A Feasibility Study of Co-Firing Biomass in the Thermal Power Plant at Soma in order to Reduce Emissions: an Exergy Approach

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ABSTRACT: Biomass co-firing with lignite represents an attractive solution for operating lignite-fired thermal power plants (TPP) with the dual advantage of using local renewable resources and simultaneously reducing emissions. The subject of this study is technical and environmental investigation of the feasibility of the co-firing of Soma lignite with some dried agricultural residues in the Soma thermal power plant from the exergy analysis perspective, using THERMOFLEX simulation software. The use of biomass cofiring with poor quality coal could allow Turkey to comply with Kyoto commitments while benefiting from using indigenous fuel resources and reducing biomass waste disposal problems. Two technologies are considered; (1) direct co-firing, in which biomass is mixed with lignite in the same mill and fed into the boiler furnace and (2) parallel co-firing method, in which biomass is fired in a separate circulating fluidized bed boiler and produced steam is supplemented into the steam network of the power plant. The investigations reveal that both direct and parallel co-firing of the biomass could result in a significant decrease in fuel consumption, emissions and exergy destruction and a slight increase in the exergy efficiency of the Soma TPP. Olive waste, in particular, has a positive effect on general performance and emissions of the TPP, with fuel consumption, CO_2, SO_2 and dust emissions, in direct co-firing dropping by approximately 20, 4, 19 and 18 percent, respectively, and in parallel co-firing by 26, 3, 20 and 25 percent, respectively.

Key words: Biomass, Emissions reduction, Co-firing, Co-combustion, Exergy analysis

INTRODUCTION

Turkey has shown that it is serious about sustainable development by signing the Kyoto Protocol and taking EU energy-environmental policies into consideration in its legislation. However, the recent extremely high oil price rises and lack of security in energy supply have led Turkey to introduce legislation to maximize the utilization of low grade lignites, in which the country is relatively rich. Since the use of such low grade fuel in a conventional thermal power plant would cause some technical problems during combustion, as well as leading to increased emissions, consideration must be given to technologies which could allow the use of these lignites, but reduce the problems caused in standard combustion technology. Biomass co-firing is one technology, which can be employed immediately in nearly all coal-fired power plants in a relatively short period of time and without the need for huge investments, in order to reduce the environmental impact of electricity generation from lignite. Biomass co-firing offers the least cost option among the several technologies/options available for greenhouse gas reduction (Basu *et al.* 2011). Biomass is the term, used for all organic materials originating from all plant types, and is essentially the storage of the sun's energy through photosynthesis (Kim *et al.,* 2012; Frahadi *et al.,* 2011; Gomes *et al.,* 2011; Trogl and Benediktova, 2011; Khurram, 2011; Castro-Gutierrez *et al.,* 2012). Biomass can either be obtained directly from plants or indirectly from industrial, domestic, agricultural and animal wastes (Erdogdu, 2008; Lalevic *et al.,* 2012; Gousterova *et al.,* 2011; Ekmekyapar *et al.,* 2011; Moliterni *et al.,* 2012; Krika *et al.,* 2012). The benefits of co-firing for the electricity generation are obvious: low cost, low risk, short development time renewable energy, reduced airborne emissions, diversified fuel

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sources, use of otherwise landfilled residues, increased employment in local areas, and reduction in the externalities associated with fossil energy generation (Armesto *et al.,* 2003; Baxter, 2005). Generally, Biomass not only has a significant potential for emissions reduction and indigenous energy sources utilization but it also reveals a reasonable cost level in comparison to other renewable energies (Spliethoff and Hein 1998). There are some studies dealing with the technical and economic feasibility of the co-firing of biomass and lignite and its effect on the reduction of the environmental impact of the power plants (Gungor, 2010; McIlveen-Wright *et al.,* 2007; McIlveen-Wright *et al.* 2011; Huang *et al.,* 2006; Nieminen and Kivela, 1998; Nevalainen *et al.,* 2007; De and Assadi *et al.,* 2009). The results of these studies can be summarized as following:

a. Reduced total emissions of power plant
b. Decreased fuel consumption
c. In some cases increased boiler efficiency

However, co-firing of biomass has some disadvantages. The major problems associated with biomass co-firing can be listed as below (Baxter, 2005; Yamamoto , 2007; U. S. Environmental Protection Agency 2007):

a. Quality is not uniform and moisture (and ash) content can be high.
b. Availability varies in seasons.
c. Ash deposition on heat exchange and ash-handling surfaces
d. Chlorine in combustion gases, particularly at high temperatures, can cause accelerated corrosion of combustion system and flue gas cleanup components.

The implementation of the biomass co-firing in power plants can be achieved via three different technologies. These methods are; direct co-firing (co-combustion), indirect co-firing, and parallel co-firing (parallel co-combustion). In the direct method, biomass is fed to the boiler furnace with lignite through the same mill without installation of any new unit to the existing boiler. In this method, however, some equipment modification may be necessary if biomass/lignite ratio is higher than 10% (Huang *et al.,* 2006). One Indirect method is a combination of combustion and gasification. In this method, biomass is gasified in a gasifier and product fuel gas is sent to the furnace of the lignite-fired boiler to fire with lignite. This approach offers a high degree of fuel flexibility. Another indirect method is parallel combustion, in which the installation of a completely separate unit is required. Biomass is burnt in an external boiler and the produced steam added to the existing steam flow of the parent lignite-fired boiler. However, the selection of the appropriate co-firing option depends on a number of fuel and site specific factors (Basu *et al.,* 2011).

In this study extensive investigation has been carried out to date on the feasibility and performance of three different biomass fuels co-firing such as corn cobs, cotton gin and olive pit in Soma TPP. In this respect, two of the mentioned technologies, e.g. (direct) co-firing and (indirect) parallel co-firing are assessed. For each case, the general thermodynamic performance and total emissions are calculated using the standard First Law conservation of mass and energy analysis (mass and energy balances) and compared with each other. Exergy, however, is not conserved; it is consumed or destroyed by irreversibilities in any real process (Rosen and Dincer, 1999). For this reason an exergy analysis, which also considers the Second Law of Thermodynamics as well as the conservation of mass and energy, was carried out in order to evaluate the exergy efficiency and exergy destruction of the overall power plants and each of their components. The exergy analysis is useful for the analysis of energy systems since it can identify the location, type and true magnitude of wastes and losses (the exergy destruction) in the system (Rosen and Dincer, 1997). In this regard, first Soma TPP has been simulated in THERMOFLEX simulation software, and then modified for co-firing with different types of biomass indirect and parallel co-firing methods.

MATERIALS & METHODS

Fig.1. shows a schematic diagram of one unit of Soma TPP, demonstrating all of its relevant components. The continuous supply of water is ensured to the system for the normal running of the plant at 165 MW_{el} load condition. The low pressure condensate pump (Pump1) feeds the condensed water to the low pressure feed water pre-heaters (P.3-6). After pre-heater 3, the feed water enters into the deaerator. A high pressure feed pump (Pump2) just after the deaerator is provided to supply the condensate from the deaerator to the high pressure pre-heaters (P.1-2). Then the feed-water passes through the economizer and then it enters into the boiler drum. There is a continuous circulation of water between the drum and the water walls and a part of the feed water is converted into steam. The steam is separated in the boiler drum and supplied to the super-heater section and the boiler condenser section. The super-heated steam produced in the super-heater then enters into the turbine through the turbine stop valve. After expansion in the high-pressure turbine the exhaust steam is supplied into the re-heater in order to be super-heated again and then it enters the intermediate pressure turbine. And after final expansion in low-pressure turbine, the exhaust steam is condensed in the condenser. The steam extracted from the various points is also shown in the schematic diagram. The main operation conditions of Soma thermal power plant are summarized in Table 1.

Fig.1. Schematic diagram of the Soma thermal power plant (with direct co-firing)
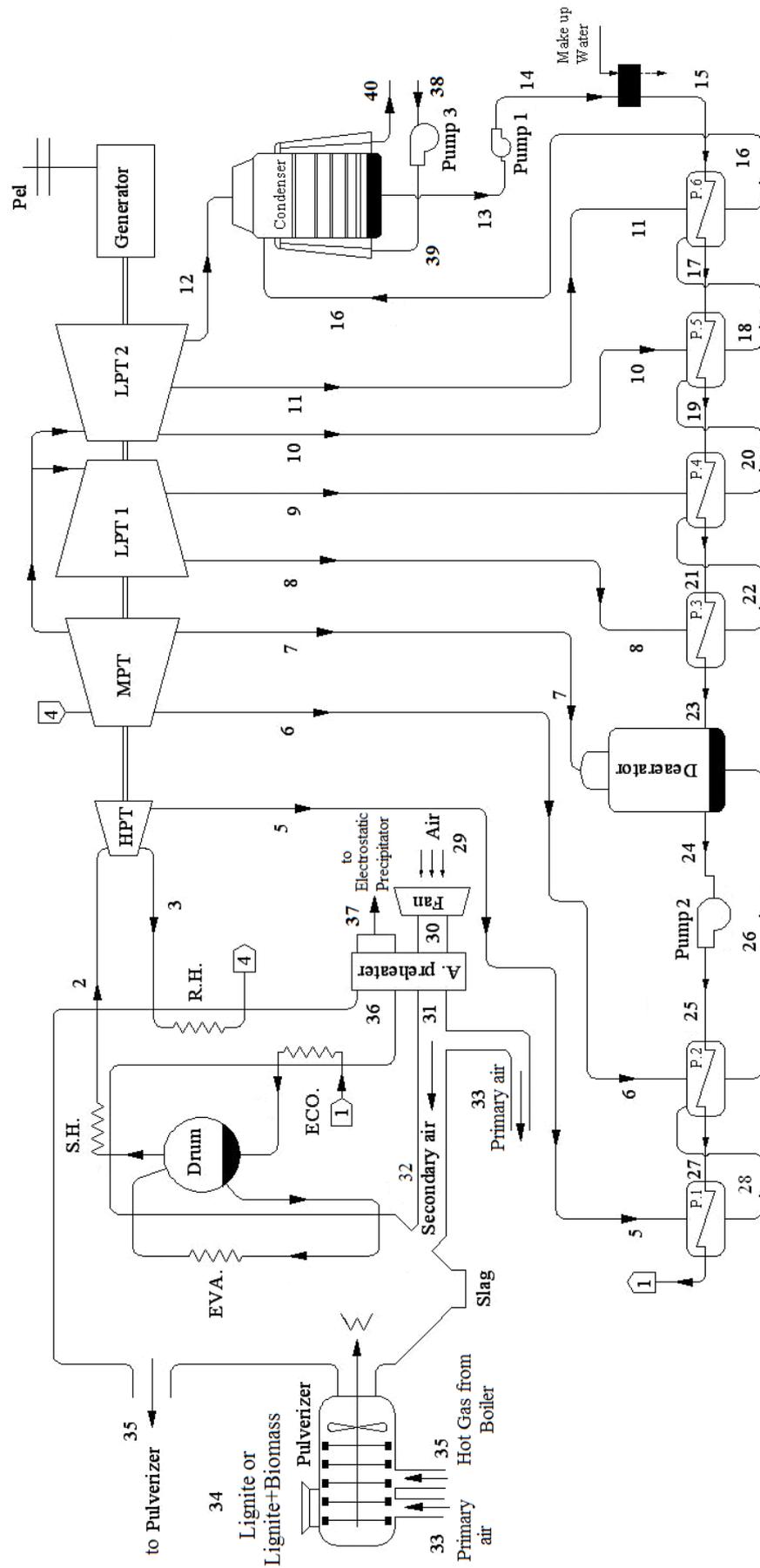
Table 1. The main operational data of the Soma TPP

| Characteristic	Unit	Value
Feed water Temperature	$^{\circ}$C	232
Steam temperature	$^{\circ}$C	540
Steam pressure	bar	140
Total evaporation rate	kg/s	145.8
Re-heat pressure	bar	30
Re-heat evaporation rate	kg/s	131.8
Condenser pressure	bar	0.08
Total net output power	MW	165
Total fuel consumption	kg/s	46.41
Net energy efficiency	%	35

RESULTS & DISCUSSION

The first option is direct co-firing of biomass and lignite in Soma power plant (Fig.1).For this purpose, the pre-processed and dried biomass is mixed with lignite just before the pulverizer. Then fuel mixture is injected into the fuel pulverizer, based on the required co-firing rate. Therefore there is no need to the separate special burners of biomass or any fundamental change in the conventional fuel delivery system.

This method has several effects on power plant emissions. Positive effects are that SO_X and NO_X emissions usually decrease due to the lower sulphur and nitrogen content in biomass than in lignite. Furthermore, alkali components in biomass ash can have a positive effect on SO_X removal. Since biomass has a high volatile content, it can also be used as re-burn fuel for NO_X reduction from the lignite combustion, which gives a further potential for significant decrease of the NO_X emissions (Nussbaumer, 2003). Negative effects of co-firing are higher operating and maintenance costs due to increased fouling and corrosion, and a possible decrease of the electric efficiency (if the superheater temperature has to be decreased due to high temperature corrosion). Moreover, different combustion characteristics of lignite and biomass may affect the stability and heat transfer characteristics of the flame (De and Assadi *et al.* 2009). Besides, the ash quality can be negatively influenced mainly by alkali metals and chlorine contained in biomass, and depending on which biomass is used, ash melting temperatures may be lowered, resulting in the potential for more slagging. However, the amount of lignite used will be reduced when cofiring is employed, which reduces the amount of ash in the bed. Furthermore, the content of un-burnt carbon can increase (Nussbaumer, 2003). Thus, direct co-firing option is applicable to a limited range of biomass types and at very low biomass-to-lignite co-firing ratios. Usually a biomass input in the range of 5% to 10% according to the energy input is acceptable without major influence on the residues (Nussbaumer, 2003).

Parallel co-firing is the second option, in which the biomass is combusted in a separate boiler. Parallel combustion enables a complete separation of the ashes and flue gases from different fuels. Hence, no disadvantages or limitations result from undesired alkali metals or contaminants in the ash. Further, the combustion gas cleaning equipment can be optimized for each fuel (Nussbaumer, 2003). Furthermore, combustion gas of the separate boiler releases at relatively high temperature and joins the existing flow stream of the parent lignite-fired boiler after air pre-heater. Therefore, the combustion gas from the biomass firing unit does not come in contact with any heating elements of the existing boiler, thus avoiding the biomass related fouling or corrosion problem, which is the largest concern of biomass cofiring (Basu *et al.* 2011).To investigate parallel co-firing, the simulated thermal power plant is modified and a separate circulating fluidized bed (CFB) boiler is modeled and added to the main power plant. Biomass is fired in the CFB and produced steam is supplemented into the main steam network of the power plant. Fig.2 demonstrates the schematic diagram of the simulated system.

Fuel properties have great effect on the technical and environmental performance of the power plants; therefore, the relevant details of the used lignite and biomasses are given in Table 2. In the Soma thermal power plant, low grade Soma lignite is used as the base fuel. This lignite type has a quite low calorific value of 13452 kJ/kg (lower heating value, LHV), because of its high ash and moisture. Using biomass with a higher LHV can not only reduce the environmental impact of the power plant, but also increase its net electric efficiency. In this regard, for co-firing with lignite, the following biomass types have been chosen; cotton gin, corn cobs and olive pit with lower heating values (LHV) of 15,600, 17,350 and 18,800 kJ/kg, respectively.

Fig. 2. Schematic diagram of the Soma thermal power plant with parallel co-firing
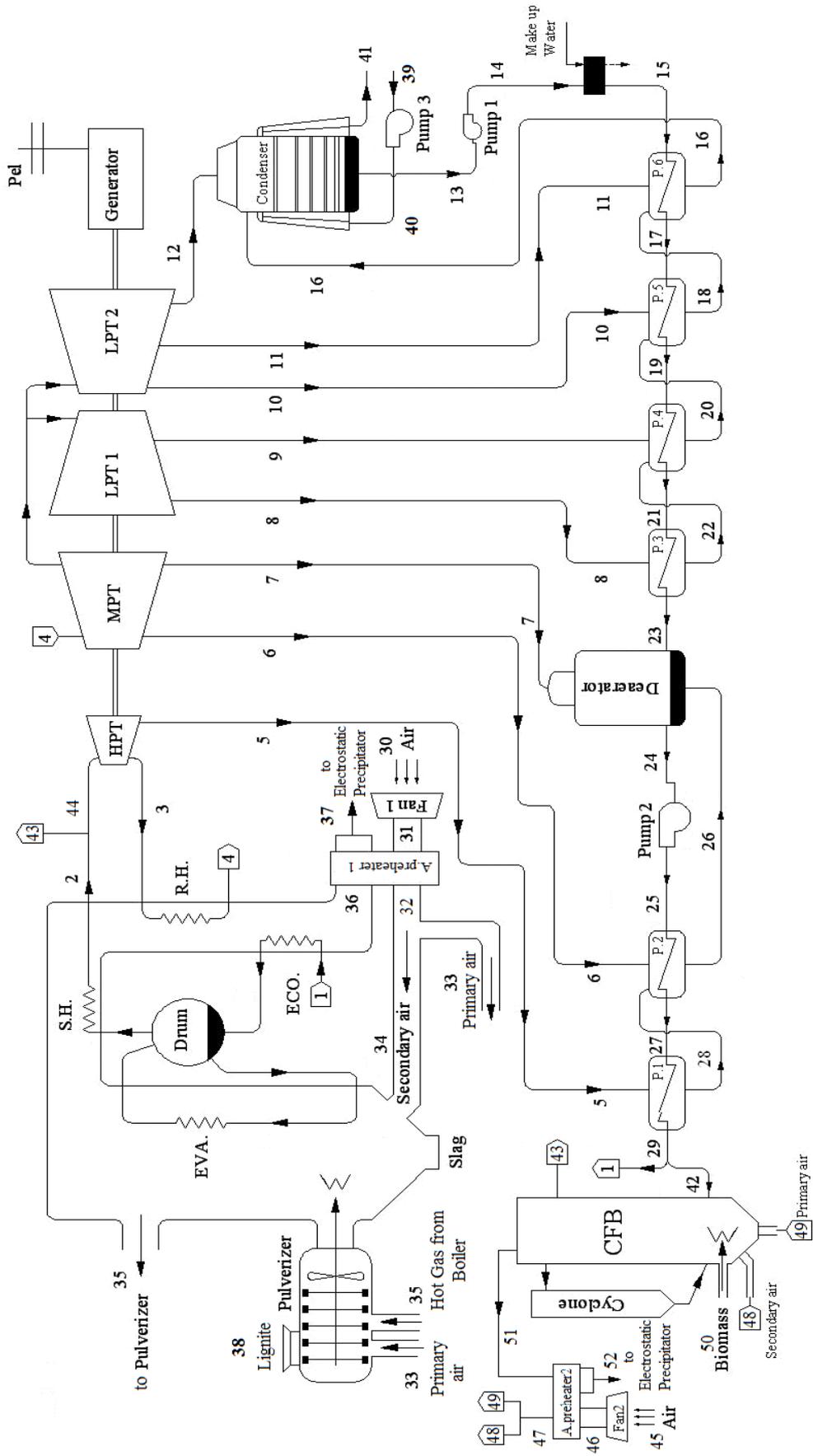
Table 2. Chemical analysis (proximate and ultimate) of Soma lignite and selected biomasses

Fuel	Soma lignite	Corn cobs[1]	Cotton gin[1]	Olive pit[2]
Moisture	27	15	11.5	6.1
Ash	41	1.4	14.5	1.6
Volatiles	20	76.6	-	77
Fixed carbon	12	7	-	15.3
C	27.5	48.4	42.8	54.7
H	1.8	5.6	5.4	7.3
O	0.7	44.3	35	36
N	0.5	0.3	1.4	0.4
S	1.5	-	0.5	0.05
LHV[kJ/kg]	13452	17350	15600	18800

Source 1: Balat, 2006
Source 2: Thermoflex (2011).

The exergy of a system is defined as the maximum available work that can be done by the system-environment combination. A higher value of exergy means a higher value of obtainable work. The exergy analysis is the composite of the first and second laws of thermodynamics.

In this analysis, heat does not have the same value as work, and exergy loss represents real loss of work. When analyzing novel and complex thermal systems, experience needs to be supplemented by more rigorous quantitative analytical tools. Exergy analysis provides these tools and helps in locating weak spots in a process. This analysis provides a quantitative measure of the quality of the energy in terms of its ability to perform work and leads to a more rational use of energy (Oktay, 2009). For a real process, the exergy input always exceeds the exergy output; this imbalance is due to irreversibilities, which are known as exergy destruction (Dinçer and Muslim, 2001; Dinçer and Muslim, 2001).

The general form of the exergy equation for the system at steady state conditions is given in Eq.1 (Bejan et al.1996; Bejan, 1988).

$$0 = \sum_j \left(1 - \frac{T_0}{T_i}\right) \dot{Q}_j - \left(\dot{W}_{cv}\right) + \sum_i \dot{m}_i e_i - \sum_e \dot{m}_e e_e - \dot{E}_D \tag{1}$$

Rearranging Eq.3 gives the exergy destruction of a steady state open system for a control volume;

$$\dot{E}_D = \sum_j \dot{E}_{qj} \dot{Q}_j - \left(\dot{W}_{cv}\right) + \sum_i \dot{E}_i - \sum_e \dot{E}_e \tag{2}$$

It must be noted that, in this study, the exergy destructions caused by the heat losses from the components are neglected, since it has been assumed that the boundary temperature of each component, due to ideal insulation, (T_j) is equal to the ambient temperature (T_0). Therefore;

$$\dot{E}_D = -\left(\dot{W}_{cv}\right) + \sum_i \dot{E}_i - \sum_e \dot{E}_e \tag{3}$$

In the absence of nuclear, magnetic, electrical, and surface tension effects, the total exergy of a system $\dot{E}$ can be divided into four components;

$$\dot{E} = \dot{E}_{PH} + \dot{E}_{CH} + \dot{E}_{PT} + \dot{E}_{KN} \tag{4}$$

By neglecting potential and kinetic energy Eq.4 can be rewritten as indicated in Eq.5;

$$\dot{E} = \dot{E}_{PH} + \dot{E}_{CH} \tag{5}$$

The specific physical exergy (e_{PH}) can be expressed as follows, where subscript "0" indicates reference conditions;

$$e_{PH} = h - h_0 - T_0(s - s_0) \tag{6}$$

The total exergy rate ($\dot{E}$) can be written as a function of mass flow rate ($\dot{m}$) and specific physical and chemical exergies and is given as follow:

$$\dot{E} = \dot{m}[h - h_0 - T_0(s - s_0) + \bar{e}_{CH}] \tag{7}$$

The molar specific chemical exergy ($\bar{e}_{CH}$) of a substance can be obtained from standard chemical exergy tables (Bejan *et al.*,1996; Bejan, 1988; Kotas, 1985) relative to specification of the environment. For

mixtures containing gases other than those present in the reference tables, molar chemical exergy can be evaluated with the following equation (Bejan et al.1996).

$$\overline{e}_{CH} = \Sigma\, x_n\, (\overline{e}_{CH})_n + \overline{R}T_0 \Sigma\, x_n \ln x_n \qquad (8)$$

In Eq. 8, x_n is the mol fraction of the k_{th} gas in the mixture and $\overline{R}$ is the universal gas constant. Procedure for the determination of the chemical exergy based on stoichiometric combustion of coal has been developed by Bejan (Bejan *et al.,*1996). In this study, for the calculation of the specific chemical exergy of Soma lignite and different types of biomass, the same method was utilized. In this study, the atmospheric temperature and pressure are taken as reference conditions, 25ºC and 101.32 kPa, respectively.

Another parameter in the exergy analysis of a system is the exergy efficiency, which is the percentage of the exergy of the product (desired output) over the fuel exergy provided to a system. Here, fuel exergy in general is defined as the entire resources supplied to the system (e.g., fuel, air, water and etc). Considering this fact, the desired outcome and the given resource of the different components of the power plant can have different definitions. However, second law energy efficiency (exergy efficiency) ε, can be expressed as;

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} \qquad (9)$$

Further expressions and efficiencies of exergy of each component of the investigated power plant are summarized in Appendix 1.

The two processes, direct and parallel co-firing of biomass with lignite were successfully simulated using Thermoflex. Both processes were investigated using three types of biomass (corn cobs, cotton gin and olive pits) to simulate the Soma TPP, which is based on ''real'' data for the power plant, as described in Section 3.

As it can be seen from Fig.3, both direct and parallel co-firing of biomass can cause a noticeable decrease in lignite consumption of the power plant. Since, in the parallel method, combustion of the biomass occurs in a separate boiler, the flue gas from biomass combustion, which can contain highly corrosive elements, does not come into contact with any component of the existing TPP, therefore, in this method, a higher ratio of biomass/lignite can be utilized in compare with direct method. Thus, in the parallel method, the lignite consumption of the power plant decreases by approximately 45 ton/h, whereas in the direct method, just half of this amount can be realised.

The biomass consumption differs for each co-firing method. Fig.4 shows the biomass consumption rate of the power plant in each case. For the direct method, about the same amount, circa 14 ton/h, is required for co-firing all types of biomass. On the other hand, the biomass requirement for the external circulating fluidized bed (CFB) boiler co-firing varies with the type of biomass, with cotton gin the highest at around 34 t/h. Corn cobs and olive pits follow it with 24 and 22 ton/h, respectively.

The effect of co-firing biomass and lignite by direct and indirect (parallel combustion) methods on the CO_2 emissions are displayed in Fig. 5. Since all biomass types used in this study have a significantly
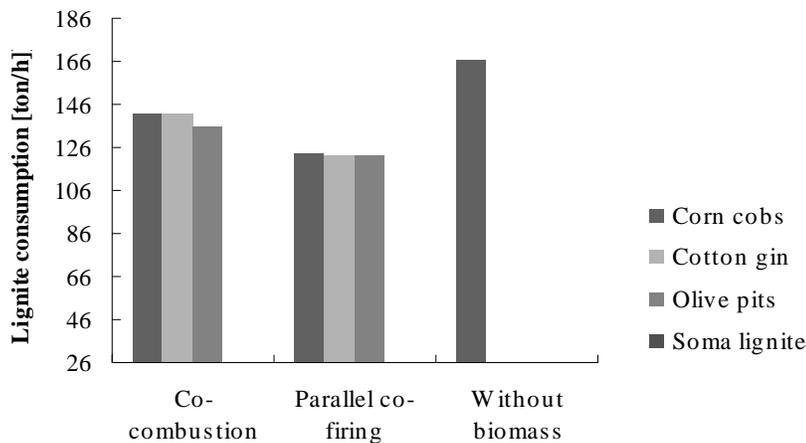

Fig. 3. A comparison of the lignite consumption rate of the power plants with direct and parallel co-firing and without co-firing
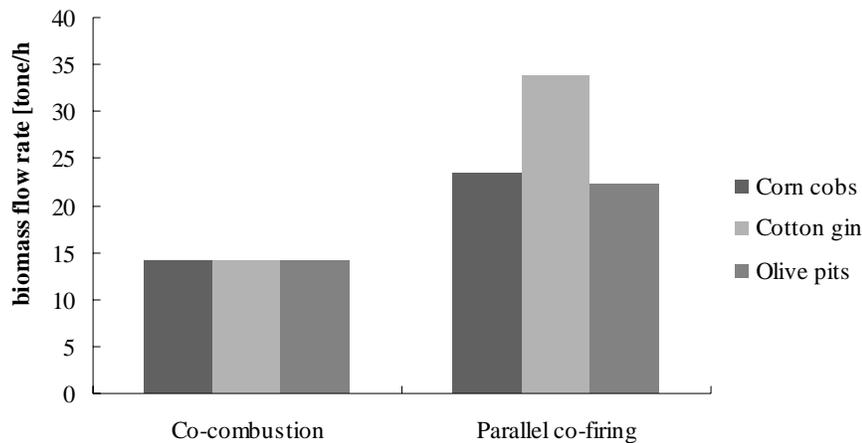
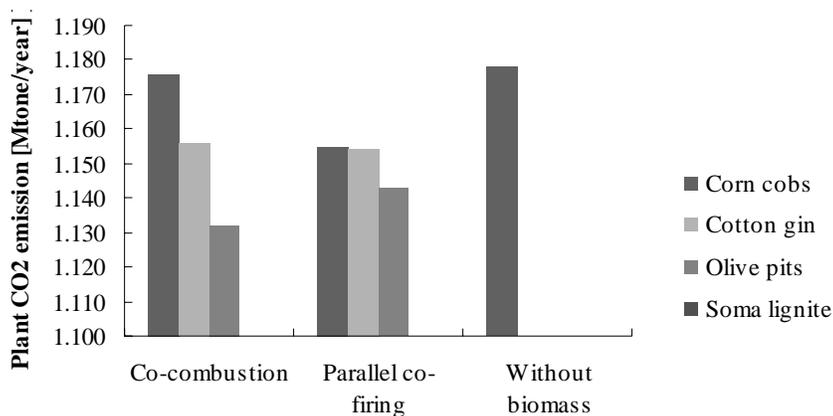Fig. 4. A comparison of the biomass consumption rate of the power plants with direct and parallel co-firing

Fig. 5. A comparison of the total CO_2 emissions of the power plants with direct and parallel co-firing and without co-firing

higher LHV than Soma lignite, therefore, adding them could cause a reduction in the fuel consumption of the power plant, and consequently, a significant decrease in the gross CO_2 emissions of the system. This reduction in the parallel co-combustion method is almost the same for all three types of biomasses, but in the direct method, their effects vary. Feeding olive pits into the furnace of the Soma TPP has the highest effect on the gross CO_2 emission of the power plant with approximately 46,000 ton/year reduction, and cotton gin follows it with 22,000 ton/year. while corn cobs produce the minimum effect with only 2,000 ton/year gross CO_2 emissions reduction for the power plant. Nevertheless it can be seen that, indirect co-firing has a better effect on the reducing the emissions of the Soma TPP. However, if the net CO_2 emissions to the environment were calculated, i.e. assuming that the biomass is considered to be CO_2 neutral due to its CO_2 absorption from the atmosphere during growth or re-growth, then the co-firing processes could demonstrate a much lower level of CO_2 emissions (Huang *et al.,* 2006).

Since biomass generally contains considerably less sulphur than lignite, by adding of the biomass in the power plant fuel, the net SO_2 emissions of the power plant are reduced significantly. Also, the calcium content in biomass, in general, promotes SO_x capture (Huang *et al.,* 2006). Moreover, in parallel co-firing, since the biomass co-firing occurs in an external CFB boiler, the possibility of the further reduction of SO_2 emissions originating from biomass can also be considered by using SO_2 sorbents. Fig. 6 displays the comparison of the SO_2 emission of modified Soma TPP with regard to changes in the co-firing methods. As shown in this figure for both technologies, all types have almost the same effect, the average rate of the SO_2 emission reduction in parallel co-firing is approximately 10,000 ton/year while in co-combustion it is almost half of this amount.

Fig. 7 displays the effect of co-firing of biomass on the total dust emission of Soma TPP for direct and parallel co-firing methods. Considering the fact that, the dust emission is highly dependent on the ash
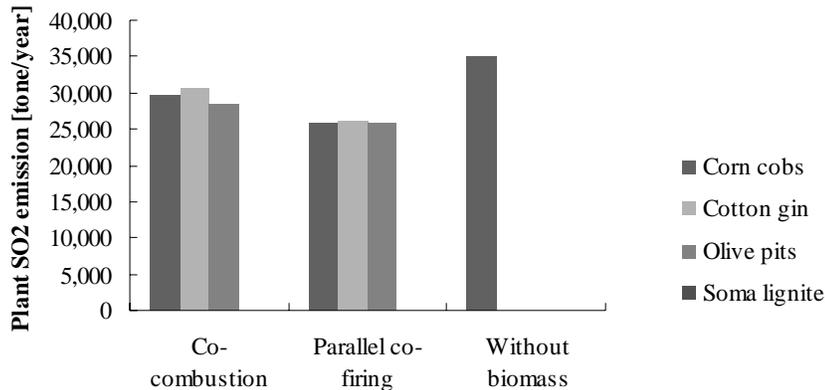
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Fig. 6. A comparison of the total SO$_2$ emissions of the power plants with direct and parallel co-firing and without co-firing
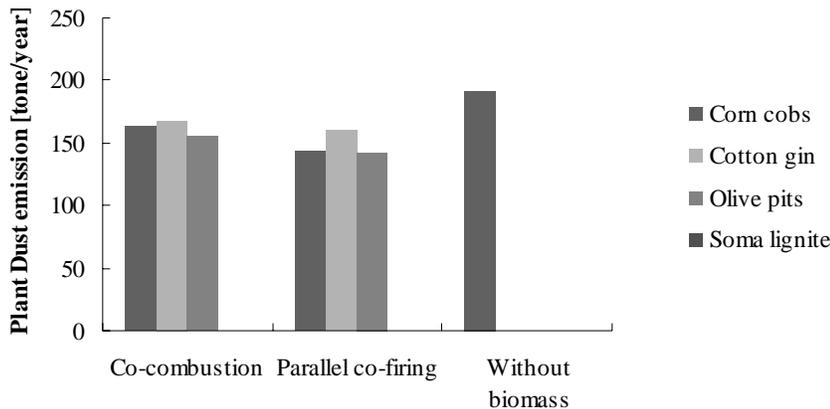

Fig.7. A comparison of the total dust emission of the power plants with direct and parallel co-firing and without co-firing

content of the fuel, and because the ash content of the all three biomass types used in this study are remarkably lower than Soma lignite (Table 3), adding biomasses reduces the dust emissions of the power plant in both cases. Similar to the other emissions, dust reduction is higher in parallel co-firing compared to the direct co-firing. Parallel co-firing of the corn cobs and olive pits with circa 49 ton/year can be chosen as the best biomass for decreasing the dust emission of the power plant.

Fig. 8 depicts the effect of the co-firing of biomass with lignite on the exergy destruction of Soma TPP. It shows that, for all biomass types apart from cotton gin, co-firing causes a slight drop in exergy destruction for both direct and parallel method, compared with the ''lignite only'' case. The major reason for exergy destruction increase of parallel co-firing of cotton gin may be its lower calorific value and higher ash content in contrast with other biomass types (Table 3), which

can directly effects CFB performance. This also causes a remarkable rise in biomass consumption rate as displayed in Fig.4.

The effect of the co-firing on exergy efficiency (second law) of Soma TPP is clearly shown in Fig. 9. Direct co-firing of corn cobs and cotton gin increase the exergy efficiency of the power plant by 0.19 and 0.47%, respectively and olive pits reduces it by 0.36%. On the other hand, the parallel co-firing effect on exergy efficiency is quite different. Olive pits and corn cobs increase the efficiency by 0.9% and 1.2 % respectively, while cotton gin reduces the second law efficiency by 0.58%. Likewise for the exergy destruction, the lower calorific value and higher ash content of cotton gin can be considered as the main reason for the exergy efficiency reduction of the power plant.

Exergy destruction is a function of entropy generation. Entropy is a measure of the 'randomness' of a system. A process with less exergy destruction

Table 3. Thermodynamic properties, physical, chemical and total exergy of each stream

| point	state	T (°C)	P (kpa)	m (kg/s)	h (kJ/kg)	s (kJ/kg K)	E^{PH} (MW)	E^{CH} (MW)	E^{Tot} (MW)
1	Water	232.0	14488.0	100.2	999.07	2.6273	22.08	17.35	39.44
2	Steam	540.0	13925.0	100.0	3432.60	6.5324	148.96	17.32	166.28
3	Steam	314.0	3131.0	131.7	3023.83	6.5724	140.78	22.81	163.59
4	Steam	540.0	3100.0	131.7	3546.00	7.3285	179.86	22.81	202.67
5	Steam	314.0	3131.0	14.1	3023.83	6.5724	15.03	2.44	17.46
6	Steam	426.6	1400.0	4.1	3315.18	7.3825	4.60	0.71	5.31
7	Steam	324.8	650.0	8.0	3112.18	7.4242	7.21	1.38	8.59
8	steam	235.4	300.0	4.6	2937.84	7.4568	3.33	0.80	4.14
9	Steam	145.1	120.0	4.4	2765.00	7.5219	2.31	0.76	3.06
10	Steam	87.0	60.0	4.5	2655.56	7.5398	1.86	0.78	2.64
11	Steam/Water	67.5	28.0	3.6	2549.31	7.5774	1.06	0.62	1.69
12	Steam/Water	41.5	8.0	102.5	2396.18	7.6544	12.16	17.75	29.92
13	Water	39.5	106.1	119.6	165.52	0.5667	0.14	20.713	20.858
14	Water	39.7	1144.4	119.6	166.19	0.5665	0.23	20.713	20.945
15	Water	39.6	1144.4	120.0	165.98	0.5674	0.18	20.78	20.96
16	Water	67.5	28.0	17.1	282.61	0.9245	0.20	2.96	3.16
17	Water	58.0	1094.4	120.0	242.77	0.8059	0.86	20.78	21.64
18	Water	85.9	60.0	13.5	360.10	1.1451	0.32	2.34	2.66
19	Water	80.0	1044.4	120.0	334.91	1.0753	2.28	20.78	23.06
20	Water	104.8	120.0	9.0	439.30	1.3607	0.34	1.56	1.91
21	Water	101.0	994.4	120.0	423.00	1.3181	4.16	20.78	24.94
22	Water	126.0	239.5	4.6	529.30	1.5919	0.28	0.80	1.08
23	Water	123.0	944.4	120.0	516.47	1.5599	6.72	20.78	27.51
24	Water	162.0	944.4	146.2	684.24	1.9640	15.11	25.32	40.43
25	Water	165.5	14629.0	146.2	699.62	1.9810	16.61	25.32	41.93
26	Water	170.5	1400.0	18.2	721.51	2.0471	2.10	3.15	5.25
27	Water	187.0	14588.0	146.2	793.00	2.2073	20.40	25.32	45.72
28	Water	217.8	3131.0	14.1	933.50	2.4975	2.72	2.44	5.16
29	Water	232.0	144.9	146.2	999.54	2.6283	32.25	25.32	57.57
30	Air	25.0	99.4	165.7	0.00	0.0000	0.00	0.00	0.00
31	Air	30.6	104.8	165.7	-159.74	6.9634	0.76	0.00	0.76
32	Air	206.3	104.0	150.6	21.44	7.4357	6.77	0.00	6.77
33	Air	206.3	104.0	55.8	21.44	7.4357	2.51	0.00	2.51
34	Air	206.3	104.0	94.8	21.44	7.4356	4.27	0.00	4.27
35	Comb[1]. Gas	1176.7	101.7	3.9	-1696.79	8.9305	3.36	0.49	3.85
36	Comb. Gas	237.0	101.0	170.7	-2894.37	7.6207	9.92	21.34	31.26
37	Comb. Gas	95.8	100.2	170.7	-2813.83	7.2609	1.18	19.14	20.42
38	Lignite	25.0	200.0	34.1	0.00	0.0000	0.00	431.18	431.18
39	Water	25.0	99.4	5512.8	104.97	0.3687	-1.70	954.76	953.06
40	Water	25.2	1510.0	5512.8	105.84	0.3681	4.09	954.76	958.84
41	Water	35.3	1500.0	5512.8	147.72	0.5087	3.87	954.76	958.62
42	Water	232.0	14205.0	45.9	999.59	2.6283	10.13	7.95	18.08
43	Water	519.1	13925.0	45.8	3332.26	6.4066	65.35	7.93	73.28
44	Water	533.4	13925.0	145.8	3400.00	6.4923	214.19	25.25	239.44
45	Air	25.0	99.4	50.8	0.00	0.0000	0.00	0.00	0.00
46	Air	37.0	111.2	50.8	-153.19	6.9673	0.5079	0.00	0.5079
47	Air	206.3	110.4	46.2	21.45	7.4183	2.32	0.00	2.32
48	Air	206.3	110.4	18.5	21.45	7.4183	0.93	0.00	0.93
49	Air	206.3	110.4	27.7	21.45	7.4183	1.39	0.00	1.39
50	Biomass	100.0	101.5	6.2	0.00	0.0000	0.00	136.10	136.10
51	Comb. Gas	237.0	101.0	52.2	-2783.40	7.5631	3.01	4.98	7.99
52	Comb. Gas	92.6	100.2	52.2	-2713.21	7.2005	0.32	4.45	4.8

([1]Comb.; combustion)
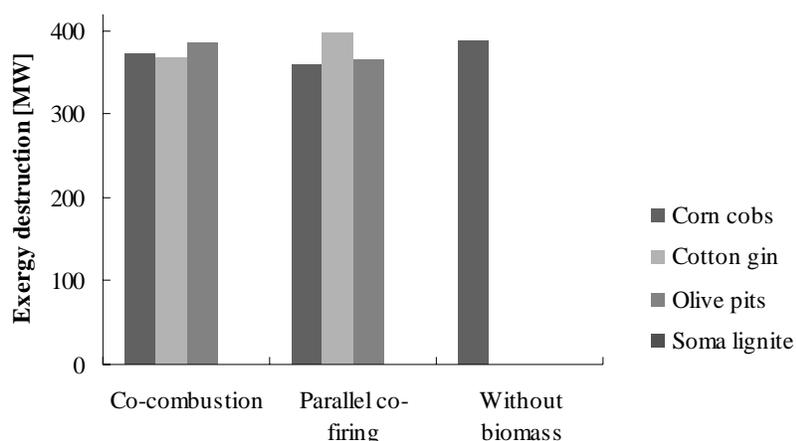
Fig. 8. A comparison of the exergy destruction of the power plants with direct and parallel co-firing and without co-firing
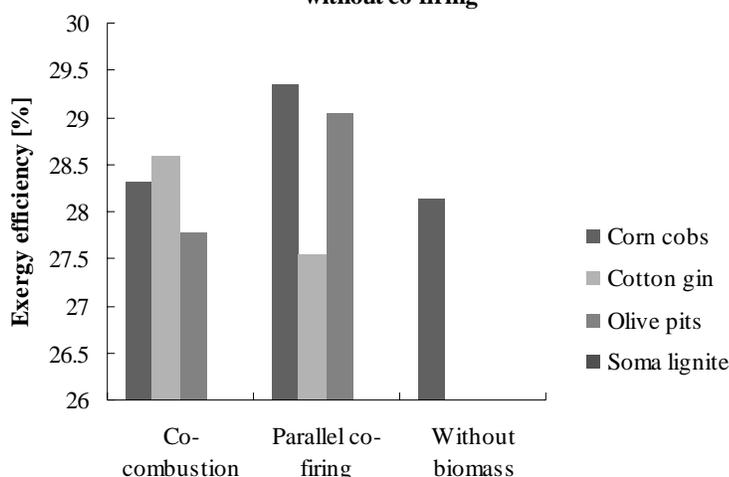

Fig. 9. A comparison of the exergy efficiency of the power plants with direct and parallel co-firing and without co-firing

has a higher potential to produce work. Exergy analysis helps system designers to locate the exact areas that have the highest entropy production. Therefore, designers will be able to focus on those key areas in order to be able to decrease the entropy generation, and to lower impact on the system surroundings and the environment (Regulagadda, 2010). The thermodynamic properties of each stream of the power plant with parallel co-firing of olive pits are presented in Table 3. Moreover, the physical, chemical and total exergy rates of air, lignite, biomass, combustion gases, steam and water at various points are also computed via the equations given in section 5, and summarized in the same table. The chemical exergy of air is assumed to be zero. Since the air composition at these points resembles the reference environment (Bejan *et al.,* 1996). In addition the physical exergy of lignite and biomass are ignored due to negligible changes in their entropies. Some

operational data and power consumptions of auxiliary devices of Soma power plant with parallel co-firing of olive pits are given in Table 4.

Table 4. Some operational data and power consumption of auxiliary devices of the TPP

Component	W [MW]
W_{Net}	164.75
$W_{S.T}$	164.75
$W_{Pulverizer}$	3.95
$W_{Fan\ 1}$	1.22
$W_{Fan\ 2}$	0.65
$W_{Pump\ 1}$	0.21
$W_{Pump\ 2}$	3.60
$W_{Pump\ 3}$	12.70
$W_{C.F.B}$	0.05
Net energy efficiency	35.91 [%]

Table 5. Exergy destruction data and exergy efficiencies of each component of the TPP

Component	exergy destruction[MW]	percent exergy destruction[%]	percent exergy efficiency[%]
Air fan 1	0.46	0.13	62.18
Air pre-heater	4.83	1.32	55.46
Boiler	244.73	66.89	40.40
Steam turbine	12.83	3.51	93.76
Condenser	12.44	3.40	98.75
Preheater 6	0.50	0.14	57.85
Preheater 5	0.47	0.13	75.20
Preheater 4	0.35	0.10	84.28
Preheater 3	0.49	0.13	83.86
Deaerator	0.93	0.25	97.76
Preheater 2	1.42	0.39	72.68
Preheater 1	0.46	0.13	96.24
Pump 1	0.12	0.03	41.55
Pump 2	2.09	0.57	41.88
Pump 3	6.92	1.89	45.53
Air fan 2	0.149	0.04	77.30
Air pre-heater 2	1.38	0.38	56.75
Boiler (CFB)	75.27	20.58	42.31
Overall plant	365.85	100.00	29.04

Table 5 provides a list of the exergy destruction and exergy efficiency data for various components of the power plant. As it is obvious from the table, the largest exergy destruction occurs in both boilers. The exergy destruction in the main boiler and CFB boiler are calculated to be 66.89 and 20.58 % of the total exergy destruction, respectively. Irreversibilities associated with heat transfer to the working fluid and chemical reactions could be considered as the main sources of the exergy destruction in these components. Boilers typically have low exergy efficiencies and high energy efficiencies, which implies that a large percentage of the energy from the fuel entering a boiler would be transferred, but the quality of the energy is significantly degraded during the transfer (Rosen, 1987). The other prominent component in exergy destruction is the steam turbine, which contributes 3.51% of the total exergy destruction. In spite of the First Law analysis indicating that the greatest energy loss occurs at the condenser, the exergy analysis of this plant shows that only 3.40 % of the total exergy is lost in the condenser; which is even less than the turbine. The total exergy destruction of the power plant is 365.85 MW, and the exergy efficiency of the overall power plant is 29.04 %. The net electric efficiency of the simulated cycle, given in Table 4 (35.91 %), is higher than the exergy efficiency of the power plant. As a result, in order to improve the performance of the power plant, efforts should be directed at improving the boiler performance.

CONCLUSION

Large scale biomass co-firing can be considered as one of the most efficient and cost effective approaches to conserving fossil fuel resources and reducing net CO2 emissions. In this study, with regard to the fact that lignite co-firing with biomass in existing power plant can be considered as the best alternative for voluntary reduction of emissions, a technical and environmental feasibility of the direct and parallel co-firing of Soma lignite with some dried biomass in Soma TPP, from an exergy analysis perspective is investigated. The important conclusions drawn from this study can be summarized as follow:

• Both direct and parallel co-firing of the biomass could cause a remarkable decrease in fuel consumption, emissions and exergy destruction and a slight increase in the exergy efficiency of the Soma TPP.

• Using olive pits, in both co-firing configurations, had the best effect on the power plant performance in comparison with other biomass types. Lignite consumption, CO_2, SO_2 and dust emissions, in the direct cofiring option drop by approximately 20, 4, 19 and 18 %, respectively and in the indirect parallel cofiring option by 26, 3, 20 and 25 %, respectively.

• Simulation results indicate that parallel co-firing can offer a better technical and environmental performance than direct co-firing, which also could

Appendix1. Exergy formulas of each component

Component	$\sum \dot{E}_{in}$	$\sum \dot{E}_{out}$	$\dot{W}$	$\dot{E}_D$	$\eta_{II} = \dfrac{\dot{E}_P}{\dot{E}_F}$
Air fan 1	$\dot{E}_{30}$	$\dot{E}_{31}$	$-\dot{W}_{Fanl}$	$\dot{E}_{30} - \dot{E}_{31} + \dot{W}_{Fanl}$	$\dfrac{\dot{E}_{31} - \dot{E}_{30}}{\dot{W}_{Fanl}}$
Air preheater 2	$\dot{E}_{31} + \dot{E}_{36}$	$\dot{E}_{37} + \dot{E}_{32}$	-	$\dot{E}_{31} + \dot{E}_{36} - \dot{E}_{32} - \dot{E}_{37}$	$\dfrac{\dot{E}_{32} - \dot{E}_{31}}{\dot{E}_{36} - \dot{E}_{37}}$
Boiler	$\dot{E}_1 + \dot{E}_3 + \dot{E}_{33} + \dot{E}_{34} + \dot{E}_{38}$	$\dot{E}_2 + \dot{E}_4 + \dot{E}_{36}$	$-\dot{W}_{Plvrzr}$	$\dot{E}_1 + \dot{E}_3 + \dot{E}_{33} + \dot{E}_{34} + \dot{E}_{38} - \dot{E}_2 - \dot{E}_4 - \dot{E}_{36} + \dot{W}_{Plvrzr}$	$\dfrac{\dot{E}_2 - \dot{E}_1 + \dot{E}_4 - \dot{E}_3}{\dot{E}_{33} + \dot{E}_{34} + \dot{E}_{38} - \dot{E}_{36} + \dot{W}_{Plvrzr}}$
Steam turbine	$\dot{E}_2 + \dot{E}_4$	$\dot{E}_3 + \dot{E}_5 + \dot{E}_6 + \dot{E}_7 + \dot{E}_8 + \dot{E}_9 + \dot{E}_{10} + \dot{E}_{11} + \dot{E}_{12}$	$\dot{W}_{S.T}$	$-\dot{W}_{ST} + \dot{E}_2 + \dot{E}_4 - \dot{E}_3 - \dot{E}_5 - \dot{E}_6 - \dot{E}_7 - \dot{E}_8 - \dot{E}_9 - \dot{E}_{10} - \dot{E}_{11} - \dot{E}_{12}$	$\dfrac{\dot{W}_{ST}}{\dot{E}_2 + \dot{E}_4 - \dot{E}_3 - \dot{E}_5 - \dot{E}_6 - \dot{E}_7 - \dot{E}_8 - \dot{E}_9 - \dot{E}_{10} - \dot{E}_{11} - \dot{E}_{12}}$
Condenser	$\dot{E}_{12} + \dot{E}_{16} + \dot{E}_{40}$	$\dot{E}_{13} + \dot{E}_{41}$	-	$\dot{E}_{12} + \dot{E}_{16} + \dot{E}_{40} - \dot{E}_{13} - \dot{E}_{41}$	$\dfrac{\dot{E}_{13} + \dot{E}_{41}}{\dot{E}_{12} + \dot{E}_{16} + \dot{E}_{40}}$
Preheater 6	$\dot{E}_{11} + \dot{E}_{15} + \dot{E}_{18}$	$\dot{E}_{16} + \dot{E}_{17}$	-	$\dot{E}_{11} + \dot{E}_{15} + \dot{E}_{18} - \dot{E}_{16} - \dot{E}_{17}$	$\dfrac{\dot{E}_{17} - \dot{E}_{15}}{\dot{E}_{11} + \dot{E}_{18} - \dot{E}_{16}}$
Preheater 5	$\dot{E}_{10} + \dot{E}_{17} + \dot{E}_{20}$	$\dot{E}_{18} + \dot{E}_{19}$	-	$\dot{E}_{10} + \dot{E}_{17} + \dot{E}_{20} - \dot{E}_{18} - \dot{E}_{19}$	$\dfrac{\dot{E}_{19} - \dot{E}_{17}}{\dot{E}_{10} + \dot{E}_{20} - \dot{E}_{18}}$

	Fuel	Product	Work	Exergy balance	Efficiency
Preheater 4	$\dot{E}_9 + \dot{E}_{19} + \dot{E}_{22}$	$\dot{E}_{20} + \dot{E}_{21}$	-	$\dot{E}_9 + \dot{E}_{19} + \dot{E}_{22} - \dot{E}_{20} - \dot{E}_{21}$	$\dfrac{\dot{E}_{21} - \dot{E}_{19}}{\dot{E}_9 + \dot{E}_{22} - \dot{E}_{20}}$
Preheater 3	$\dot{E}_8 + \dot{E}_{21}$	$\dot{E}_{22} + \dot{E}_{23}$	-	$\dot{E}_8 + \dot{E}_{21} - \dot{E}_{22} - \dot{E}_{23}$	$\dfrac{\dot{E}_{23} - \dot{E}_{21}}{\dot{E}_8 - \dot{E}_{22}}$
Deaerator	$\dot{E}_7 + \dot{E}_{23} + \dot{E}_{26}$	$\dot{E}_{24}$	-	$\dot{E}_7 + \dot{E}_{23} + \dot{E}_{26} - \dot{E}_{24}$	$\dfrac{\dot{E}_{24}}{\dot{E}_7 + \dot{E}_{23} + \dot{E}_{26}}$
Preheater 2	$\dot{E}_6 + \dot{E}_{25} + \dot{E}_{28}$	$\dot{E}_{26} + \dot{E}_{27}$	-	$\dot{E}_6 + \dot{E}_{25} + \dot{E}_{28} - \dot{E}_{26} - \dot{E}_{27}$	$\dfrac{\dot{E}_{27} - \dot{E}_{25}}{\dot{E}_6 + \dot{E}_{28} - \dot{E}_{26}}$
Preheater 1	$\dot{E}_5 + \dot{E}_{27}$	$\dot{E}_{28} + \dot{E}_{29}$	-	$\dot{E}_5 + \dot{E}_{27} - \dot{E}_{28} - \dot{E}_{29}$	$\dfrac{\dot{E}_{29} - \dot{E}_{27}}{\dot{E}_5 - \dot{E}_{28}}$
Pump1	$\dot{E}_{13}$	$\dot{E}_{14}$	$-\dot{W}_{P.1}$	$\dot{E}_{13} - \dot{E}_{14} + \dot{W}_{P.1}$	$\dfrac{\dot{E}_{13} - \dot{E}_{14}}{\dot{W}_{P.1}}$
Pump2	$\dot{E}_{24}$	$\dot{E}_{25}$	$-\dot{W}_{P.2}$	$\dot{E}_{24} - \dot{E}_{25} + \dot{W}_{P.2}$	$\dfrac{\dot{E}_{24} - \dot{E}_{25}}{\dot{W}_{P.2}}$
Pump3	$\dot{E}_{39}$	$\dot{E}_{40}$	$-\dot{W}_{P.3}$	$\dot{E}_{39} - \dot{E}_{40} + \dot{W}_{P.3}$	$\dfrac{\dot{E}_{39} - \dot{E}_{40}}{\dot{W}_{P.3}}$
Air fan 2	$\dot{E}_{45}$	$\dot{E}_{46}$	$-\dot{W}_{Fan2}$	$\dot{E}_{45} - \dot{E}_{46} + \dot{W}_{Fan2}$	$\dfrac{\dot{E}_{45} - \dot{E}_{46}}{\dot{W}_{Fan2}}$
Air preheater 2	$\dot{E}_{46} + \dot{E}_{51}$	$\dot{E}_{47} + \dot{E}_{52}$	-	$\dot{E}_{46} + \dot{E}_{51} - \dot{E}_{47} - \dot{E}_{52}$	$\dfrac{\dot{E}_{47} - \dot{E}_{46}}{\dot{E}_{51} - \dot{E}_{52}}$
Boiler (CFB)	$\dot{E}_{42} + \dot{E}_{48} + \dot{E}_{49} + \dot{E}_{50}$	$\dot{E}_{43} + \dot{E}_{51}$	$-\dot{W}_{CFB}$	$\dot{E}_{42} + \dot{E}_{48} + \dot{E}_{49} + \dot{E}_{50} - \dot{E}_{43} - \dot{E}_{51} + \dot{W}_{CFB}$	$\dfrac{\dot{E}_{43} - \dot{E}_{42}}{\dot{E}_{48} + \dot{E}_{49} + \dot{E}_{50} - \dot{E}_{51} + \dot{W}_{CFB}}$
Overall plant	$\dot{E}_{38} + \dot{E}_{50}$	$\dot{E}_{37} + \dot{E}_{52}$	$\dot{W}_{Net}$	$\dot{E}_{38} + \dot{E}_{50} - \dot{E}_{37} - \dot{E}_{52} - \dot{W}_{Net}$	$\dfrac{\dot{W}_{Net}}{\dot{E}_{38} + \dot{E}_{50}}$

suffer from some serious corrosion problems in the boiler.

• The detailed exergy analysis results of the case study (parallel co-firing of the olive pits) shows that the total exergy destruction of the plant is 365.85 MW and the net exergy efficiency is 29.04%. The exergy analysis shows that the majority of the exergy destruction (244.73 MW) takes place in the main boiler and comprises 66.89% of total exergy destruction of the TPP.

These results suggest that co-firing of almost all biomass types considered in this study, regardless of the co-firing methods, could result in cleaner and more efficient electricity production in the Soma TPP. Consumption of the 'dirty' lignite fuel drops during biomass cofiring, and gaseous emissions are also reduced, helping Turkey to fulfill its environmental commitments for power generation. If the higher investment cost is neglected, parallel co-firing of the olive pits can be considered as the best option for co-combustion in the Soma TPP, since it has almost the best environmental performance of the biomass types considered and there is a considerable olive tree resource close to the Soma TPP.

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