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ORIGINAL PAPER

Possibilities and sustainability of "biomass for power" solutions in the case of a coal-based power utility

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Abstract This paper investigates the possibilities and the sustainability of "biomass for power" solutions on a real power system. The case example is JP Elektroprivreda BiH d.d.—Sarajevo (EPBiH), a typical conventional coal-based power utility operating in the region of South East Europe. Biomass use is one of the solutions considered in EPBiH as a means of increasing shares of renewable energy sources (RES) in final energy production and reducing CO_2 emissions. This ultimately is a requirement for all conventional coal-based power utilities on track to meet their greenhouse gas (GHG) cut targets by 2050. The paper offers a discussion of possible options as a function of sustainability principles, considering environmental, economic and social aspects of biomass use. In the case of EPBiH, the most beneficial would be waste woody biomass and energy crop co-firing on existing coal-based power plants, as suggested by biomass market analyses and associated technological studies. To assess the sustainability of the different biomass co-firing options, a multicriteria sustainability assessment (MSA) and single criteria analysis (SCA) were used. Four different options were considered, based on different ratios of biomass for co-firing: 0 wt%-reference case, and 5, 7 and 10 wt% of biomass. Both the MSA and the SCA confirmed that the option with the highest share of biomass is the most preferable one for the considered case. In addition to that, the CO_2 parameter proved to be a key sustainability indicator, effecting the most decision making with regard to preference of options from the point of sustainability. Following up on the results of the analyses, the long-term projection of biomass use in EPBiH has shown an increase in biomass utilization of up to 450,000 t/y in 2030 and beyond, with associated CO_2 cuts of up to 395,000 t/y. This resulted in a 4 % CO_2 cut achieved with biomass co-firing, compared to the 1990 CO_2 emission level. It should be noted that the proposed assessment model for biomass use may be applied to any conventional coal-based power utility as an option in contributing to meeting specific CO_2 cut targets, provided that the set of input data is available and reliable.

Keywords Biomass · Coal · CO_2 emissions · Power plants · Sustainability

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Introduction

Co-firing biomass and bio-waste in coal-fired power plants is one of the most straightforward biomass applications in the short-to-medium term, as set out in the European Commission's White Paper on Energy for the Future: Renewable sources of energy (European Commission 1997). The main reason for the use of biomass as a co-fuel is its dual role in greenhouse gas (GHG) mitigation, by being a substitute for fossil fuels (bio-energy) and a carbon sink (Wischnewski et al. 2006). Fuels derived from biomass contain less sulphur, ash and trace elements as well. Current research on co-firing is focused on controlling combustion behaviour, emissions, corrosion, agglomeration, and fouling-related problems. Biomass used for combustion in industrial-scale furnaces must meet a number of criteria, including availability throughout the year to ensure security of supply, high density to minimize transportation costs, a sufficiently high heating value and an acceptable price (Wischnewski et al. 2006). As reported by Baxter et al. (2000) and Koppejan (2004), wood residues meet these requirements.

In the last decade, significant progress was made in the utilization of biomass in coal-fired power plants. Over 250 units worldwide have either tested or demonstrated co-firing of biomass or are currently co-firing on a commercial basis (KEMA 2009). Coal is often replaced with up to 30 % of biomass by weight in pulverized coal-based power plants, as in Belgium, Canada, Denmark, Finland, the Netherlands, Sweden, the United Kingdom, Germany, Poland and the United States. Most of these projects refer to co-firing biomass with high-rank coal (both bituminous and anthracite), while availability of projects on biomass co-firing with low-rank sub-bituminous coal and lignite is more scarce, like the project involving Greek lignite reported in the work by Kakaras (2000). Estimates made by Poyry for the International Energy Agency (IEA) World Energy Outlook suggest that there is a certain potential for biomass sufficient to replace a 10 % th of coal in all coal-based power plants in the world (IEA 2014). Furthermore, progress is made in application of different types of municipal solid waste as a fuel in coal-based power plants (solid recovered fuel—SRF or refuse derived fuel—RDF, including their gasification). However, along with research, development and demonstration projects and technologies, economic and social issues of biomass to power solutions have to be investigated as well, to achieve sustainable biomass-based power systems.

State-of-the-art

The co-combustion of biomass or waste with a base fuel in a boiler is a simple and economically suitable way to replace fossil fuels and utilize waste (Williams et al. 2001). In addition to that, co-combusting in a high-efficient power station means utilizing biomass and waste in a process with a higher thermal efficiency than what other ways had been possible, as reported by Leckner (2007). However, due to transportation limitations, the additional fuel will only supply a minor part (less than a few hundred MW fuel) of the energy in a plant. As according to the same author there are several options of "biomass for power" in large combustion plants, as for example,

- co-combustion with coal in pulverized or fluidised bed boilers,
- combustion on added grates inserted in pulverized coal boilers,
- combustors for added fuel coupled in parallel to the steam circuit of a power plant,
- external gas producers delivering its gas to replace an oil and
- gas or pulverized fuel burners.

Biomass can further be used for reburning in order to reduce NOx emissions (Hodzic et al. 2016), or for after burning to reduce N_2O emissions in fluidised bed boilers. A combination of fuels can give rise to positive or negative synergy effects, of which the interactions between S, Cl, K, Al and Si are the best known, which may give rise to or prevent deposits on tubes (Kazagic and Smajevic 2009) or may have an influence on the formation of dioxins (Leckner 2007).

Co-combustion has a number of potential advantages. A brief list, as reported by Leckner (2007), is given below:

- reduction of CO_2 emissions from fossil fuels;
- increased use of local fuels;
- conversion of biomass and waste fuels with a high efficiency and under controlled environmental conditions;
- there are no formal size limitations, although there are certain economic restrictions on how far voluminous and disperse materials such as biomass and waste can be transported, which can limit the size of a plant using such fuels;
- seasonal variations inherent in some biofuels can be adequately handled, because the ratio of the added to the base fuel can easily be scaled down from its maximum value;
- less complicated than other alternative conversion methods for biofuels and, hence, potentially economically advantageous,
- the amount of added fuel employed can be adjusted to the availability of biofuels and wastes within a reasonable transportation distance from the conversion plant and
- possible positive synergy effects with different fuels can be utilized.

Disadvantages can also be expected:

- the costs of some additional equipment or treatment processes need to be considered,
- the threat of harmful influence on the power plant, caused by the added fuel,
- possible negative synergy effects if the added fuel has some extreme properties (like some wastes) or if the combination of fuels is unfavourable and
- lack of experience, as reflected from two of the above points.

With a better knowledge of these effects, the positive ones can be used and the negative ones avoided (Leckner 2007).

Over the last decade, many research studies were conducted in order to investigate the biomass co-firing phenomenon. As an example, Wang et al. (2014) evaluated the combustion behaviour and ash properties of a number of renewable fuels, like rice husk, straw, coffee husk and RDF derived from municipal waste. The work used a drop tube furnace to evaluate the combustion behaviour and ash properties of biomass, waste derived fuels, pine and coal. Kupka et al. (2008) investigated the ash deposit formation during the process of co-firing coal with sewage sludge, sawdust and refuse derived fuels in a drop tube furnace, to optimize biomass co-firing blends. Williams et al. (2012) investigated the emission of pollutants from solid biomass fuel combustion. Emissions and ash-related problems were investigated in the Bosnian case as well, by co-firing Bosnian coal with waste woody biomass (Kazagic and Smajevic 2007, 2008), where some specific benefits and synergy effects were observed. Co-firing Bosnian coal with woody biomass in existing coal-fired power plants is hence considered a perspective combustion technology in the Bosnian case. Examples of biomass co-firing can be found in other industries as well, similar to the example of biomass co-firing in the cement industry, reported by Mikulcic et al. (2014).

When it comes to GHG emissions and policy related issues, which present important supporting tools when considering more extensive biomass use, further considerable research can be found as well. GHG and pollutant emissions coming from the energy sector are very high today, which forces states all over the world to take cost-effective steps for their mitigation, by creating adequate policies (Klemes 2010; Fan et al. 2014). CO_2 storage in underground reservoirs can result in very low—perhaps even near-zero—net GHG emissions, depending on the share of biomass used as input and its CO_2 signature, as reported by Aitken et al. (2015). Royo et al. (2012) developed a methodology applied to the Spanish case, by which a significant biomass co-firing potential and a subsequent GHG emission reduction could be achieved over large territories.

Overall, the given examples illustrate that research in biomass co-firing has so far mainly been performed in order to optimize the fuel mix through minimizing ash-related problems and emissions. Biomass co-firing in large power plants is mainly considered in reducing CO_2 emissions, improving security of supply and reducing operational costs by fuel cost optimization. However, less attention was given to sustainability issues of “biomass to power” solutions, where authors found only some related work. As an example, Umar et al. (2014) investigated the market response to six sustainability-related topics, thereby identifying several key factors for consideration by the government. The research involved an electronic and conventional postal dissemination of questionnaires to palm oil producers in Malaysia. Samsatli et al. (2015) gave a novel MILP formulation of the biomass value chain model (BVCM), which accounts for the economic and environmental impacts associated to the end-to-end elements of a pathway: crop production, conversion technologies, transport, storage, local purchase, import (from abroad), sale and disposal of resources, as well as CO_2 sequestration by carbon capture and storage (CCS) technologies and forestry. It supports decision making around optimal use of land, biomass resources and technologies with respect to different objectives, scenarios and constraints. Objectives include minimizing cost, maximizing profit, minimizing GHG emissions, maximizing energy/exergy production or any combination of these.

In this work, a sustainability assessment of different biomass co-firing options is performed, with the aim of investigating and identifying the most preferable one from the point of sustainability. Four different options were considered, based on different ratios of biomass for co-firing: 0 wt%-reference case, and 5, 7 and 10 wt% of biomass. A multicriteria sustainability assessment (MSA) and single criteria analysis (SCA) were then applied to assess the sustainability of the different biomass co-firing schemes, using sustainability indicators based on real measurements. The assessments are presented on an example of a thermal power plant using indigenous low-rank coal. The main contribution of this work is reflected in demonstrating the additional merit of biomass co-firing in this specific case and its contribution to sustainability.

System under consideration—EPBiH power utility

General description of the system under consideration—EPBiH power utility

The analyses performed in this work are demonstrated on an example of a real power system. The case example is JP Elektroprivreda BiH d.d.—Sarajevo (EPBiH), a typical conventional coal-based power utility operating in the region of South East Europe. EPBiH is part of the Energy Community of South East Europe (SEE) and is situated in Bosnia and Herzegovina (BiH). The total power output of EPBiH amounts to approximately 8000 GWh/y and is generated at two coal-based thermal power plants (TPP), i.e. TPP Tuzla and TPP Kakanj, three large hydro power plants (HPP) on the river of Neretva and a small number of small HPPs (sHPP) with a share of approximately 1 %.

Table 1 provides an overview of some basic information for existing TPPs addressed in the case study. The data are later on used as input parameters for the calculation and assessment of sustainability indicators. Both TPPs use

Table 1 Basic data on existing TPP units of EPBiH

Generation facilities	Installed capacity (MW)	Efficiency (%)	Domestic fuel cost (€/10^6kcals)	Variable O and M costs (€/kW per month)	Fixed O and M costs (€/kW per month)	Planned retirement year
TPP Tuzla unit 3	100	24.78	2.99	1.00	2.7	2018
TPP Tuzla unit 4	200	30.13	3.09	1.37	2.4	2021
TPP Tuzla unit 5	200	29.88	2.82	0.72	2.6	2030
TPP Tuzla unit 6	223	32.73	2.86	0.41	1.4	2030
TPP Kakanj unit 5	118	31.55	2.78	0.65	3.5	2023
TPP Kakanj unit 6	118	32.14	2.72	0.39	2.0	2030
TPP Kakanj unit 7	230	30.93	2.68	0.67	7.3	2030

indigenous low-rank coal, consuming about 6,500,000 t/y and generating around 6,500,000 tCO_2/y. Annual output of heat generated at the cogeneration units of TPP Tuzla and TPP Kakanj accounts for approximately 400 GWh/y (Kazagic et al. 2014).

Development targets for thermal power plants of EPBiH

Over the past 10 years, the total net efficiency of EPBiH's power plants has increased from 24 to 31 %. This was accomplished by applying specific measures such as decommissioning old thermal power units (4 × 32 MW in TPP Kakanj and 2 × 32 MW in TPP Tuzla) and modernizing all of the other existing coal-based power units. At the same time, CO_2 emissions were reduced from 9,500,000 t/y (1990) to the current level of 6,500,000 t/y (Kazagic et al. 2014).

EPBiH, however, is still facing challenges despite the improvements made. Requirements for further energy efficiency and CO_2 emission reduction measures are mandatory for the company to keep and improve its position on the market. It should also help the company comply with the energy efficiency and environmental regulation, as well as give support to a low-carbon future. Based on a planned generation portfolio development and an annual power demand projection till 2030, a new generation portfolio was optimized and projected in order to reach specific energy and decarbonisation targets. The portfolio expansion took into account plans of EPBiH to construct new generation facilities, while at the same time taking consideration of requirements for replacement capacities. Replacement capacities are considered with respect to TPPs planned to be decommissioned by 2030. The dynamics for their decommissioning are defined as part of the long-term development plan of EPBiH. The choice of the commissioning dynamics of all other TPP-associated facilities is subject to analysis, performed with regard to sustainability and decarbonisation criteria, partially conducted as part of this work as well. Additional inputs involve the current investment plans for desulphurization (DeSOx) and denitrification (DeNOx) facilities, planned in order to address obligations arising from the Large Combustion Plants Directive (LCPD) and Industrial Emission Directive (IED) (Directive 2009/28/EC, Directive 2012/27/EU).

The development plan will overall result in new TPP, HPP, wind power plant (WPP), photovoltaic power plant (PVPP) and biomass power plant (BPP) projects. To effect further CO_2 emissions reduction, co-firing coal with biomass is planned in all EPBiH TPPs (Kazagic et al. 2014).

Biomass for EPBiH power plants

Residues of the wood processing industry, agricultural and forest residues, as well as dedicated energy crops, are among the most abundant sources of energy in Europe. Making use of forest and agricultural residues in the power industry does not only help replace a certain amount of fossil fuels, but it also helps reduce their disposal in the environment, cutting down emissions of the greenhouse gas CH_4 (by avoiding biomass decomposition). Additional benefits include new job creation in establishing the required biomass supply chain (collection, transportation) and an overall better perspective for the development of energy, forestry and agriculture in the country.

Biomass has a significant potential as a source of energy in BiH. It is estimated that the BiH total annual technical biomass energy potential is over 33 PJ, which is equivalent to more than 3 million t of BiH lignite (Schneider et al. 2007). The most significant source of biomass for energy production in BiH is waste woody biomass originating from forestry (forest residues), as well as from the wood industry (wood chips, sawdust). Agricultural residues have a significant energy potential in BiH as well and are mainly located in the northern, central and southern parts of the country. Several assessments of the BiH biomass potential were performed so far and the results of one of these studies (EU/FP6/INCO/ADEG), reported by Schneider et al. (2007), are presented in Table 2.

BiH has also certain conditions suitable for the cultivation of fast-growing energy crops. This option is currently subject to research, and power plants are one of the potential beneficiaries of such a CO_2 neutral fuel.

Projections and "biomass for power" options in the case of EPBiH

It is anticipated that the future of coal-fired power plants will only be certain if their CO_2 emissions are below 550 kg/MWh. In order to fulfil such conditions in a long-term view and in the absence or delay of CCS implementation and development, the new coal-fired power units of EPBiH are required to reach a net efficiency of 43 %, using at the same time 25 % of biomass.

First steps of introducing biomass in the power generation portfolio of EPBiH were already made. After years of laboratory research, the implementation of a pilot project trial run on the TPP Kakanj Unit 5 in April 2011, has proven a technological viability of using at least 7 w% of waste woody biomass (sawdust) in a mixture with specific brown coal, as reported by Smajevic et al. (2012). The method involved a previous mixing of biomass and coal on the coal depot, transport of the mixture by the belt conveyor to the bunker and the mills and the injection into the boiler through existing coal burners. This method of direct co-combustion allows a use of 7–10 % of biomass in the fuel mix without causing any operational problems, in the case of TPP Kakanj. Other forms of co-combustion, allowing higher shares of biomass in the mixture (10–30 %), are also considered. These involve indirect mixing and co-combustion of the fuel blend in the boiler via biomass gasification or special biomass burners.

Overall a projected use of 7 w% of biomass at all power units of EPBiH, used at an average rate of 3000 h/y, would reduce the total CO_2 emissions of EPBiH by 4 %, as reported by Smajevic et al. (2012). EPBiH has therefore announced plans to introduce biomass into its generation portfolio, in order to reach long-term CO_2 cuts. These are concurrent with plans of energy efficiency improvements and the construction of new more efficient thermal power plants (Kazagic et al. 2014). As according to the plan, by the end of the planning period covered by the long-term development plan of EPBiH, it is technologically feasible and therefore can be planned to exploit biomass in existing and new thermal power units of EPBiH. The projected share of biomass in the fuel mix is indicated in Table 3.

Therefore, the primary objective of biomass use in existing and new power units of EPBiH in the coming years is to reduce CO_2 emissions, as well as to optimize fuel and operation and maintenance (O&M) costs. The 2030 projections show that there is a technological potential for the TPPs of EPBiH to have an annual power generation of up to 243 GWh at existing and 885 GWh at new units coming from biomass. Taking only a 50 % of the estimated fuel consumption at the new units alone, an annual volume of at least 225,000 t/y in long-term biomass use would be achieved.

Sustainability assessment of "biomass for power" options in case of the EPBiH power utility

Methodology

In this chapter, the sustainability of "biomass for power" options is considered for the EPBiH case. The main objective is to investigate the optimal biomass co-firing scheme for existing power units of EPBiH from the point of sustainability. The analysis includes seven existing power units of EPBiH listed in Table 1. The following biomass co-firing options were considered:

Option 1—coal only (U100)—business as usual scenario,

Option 2—co-firing coal with 5 w% of woody biomass (U95B5),

Table 2 Data on annual potential of biomass in BiH (FP6 project ADEG) (Schneider et al. 2007)

	Available amounts (per year)	Energy potential (PJ)	Origin
Biogas from farms	200,000 m^3	0.51	Agriculture
Fruit growing waste	211,257 t	0.74	Agriculture
Grains residues	634,000 t	8.88	Agriculture
Leguminous plants and oilseeds remains	3,858 t	0.04	Agriculture
Woody waste from industry	1,142,698 m^3	7.53	Forestry
Firewood	1,466,973 m^3	13.2	Forestry
Woody residues from forestry	599,728 m^3	2.62	Forestry
Total technical potential		33.52	

Table 3 Projection of the biomass share in the fuel mix of EPBiH thermal power plants

	Power from biomass (MWe)*	Annual generation (MWh)*	Annual biomass consumption (t)**	Annual CO_2 cut (t)
Kakanj TPP unit 5 (118 MWe)	7.5	24,000	16,000	18,500
Kakanj TPP unit 6 (118 MWe)	7.5	24,000	16,000	18,500
Kakanj TPP unit 7 (230 MWe)	17	54,000	35,000	40,000
New Kakanj TPP unit 8 (450 MWe)	75	225,000	130,000	115,000
Tuzla TPP unit 4 (200 MWe)	16	45,000	30,000	36,000
Tuzla TPP unit 5 (200 MWe)	16	45,000	30,000	36,000
Tuzla TPP unit 6 (223 MWe)	17	45,000	35,000	40,000
New Tuzla TPP unit 7 (450 MWe)	110	330,000	160,000	140,000
New Tuzla TPP unit 8 (450 MWe)	110	330,000	160,000	140,000
Existing units	81	243,000	162,000	188,000
New units***	295	885,000	450,000	395,000

* The projection of power and power generation based on energy from biomass is projected based on a share of 7 w% of biomass in the mixture with coal for existing units and a 25 % share of biomass in the mixture for new units, along with an operating rate of 3000 h/y under the regime of co-combustion at each unit (for the remaining time of the year the units are operated on coal only)

** Annual consumption of biomass for the projected power generation and net efficiency of a given unit, and for an average net calorific value of biomass of 14,000 kJ/kg

*** If a CCS technology is not implemented

Option 3—co-firing coal with 7 w% of woody biomass (U93B7) and

Option 4—co-firing coal with 10 w% of woody biomass (U90B10).

To investigate sustainability effects of different "biomass for power" options in the case of EPBiH, a sustainability assessment is performed with reference to environmental and economic criteria. For this purpose, specific environmental and economic sustainability indicators are estimated, as presented in Table 4. These are typically used when considering a power system, due to their high-effecting influence on the sustainability of such a system (Afgan et al. 2007; Kazagic et al. 2014). The indicators are estimated based on real "measurable" input data such as net efficiency, fuel consumption, emissions, construction costs, O&M costs, fuel costs and CO_2 tax as indicated in Fig. 2. All of these parameters are derived from the design properties of the thermal power units of EPBiH, the operational outputs of the biomass co-firing pilot project on TPP Kakanj reported by Smajevic et al. (2012) as well as associated projections made on TPP Tuzla. The obtained results are finally discussed by means of a single criteria analysis (SCA) and multicriteria sustainability assessment (MSA). The results are based on real measurements and projections. These facts should be taken into account in considering the reliability of the obtained results.

A realistic projection of parameters used in the estimate of indicators for the considered options is given in Table 5, while in Table 6, the calculated indicators are presented. The data in Table 5 were derived from internal reports of EPBiH, including financial sheets, emission reports, power plant energy indicator reports and biomass co-firing trial run projects.

Single criteria analysis

In this part, the projections for all options under consideration were estimated in relation to a realistic total power generation. This refers to a power output of 64.5 GWh in the timeframe 2016–2030 for all of the seven existing thermal power units of EPBiH, as presented in Table 5. The inputs are derived from development plans of EPBiH, providing a good basis for the comparison of indicators and a better reliability of the analysis. As can be seen from Table 5, emissions of SO_2 and NOx, and consequently costs associated to SO_2 and NOx taxes, are comparable for all options under consideration, with a slight decrease for options with a higher biomass share (U93B7, U90B10). The assessments took into account dynamic plans for DeSOx and DeNOx equipment installation, based on projections associated to the Bosnian National Emission Reduction Plan (NERP) and the decisions enacted through the Energy Community Treaty. It should be pointed out that the third environmental component—CO_2—improves a lot in the case of options with a higher biomass share, giving significant advantage to such options, as can be seen in Fig. 1.

This consequently implies much higher CO_2 tax costs in the case of the business as usual option (U100), see Table 5

Table 4 Sustainability indicators considered

Type of indicator	Single indicators	Unit
Environmental indicator (EI)	CO_2 indicator—EICO2	kg/kWh
	SO_2 indicator—EISO2	kg/kWh
	NO_x indicator—EINOx	kg/kWh
Economic indicator (EcI)	Investment indicator—EcICAPEX	EUR/kWh
	Energy costs indicator—EcIOPEX	EUR/kWh

Table 5 Operational characteristics and parameters aggregated for the timeframe 2016–2030

Parameter	Unit	Option 1 U100	Option 2 U95B5	Option 3 U93B7	Option 4 U90B10
Generation	GWh	64,544	64,544	64,544	64,544
B coal	t	60,703,556	57,040,680	55,839,838	54,256,411
B biomass	t	0	3,002,141	4,150,412	6,028,490
SO_2	t	452,140	457,109	452,765	446,526
NOx	t	110,347	109,145	109,109	109,111
CO_2	t	71,328,134	65,029,875	63,556,107	61,570,569
CAPEX	EUR	156,000,000	160,340,000	161,410,000	163,295,000
Fix and vary cost	EUR	478,210,240	478,210,240	478,210,240	478,210,240
Coal costs	EUR	2,015,775,834	1,900,868,480	1,862,078,029	1,810,790,462
Biomass costs	EUR	0	99,031,638	138,493,580	198,779,465
SO_2 tax costs	EUR	10,015,269	10,181,923	10,086,159	9,944,211
NOx tax costs	EUR	2,483,159	2,456,294	2,455,556	2,456,137
CO_2 tax costs	EUR	1,907,387,824	1,765,630,517	1,726,327,127	1,673,398,353
OPEX	EUR	4,413,872,326	4,256,379,093	4,217,650,691	4,173,578,867
Fuel costs	EUR	2,015,775,834	1,999,900,118	2,000,571,608	2,009,569,926

Table 6 Estimation of Indicators

Indicator	Unit	Option 1 U100	Option 2 U95B5	Option 3 U93B7	Option 4 U90B10
EISO2	kg/MWh	7005	7082	7015	6918
EINOx	kg/MWh	1710	1691	1690	1690
EICO2	kg/MWh	1105	1008	985	954
EcICAPEX	EUR/MWh	2417	2484	2501	2530
EcIOPEX	EUR/MWh	6839	6595	6535	6466

and Fig. 2 and a more favourable CO_2 indicator in the case of options with a higher biomass share, see Table 6. On the other side, due to projections of a higher biomass price as compared to coal for the considered time frame, fuel costs result to be lower in the case of the business as usual option. However, the total OPEX costs of U100 are still much higher compared to other scenarios, due to the specific CO_2 tax scheme. The scheme was applied with respect to the current situation, expectations and long-term projections given in the reports by the European Climate Foundation (2010, 2011). It should also be taken into consideration that the breakdown of capital costs took into account investments needed for desulphurisation and denitrification, as well as investments related to biomass

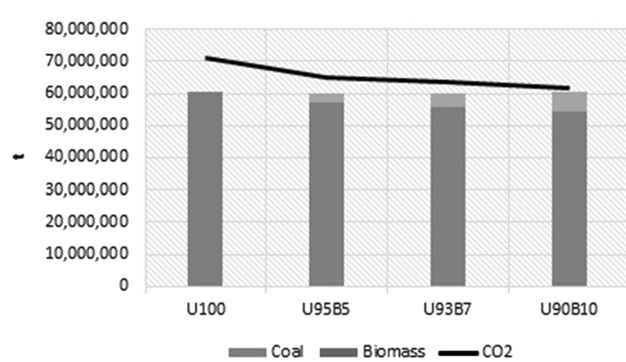

Fig. 1 Coal and biomass consumption and CO_2 emissions of existing power plants of EPBiH in the time frame 2016–2030 for different biomass options

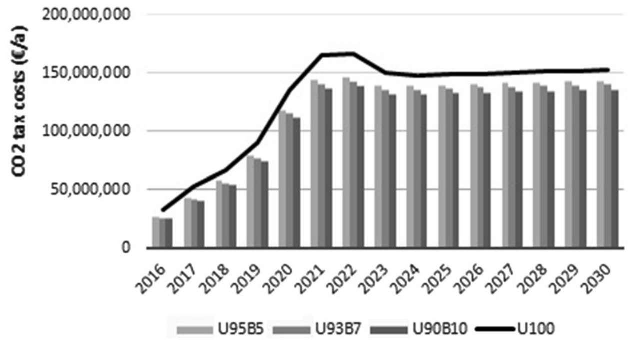

Fig. 2 CO_2 tax costs in the time frame 2016–2030 for different biomass options considered

preparation and the adaptation of the transportation infrastructure and boiler plants for the biomass options.

Multicriteria sustainability analysis

Within the MSA performed in this work, according to the standard MSA procedure described and applied by Afgan et al. (2007) and Kazagic et al. (2014), equal weighting factors were assigned to the group of environmental and economic indicators as a base case. Following the procedure of the MSA, the values of the weighting factors (*wi*) and the vectors of specific criteria, representing normalized sustainability indicator values (*SI*), were assigned and calculated. In addition to that, the general index values (*Q*) and the ranking of the options under consideration were calculated as well. The results are presented in Table 7.

Overall, it can be observed that the results obtained with the MSA improve the results of the SCA. In principle, by assigning equal importance to EI and EcI, the option of co-firing coal with 10 % of waste woody biomass results to be the preferable one, see Table 7. Generally, the options with a higher biomass share are preferred over other options for this specific case.

As part of the sensitivity analysis of the MSA, a wide range of values of weighting factors were investigated, see Table 8. By giving any advantage to the environmental criteria over the economic criteria, the ranking of option 4 resulted to be the preferable one, see Table 8. Similarly, when giving advantage to the economic criteria over the environmental criteria, option 4 still resulted to be the most preferable. This proved option 4 to be the most sustainable among all considered "biomass to power" scenarios in the case of the EPBiH power utility, based on this methodology.

Table 8 Sensitive analysis of the general index of sustainability for the options considered

Q Case	Option 1 U100	Option 2 U95B5	Option 3 U93B7	Option 4 U90B10
EI:EcI = 0.50:0.50	0.9880	0.9710	0.9653	0.9588
EI:EcI = 0.55:0.45	0.9880	0.9697	0.9636	0.9564
EI:EcI = 0.60:0.40	0.9889	0.9694	0.9629	0.9549
EI:EcI = 0.45:0.55	0.9861	0.9703	0.9651	0.9594
EI:EcI = 0.40:0.60	0.9851	0.9706	0.9659	0.9608
Ranking	4	3	2	1

Conclusions

In the last decade, significant progress was made in the utilization of biomass in coal-fired power plants. While many research studies were conducted to investigate the biomass co-firing phenomenon, like ash-related problems or emissions, far less attention was given to the investigation of sustainability of "biomass for power" solutions. In this work, a sustainability assessment of different biomass co-firing options is performed, with the aim of investigating and identifying the most preferable one from the point of sustainability. The assessment is performed for EPBiH, a typical conventional coal-based power utility operating in the region of South East Europe. Four different options were considered, based on different ratios of biomass for co-firing: 0 w%-reference case, and 5, 7 and 10 w% of biomass. The scenarios were assessed for existing coal-based power units of EPBiH. Environmental and economic criteria were considered, including a number of sustainability indicators calculated based on real measured inputs. The sustainability of the different biomass co-firing options was assessed by means of a multicriteria sustainability assessment and a single criteria analysis.

Table 7 Weighting factors, specific criteria vectors, general index and ranking of the options, Case $\sum w_i EI:\sum w_i EcI = 0.5:0.5$

SI	*wi*	Option 1—U100	Option 2—U95B5	Option 3—U93B7	Option 4—U90B10
EICO2	0.167	1.000	0.912	0.891	0.863
EISO2	0.167	0.989	1.000	0.990	0.977
EINOx	0.167	1.000	0.989	0.989	0.989
EcICAPEX	0.25	0.955	0.982	0.988	1.000
EcIOPEX	0.25	1.000	0.964	0.956	0.946
Q		0.9880	0.9710	0.9653	0.9588
Ranking		4	3	2	1

Based on the performed analyses, it was concluded that the CO_2 parameter proves to be a key sustainability indicator in the considered case, effecting the most decision making with regard to preference of options from the point of sustainability. Both single and multicriteria sustainability assessments confirmed the option of the highest biomass share to be the preferable one. The decisive influence of a lower CO_2 emission and a consequent lower CO_2 tax cost for options with a higher biomass share has fully compensated for the higher fuel costs associated to the somewhat higher price of biomass as compared to coal, for the considered time frame. Overall, the scenarios with a higher biomass share have proven to be more favourable from the point of sustainability in the case of the EPBiH power utility, based on this methodology.

The results demonstrate the additional merit of biomass co-firing for this specific case and its contribution to sustainability. The model presented in the paper can be applied to any power utility provided that the set of input data are available and reliable.

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