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ORIGINAL PAPER

Assessing Options for Electricity Generation from Biomass on a Life Cycle Basis: Environmental and Economic Evaluation

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Abstract Co-firing biomass with coal is being increasingly seen in the EU region as an option that could contribute not only towards reaching the Kyoto targets on greenhouse gas emissions but also towards compliance with the EU directives on renewable energy and large combustion plants. Perennial grasses, short rotation coppice, seasonal agricultural residues and waste forestry wood are all considered as viable alternatives. However, although the use of biomass for electricity generation could help reduce direct emissions of pollutants generated during combustion of coal, including carbon dioxide, sulphur dioxide and nitrogen oxides, the whole life cycle implications of using biomass are less clear. This paper uses a life cycle approach to evaluate the environmental impacts and economic costs of co-firing with coal three types of biomass: miscanthus, willow and waste forest wood. Both direct combustion and gasification of biomass are considered. The results of life cycle assessment indicate that all biomass options lead to a substantial reduction in the environmental impacts compared to the coal-only power generation. Overall, use of waste wood appears to be environmentally the most sustainable option. In comparison to direct combustion, biomass gasification has higher global warming potential due to the higher consumption of biomass and energy for gasification. The results of the life cycle economic costing show that electricity from biomass is economically less attractive than from coal. Direct firing is two times more expensive than coal and gasification up to three times. Therefore, while attractive from the environmental point of view, biomass appears currently to be less sustainable economically.

Keywords Biomass · Climate change · Electricity generation · Economic assessment · Life cycle assessment

Introduction

Over 65% of world electricity is generated from fossil fuels, 40% of which is supplied by coal [1]. Consequently, coal contributes 43% of CO_2 emissions from electricity generation worldwide [2]. Without fuel switching and widespread deployment of carbon capture and storage measures, it is predicted that emissions from coal will grow from 12.6 Gt CO_2 in 2008 to 18.6 Gt CO_2 in 2030 [3]. Coupled with an estimated 60% increase in energy demand, this would lead to a 60% rise in global CO_2 emissions [1]. In an attempt to reduce the energy-related CO_2 emissions as well as our reliance on the diminishing fossil-fuel reserves, various renewables are being considered as potentially more sustainable sources of electricity, including biomass. Biomass has an estimated global potential to generate 100 EJ of energy per year, with 80% derived from energy crops and forestry waste products (each contributing 40%) and the remaining 20% from agricultural waste products [4, 5]. In the EU, this potential is 7.75 EJ per year, with the estimated saving of 209 million tonnes of CO_2 eq./year; this is equivalent to 5% of the energy-related emissions in 1990 [6].

In addition to the climate change-related drivers, a further impetus for reducing the use of coal in power stations in the EU is provided by the revised Large Combustion Plants Directive (LCPD) which from 2008 introduced more stringent limits on power plant emissions of sulphur dioxide, nitrogen oxides and particulates [7].

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Co-firing coal with biomass is being increasingly seen in the EU region as an option that could contribute not only towards reaching the Kyoto targets on CO_2 emissions but also help satisfy the requirements of the LCPD. The increased use of biomass for electricity generation is also driven by the implementation of the EC Directive on Renewable Energy in Electricity Generation [8]. Moreover, achieving the renewable energy targets [6] without using more biomass looks unlikely.

Perennial grasses, short rotation coppice, seasonal agricultural residues and waste forestry wood are all considered as viable alternatives that can be used efficiently with currently available technology at nominal additional costs [9]. However, although electricity from biomass could help reduce direct emissions of CO_2, SO_2 and NOx, it is less clear what are the whole life cycle implications of using biomass. It is known, for example, that growing energy crops can cause eutrophication through leachates of nutrients from fertilisers; cultivation can release carbon stored in the land and hence contribute to carbon emissions; biomass has low energy density and high water content, making it thus a less efficient fuel [10]. Furthermore, growing energy crops requires large areas of land and may be in competition with food production—it is estimated that providing 100 EJ of energy per year from biomass with an average yield of 6–7 tonnes of dry weight per hectare and year would require 2.5% of the total land surface [11]. In the UK alone, an estimated 125,000 ha. would be required to meet the Government's target for electricity generation from biomass [12].

A number of Life Cycle Assessment (LCA) studies have attempted to address some of these issues, looking at the use of different biomass for heat and electricity generation, including perennial rhizomatous grasses [9, 11, 13], short rotation coppice (SRC) and straw and residual wood [14]. In an attempt to inform further the debate on energy from biomass, this paper discusses both environmental and economic impacts of electricity generation from power plants co-firing coal with three types of biomass: miscanthus (perennial grass), willow (short rotation coppice, SRC) chips and waste wood (forest residue). Several scenarios are examined, using different types and combinations of biomass in either direct co-firing or gasification plants. The environmental and economic implications of the different scenarios are evaluated on a life cycle basis using life cycle assessment (LCA) and life cycle costing. The study is based in the UK.

Methodology and Assumptions

The basis for analysis here is a 500 MW power plant co-firing coal with different types of biomass. It is assumed that 10% (50 MW) of this capacity is generated using biomass. Therefore, since 450 MW of electricity is produced by coal in all the options considered, for the purposes of comparison, the LCA and economic analysis are carried out for the remaining 50 MW produced from different types of biomass. Thus, the analysis is based on the functional unit defined as *generation of 50 MW of electricity over 1 year*.

As shown in Table 1, twelve scenarios (B–M) are considered and compared with the reference scenario (A). The latter is based on 100% electricity from coal imported from South Africa. Scenarios B–F and G–K consider direct co-firing and gasification of biomass from the UK, respectively. Scenarios L and M also assume direct co-firing but with the biomass imported from Sweden and Ukraine, respectively. Table 1 also shows the quantities of biomass used in each scenario.

Figure 1 outlines the life cycle system boundaries for the scenarios. As shown, the system boundary is from 'cradle-to-grave', accounting for all the relevant activities involved in the extraction of primary resources, mining and transport of coal, cultivation and transport of biomass, generation of electricity and disposal of waste. All the related infrastructure, including the power plant, is also included in the system boundary. It is assumed that the plant generates electricity only and that no heat is exported outside the system boundaries; this is typically the case in the UK. Therefore, the system has not been credited for heat co-generation in any of the scenarios. Electricity distribution is not considered as it is common to all scenarios. Key assumptions for different scenarios are outlined below.

As summarised in Table 2, coal (scenario A) is imported to the UK from South Africa. In scenarios B–K, biomass (miscanthus, SRC chips or waste forest wood) are sourced locally. Scenarios L and M consider the case where importing the biomass may become necessary to meet the targets on CO_2 emissions so that for these purposes, importing SRC chips from Northern Europe (Sweden) and from Eastern Europe (Ukraine) has been assumed as the most likely sources of biomass for the UK. Table 2 shows the assumptions for the transportation mode and distances for each type of fuel.

Scenarios G–K consider gasification of biomass in a circulating fluidised bed (CFB) gasifier. The CFB gasifier has an efficiency of 81% (Table 3) and operates at the atmospheric pressure and temperature of 900°C. The produced synthesis gas is then direct-fired into the combustion chamber. The use of syngas in boilers does not require feedstock drying and advanced fuel gas clean-up. Therefore, it consumes less resources and is less expensive than integrated gasification combined cycle (IGCC) systems. Some successful examples of this include: Zeltweg power plant in Austria, Kymijarvi CHP power plant in Finland,

Table 1 Summary of scenarios

Scenarios	Percentage electricity generated from different fuels[a]	Fuel origin	Quantity used to generate 50 MW (tonnes/year)[b]
A (reference)	100% from coal	South Africa	138,430
B	10% from miscanthus (direct firing)	UK	291,060
C	10% from SRC chips[c] (direct firing)	UK	270,270
D	10% from waste wood[d] (direct firing)	UK	254,705
E	7.5% from SRC chips (direct firing)	UK	202,705
	2.5% from miscanthus (direct firing)		72,765
F	7.5% from waste wood (direct firing)	UK	191,030
	2.5% from miscanthus (direct firing)		72,765
G	10% from miscanthus (gasification)	UK	359,335
H	10% from SRC chips (gasification)	UK	333,667
I	10% from waste wood (gasification)	UK	314,450
J	7.5% from SRC chips (gasification)	UK	250,250
	2.5% from miscanthus (gasification)		89,835
K	7.5% from waste wood (gasification)	UK	235,840
	2.5% from miscanthus (gasification)		89,835
L	10% from SRC chips (direct firing)	Sweden	270,270
M	10% from SRC chips (direct firing)	Ukraine	270,270

[a] In scenarios B–M, 10% of electricity is generated from biomass and the remaining 90% from coal

[b] Power plant specifications are given in Table 3

[c] SRC chips—Short Rotation Coppice (willow)

[d] Waste wood—residual forest wood

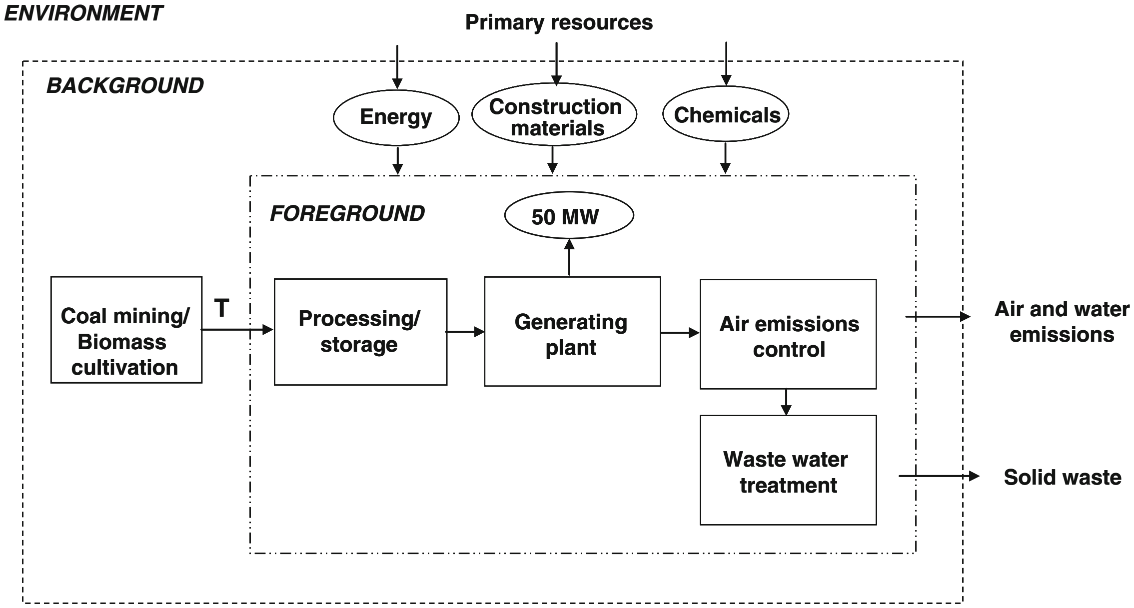

Fig. 1 System boundaries and life cycle stages considered in the study [T-transport]

Ruien plant in Belgium and Amer 9 co-gasification plant in the Netherlands [15]. However, as can be noted from Table 1, considerably more biomass is required for electricity generation via the gasification route compared to direct co-firing of biomass, due to the inefficiencies in the gasification process.

The power plant includes a co-firing boiler, a heat recovery steam generator and a steam turbine (Table 3). Electrostatic precipitator, flue gas desulphurisation and

Table 2 Transportation mode and travel distances for different fuels

Fuel	Sea shipping (km)	Road transport (40 t truck) (km)
Coal (South Africa)	11,000	–
Miscanthus, SRC chips, waste wood (UK)	–	40 (Return trip)
SRC chips (Sweden)	1,200	200 (Return trip)
SRC chips (Ukraine)	2,100	200 (Return trip)

Table 3 Power plant and gasifier specification

	Power plant [16]	Gasifier [18]
Plant type	Co-firing boiler with steam turbine	Circulating fluidised bed (CFB)
Rated power	500 MW (electrical)	135 MW (thermal)
Efficiency (%)	37	81
Operating hours (h/year)	7,000	7,000
Plant lifetime (years)	40	15
Emission reduction technologies (efficiency)		–
Particulates	Electrostatic precipitator (98%)	
SO_2	Flue gas desulphurisation (90%)	
NOx	Selective catalytic reduction (90%)	

selective catalytic reduction are installed to control the emissions of particulates, sulphur dioxide and nitrogen oxides, respectively.

The heating values and prices of the fuels used in the power plant are summarised in Table 4.

For the purposes of LCA, the system is divided into the ‘foreground’ and ‘background’ as shown in Fig. 1. The foreground processes are those which are directly related to the electricity production and occur at the location of the plant, hence contributing to direct environmental impacts; the background activities occur elsewhere to support electricity generation in the foreground and they contribute to indirect impacts. The foreground thus comprises the power plant as well as biomass drying and gasification where applicable. Everything else is in the background, including the extraction and processing of auxiliary materials and energy, manufacture of the infrastructure, mining of coal, cultivation of biomass, transport of fuels and waste disposal.

The LCA study has been carried out following the ISO 14044 methodology [19] and using LCA software GaBi v4.3; the data have been obtained from the GEMIS v4.5 [17] and Ecoinvent v1.3 [20] databases as well as from open literature. The environmental impacts have been calculated using the problem-oriented (midpoint) approach [21].

Table 4 Fuel heating values and prices

Fuel	Heating value (MJ/kg) [17]	Fuel price (at the plant gate) (US\$/tonne) [18]
Coal (South Africa)	24.6	48
Miscanthus (UK)	11.7	90
SRC chips (UK, Sweden, Ukraine)	12.6	120
Waste wood (UK)	13.4	105
Biogas	3.77	–

Results and Discussion

Environmental Impacts

Figures 2, 3, 4, 5, 6 show the life cycle impacts for all the scenarios, both in the foreground and background. These results are discussed below in turn.

Global Warming Potential (GWP): The total GWP for the reference scenario (A, 100% coal) is equal to 362,500 tonnes CO_2 eq. per year. As shown in Fig. 2, the use of biomass instead of coal could reduce the total GWP by 88–97% for the same energy output. Most of the reduction occurs in the foreground for all the scenarios, due to the displacement of fossil CO_2 from the combustion of coal by biogenic CO_2 from the biomass. The background GWP is also reduced by 40–80% in scenarios B–F (direct co-firing) compared to the background impacts from coal, indicating that biomass cultivation and transport have lower GWP than coal mining and transportation to the UK from South Africa. The greatest reduction of the background GWP is in scenario D (direct co-firing of waste wood) since the fuel is available as ‘waste’ rather than having to be cultivated as in the case of miscanthus and willow.

However, the background GWP from scenarios G–K is equal to or higher than that for coal, suggesting that coal mining, its transport to the UK and other background processes have a similar or lower GWP than that of biomass cultivation, its transport, and other background processes related to biomass. The reason for this is mainly due to the higher amount of biomass required and the additional use of energy in the gasification process,[1] which results in higher background emissions of CO_2 related to the biomass. Similarly, the background impact for scenarios L and M (imported biomass from Sweden and Ukraine, respectively) is comparable to the background GWP from coal

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[1] It is assumed that the electricity consumed in the gasification process is obtained from the UK grid and hence considered as part of the background system.

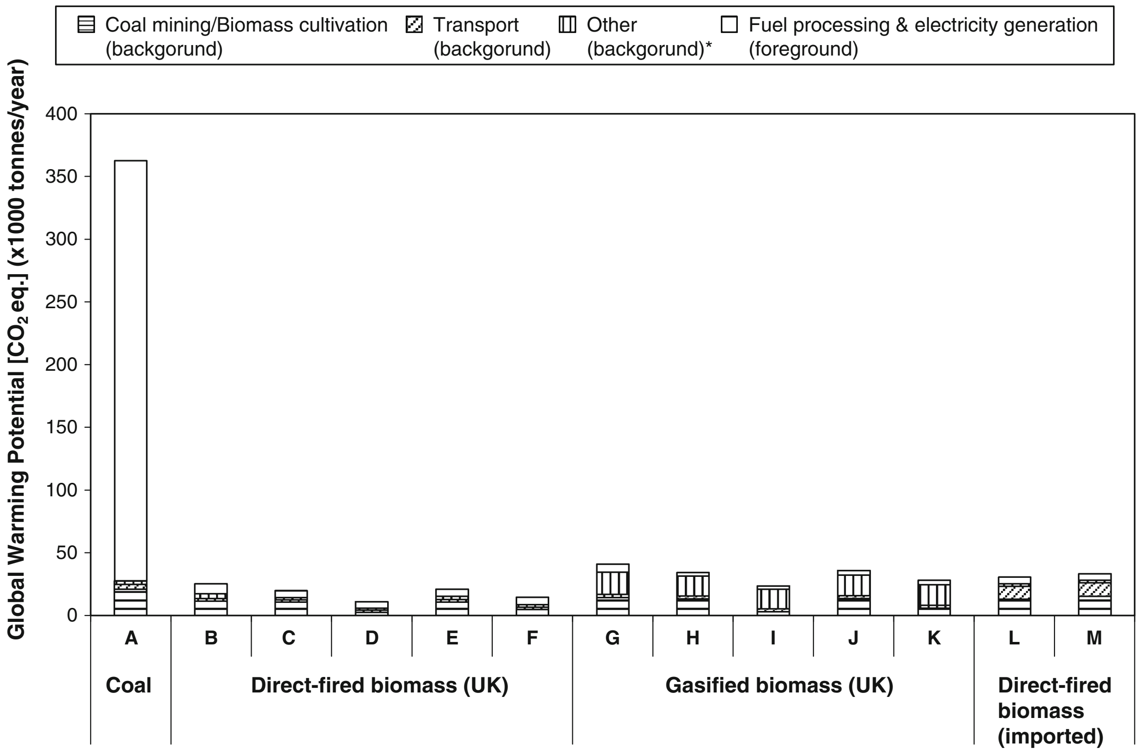

Fig. 2 Comparison of global warming potential (foreground and background) for different scenarios (*Other (background) includes waste disposal, infrastructure and auxiliary materials and energy)

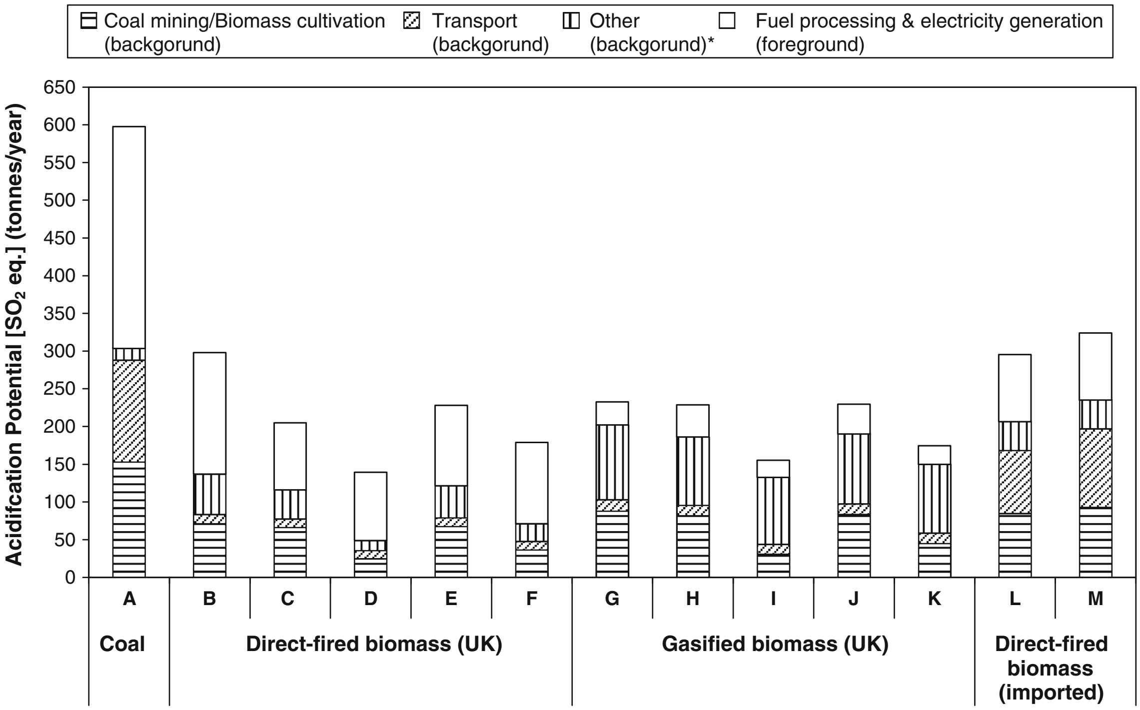

Fig. 3 Comparison of the acidification potential (foreground and background) for different scenarios (*Other (background) includes waste disposal, infrastructure and auxiliary materials and energy)

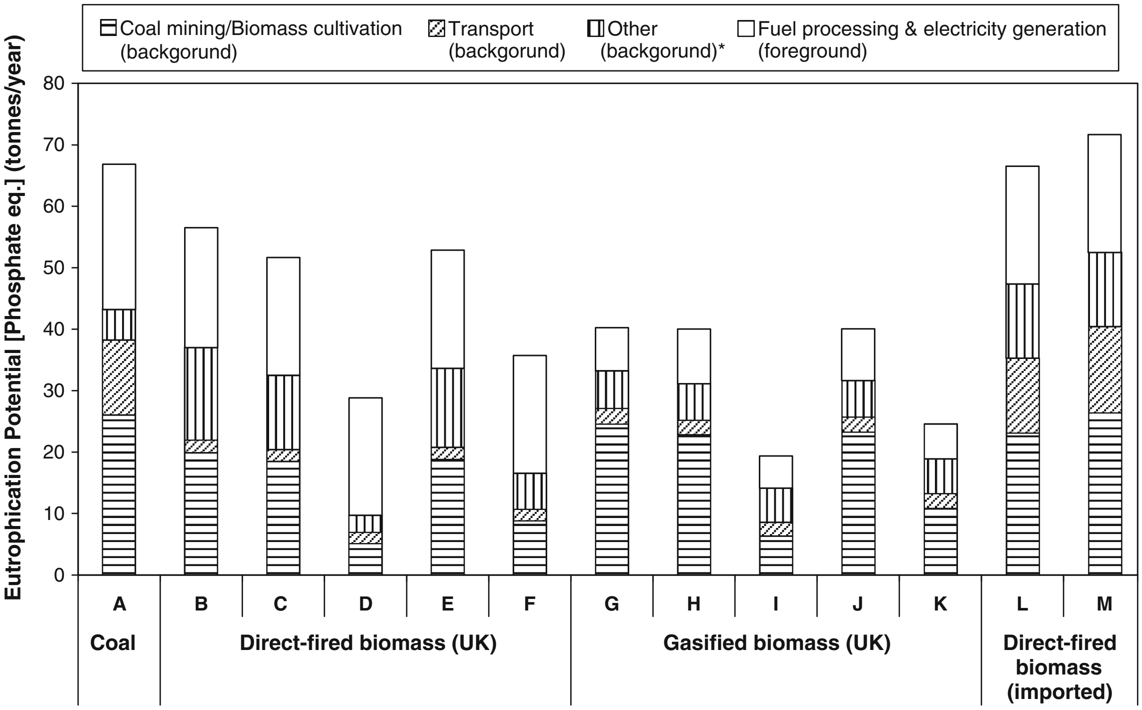

Fig. 4 Comparison of the eutrophication potential (foreground and background) for different scenarios (*Other (background) includes waste disposal, infrastructure and auxiliary materials and energy)

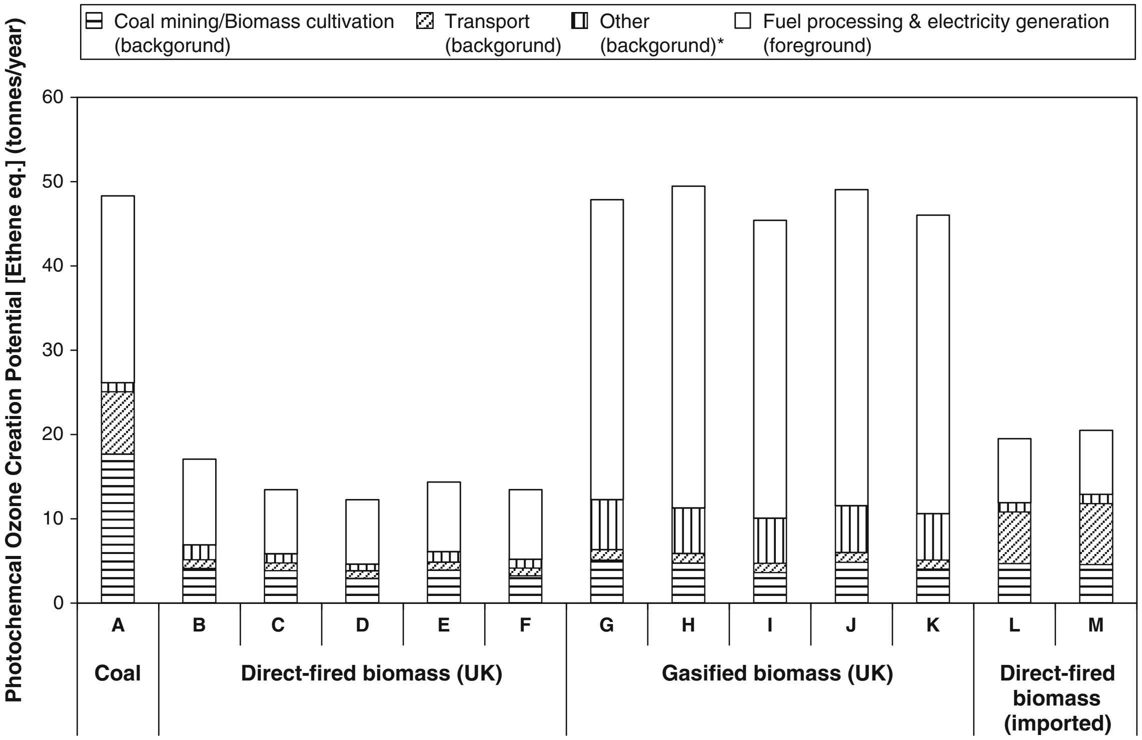

Fig. 5 Comparison of the photochemical ozone creation potential (foreground and background) for different scenarios (*Other (background) includes waste disposal, infrastructure and auxiliary materials and energy)

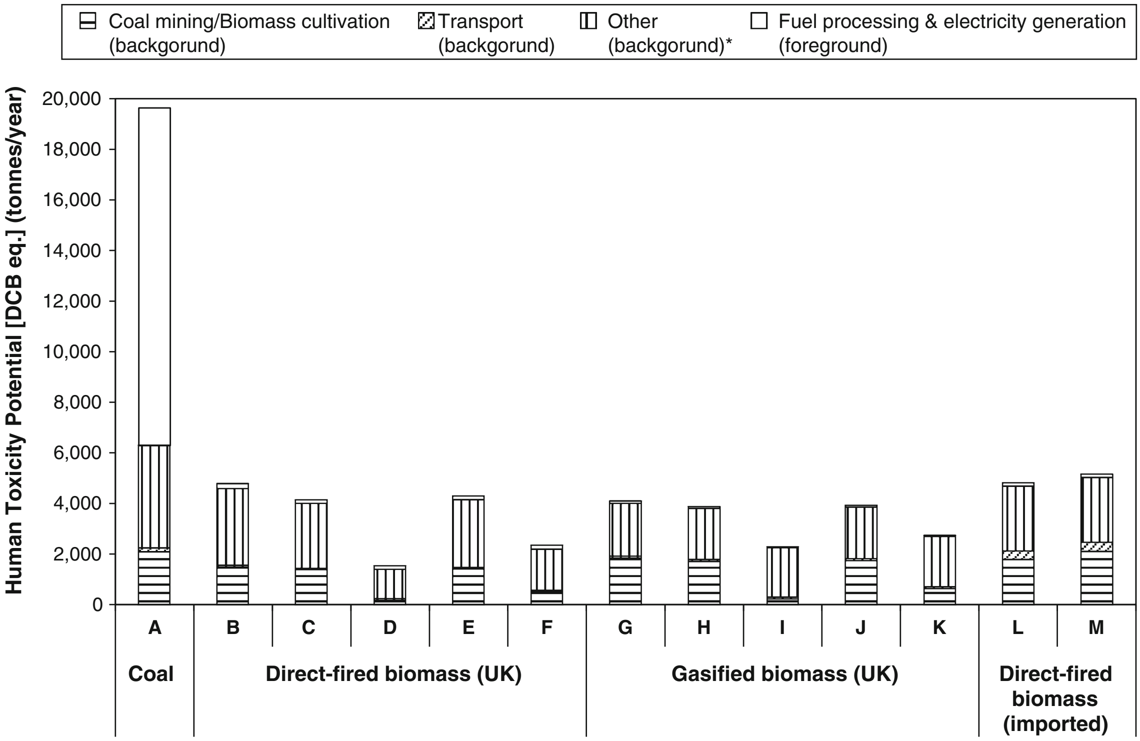

Fig. 6 Comparison of the human toxicity potential (foreground and background) for different scenarios (*DCB* dichlorobenzene; *Other (background) includes waste disposal, infrastructure and auxiliary materials and energy)

due to the combined effect of biomass cultivation and transportation.

Acidification Potential (AP): This impact, estimated for coal at 600 SO_2 eq. tonnes/year is also reduced significantly (up to 75%; see Fig. 3) for all biomass options. The reduction occurs both in the foreground and background with the greater reduction in the foreground noticed for scenarios G–K (gasification). The reason for this is that combustion of biogas results in lower emissions of SO_2 and NOx compared to direct firing of biomass. On the other hand, the reduction in the background AP for these scenarios is less significant due to the increased amount of biomass and additional energy used in gasification.

The lowest overall AP is for scenario D (direct firing of waste wood), mainly due to a much lower background impact compared to the other scenarios. The reasons for this are the emissions of NH_3 and N_2O from the use of fertilisers in the cultivation of miscanthus and willow, which are avoided in the case of waste wood.

The highest impact from the biomass is for scenarios L and M (imported SRC chips). Again, similar to the GWP, the background impact in these scenarios is comparable to that of coal, again because of the combined effect of biomass cultivation and transportation.

Eutrophication Potential (EP): Fig. 4 indicates that the use of biomass instead of coal leads to a reduction of the EP for most scenarios, except for L and M which have comparable impact to that of coal. The latter is estimated at 77 t PO_4^{2-} eq./year. This is mainly due to the additional fertiliser inputs for cultivation in the importation countries compared to the UK as well as the additional NOx emissions from transportation. Therefore, these results suggest that importing biomass to the UK offers no advantages compared to coal with respect to the EP impact.

Regarding the foreground impact, some reduction compared to coal is achieved by using biomass, particularly in the gasification scenarios. This is mainly due to the lower emissions of NOx from the combustion of syngas compared to biomass. However, the background impact remains more or less the same as for coal in most scenarios, except for D, F, K and I (mostly waste wood, direct firing and gasification). This is because of the avoided use of fertilisers and the related emissions of NH_3 and NOx which are emitted in the cultivation of miscanthus and willow.

Photochemical oxidant creation potential (POCP): As shown in Fig. 5, the use of biomass in direct combustion (scenarios B–F) reduces the coal POCP of 47 t C_2H_4 eq./year by 65–75%. The best biomass option is direct co-firing of waste wood (scenario D). The reduction in this impact is mainly due to the lower emissions of CO, NOx, SOx and volatile organic compounds (VOC) during combustion of biomass compared to coal. Furthermore, VOC emissions from the mining of coal and NOx and SOx emissions from coal transport are also avoided. The impact from the imported biomass (scenarios L and M) is also relatively low and comparable to scenarios B–F, except for the additional impact from the transport. However, for the gasification route (scenarios G–K), POCP is similar to that from the coal-fired system. The main reason for this are the higher foreground emissions of VOC generated during gasification which are, together with NOx, precursors for POCP.

Human Toxicity Potential (HTP): This impact is also significantly reduced with the use of biomass (Fig. 6). In comparison to the coal fired-power plant, the use of waste wood (scenario D) could reduce about 90% of HTP while miscanthus and SRC chips could reduce this impact by up to 75%, from the total of 20,000 t dichlorobenzene eq./years. The reduction is particularly noticeable in the foreground, due to the avoidance of the emissions of heavy metals such as chromium, arsenic, nickel and selenium generated during the combustion of coal. The gasification route has lower HTP compared to direct firing of the biomass due to the reduction of freshwater impacts associated with the disposal of ash from biomass (and coal). The importation options (scenarios L and M) have overall the highest HTP of all the biomass options, mainly related to the toxic emissions from fertilisers, transportation and disposal of ash.

Therefore, these results suggest that overall, the use of biomass is environmentally more sustainable than coal. Direct firing of the biomass sourced in the UK outperforms coal for all the impacts considered here; similar is true for gasification except for POCP which is comparable to that of coal. Direct firing of imported biomass also has lower environmental impacts than coal, but its EP is similar to that from coal. The different biomass options have comparable environmental impacts for acidification and human toxicity and to a certain extent for global warming, although direct firing has a slightly lower impact. In summary, scenarios D and I (direct firing and gasification of waste wood, respectively) are arguably the most sustainable options with respect to most of the environmental impacts considered here.

We now turn our attention to the economic evaluation, to find out which option may be more sustainable from the economic point of view.

Economic Evaluation

The options considered are evaluated on the investment, fuel, maintenance and other related costs over the whole life cycle of each scenario. The cost data for the individual parts of the system have been obtained from literature [17, 18] and the total annualised costs estimated according to the following formulae:

$$T_C = \sum C_C + \sum F_C + \sum V_C + \sum f_C \tag{1}$$

where T_C, total annualised cost (US\$/year); C_C, annualised capital cost (US\$/year); F_C, fixed annual costs (maintenance and repair) (US\$/year); V_C, annual variable costs, excluding fuel costs (US\$/year); f_C, annual fuel costs (US\$/year).

The annualised capital cost (C_C) is calculated by multiplying the capital investment cost (I_C) by an annuity factor (f) as follows:

$$C_C = I_C \times f \tag{2}$$

$$f = z \times (1+z)^t / \left[(1+z)^t - 1\right] \tag{3}$$

where z, discount rate (assumed at 7%); t, lifetime of technology (years).

The results of cost evaluation are presented in Table 5. As can be seen, in comparison to the reference scenario (coal), the use of biomass results in additional investment costs and higher operating costs. The total annualised costs for direct-fired biomass plants are approximately two times higher than for coal, with miscanthus and waste wood (scenarios B, D and F) having the lowest total annualised costs. The results also suggest that gasification is more expensive in all cases than the direct-fired biomass option (up to three times for SRC chips). This is due to the additional investment costs for the gasification plant and additional fuel costs due to increased biomass demand in gasification. Therefore, while biomass is more advantageous environmentally, it is less attractive economically.

Conclusions

The LCA results demonstrate that co-firing the biomass with coal for power generation leads to a substantial reduction in the environmental impacts from coal-fired power generation. The reduction occurs for all three biomass fuels studied (miscanthus, SRC chips and waste forestry wood); however, the use of waste wood is overall the best option. The results also indicate that importing SRC increases environmental impacts compared to local sourcing. Of the two importation options considered here, the import from Sweden has lower impacts than that from Ukraine.

Biomass gasification has both advantages and disadvantages in comparison to direct-firing of biomass. Since biogas is a cleaner fuel, its combustion results in reduced direct acidification, eutrophication and human toxicity impacts. However, additional requirement for biomass due to the inefficiencies in the gasification process and the energy consumed in gasification not only result in higher GWP and POCP than for direct-fired biomass but also

Table 5 Comparison of costs for different scenarios (all costs in '000 US$)

Scenarios	Capital investment costs (I_c)	Annualised capital costs (C_c)	Fixed annual costs (F_c)	Variable annual costs (V_c)	Fuel annual costs (f_c)	Total annualised costs (T_c) [increase on coal costs]
A coal	85,500	6,500	2,300	5,400	6,700	20,900 [–]
B (miscanthus)	97,000	7,300	2,700	5,600	26,000	41,600 [2.0×]
C, L & M (SRC chips)	97,000	7,300	2,700	5,600	32,600	48,200 [2.3×]
D (waste wood)	97,000	7,300	2,700	5,600	26,600	42,200 [2.0×]
E (SRC chips and Miscanthus)	97,00	7,300	2,700	5,600	31,000	46,600 [2.2×]
F (waste wood and Miscanthus)	97,000	7,300	2,700	5,600	26,600	42,200 [2.0×]
G (miscanthus gasification)	117,800	9,900	5,700	8,000	32,300	55,900 [2.7×]
H (SRC chips gasification)	117,800	9,000	5,700	8,000	40,200	62,900 [3.0×]
I (waste wood gasification)	117,800	9,000	5,700	8,000	33,000	55,700 [2.7×]
J (SRC chips and miscanthus gasification)	117,800	9,000	5,700	8,000	38,000	60,700 [2.9×]
K (waste wood and miscanthus gasification)	117,800	9,900	5,700	8,000	33,000	56,600 [2.7×]

contribute to an increase in the overall costs of electricity production. As shown in the economic analysis, gasification has up to three times higher total annualised cost than the coal option; by comparison, direct-firing costs are approximately two times higher. Therefore, coal is economically a more sustainable option than either of the biomass options considered here. However, this may change in the future if the economies of scale for biomass change.

Finally, although the findings of this study suggest that there are significant environmental benefits associated with the use of biomass, it is important to mention that there are other environmental impacts associated with the use of biomass which cannot be fully captured by LCA. Biomass production could have beneficial impacts such as enhanced landscape diversity and wildlife habitat, erosion reduction, as well as harmful impacts, such as land use and effect on food crops production. These and other sustainability aspects should all be considered in making any decisions on biomass as a future source of energy.

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