Delivery of sustainable supply of non-food biomass to support a
"resource-efficient" Bioeconomy in Europe

S2Biom Project Grant Agreement n°608622

Task 9.3.2 Strategic Case Study:

Biomass co-firing in lignite-fired power plants as a means of mobilizing agro-biomass resources

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About S2Biom project

The S2Biom project - Delivery of sustainable supply of non-food biomass to support a “resource-efficient” Bioeconomy in Europe - supports the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies, and roadmaps that will be informed by a “computerized and easy to use” toolset (and respective databases) with updated harmonized datasets at local, regional, national and pan European level for EU28, Western Balkans, Moldova, Turkey and Ukraine. Further information about the project and the partners involved are available under www.s2biom.eu.

Project coordinator

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Project partners

About this document

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Executive summary

Lignite mining and power generation takes place in most SEE countries: Greece, Serbia, Kosovo, Bulgaria, Bosnia-Herzegovina, FYROM, Montenegro, Romania, Slovenia and Turkey. The contribution of lignite in the electricity mixture of these countries is sizeable and is expected to remain so in the near future through the continued operation of existing units or the construction of new ones.

The S2Biom toolset has been used to investigate the agrobiomass residue potential in all SEE countries where there is presence of lignite mining and power generation. The results indicate that it is theoretically possible to implement co-firing at thermal shares ranging from 5% to 20% to selected lignite units while sourcing agro-biomass from the same NUTS3 region where the units are located.

A preliminary investigation of the supply chains indicates that it is more cost efficient to source wheat straw in the form of bales compared to pellets when the transport distance does not exceed 300 km.

An investigation of the levelized cost of electricity (LCOE) of co-firing in selected lignite units of SEE countries has demonstrated that the support level required for the implementation of co-firing can be set at a lower level compared to the European average for bioenergy.

Overall, in most of the SEE countries studied, co-firing should be seriously considered as an alternative to reach renewable energy targets and mobilize agro-biomass resources.

Table of contents

List of Figures

List of Tables

1. Introduction

1.1. Biomass co-firing in general

Co-firing can be defined as the simultaneous combustion of two or more fuels in the same energy plant in order to produce one or more energy carriers [1]. The most common application of co-firing involves the partial replacement of coal in large-scale, pulverized fuel power plants by solid biomass fuels. Recent reviews of co-firing experiences identify over 100 successful field demonstrations in 16 countries that use essentially every major type of biomass (herbaceous, woody, animal-wastes and wastes) combined with essentially every rank of coal and combusted in essentially every major type of pulverized fuel boiler (tangential, wall, and cyclone fired) [2, 3].

The main advantage of co-firing is its potential to mitigate the CO2 emissions of the coal sector at a very low cost and short implementation time [4, 5] compared to other technologies. The reported investment costs for a co-firing retrofit range from 140 – 850 USD/kWe of biomass capacity, compared to 1,880 – 6,820 USD/kWe for dedicated biomass power plants [6]. This is achieved through the utilization of the existing infrastructure of a coal power plant.

Since it is a thermal process, biomass co-firing, as well as dedicated biomass combustion, can produce power on demand, unlike intermittent energy sources such as solar or wind. This contributes to the stability of electric grids and accelerates the capital investment payoff rate by utilizing higher capacity factors [1].

Moreover, co-firing is currently the biomass conversion technology with the highest electrical efficiency. The net electrical efficiency of dedicated biomass power plants ranges from 25% to 36 for state of the art units [7]. Conventional, sub-critical coal-fired power plants in OECD countries operate at efficiencies around 36% [8], with state of the art units reaching or exceeding 43% [9]. Given the negligible impact of co-firing on the generating efficiency of a coal plant [10, 11], these are essentially the same efficiencies in which co-firing power plants operate.

The implementation of biomass co-firing at a coal power plants presents some technical and environmental challenges involving impact on the fuel handling, fuel conversion, slagging/fouling and corrosion, emissions formation and gas cleaning equipment and, finally, ash utilization [2, 12]. Typical co-firing arrangements using co-milling of the two fuels could reach a thermal substitution share of 10%. More modern arrangements, using injection of milled biomass in the coal pipes or dedicated biomass burners can reach much higher substitutions, even up to 100% [13].

Despite its advantages, biomass co-firing is not universally adopted since it faces two main restrictions: policies and biomass availability.

With the exception of some opportunity or waste fuels, the biomass fuel price at a coal plant gate is generally higher than the equivalent coal one; therefore some financial support is required to cover the additional fuel expenses. However, even in countries where there are established mechanisms for the financial support of renewable electricity generation, biomass co-firing may be excluded and not considered eligible for support. Variations in the support schemes of different EY countries have led to different co-firing deployments in the power sector [14].

On the other hand, even when implemented at low thermal shares, the implementation of co-firing requires large volumes of biomass due to the large installed capacity of coal plants. Low levels of local biomass availability place an additional restraint, especially considering that the low energy density of biomass can put a limit to its transport over long distances.

Provided that regulatory constraints are not in effect, biomass availability issues can be solved through international sourcing of the fuel, which is usually wood pellets. Coal fired plants converted to 100% wood pellets combustion, e.g. Drax, Rodenhuize IV, are a reality in the EU [13].

1.2. Biomass co-firing in lignite power plants

Lignite is considered the lowest rank of coal due to its high moisture and low carbon content, as well as typically high ash content. It is a fuel used almost exclusively in power generation; on a global basis, it corresponds to about 4% of the total electricity production [15].

In a European level, lignite is an important indigenous fuel source in several EU countries, as can be seen in Figure 1 [17] ; for example the percentage of lignite in the electricity production of Germany, Poland and Czech corresponds to 24.6%, 33.6% and 41.5% respectively for 2014 [18].

In South East Europe (SEE), lignite is not only present in the electricity mix of all countries (with the exception of Albania and Croatia); its share in the gross electricity generation is higher than the EU-28 average (9.9%) in all cases, as can be seen in Figure 2 [18].

Figure 1: Overview of lignite production and power generation capacity in Europe (red: installed capacity > 2 GW, orange: installed capacity< 2 GW) [17].

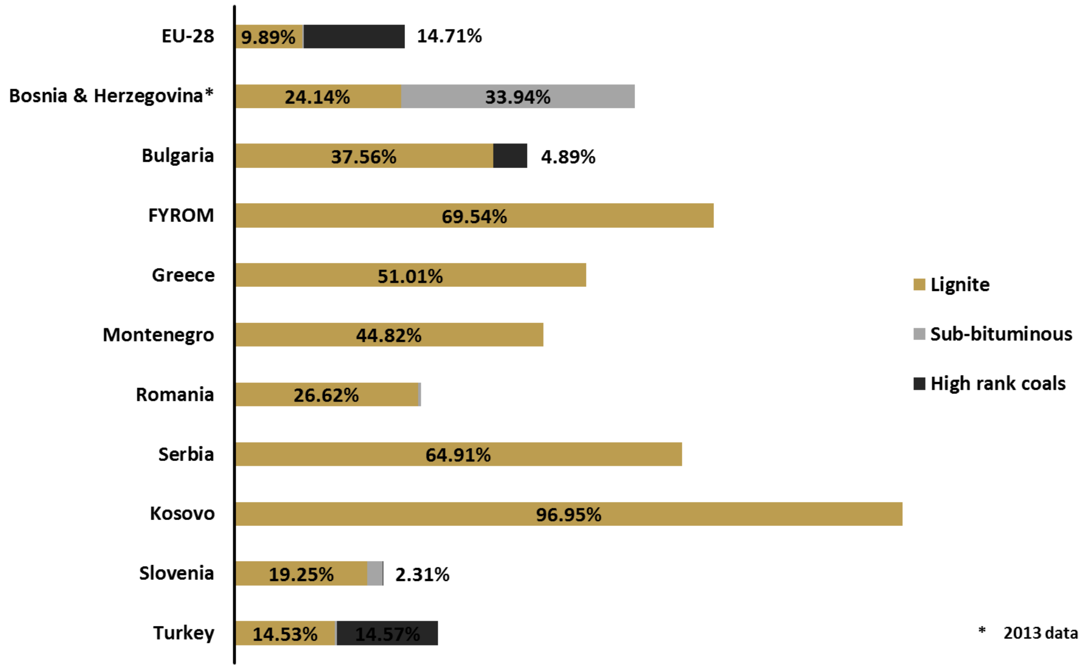

Figure 2: Share of lignite and other coal types in gross electricity generation in SEE (2014).

The implementation of biomass co-firing in lignite-fired power plants can be considered as relatively easy from a technical perspective. While the heating value of most solid biofuels is lower compared to hard coal, for lignite-fired plants the addition of biomass actually improves the heating value of the fuel mixture and has the potential to improve combustion conditions in the furnace. Additionally, the large size of lignite furnaces can provide sufficient residence times for the combustion of even large biomass particles. Finally, the higher ash content of lignite compared to most types of biomass means that any ash-related issues in the furnace, such as slagging/fouling are expected to be unaffected by the impact of biomass addition. This can prove particularly useful during the co-firing of herbaceous biomass types, which are characterized by high concentrations of problematic compounds such as chlorine and alkalis.

On the other hand, the cost of solid biofuels delivered at a lignite plant gate[1] is generally more expensive than the cost of lignite itself; the difference can be bridged through CO2 savings and additional financial support received for the production of electricity from biomass (feed-in tariffs and premiums, green certificates, etc.). However, many SEE countries lack the legal framework that would allow utilities to proceed with biomass co-firing in their lignite-fired plants. Indeed, of the lignite producing countries in the EU, only Poland has a legal framework favorable to biomass co-firing in coal plants; in Germany, co-firing with lignite has been performed on a commercial basis mostly with alternative fuels with very low or even negative cost, such as RDF and sewage sludge.

The largest documented demonstration of biomass co-firing in a lignite plant of a SEE country was performed with the framework of the FP7 DEBCO project, where herbaceous biomass coming from the energy crop cardoon was successfully co-fired with Greek lignite at a thermal share of 10% in a 300 MWe unit in Northern Greece. Chlorine and alkali induced corrosion or fouling was not identified as an issue, while the possibility of reducing NO_x emissions by up to 10% was a significant environmental benefit [19]. Further project results concerning biomass logistics make note of the large volumes of biomass required for the implementation of co-firing which may require fuel sourcing over an extended area of a radius up to 300 km [20]. Finally, from an economic point of view, it was found that although a feed-in tariff was required to ensure the viability of co-firing, its value could be set at a lower level compared to the one that Greek legislation foresaw for dedicated biomass power plants [20, 21].

[1] It can also be noted that lignite plants are typically located close to inland lignite mines. Thus, they do not have easy access to fuels imported via seaborne routes, such as wood pellets, contrary to hard coal plants in Western Europe which were built in locations that would allow them easy access to imported hard coal.

2. Purpose and approach of the present Strategic Case Study

The purpose of the present Strategic Case Study of the S2Biom project is to investigate the potential of implementing biomass co-firing at the lignite-fired power plants of the main SEE countries where lignite is produced: Greece, Serbia, Kosovo, Bulgaria, Bosnia and Herzegovina, FYROM, Montenegro, Romania, Slovenia and Turkey.

Finally, as regards biomass types considered for co-firing, the present study focuses on herbaceous agrobiomass resources, the most important of which are cereal straw and maize stover. Imported wood pellets from overseas are also used as a comparison, in order to investigate the cost-effectiveness of using local biomass resources.

In order to investigate the co-firing potential in lignite-fired power plants of different SEE countries, a unified methodology was developed. The following sections present the main aspects of this methodology.

The timeframe for this study are the years 2020 and 2030, therefore only lignite-fired power plants which are expected to be operational during these years are of interest. This includes some of the most efficient currently operating lignite units or new units which are expected to be commissioned in the coming years.

2.1. Lignite sector overview

The first step is to describe the current and future state of the lignite sector in each country. In particular, the goal is to identify the lignite-fired power plants which can be the target for a biomass co-firing retrofit.

Generally, the power plants targeted for co-firing are the newest units, which are characterized by higher electrical efficiencies. For newer, lignite-fired units, the efficiency can be up to 40% or higher, which is considerably higher than the typical or even the highest recorded efficiencies from dedicated biomass power plants.

In order to approach this task, data is collected from various sources. The most relevant are EURACOAL reports [15, 16] and company reports of the main utilities operating in each country. Since some power plants under consideration have not yet been built but are rather in the design or planning phase, additional information is collected from announcements, environmental impact studies, etc.

For the lignite-fired power plants under consideration, the following data are relevant:

- Gross and net generating capacity;

- Capacity factor[2];
- Net electrical efficiency;
- Lignite characteristics, in particular LHV and CO_2 emission factor.

From these characteristics, the typical annual consumption of lignite can be estimated. Then, the potential for biomass consumption is calculated assuming typical thermal substitution shares of 5, 10, 15 and 20% and considering two types of biomasses, herbaceous (agro) biomass with a typical LHV of 14.5 MJ/kg (as received, corresponding to a moisture content of 15%) and wood pellets with a typical LHV of 17.5 MJ/kg (as received, corresponding to a moisture content of 10%).

2.2. Agro-biomass availability for co-firing

As previously mentioned, the present study focuses on the possibility of utilizing agricultural, herbaceous residues as a co-firing fuel, since they represent an untapped biomass potential in all of the selected countries.

Other biomass types, e.g. wood prunings, forest residues, etc., are not considered in this study, since it is expected that their mobilization would result in different end-uses, such as decentralized biomass heating or small-scale DH systems.

Table 1 summarizes the main biomass types considered as potential co-firing fuels in the framework of this study[3]. The typical dry matter (DM) content for each residue is taken from Scarlat et. al [22]; the same study assumes a typical LHV of 17.5 MJ/kg on a dry basis, which corresponds to 14.5 MJ/kg on an as received basis for a moisture content of 15%.

Biomass type	DM (%)
Cereal straw	85%
Maize stover	70%
Sunflower straw	75%
Oil seed rape straw	60%
Rice straw	60%

Table 1: Investigated biomass types for the co-firing study.

In order to estimate the biomass availability in the areas near the targeted lignite-fired power plants, the S2Biom biomass supply tool is used (Figure 3). The following settings are used for estimating the values used in this study [23]:

[2] The capacity factor of a power plant is defined as the ratio of its actual output over a period of time to its potential output if it was possible to operate at full nameplate capacity continuously over the same period of time.

[3] Sugarbeat leaves are not considered in this study, since their moisture content is considered too high for direct combustion.

- **Spatial resolution:** the study focuses on **NUT3 data**, in particular in the areas where the lignite-fired power plants are located. Nearby NUTS3 areas, located at a reasonable distance from the power plants are also considered in cases where the local biomass potential cannot meet the co-firing demand.
- **Scenarios:** 2020 and 2030 are the main years of reference. The data for 2012 is also presented for comparison.
- **Potential:** the user-defined potential is taken as a reference, in order to consider soil sustainability criteria and competing uses of those materials, in particular cereal straw.

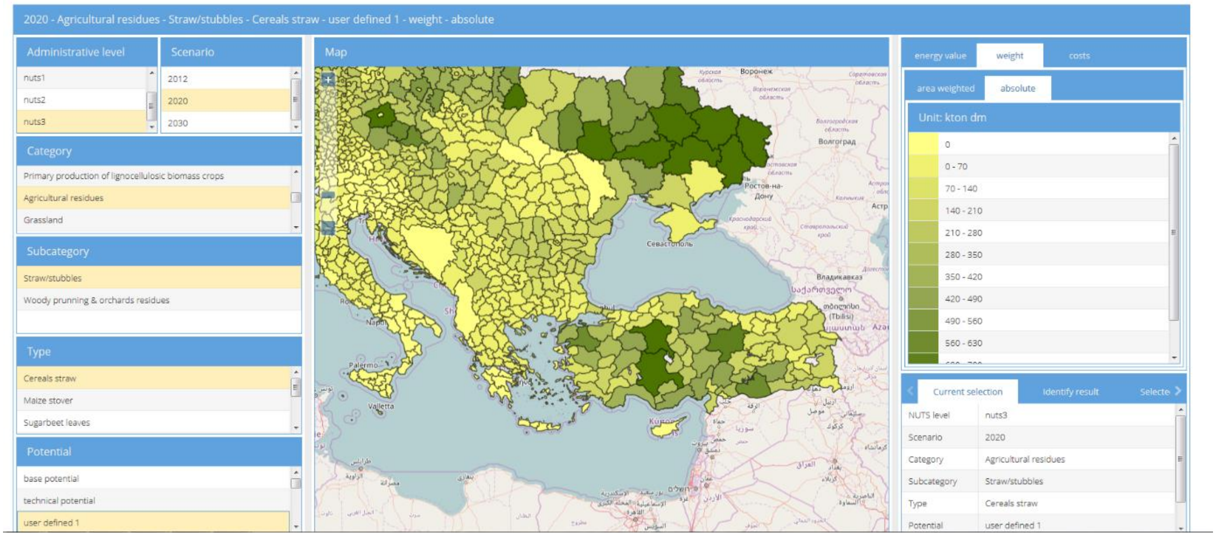

Figure 3: The S2Biom biomass supply tool.

3. Biomass co-firing in Greece

3.1. The lignite sector of Greece

Lignite production in Greece takes place in two main areas: Western Macedonia, where the mines of the Main Field, South Field and the Kardia, Amyntaio and Florina Fields are located and in Peloponnese, where the Megalopolis Field is located. With mined quantities of 45.4 Mt for 2015 [16], Greece is the third major producer of lignite in the EU-28 following Germany and Poland and second only to Turkey in the SEE region. The country features 4,600 Mt of reserves, of which 2,900 Mt are economically recoverable resources; they include quantities from the currently unexploited lignite fields in Elassona and Drama.

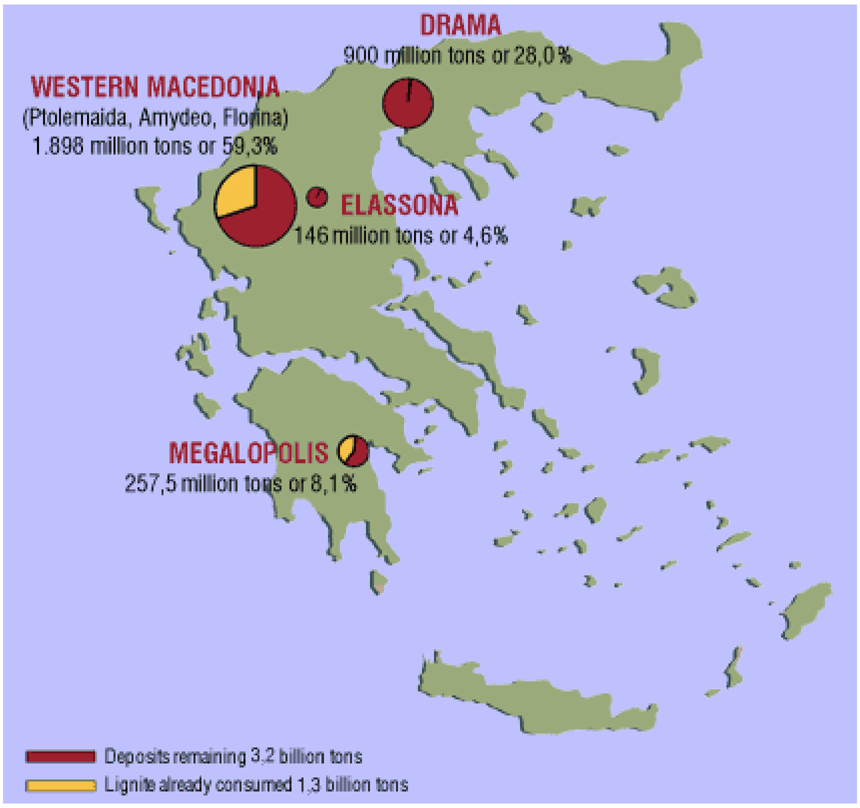

Figure 4: Location of lignite resources in Greece (Source: PPC)

Public Power Corporation (PPC) is the main lignite producer in Greece; in 2015 it produced 35.7 Mt of lignite in Western Macedonia and another 8.1 Mt in Megalopolis; an additional quantity of 2.2 Mt was extracted by privately owned mines in Western Macedonia [16].

Greek lignite is characterized by very high moisture and ash contents [24] and is one of the poorer solid fuels used in a global basis. Due to its fuel properties, it is used almost exclusively in electricity generation. A recent study performed on behalf of PPC outlined that Greek lignite had the second lowest extraction cost compared to the eight major lignite producing countries (Germany, Czech, Poland, Romania, Serbia, Turkey, Bulgaria and Greece) but its very low heating value had a direct impact on its cost expressed as €/GJ and, as a result, to the lignite electricity generating cost [17].

PPC currently operates the following lignite-fired power plants in Greece[4] [25, 26]:

- The Agios Dimitrios PP, featuring five units with a total capacity of 1,595 MWe gross / 1456 MWe net. The power plant is of a fairly young age (Unit I was commissioned in 1984, while Unit V in 1997) and is considered an important asset by PPC. As a result, it will undergo several environmental upgrades which will push back decommissioning of to 2029 for Units I-IV and 2039 for Unit V
- The Kardia PP, featuring four units with a total capacity of 1,212 MWe gross / 1,110 MWe net. All four units are expected to be decommissioned till 2019 and currently operate in the opt-out regime, due to the fact that they cannot meet the emission limits of Directive 2010/75/EC.
- The Amyntaio PP with two units of total capacity 600 MWe gross / 546 MWe net. Both units are expected to be decommissioned till 2019 and currently operate in the opt-out regime, due to the fact that they cannot meet the emission limits of Directive 2010/75/EC.
- The Meliti PP, featuring one unit with a total capacity of 330 MWe gross / 289 MWe net. Commissioned in 2003, it is currently the newest lignite unit in PPC's portfolio and is expected to continue to operate till 2048.
- The Megalopolis PP with two operating units of total capacity 600 MWe gross / 511 MWe net. It is the only lignite-fired power plant in Greece located in the Peloponnese. Unit III is expected to be decommissioned by 2020, while Unit IV will continue operation till 2032, when the lignite resources of the mine are expected to run out.

Apart from the above, PPC has awarded the construction of the new Ptolemaida V unit [27] in 2013. Ptolemaida V will be a supercritical power plant, with a very high net efficiency (41.5%). The construction of the unit has started in 2016 and is expected to be commissioned around 2020.

When considering the possibility of implementing co-firing in the lignite-fired power plants in Greece, it is necessary to distinguish between the units operating in Western Macedonia and the Megalopolis PP in Southern Greece.

The Megalopolis PP is located in the NUTS3 area of Argolis and Arcadia; the availability of agro-biomass residues in the region is practically zero. As a result, this power plant is not considered further for this study. However, it is interesting to note

[4] Units that have been put in cold reserve or are not operational due to damages, etc. are not included in the list.

that there is potential to co-fire exhausted olive cake in Megalopolis. Exhausted olive cake is a solid residue of the olive oil production process and Peloponnese is a major olive oil producing region in Greece.

In Western Macedonia, the units that can be considered for co-firing are the ones that will remain in operation after 2020: Meliti I, Agios Dimitrios, and in particular Unit V being the most efficient one, and the new-built Ptolemaida V. Table 2 summarizes the main characteristics of these units; gross and net efficiency is taken from published data of the Power Transmission Operator [26], the lignite LHV and emission factors values are based on design values [28] and typical ranges [24], while the capacity factor and lignite consumption are based on PPC projections [25]; the net efficiency is calculated. Table 3 summarizes the calculated biomass demand for different co-firing scenarios at those three units.

	Agios Dimitrios V	Meliti I	Ptolemaida V
Gross Capacity (MWe)	375	330	660
Net Capacity (MWe)	342	289	615.7
Capacity factor	83.4%	71.1%	79.7%
Net efficiency	31.8%	32.6%	41.2%
Lignite LHV (MJ/kg)	5.44	7.95	5.44
μCO2 (t/t)	0.686	0.994	0.686
Lignite cost (EUR/GJ)	N/A	N/A	N/A
Commissioning	1997	2003	2020
Decommissioning	2039	2048	> 2050
Lignite consumption (Mt/y)	5.20	2.50	6.90

Table 2: Main characteristics of the Greek lignite-fired units in Western Macedonia.

Biomass type	Thermal substitution (%)	Quantity (kt, dm)		
		Agios Dimitrios V	Meliti I	Ptolemaida V
Agrobiomass LHV, ar (MJ/kg) = 14.5	5%	83	58	110
	10%	166	117	220
	15%	249	175	330
	20%	332	233	440
Wood pellets LHV, ar (MJ/kg) = 17.5	5%	73	51	97
	10%	146	102	193
	15%	218	153	290
	20%	291	205	386

Table 3: Calculated biomass demand for the Greek lignite-fired units in Western Macedonia.

3.2. Agro-biomass potential for co-firing in Greece

Table 4 presents the agro-biomass user-defined potential in several NUTS3 and NUTS2 areas in Norther Greece. In EL531, Ptolemaida V and Agios Dimitiros V are located, while EL533 hosts the Meliti I unit. EL52 (Central Macedonia) and EL61 (Thessaly) are NUT2 regions with a large agricultural presence and located fairly close to the lignite fired power plants so that they can be considered as biomass sourcing areas.

NUTS3	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
EL531: Grevena, Kozani	Cereal straw	63	69	71
	Maize stover	28	38	52
EL532: Kastoria	Cereal straw	19	21	21
	Maize stover	8	11	15
EL533: Florina	Cereal straw	21	23	24
	Maize stover	9	12	17
EL52: Central Macedonia	Cereal straw	424	193	187
	Maize stover	223	153	162
	Sunflower straw	37	25	36
	Rice straw	162	104	113
EL61: Thessaly	Cereal straw	20	55	67
	Maize stover	45	63	70
Sum (West & Central Macedonia, Thessaly)	Cereal straw	547	361	370
	Maize stover	313	277	316
	Sunflower straw	38	26	38
	Oil seed rape straw	0	0	0
	Rice straw	163	105	114

Table 4: Agro-biomass potential in several NUTS3 ares of Northern Greece.

The comparison of Table 4 with Table 3 gives an indication of the different scenarios that can be followed for the implementation of co-firing. Some observations are noted below:

- All the user-defined biomass potential in EL531 for both wheat straw and maize stover could cover the demand for Agios Dimitrios V for a 5% thermal share or almost all the demand for Ptolemaida V. The implementation of higher shares requires sourcing from other areas, e.g. Central Macedonia or Thessaly.
- All the user-defined biomass potential in EL533 for both wheat straw and maize stover is not enough to meet the biomass demand for a thermal share

of 5% at the Meliti I unit. Either extended sourcing or lower thermal shares are required in this case.
- In most cases, the user-defined biomass potential from 2020 to 2030 remains relatively stable or increases by a little.

Overall, the implementation of biomass co-firing in all the investigated units is a scenario that seems unlikely to be implemented due to the large biomass demand. A more likely scenario is that co-firing can be implemented in one lignite unit, ideally the more efficient Ptolemaida V, and that the sourcing would extend beyond the Western Macedonia area to Central Macedonia. This is not impossible to be managed, but the transport distance to the power plant can exceed 200 km and therefore careful consideration of the logistics and costs should be taken.

4. Biomass co-firing in Serbia

4.1. The lignite sector of Serbia

Lignite extraction in Serbia amounted to 37 Mt in 2015. Mining takes place in two main areas: the Kolubara mining basin, which accounts for 75% of the Serbian lignite production and supplies the Kolubara, Nikola Tesla A and B and Morava power plants, and the Kostolac mining basin, which supplies the Kostolac A and B power plants and accounts for the remaining 25% of the lignite production [16]. The main stakeholder of the lignite sector in Serbia is the state-owned ELEKTROPRIVREDA SRBIJE (EPS).

Table 5 summarizes the main characteristics of the currently operating lignite-fired power plants in Serbia. The power plants are grouped depending on whether they are supplied by the Kolubara or Kostolac lignite basin. The information is coming from several reports of EPS [29 - 32] and government presentations [33]. For the emission factor of the Kolubara lignite, we use a correlation found in the literature [34].

	Kolubara basin				Kostolac basin	
	Nikola Tesla A	Nikola Tesla B	Kolubara	Morava	Kostolac A	Kostolac B
Gross Capacity (MWe)	N/A*	1335	270	125	310	697
Net Capacity (MWe)	1597	1190	216	108	281	640
Capacity factor	69.3%	78.6%	42.4%	35.5%	70.8%	75.7%
Net efficiency	32.1%				31.7%	
Lignite LHV (MJ/kg)	7.70				8.30	
μCO2 (t/t)	0.826				N/A	
Commissioning	1970-1979	1983, 1985	1956-1979	1969	1967, 1980	1987, 1991
Decommissioning	N/A	N/A	N/A	N/A	N/A	N/A
Lignite consumption (Mt/y)	27.70				8.19	
* Gross efficiency not presented for Nikola Tesla PP due to revitalization						

Table 5: Main characteristics of the existing Serbian lignite-fired power plants.

EPS has intentions of significantly expanding the lignite-fired generation capacity by constructing two new units of 350 MW each at Kolubara B and the new, 744 MW unit Nikola Tesla B3. Expansion is also foreseen at the Kostolac area, with the foreseen construction of 350 MW Kostolac B3 unit [35].

Table 6 presents the calculated biomass demand for different co-firing scenarios and considering the implementation of co-firing at one unit of Nikola Tesla B and one unit of Kostolac B. The amounts listed are indicative and assume that the lignite consumption per unit follows the same pattern as the whole of the mining area.

Biomass type	Thermal substitution (%)	Quantity (kt, dm)	
		Nikola Tesla B, 1 unit	Kostolac B, 1 unit
Agrobiomass LHV, ar (MJ/kg) = 14.5	5%	135	71
	10%	269	141
	15%	404	212
	20%	538	283
Wood pellets LHV, ar (MJ/kg) = 17.5	5%	118	62
	10%	236	124
	15%	354	186
	20%	472	248

Table 6: Calculated biomass demand for the two Serbian lignite-fired units.

4.2. Agro-biomass potential for co-firing in Serbia

The following table summarizes the results of the S2Biom tool regarding the user-defined biomass potential in the NUTS3 areas of Kolubara (RS212) and Kostolac (RS222). Additionally, data for the wider NUTS2 areas are displayed.

NUTS3	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
RS212	Cereal straw	36	36	42
	Maize stover	119	116	113
	Sunflower straw	14	14	14
RS222	Cereal straw	56	57	65
	Maize stover	186	181	176
	Sunflower straw	22	23	21
RS21	Cereal straw	381	387	444
	Maize stover	1270	1234	1203
	Sunflower straw	148	154	145
RS22	Cereal straw	379	384	441
	Maize stover	1262	1227	1195
	Sunflower straw	147	153	145

Table 7: Agro-biomass potential near Kolubara and Kostolac mining basins.

Results make it clear that the main agro-biomass residue that can be utilized for co-firing in Serbia is maize stover. Local resources are enough to implement co-firing at a thermal share of 10% in one unit at Kostolac, while in Kolubara the potential is a little below that required for implementing co-firing at 5% thermal share in one unit of Nikola Tesla B power plant. The values from the wider NUTS2 areas indicate that there is a much larger potential that can be tapped, although its utilization is subject to restrictions related to transport distance.

5. Biomass co-firing in Kosovo

5.1. The lignite sector of Kosovo

Kosovo has very large lignite resources, totalling 10.8 billion tonnes and fourth only to Poland, Germany and Serbia in Europe. Reserves are located in the Kosova, Dukagjini, Drenica and Skenderaj basins, although mining has been limited to the Kosova basin to date. Lignite production in 2012 was 8.9 million tonnes [15].

The state-owned KORPORATA ENERGJETIKE E KOSOVES (KEK) has a monopoly position in lignite mining and electricity generation. KEK operates two old lignite-fired power plants located near Pristina - Kosova A (5 units totalling 800 MW) and Kosova B (2 x 339 MW) – which supply almost all of the electricity produced in the country [15].

The current plan is to retire Kosova A and B in the coming years and replace them with a new unit (Kosova C), which will act as the base-load unit in Kosovo. The planning for this unit has undergone several changes, with the initial foreseen capacity of 2,000 MW scaled down to 600 MW and then further down to 500 MW in November 2015 [36]. The current characteristics of this proposed plant are summarized in the following table [37, 39].

	Kosova C
Gross Capacity (MWe)	500
Net Capacity (MWe)	465
Capacity factor	75%
Net efficiency	40%
Lignite LHV (MJ/kg)	7.645
μCO_2 (t/t)	0.865
Lignite cost (EUR/GJ)	N/A
Commissioning	2020 - 2022
Decommissioning	N/A
Lignite consumption (Mt/y)	3.60

Table 8: Main characteristics of the Kosova C PP.

The calculated potential biomass demand of Kosova C is presented in Table 9.

Biomass type	Thermal substitution (%)	Quantity (kton, dm)
Agrobiomass LHV, ar (MJ/kg) = 14.5	5%	81
	10%	161
	15%	242
	20%	322
Wood pellets LHV, ar (MJ/kg) = 17.5	5%	71
	10%	141
	15%	212
	20%	283

Table 9: Calculated biomass demand for Kosova C PP.

5.2. Agro-biomass potential for co-firing in Kosovo

The biomass availability for Kosovo are presented in Table 10. The whole of Kosovo is a single NUT3 administrative unit. The data suggest that there is a slight increase in the cereal straw potential up to 2030, while maize stover potential is reduced compared to 2012 levels. Other biomass types are negligible in potential.

The comparison of Table 9 and Table 10 yields the conclusion that it is possible to implement biomass co-firing at the Kosova C power plant up to a thermal substitution rate of 10% using only local biomass resources.

A reduced thermal share of 5% would mean that about 40% of the sustainable cereal straw potential of 2030 has to be mobilized for the co-firing application.

NUTS3	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
KS111	Cereal straw	185	195	207
KS111	Maize stover	50	23	27
KS111	Sunflower straw	2	1	2
KS111	Oil seed rape straw	0	0	0
KS111	Rice straw	0	0	0

Table 10: Sustainable agro-biomass potential and costs in Kosovo.

6. Biomass co-firing in Bulgaria

6.1. The lignite sector of Bulgaria

With a production of 35.9 Mt in 2015, Bulgaria is the fourth major producer of lignite in the EU-28, following Germany, Poland and Greece [EURACOAL]. Lignite resources in Bulgaria are estimated at 4,300 Mt, with additional 950 Mt of reserves. The high sulphur content (2.2 – 2.8% wt as received) [16] is one particular characteristic of Bulgarian lignite.

MINI MARITSA IZTOK EAD is the main (90%) lignite producer in the country. Its mining activities take place in the Stara Zagora province and cover an area of around 240 km^2, the largest mining site in SEE. The lignite supplies four power plants in the area: BRIKEL EAD (200 MWe and also producer of lignite briquettes), the state-owned Maritsa East 2 (1,620 MWe) and the privately owned Maritsa Iztok East 3 (908 MWe) and AES Galabovo (670 MWe) [16].

For the purpose of the present study, we focus on the AES Galabovo PP. Commissioned in June 2011, it is one of the newest power plants in SEE. With an estimated investment of nearly € 1.3 billion, it is also the largest foreign direct investment in Bulgaria since the start of the market reforms in 1989 [40]. In its five years of commercial operation AES Galabovo produced 16.6 TWh of electricity using 24 Mt of lignite. At 98%, its average annual availability is also very high [41].

Table 11 summarizes the main characteristics of the AES Galavobo PP considered in this study, which are based on the previously mentioned public data as well as the typical characteristics of Maritza lignite [42] and the net efficiency quoted by the plant's environmental impact study [43].

	AES Galabovo
Gross Capacity (MWe)	670
Net Capacity (MWe)	600
Capacity factor	63.2%
Net efficiency	36.0%
Lignite LHV (MJ/kg)	6.43
μCO2 (t/t)	0.746
Lignite cost (EUR/GJ)	N/A
Commissioning	2011
Decommissioning	N/A
Lignite consumption (Mt/y)	4.80

Table 11: Main characteristics of the AES Galabovo PP.

Table 12 presents the calculated biomass demand for the AES Galabovo power plant. Since, the plant includes two units, the values can be halved if co-firing is to be implemented in only one of them.

Biomass type	Thermal substitution (%)	Quantity (kton, dm)
Agrobiomass LHV, ar (MJ/kg) = 14.5	5%	90
	10%	181
	15%	271
	20%	362
Wood pellets LHV, ar (MJ/kg) = 17.5	5%	79
	10%	159
	15%	238
	20%	317

Table 12: Calculated biomass demand for the AES Galabovo PP.

6.2. Agro-biomass potential for co-firing in Bulgaria

The agrobiomass potential for the Stara Zagora (BG344) NUTS3 area in Bulgaria where the AES Galabovo and other lignite-fired power plants are located is presented in the following table. As can be seen, the cereal straw potential of the area alone is theoretically enough to support co-firing at 5% thermal shares. It is also interesting to note the significant sunflower straw potential of the region.

NUTS	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
BG344	Cereal straw	86	103	103
BG344	Maize stover	4	7	8
BG344	Sunflower straw	45	51	49
BG344	Rice straw	11	11	9

Table 13: Sustainable agro-biomass potential and costs in Bulgaria.

7. Biomass co-firing in Bosnia-Herzegovina

7.1. The lignite sector of Bosnia-Herzegovina

Bosnia-Herzegovina produced 12.6 Mt of brown coal and lignite in 2015 [16]. The reserves of lignite and brown coal are estimated at 1,272 and 827 Mt respectively, with another 1,801 Mt of lignite resources reported [15].

JP Elektroprivreda Bosne i Hercegovine d.d. (EPBiH) operates the Kakanj (2x110 and 1x230 MW) and Tuzla (1x100, 2x200, 1x215 MW) power plants. The company reports that the units have a net efficiency of 30 – 31.5%, which is typically for their age [44]. The units are supposed to be gradually decommissioned till 2030 [45].

Elektroprivreda Republike Srpske operates the Ugljevik and Gacko power plants, each of a 300 MW capacity [15]. The plants are expected to be decommissioned in 2025 and 2030 respectively [45].

Finally, in 2016, the privately owned Stanari PP of the EFT Group was commissioned. The plant operates with the Circulating Fluidized Bed (CFB) technology [46]; based on the operating characteristics provided by the EFT Group, its efficiency is calculated as around 34.4%, which is lower than new-built lignite-fired power plants using pulverized fuel technology.

EURACOAL mentions that there are seven other coal-fired power plant projects under discussions in Bosnia & Herzegovina, including expansions of existing units [16]. However, other than values regarding the capacities of these plants, no further public information if available.

For the present co-firing study, we focus on the Stanari power plant, since it is currently the newest coal-fired plant in the country and the one for which we have the most data available. Table 14 summarizes the main characteristics of this plant; capacity, annual electricity production and lignite consumption is publicly listed by the plant operator [46], while typical fuel characteristics are taken from an older study [39]. Table 15 presents the calculated biomass demand for different co-firing scenarios for this power plant.

Lignite costs for the Stanari PP are not available; however, published information about the lignite sale price for power plants in the Federation of BiH mines was 4.90 KM/GJ in 2014 (2.5 €/GJ) [38].

	Stanari
Gross Capacity (MWe)	300
Net Capacity (MWe)	265
Capacity factor	86.2%
Net efficiency	34.4%
Lignite LHV (MJ/kg)	9.10
μCO2 (t/t)	1.008
Commissioning	2016
Decommissioning	N/A
Lignite consumption (Mt/y)	2.3

Table 14: Main characteristics of Stanari PP.

Biomass type	Thermal substitution (%)	Quantity (kton, dm)
Agrobiomass LHV, ar (MJ/kg) = 14.5	5%	61
	10%	123
	15%	184
	20%	245
Wood pellets LHV, ar (MJ/kg) = 17.5	5%	54
	10%	108
	15%	161
	20%	215

Table 15: Calculated biomass demand for the Stanari PP.

7.2. Biomass availability in Bosnia-Herzegovina

The whole of Bosnia-Herzegovina is a single NUT3 administrative unit. The S2Biom database has no data for the agricultural residue availability in the country. However, the herbaceous energy crops potential is substantial, as can be seen in Table 16.

NUTS3	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
BA111	Miscanthus	2061	2060	2030
BA111	Switchgrass	1527	1527	1504

Table 16: Sustainable herbaceous energy crops potential and costs in Bosnia-Herzegovina.

Based on the above, it can be concluded that agro-biomass co-firing at the Stanari PP is not expected to be limited by biomass availability.

8. Biomass co-firing in FYROM

8.1. The lignite sector of FYROM

The main stakeholder in the lignite sector of FYROM is the state-owned ELEM (JSC Elektani na Makedonija – Skopje). ELEM operates the Suvodol - Brod Gneotino and Oslomej - Zapad surface mines, which produced in total 6.158.402 t of lignite in 2014 [47]. There are 332 million tones of lignite reserves in the Pelagonija and Kicevo deposits, with further potential in the Mariovo and Tikves deposits [15].

The two mining areas feed the existing thermal power plants (TPP) at Bitola and Oslomej, which produce about 77% of the country's electricity (3,506.4 GWh in 2014).TPP Bitola consists of three units, commissioned in 1982, 1984 and 1988; their total gross capacity is 699 MW_e, after retrofitting in 1994. TPP Oslomej was commissioned in 1980 and consists of one unit with an installed gross capacity of 125 MW_e [48].

The Strategy for Energy Development till 2030, which was published in 2010, foresaw the decommissioning of the two existing TPPs (Oslomej around 2022, Bitola 1 & 2 around 2023 – 2026, Bitola 3 in 2030) and the construction of three new lignite units, each with a capacity of 300 MWe: Negotino 2, Bitola 4 and Mariovo [49]. However, the Draft Energy Strategy until 2035 (published in 2015) foresees a different approach, with the revitalization of the two existing TPPs and the postponement of the commissioning of the new lignite units at Mariovo and Bitola 3 till 2032; the Negotino 2 unit is not mentioned at all [50]. For TPP Oslomej, the revitalization foresees a fuel switch to imported hard coal [51].

Based on the above, the main lignite-fired power plant that is expected to operate till 2030 in FYROM is Bitola. The following points can be made regarding its main characteristics after its planned revitalization:

- The net generating capacity of the unit will increase from 627 to 650 MWe [52]
- The capacity factor will be 75%, while its electric efficiency will increase to 32% [52]. Both figures are slightly increased compared to the calculated figures for 2014.
- Regarding lignite characteristics, we consider values close to the design ones, e.g. a LHV of 7.3 MJ/kg and a carbon content of 22.55% wt as received [53, 54]. This is despite the fact that the LHV of the lignite consumed in 2014 was lower than the design [55]. The reason is that the plant is currently supplied mostly by the Suvodol mine, which is however nearing its exhaustion. For the continuation of the plant operation, new mines will have to be exploited. The LHV of lignite from this mines is expected to be closer to the Bitola design one, however the costs are expected to increase. In this study, we consider a lignite

cost of 2.7 €/GJ, which is considered reasonable given the costs at the Bitola plant gate from different mines as provided by a recent study [56].

Table 17 summarizes the main features of the revitalized Bitola TPP, while Table 18 presents the calculated biomass demand for different co-firing scenarios.

	Bitola 1-3 (Revitalized)
Gross Capacity (MWe)	N/A
Net Capacity (MWe)	650
Capacity factor	74%
Net efficiency	32%
Lignite LHV (MJ/kg)	7.3
μCO2 (t/t)	0.827
Lignite cost (EUR/GJ)	2.7
Commissioning	2018
Decommissioning	2035
Lignite consumption (Mton / y)	6.49

Table 17: Main characteristics of the revitalized Bitola PP.

Biomass type	Thermal substitution (%)	Quantity (kton, dm)
Agrobiomass LHV, ar (MJ/kg) = 14.5	5%	139
	10%	278
	15%	417
	20%	556
Wood pellets LHV, ar (MJ/kg) = 17.5	5%	122
	10%	244
	15%	366
	20%	488

Table 18: Calculated biomass demand for the revitalized Bitola PP.

8.2. Biomass availability in FYROM

The biomass availability for FYROM are presented in Table 19. Data for the NUTS3 area of Pelagoniski, where the Bitola PP is located, and the whole of the country are presented. The figures suggested that the sustainable potential for cereal straw is stable from 2020 to 2030, while that for maize stover is slightly decreased. Other types of agrobiomass resources are negligible in quantities and are not presented in the table.

The comparison of Table 18 and Table 19 yields the conclusion that the application of agro-biomass co-firing at the Bitola PP even at a thermal share of 5% would require using almost all the sustainable agro-biomass potential in FYROM. This a very ambitious scenario and unlikely to materialize. A more feasible option would be to implement co-firing only at Unit 3 of the Bitola PP; in this case, the expected biomass consumption for a 5% thermal share would be about one-third of the amount listed in Table 18 (46 kton DM) and it could almost be covered by the sustainable potential in the NUTS3 regions of Pelagoniski (MK005) and Vardaski (MK001).

NUTS	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
MK005	Cereal straw	24	20	20
MK005	Maize stover	9	8	8
MK	Cereal straw	122	100	100
MK	Maize stover	47	42	38

Table 19: Sustainable agro-biomass potential and costs in FYROM.

9. Biomass co-firing in Montenegro

9.1. The lignite sector of Montenegro

Montenegro produced around 1.7 million tonnes of lignite in 2012 [57]. Elektroprivreda Crne Gore (EPCG) utilizes this fuel in the Pljevlja PP, which consists of two blocks with an installed capacity of 218.5 MW (following refurbishment in 2009) [58] and produced about half the electricity of the country in 2015.

In 2016 and after an international tendering process EPCG awarded the construction of a second block at Pljevlja to the Czech company Skoda Praha [59]. The main characteristics of the plant are summarized in the Table 20 [60], while Table 21 presents the calculate biomass demand for different co-firing scenarios.

	Pljevlja II
Gross Capacity (MWe)	254
Net Capacity (MWe)	232
Capacity factor	87.2%
Net efficiency	39.5%
Lignite LHV (MJ/kg)	9.259
μCO_2 (t/t)	0.937
Lignite cost (EUR/GJ)	1.89
Commissioning	~ 2020
Decommissioning	N/A
Lignite consumption (Mton / y)	1.68

Table 20: Main characteristics of the Pljevlja II PP.

Biomass type	Thermal substitution (%)	Quantity (kton, dm)
Agrobiomass LHV, ar (MJ/kg) = 14.5	5%	46
	10%	91
	15%	137
	20%	182
Wood pellets LHV, ar (MJ/kg) = 17.5	5%	40
	10%	80
	15%	120
	20%	160

Table 21: Calculated biomass demand for the Pljevlja II PP.

9.2. Biomass availability in Montenegro

The whole of Montenegro is one NUTS3 administrative unit. According to the S2Biom biomass supply tool, the user-defined agro-biomass potential in Montenegro is minimal, consisting of no more than 5 kton DM in 2020 and 2030. However, there is a potential for herbaceous energy crops, depicted in Table 22, which could be used to support the implementation of biomass co-firing at Pljevlja II for biomass thermal share around 5%.

NUTS3	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
BA111	Miscanthus	68	71	69
BA111	Switchgrass	53	56	55

Table 22: Sustainable herbaceous energy crops potential and costs in Montenegro.

10. Biomass co-firing in Romania

10.1. The lignite sector of Romania

With 24 Mt mined in 2015, Romania is the fifth largest producer of lignite in the EU-28, following Bulgaria. Lignite resources are estimated at 9,920 Mt, while reserves are around 280 Mt, mostly located in the Oltenia basin [16].

COMPLEXUL ENERGETIC OLTENIA (Oltenia Energy Complex) is the main stakeholder in the Romanian lignite sector, responsible for 99% of the lignite production and owner of the main lignite-fired power plants. These plants are Turceni (1,320 MW), Rovinari (990 MW), Craiova II (300 MW) and Ișalnița (630 MW) [61].

No detailed data on the characteristics of each Romanian power plant could be found on the public domain. However, considering 2014 data for the electricity generation from lignite [18], the level of lignite production in the country used in conventional power and the typical lignite LHV for Romania as calculated by EUROSTAT data [62], the overall net efficiency of the Romania power plants is estimated at around 32.6%, while the overall capacity factor is 61.6%. For the emission factor from lignite combustion, a typical average carbon content of lignite mined in Oltenia is around 22% as received [63], therefore the emission factor is taken as 0.807 tCO_2/t lignite.

Based on the above, the combined agrobiomass demand for co-firing in all lignite PPs in Romania can reach up to 566 kt DM for a 5% thermal share and 1,133 kt DM for a 10% thermal share.

10.2. Agro-biomass potential for co-firing in Romania

Table 23 presents the user-defined agro-biomass potential for the two NUTS3 areas in Romania covering the lignite-fired PPs of the Oltenia mining basin. Considering all types of these residues, it is possible to reach a 5% thermal share in all existing lignite plants in Romania; an alternative, more-likely scenario is to implement co-firing at a higher thermal share at one or more units of a single power plant. In any case, the potential is quite high, so it can be expected that logistics will not be the main limiting factor.

NUTS	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
RO411 (Dolj) PPs: Rovinari, Turceni	Cereal straw	278	262	266
	Maize stover	186	209	197
	Sunflower straw	24	25	24
	Oil seed rape straw	14	16	24
Gorj) PPs: Islanita, Craiova II	Cereal straw	209	196	200
	Maize stover	140	157	148
	Sunflower straw	18	19	18
	Oil seed rape straw	11	12	18

Table 23: User-defined agro-biomass potential and costs in Romania.

11. Biomass co-firing in Slovenia

Slovenia is reported to have 1,268 Mt of lignite resources, of which 120 Mt correspond to lignite reserves. The only lignite deposit currently exploited is located in Velenje, in the north of the country. Lignite and brown coal production in 2015 was 3.2 Mt [16].

Lignite mined in the Velenje mine is used at the nearby Šoštanj power plant, operated by the state-owned HOLDING SLOVENSKE ELEKTRARNE (HSE). HSE has recently commissioned the new, 600 MW, Unit 6 at Šoštanj which is foreseen to gradually replace production in the older units. The characteristics of this power plant are presented in the table below [64].

	Šoštanj Unit 6
Gross Capacity (MWe)	600
Net Capacity (MWe)	545.5
Capacity factor	77.6%
Net efficiency	42.6%
Lignite LHV (MJ/kg)	10.30
μCO2 (t/t)	1.061
Lignite cost (EUR/GJ)	2.25
Commissioning	2015
Decommissioning	N/A
Lignite consumption (Mt/y)	3.04

Table 24: Main characteristics of Šoštanj Unit 6.

According to the S2Biom toolset, there is practically zero potential for agro-biomass residues in Slovenia. The potential from dedicated, herbaceous energy crops is also very low (for example, up to 39 kt DM of miscanthus in 2030). Therefore, it is not expected that agrobiomass co-firing will be of interest for the Šoštanj power plant. However, Slovenia is a heavily forested country, therefore co-firing could be implemented using locally produced woody biomass.

12. Biomass co-firing in Turkey

12.1. The lignite sector of Turkey

Lignite is the most important indigenous energy source in Turkey. Lignite production in 2014 amounted to 59.6 Mt, while in 2015 41.8 Mt were mined due to an accident at the Soma mine. Overall though, lignite production in Turkey has doubled in the last ten years [16].

The proven reserves of lignite are estimated at 15.6 billion tonnes; the most important lignite deposits are located at the Afsin – Elbistan lignite basin of south – eastern Anatolia, near the city of Maraş where the geological and economically mineable reserves are estimated at around 7 billion tonnes of low quality lignite. The Soma basin is the second largest lignite area in Turkey. Other important deposits are located in the Tuncbilek, Seyitomer, Bursa, Can, Muğla, Beypazarı, Sivas and Konya Karapınar basins [16].

The quality of Turkish lignites is generally very poor; about 8% have a calorific value of more than 3,000 kcal/kg and 58% are estimated at lower than 1,500 kcal/kg. The heating value of lignite from the Afsin – Elbistan reserves is around 1,100 kcal/kg [65].

The installed capacity of lignite-fired power plants in Turkey amounted to 8,700 MW. Turkey has a very ambitious programme to construct 7,000 MW of coal-fired power generation, the largest of its kind outside China and India [16].

Most of the lignite-fired power plants in Turkey are operated by the state-controlled Elektrik Üretim A.Ş (EÜAŞ); however some plants have been privatized (Seyitömer , Kangal) or built by private companies (Tufanbeyli) [67].

Figure 5 presents the location of the currently operating lignite-fired power plants in Turkey, while Table 25 summarizes their main characteristics. Plant capacities, number of units and year of commissioning for most plants are taken from an IEA report [68]. The same report also lists the annual generation for 2013, from which the capacity factor is calculated. For the Tufanbeyli power plant, which is the younger lignite plant in Turkey, updated information is taken from a published report [69]. Generally, the capacity factor is quite low; EÜAŞ reports it as being less than 50% for 2012 and 2013 [70]. Planned or unplanned outages, rehabilitations processes, problems during lignite supply in mines, prolonged failures and design issues are listed as reasons for the low capacities [67].

For the lignite consumption of the plants, two values are listed: the first is the one provided by the IEA report, the second is calculated taking into account the net efficiency and annual electricity production. The LHV and carbon content (for the calculation of the emission factor) is taken for most power plants from a single reference [71]; other sources are used for the lignite used at Kangal [72] and Tufanbeyli [73] power plants.

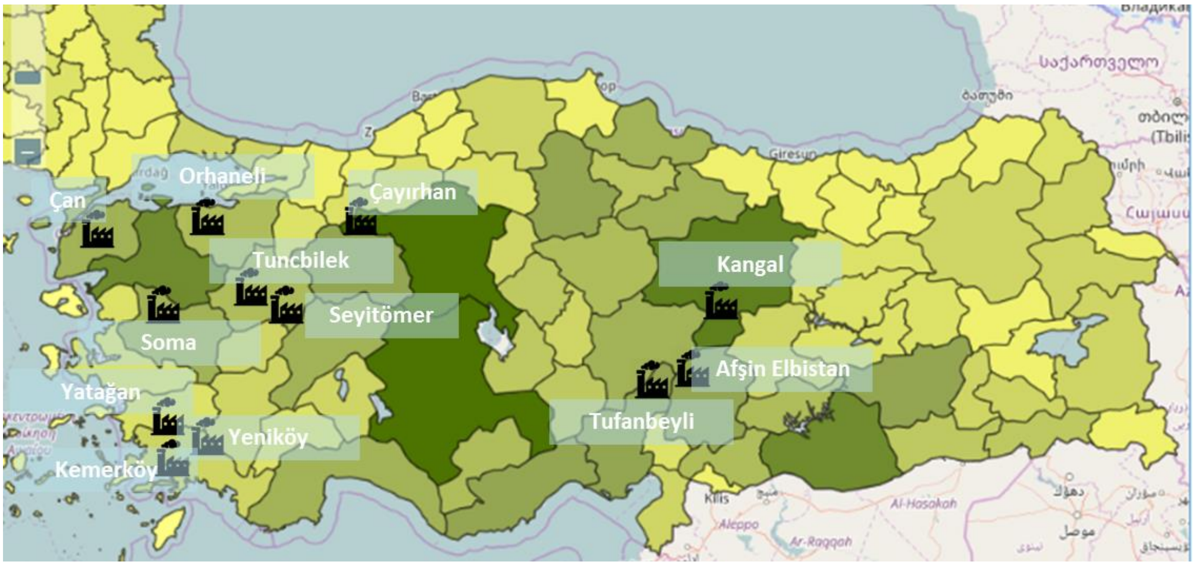

Figure 5: Location of Turkish lignite-fired power plants.

	Capacity (MWe)	Units	Cap. factor (%)	Net effic.	µCO2 (t/t)	Commissioning	Lignite consumption (Mt/y)	
							IEA	calc.
Çan	320	(2 x 160)	51.7%	41%	1.107	2004	1.80	2.03
Orhaneli	210	210	51.2%	27.0%	1.740	1992	1.50	2.00
Tuncbilek (B 4-5)	300	(2 x 150)	59.2%	33.2%	1.559	1978	2.40	2.68
Seyitömer	600	(4 x 150)	62.4%	31.98%	0.763	1973-89	7.10	5.88
Çayırhan	620	(2 x 150, 2 x 160)	N/A	35%	1.162	1987-2000	4.30	N/A
Soma B	1034	(6 x 165)	56.0%	33.1%	1.417	1981-86	8.00	8.80
Kemerköy	630	(3 x 210)	51.2%	34.51%	0.843	1993-97	5.00	4.69
Yatağan	630	(3 x 210)	54.0%	35.1%	1.069	1984-86	5.35	4.87
Yeniköy	420	(2 x 210)	78.7%	34%	1.432	1986-87	3.70	4.87
Afşin Elbistan-A	1355	(3 x 340, 1 x 335)	24.9%	28.0%	0.777	1984-87	18.00	8.26
Afşin Elbistan-B	1440	(4 x 360)	36.6%	39%	0.777	2006-07	18.50	9.27
Kangal	450	(2 x 150, 1 x 150)	32.2%	35.21%	0.722	1989-2000	5.40	2.06
Tufanbeyli	450	(3 x 150)	65.7%	34.20%	0.616	2015	7.20	4.34

Table 25: Characteristics of lignite-fired power plants in Turkey

The following table presents the calculated biomass demand for different co-firing scenarios using the lignite consumptions for each plant presented by IEA and the assumptions about the lignite LHV from this study.

	Agrobiomass LHV (MJ/kg) 14.5				Wood pellets LHV (MJ/kg) 17.5			
	5%	10%	15%	20%	5%	10%	15%	20%
Çan	56	112	168	224	49	98	147	196
Orhaneli	71	141	212	283	62	124	186	248
Tuncbilek (B 4-5)	104	207	311	415	91	182	273	364
Seyitömer	141	283	424	566	124	248	372	496
Çayırhan	141	281	422	562	123	247	370	493
Soma B	316	631	947	1,262	277	554	830	1,107
Kemerköy	153	306	459	613	134	269	403	537
Yatağan	161	322	482	643	141	282	423	564
Yeniköy	159	317	476	634	139	278	417	557
Afşin Elbistan-A	337	675	1,012	1,350	296	592	888	1,184
Afşin Elbistan-B	347	694	1,040	1,387	304	608	913	1,217
Kangal	93	186	279	372	82	163	245	326
Tufanbeyli	108	215	323	431	94	189	283	378

Table 26: Calculated biomass demand for the Turkish lignite-fired power plants.

12.2. Agro-biomass potential for co-firing in Turkey

Table 27 summarizes the results of the S2Biom toolset regarding the user-defined potential of agro-biomass residues in the NUTS3 regions of Turkey where lignite-fired power plants are currently located.

Generally, the agro-biomass potential in Turkey is huge. The following remarks can be made for each power plant / region:

- The power plants Kangal, Çayırhan, Orhaneli and Çan are located in areas where the wheat straw potential alone is enough to support co-firing shares up to 20%,
- The NUT3 area Kahramanmaras can in theory support the implementation of co-firing at a thermal share of 10% for the newest Afşin Elbistan B PP using both wheat straw and maize stover.
- In Adana, a co-firing share of 20% or more can be reached at the Tufanbeyli PP using both wheat straw and maize stover.
- The Soma PP can reach a 10% thermal share using wheat straw from the Manisa NUT3 region.

- The Seyitömer and Tuncbilek PPs are both located in the Kutahya region; local wheat straw resources are more than enough for a 20% thermal share at Tuncbilek. For both PPs, lower thermal shares have to be implemented.
- Finally, in the Mugla region three power plants operate: Kemerköy, Yatağan and Yeniköy. The wheat straw potential is quite limited so a more realistic scenario would be the implementation of co-firing at a 5% thermal share at the Yatağan PP. It should be noted that these plants are located close enough to the Aegean coast and thus could consider using imported wood pellets as a co-firing fuel.

It should be noted that several of these plants are located on the edge of NUTS3 regions, therefore not all the biomass potential could be easily transported to their coal yards. In any case, more realistic co-firing scenarios have to consider the biomass availability at a more local level and consider possible limitations due to transport routes.

NUTS3	Biomass type	Sustainable biomass potential (kton)		
		2012	**2020**	**2030**
TR621 (Adana) PPs: Tufanbeyli	Cereal straw	546	429	512
	Maize stover	342	357	385
TR632 (Kahramanmaras) PPs: Afşin Elbistan A & B	Cereal straw	512	456	579
	Maize stover	132	163	209
TR722 (Sivas) PPs: Kangal	Cereal straw	796	660	661
	Maize stover	3	4	5
TR323 (Mugla) PPs: Kemerköy, Yatağan, Yeniköy	Cereal straw	188	163	212
	Maize stover	37	42	50
TR331 (Manisa) PPs: Soma	Cereal straw	453	374	367
	Maize stover	35	44	56
TR333 (Kutahya) PPs: Seyitömer, Tuncbilek	Cereal straw	413	340	334
	Maize stover	32	40	51
TR510 (Ankara) PPs: Çayırhan	Cereal straw	1380	1162	1162
	Maize stover	2	3	3
TR411 (Bursa) PPs: Orhaneli	Cereal straw	407	338	359
	Maize stover	22	25	30
TR222 (Canakkale) PPs: Çan	Cereal straw	522	388	416
	Maize stover	9	8	8
	Sunflower straw	76	78	81
	Rice straw	62	83	89

Table 27: User-defined agro-biomass potential in selected NUTS3 regions in Turkey

13. Fuel costs delivered at the plant gate

13.1. Lignite costs

A recent study performed by booz&co. on behalf of the Public Power Corporation [17] (Greece) has evaluated the full lignite costs for the main lignite producing countries in Europe using a wide range of publicly available data (annual reports, statistics, etc.). Figure 6 summarizes the main results of this study. Generally, although there is a fairly large variation in the lignite costs quoted per country, the average values tend to be below 3 €/GJ, delivered at the plant gate. It should be noted that the heating value of the mined lignite has a big impact on the fuel cost on an energy basis. For example, although Greek lignite has the second lowest cost in €/t (after Bulgarian lignite), its very low heating value places it on the high end of the costs expressed on an energy basis.

Lignite costs for other countries not targeted by the booz&co. report range from 1.89 €/GJ (Montenegro) to 2.70 €/GJ (FYROM), as indicated in previous sections of this study.

Due to its low heating value, lignite is rarely transported over long distances. Mines and power plant form a single economic entity and lignite is transported from the one to the other mostly using dedicated infrastructure such as conveyor belts [74]. Transport over longer distances is possible only if the lignite undergoes an energy upgrade process, such as drying.

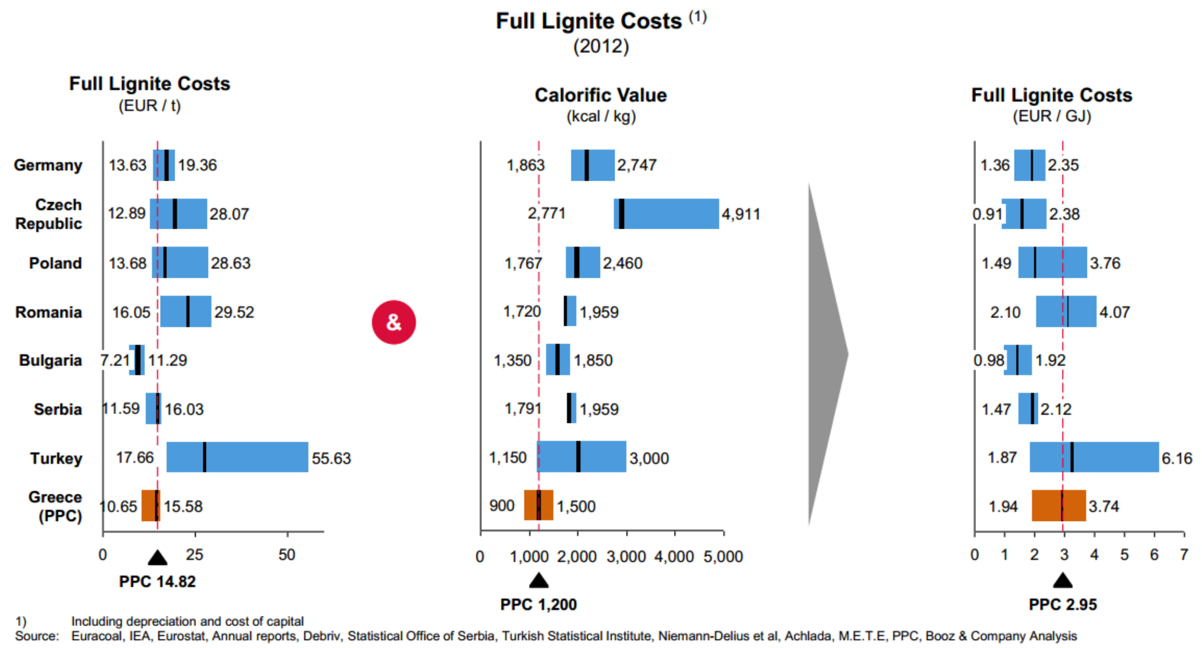

Figure 6: Lignite costs for the main lignite producing countries (source: booz&co.)

13.2. Imported wood pellets supply chain

In order to have a benchmark for the solid biofuel cost delivered at a lignite-fired plant gate, the case of imported wood pellets is investigated.

The following table summarizes the main logistic steps considered in this scenario.

Supply chain 3: wood pellets (imported)
Delivery at port facility
Download (pellets)
Storage (pellets)
Loading (pellets)
Road transport to PP (pellets)
Download (pellets)
Storage (pellets)

Table 28: Logistics steps considered for the imported wood pellets supply chain

The pellets are delivered at the nearest port facility, downloaded, stored and loaded on a truck. A typical distance of 200 km is assumed between the port and the power plant although this distance may be longer for power plants located further inland. Once at the power plant, the pellets are downloaded and stored before combustion.

Regarding the costs, the following are used as an estimation:

- The cost of wood pellets at the port facility is 150 €/t CIF.
- Download at port equal to 5.2 €/t.
- The cost of transport using a truck is 1.4746 €/km. The truck can be loaded with 12.5 t of bales or 25 t of pellets [75].
- Characteristics of truck transport logistics, download operations and storage same as in the previous case.

Overall, the imported wood pellet cost delivered at the plant gate is calculated at 10.77 €/GJ. This is higher than the typical values quoted for co-firing plants in Western Europe (9 €/GJ) [76], mostly due to the truck logistics.

13.3. Agrobiomass supply chains

The costs calculated by the S2Biom biomass supply tool are “road-side” costs, which cover the collection and field pre-treatment (e.g. baling) of the investigated biomass types. Further costs downstream the supply chain and up to the delivery at the plant gate, where the biomass fuel is co-firing are not included in the initial assessment.

The following table summarizes the roadside costs for the biomass types considered in this study for each SEE country. Both the cost in €/t DM as well as the energy cost for the as received conditions is displayed. In most cases, the energy cost of these residues is lower or comparable to that of lignite.

	Wheat straw		Maize stover		Sunflower straw		Rice straw	
	€/t DM	€/GJ	€/t DM	€/GJ	€/t DM	€/GJ	€/t DM	€/GJ
Greece	45	2.64	23	1.40	30	1.80	34	2.15
Serbia	16	0.94	10	0.61	12	0.72	16	1.01
Kosovo	16	0.94	10	0.61	12	0.72	16	1.01
Bulgaria	14	0.82	10	0.61	12	0.72	15	0.95
Bosnia-Herzegovina	17	1.00	10	0.61	13	0.78	17	1.07
FYROM	14	0.82	8	0.49	10	0.60	14	0.88
Montenegro	17	1.00	11	0.67	13	0.78	17	1.07
Romania	18	1.06	11	0.67	13	0.78	17	1.07
Turkey	20	1.17	13	0.79	16	0.96	20	1.26

Table 29: Roadside costs for agrobiomass residues in the SEE countries.

In order to produce an estimation of the plant-gate biomass cost, it is necessary to consider working models of biomass supply chains. The following paragraphs present how such models have been constructed in the framework of the present study.

The agrobiomass supply chains considered in this study are presented in Table 30. Two main chains are investigated as a reference. In the first, the material is supplied to the power plant in the form of bales, while in the second the power plant is supplied with pelletized biomass.

In both cases, the starting point is the harvesting of biomass (straw) in the form of bales. The bales are then loaded on an agricultural trailer and transported to a short distance (5 km) to a first storage site. From them on, the two supply chains diverge.

In the first case, the straw bales are loaded on a truck and transported to the power plant, where they are temporarily stored before combustion.

In the second case, the bales are loaded on a truck and transported to a pellet plant, where they are processed. The pellets are then loaded on a truck and transported to the power plant where they are temporarily stored before combustion.

Supply chain 1: straw bales	Supply chain 2: straw pellets
Straw harvesting	Straw harvesting
Loading (bales)	Loading (bales)
Road transport with agricultural trailer (bales, 5 km)	Road transport with agricultural trailer (bales, 5 km)
Download and open storage (bales)	Download and open storage (bales)
Loading (bales)	Loading (bales)
Road transport with truck to PP (bales)	Road transport with truck to pellet plant (bales)
Download and storage (Bales)	Download (bales) and pellet production
	Loading (pellets)
	Road transport with truck to PP (pellets)
	Download (pellets)

Table 30: Logistic steps considered for the agro-biomass supply chains

The “road-side” cost of the material is taken from the S2Biom biomass supply tool (Table 29). For the other costs, the assumptions are listed below and are based on the S2Biom logistical components toolset [75] or estimations from CERTH.

- The cost of transport using a farm tractor with a platform trailer is 1.4928 €/kmThe platform trailer can be loaded with 12.5 t of bales [75].
- The cost of transport using a truck is 1.4746 €/km. The truck can be loaded with 12.5 t of bales or 25 t of pellets [75].
- For the purposes of cost calculations, transport distances between a)the field and the storage place, b) the storage place and the pellet plant or the power plant, c) the pellet plant and the power plant, are effectively doubled in order to reflect the fact that the vehicles return empty to their origin.
- Loading and unloading cost is estimated at 1 €/t.
- Storage cost is estimated at 2 €/t [75].
- Pellet production costs of 30 €/t. The cost is somewhat lower than that considered by most studies due to the lack of a dryer in the pellet plant.
- A 20% markup is considered for administrative costs, etc.

The following figures compare the cost of biomass delivered at the plant case for the two supply case scenarios starting from the roadside costs for Greece and Serbia. Greece has the highest roadside wheat straw costs for all countries, while the roadside cost for Serbia is less than half of the Greek one and more typical for the other SEE countries.

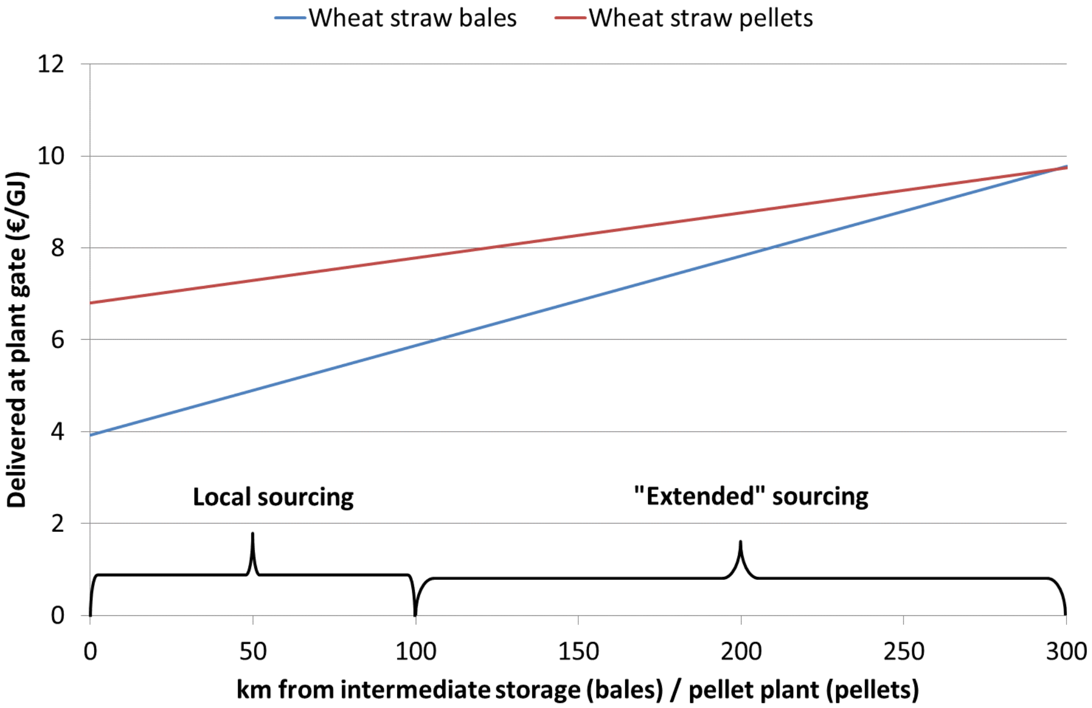

Figure 7: Comparison of wheat straw supply chains for Greece.

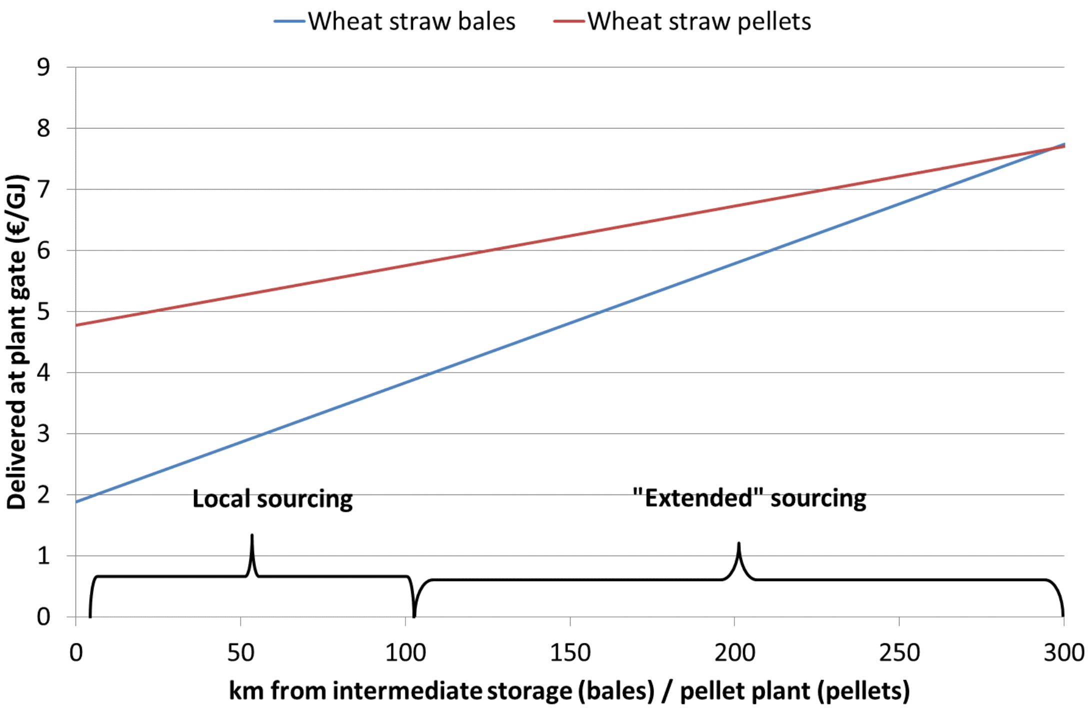

Figure 8: Comparison of wheat straw supply chains for Serbia.

It is interesting to note that the supply of wheat straw bales to power plants becomes more economic only in the case when the transport distance exceeds 300 km. In cases of “local sourcing” of biomass, which is not expected to exceed 100 km, the cost advantage of using bales is evident. It should be noted however that this option requires using fairly large storage areas.

For Greece, the straw bale supply chain starts from a delivery cost of 4 €/GJ and rises up to 6 €/GJ for a transport distance of 100 km. When extending the transport distance to 300 km, the cost rises to almost 10 €/GJ, becoming comparable with imported wood pellets.

For Serbia, the straw bale supply chain starts from a lower delivery cost of around 2 €/GJ; this is due to the lower roadside biomass cost for the country. For a transport distance of 100 km and 300 km, the cost rises up to 4 €/GJ and 7.7 €/GJ respectively. A similar trend is expected in all the other investigated SEE countries.

14. Required feed-in premium for co-firing implementation

As previously mentioned, it can be expected that, due to logistics, the average cost of biomass delivered at a lignite-fired plant gate will be higher than the corresponding lignite one.

Part of this cost difference can be reclaimed through the reduction of CO_2 emissions achieved by the co-firing of biomass. The exact level of this reduction depends both on the lignite fuel characteristics (emission factor, LHV) as well as on the market price of CO_2.Any additional cost difference can be reclaimed through the implementation of a financial support mechanism for the generation of bioenergy from a co-firing power plant.

In this study, the average lifetime levelized cost of electricity (LCOE) for specific co-firing lignite plants is calculated. The LCOE is the break-eve price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate [6]. The LCOE is given by the following equation:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

- I_t are the investment expenditures in the year t;
- F_t are the fuel expenditures in the year t;
- M_t are other net operating and maintenance expenses in the year t;
- E_t is electricity generation in the year t;
- r is the discount rate;
- n is the lifetime of the investment.

For the calculation of LCOE for the purpose of this study we consider the co-firing part of a lignite-fired power plant as a separate production module. In particular, we consider the following parameters and assumptions:

- The economic feasibility of the lignite-fired unit plant is not investigated. It is assumed that the unit will generate electricity on an annual basis according to its capacity factor and that it is duly compensated by the existing market mechanisms.
- For the fuel expenditures, we consider only the difference between the biomass fuel cost and the lignite fuel cost. The “baseline” fuel cost, corresponding to the fuel cost of lignite is assumed to be compensated by the grid price for electricity.

- Savings due to the CO_2 emissions reduction from the substitution of lignite with biomass are attributed to the LCOE of the co-firing module.
- The investment cost is incurred on year 0 and is assumed to be 500 €/kWe,net, independent of the actual co-firing share.
- The annual operating and maintenance costs due to the co-firing operation are 5% of the co-firing investment.
- The discount rate is 9%
- The lifetime of the investment is taken as 10 years, lower than typical purchasing agreements from bioenergy producers (20 years). We consider this to reflect the possibility of an unfavorable view of co-firing by the legislators.

The LCOE calculated from this approach is an indication of the required feed-in premium that a co-firing power plant requires in order to make a return of the capital. Higher feed-in premiums than the LCOE yield a greater return on capital, while lower premiums result either in lower returns or losses.

Figure 9 presents the calculated LCOE for selected lignite-fired units in SEE countries. The results are based on a biomass fuel cost of 6 €/GJ and presented for two different scenarios regarding the market price of CO_2: 20 €/t and 0 €/t. The biomass fuel cost is considered reasonable to enable logistic chains up to 100 km in Greece or about 200 km in the other SEE countries. Average country costs for lignite from the booz&co. study [17] are used in case there is no specific plant information.

Overall, the LCOE ranges from 15.55 to 40.37 €/MWh when considering a CO_2 price of 20 €/t and increases to a range of 41.37 – 63.60 €/t when CO_2 has no market price. It is interesting to note that the LCOE from the Ptolemaida V unit, which is expect to have the highest efficiency of the investigated units is having one of the lowest LCOEs. Due to its high CO_2 emissions, the Yenikoy power plant has the lowest LCOE of all when CO_2 has a market price.

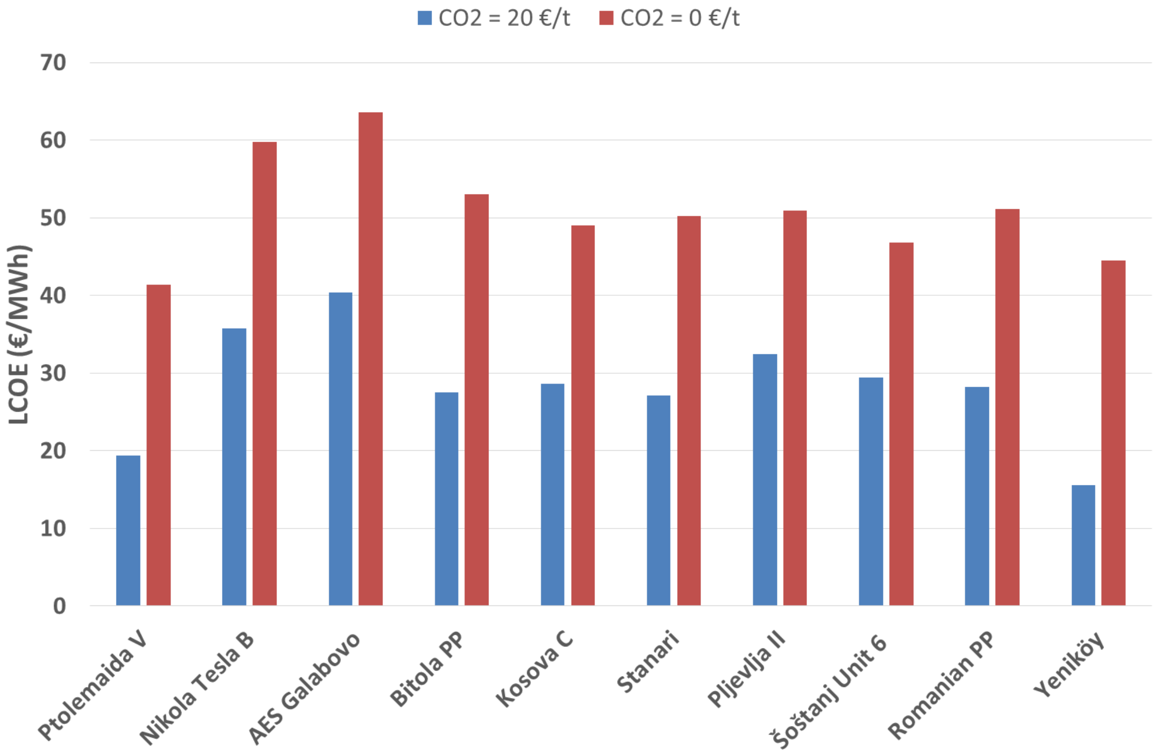

Figure 9: Calculated LCOE for selected lignite-fired PPs in SEE for a biomass cost of 6 €/GJ.

For comparison, the overall support level received for bioenergy production in several European countries ranged from 14.50 to 138.06 €/MWh in 2012 and 10.56 to 147.25 €/MWh in 2013 [77]. These figures include data for all bioenergy installations, including biogas. Values from SEE are reported only for Greece and Romania: 20.77/36.63 and 56.06/57.71 €/MWh for 2012/2013 respectively. On average though, it should be noted that for most European countries, the support received for bioenergy is well over 50 €/MWh, while the low support for Greece can also be due to the fact that bioenergy production in Greece takes place mostly from landfill gases and compensated with lower feed-ins compared to dedicated biomass power plants.

It can be concluded therefore that the level of support required for the implementation of co-firing at lignite power plants in the SEE is expected to be lower than the average one in Europe when CO_2 emissions are priced and the biomass cost is at relatively low levels.

The co-firing of imported wood pellets (fuel cost ~ 11 €/GJ) would require a level of support higher than the LCOE range of 63.04 - 91.76 €/MWh (for CO2 price equal to 20 €/t) or 85.04 – 115.81 €/MWh. This is within the limits of the European support levels, but considered unlikely to materialize.

15. Suggestions for further study

The present study focuses on the strategic aspects of agrobiomass co-firing in the SEE countries. As a result, it is based on several assumptions, which can be further refined in a more comprehensive study.

Updating and dimensioning of the logistics components

The logistic components of the supply chains can be improved by taking into account more detailed cost data for each specific country, e.g. accurate truck transport costs.

Additionally, alternative means of transport, such as trains or river barges (where applicable) should be considered as means of cost reduction, especially as regards the imported wood pellets supply chains.

Finally, since all the investigated cases require the mobilization of significant biomass resources, the careful dimensioning and impact of several logistics components should be evaluated, e.g. storage area requirements, number of trucks handled daily at the power plant, etc.

Calculation of GHG emissions

The analysis in this study has not considered the GHG emissions released by the implementation of agro-biomass residues supply chains. However, results from a previous study [20] indicate that supply chains such as those considered in the present report are well within the targets for GHG reduction set by the proposed sustainability requirements of the European Commission for solid biofuels.

Optimization of supply chains & local biomass resources

The evaluation of potential agro-biomass resources for the co-firing plants investigated in this study is based on NUTS3 data available from the S2Biom toolset. As a result, they do not consider further spatial detail or peculiarities of the local transport infrastructure. For more accurate results and the in-depth investigation of the delivery chains for co-firing lignite power plants, it is suggested to use the capabilities of the LocaGIStics tool of the S2Biom project.

Business models for mobilizing agro-biomass residues

Straw is considered an important energy source for power production in Denmark [79] and there are also power or CHP plants in other countries, including Bulgaria [80]. However, in most cases the mobilization of wheat straw or other agroresidues for energy production is minimal. We believe that further work is required to promote business models and operational plans that connect the agricultural sector and the potential fuel producers with the power sector.

16. Overall conclusions

The S2Biom toolset has been used to investigate the agrobiomass residue potential in all SEE countries where there is presence of lignite mining and power generation. The results indicate that it is theoretically possible to implement co-firing at thermal shares ranging from 5% to 20% to selected lignite units while sourcing agro-biomass from the same NUTS3 region where the units are located.

A preliminary investigation of the supply chains indicates that it is more cost efficient to source wheat straw in the form of bales compared to pellets when the transport distance does not exceed 300 km.

An investigation of the feed-in premium required by co-firing has demonstrated that it can be set at a lower level than the typical ones for dedicated biomass power plants.

Overall, in most of the SEE countries studied, co-firing should be seriously considered as an alternative to reach renewable energy targets and mobilize agro-biomass resources. The relatively low investments required for the implementation of co-firing and the high conversion efficiencies that can be achieved at lignite-fired power plants can offer a technological "shortcut" that promotes the connection between the agricultural and the farming sector.

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