadašnjeg intenzivnog korišćenja fosilnih goriva, imala značajan uticaj na nastanak, razvoj i održanje ovih problema. Shodno tome, veliki broj istraživača je dalo svoj doprinos u oblasti primene obnovljivih izvora energije u industriji. Diverzitet obnovljivih izvora energije koji se mogu koristiti u industriji uslovljen je radnom temperaturom koja u najvećem broju slučajeva dostiže i vrednosti od 1000°C. Jedan on obnovljivih izvora energije koji može postići ove radne temperature je biomasa. Ovaj rad pruža pregled trenutnih tehnologija primene biomase u cementnoj industriji, razmatra mogućnosti njihove primene u Republici Srbiji i analizira benefite koji se njima postižu.*

Ključne reči *- dekarbonizacija, biomasa, cementna industrija*