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Life cycle energy-economic-CO_2 emissions evaluation of biomass/coal, with and without CO_2 capture and storage, in a pulverized fuel combustion power plant in the United Kingdom

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ABSTRACT:

Biomass to power generation is an alternative for fossil fuel to power pathways and plays a significant role in electricity supply and CO_2 emissions reduction of the United Kingdom (UK). Additionally, the UK government plans to phase out coal to power in the near future (2025), implying that all coal power plants in the future must be deployed with CO_2 capture and storage (CCS). In this study, life cycle evaluation of energy use, CO_2 emissions and cost requirements for pulverized fuel combustion power plants using white wood pellets and bituminous coal, a typical coal widely consumed in coal power station in the UK, as feedstocks, with and without (w/o) post-combustion

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CCS are investigated for deep understanding application and challenges of these technologies. The life cycle evaluation covers the whole power generation process including wood pellets/coal supply chain and electricity generation at the power plant. The analysis demonstrates that biomass or biomass/coal co-fired plants w/o CCS has no advantage in comparison to coal fired plant w/o CCS regarding the energy use due to the high energy consumption during the biomass supply chain process. From a life cycle viewpoint, CO_2 released when combusting biomass will be consumed during plant growth, resulting in an approximate carbon neutral combustion process with additional CO_2 emissions from the supply chain process. The biggest handicap for biomass power plants is the high operational cost of the feedstock supply chain process, with the additional high capital cost of the carbon capture plant, if considered. These results are a comprehensive guide which can help decision makers perform suitable measures to push forward development and application of coal/biomass power generation with CCS.

Keywords: life cycle; biomass; coal; CO_2 capture; power plant

1. Introduction

Global climate change as a result of anthropogenic greenhouse gas (GHG) emission has drawn wide attention from the international community. The Paris Agreement called for an urgent action to limit warming levels well below 2 °C and pursuing efforts to limit it to 1.5 °C. The Agreement additionally sets a target for net zero global emissions in the second half of this century [1].

Fossil fuel is the primary source of high amounts of CO_2 emission. About 70% of CO_2 emissions are from coal-based power generation plants [2]. It is a primary task to reduce CO_2 emissions of coal-based power plants throughout this century. GHG emissions can be reduced by means of improving energy efficiency, applying CO_2 capture and recovery technology as well as using non-fossil or renewable energy alternatives. By the end of year 2016, renewable energy targets were in place in 176 countries. The majority of aims continue to focus on renewable energy use in the power sector, with targets for a specific share of renewable power instituted in 150 countries [3]. The EU proposed a new 2030 Framework under which it aims for renewables to account for at least 27% of total energy consumption and at least a 27% improvement in energy efficiency (relative to a business-as-usual scenario) to help reduce greenhouse gas emissions by 40% in 2030, relative to 1990 levels [4]. China's newest Five-Year Plan sets an overall goal of increasing renewable energy capacity to 680 GW by 2020, accounting for 27% of total power generation [5]. Leaders of Canada, Mexico and the United States reached a deal to source 50% of the region's electricity from non-carbon sources by 2025 (including renewable energy, nuclear energy, and carbon capture and storage technologies) [6]. Carbon Capture and Storage (CCS) technologies are considered to be a promising countermeasure to mitigate CO_2 emission, and provide nearly 20% of the global emission reduction required by 2050 [7]. Post-combustion capture technologies provide essential means for CO_2 capture from the flue gas streams of traditional power generation plant [8-9]. For example, the monoethanolamine (MEA) solvent absorption method is one of the most mature technologies and is the most widely used approach for post-combustion CO_2 capture from coal-fired power plants due to its high CO_2 capture efficiency and selectivity [10-12]. It has been demonstrated that the aforementioned post combustion capture (PCC) technology can capture above 90% of CO_2 from power generation plant.

Possible renewable alternatives for existing power plants are based on the use of biomass. Biomass is considered as a CO_2-neutral fuel, since it releases the same quantity of CO_2 into the atmosphere during its combustion as that absorbed during its growth. As a result, bio energy with carbon capture and storage (BECCS) is regarded as the only up to date large scale technology solution for CO_2 negative emissions. The study showed that the utilization of white wood pellets (WWP) in electricity generation can avert about 3 million tonnes of CO_2 emissions per year from a 650 MW power plant [13]. Biomass-coal co-firing has also been widely acknowledged as a feasible and economic way for CO_2 reduction [14-17]. What's more, biomass-fired or co-firing implementation in power plant will lead to a significant reduction of SO_2 and NOx emissions due to low content of sulphur and nitrogen in biomass [18-20].

Up till now, approximately 30.71 TWh of electricity comes from coal-based power plants in the United Kingdom (UK) [21], while facing tremendous pressure on cutting down greenhouse gas emissions. The UK's current long-term target is a reduction in greenhouse gas emissions by at least 80% by the year 2050, relative to 1990 levels. This 2050 target was conceived as a contribution to a global emissions reduction target aimed at keeping global average temperature at around 2°C above pre-industrial levels [1]. In order to complete this arduous task, coal power generation with CCS and bioenergy to power generation strategies are implemented. The forthcoming policy from UK government implies that new generations of coal-fired power plants beyond 2025, should only be considered if CO_2 is captured and stored (CCS). This provides opportunity for CCS from both coal and biomass fired plant with a common infrastructure for transport and storage and could significantly affect the economic viability of investment in post capture pipeleines etc. in terms of scale of operation. Bioenergy production and low carbon electricity deployment has increased significantly since 2013. The 2016 energy statistics report from the UK Department for Business, Energy & Industrial Strategy indicates an increase of 102% (4.93 to 9.99 million tonnes of oil equivalent) in bioenergy used for power generation from 2012 to 2016 [21], power generation from bioenergy (including biodegradable wastes) are 30 TWh, about 32% of which are from pellets and woodchips resource [22-23].

Many investigations have been focusing on economic and environmental analysis and the cost effectiveness of biomass or co-firing power plants [13,17,24-29] with/without (w/o) CCS technologies in the UK. However, the scope of these studies considered analyzing internal factors of the power plant. Life cycle assessment (LCA) of power generation, including analysing both internal and external factors of a power plant that affect energy, economic and environmental performance of power plants, have been widely conducted worldwide in the past ten years [15,30-39]. Several LCA studies on coal-fired power generation were undertaken in the UK [40-42]. Since LCA study is an important contributor to understanding impacts of renewables on power generation systems in the country of interest, a detailed investigation of power generation systems specific to that country is required in advance [40]. However, there are only a few studies that refer to LCA analysis of biomass or co-firing power stations w/o CCS in the UK, hence there is a need to provide more data for performance comparisons in term of energy-economy-environment from the viewpoint of lifecycle.

The life cycle analysis of energy input, CO_2 emissions and cost input of biomass/coal power plants w/o CCS technologies are based on data reflecting the current status in the UK. The objectives of this paper are to: (i) undertake the life cycle analysis of energy use, CO_2 emissions and cost effectiveness of combustion based power plants using white wood pellets and coal w/o CCS technologies in the UK; (ii) quantify and compare the energy-economy-CO_2 emissions of different power generation pathways; (iii) disclose the key factors that affect comprehensive performance of power plants from the life cycle point of view. Furthermore, a sensitivity analysis for the final results will be investigated. Based on the findings from this study, policy makers can decide on appropriate policies and measures to promote deployment of biomass/coal power plants with CCS technologies in the framework of GHG emissions mitigation.

2. Methodology

The methodology used to perform the life cycle assessment is the one described by the ISO standard 14040, which generally consists of four steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation [43]. The Integrated Environmental Control Model (IECM, version 8.02), which provides a relatively complete process package for the modelling of fossil energy and biomass energy to power generation with/without CCS options, was used to calculate the techno-economic performance of the plants on the basis of previous work [13,28]. The IECM is a widely used computer-modelling program for calculating the performance, emissions, and cost of power plant with/without CCS developed by Carnegie Mellon University with support from the US Department of Energy's National Energy Technology Laboratory (DOE/NETL) [44]. The process performance model calculations are based on fundamental mass and energy balances. The initial investments of the power plants were calculated by Aspen Plus interfaced with the Aspen process economic analyzer for its complete process package of combustion power plant with CCS technologies [13].

2.1 Scope definition, objective and calculation method

Coal/biomass power plants with CCS have the potential to play a critical role in the UK's future low carbon energy mix. In order to guarantee the security of power supply and requirements of CO_2 emissions reduction, these low carbon power generation schemes will be deployed in the near future according to the new low carbon power strategy of the UK government. Hence, six types of power plants w/o CCS are investigated herein: pulverized coal power plant (PC), pulverized coal power plant with post-combustion CO_2 capture (PC-CCS), pulverized biomass power plant (PB), pulverized biomass power plant with post-combustion CO_2 capture (PB-CCS), pulverized coal/biomass co-firing power plant (PCB) and pulverized coal/biomass co-firing power plant with post-combustion CO_2 capture (PCB-CCS). A generic wood pellets biomass used in power plants in the UK are imported from America. Pellet manufacturers in the U.S. South have been a reliable and steadily growing supplier to the U.K. over the past five years, accounting for over 50 percent of the total import volume [45]. The ash yield of wood pellets is 0.2 wt% on a dry basis and moisture content is 7.1 wt%. The elemental composition of biomass sample is C, 44.4; H, 4.6; N, 0.2; S, 0.01; O, 43.5 and the high heat value (HHV) is 18.7 $MJ \cdot kg^{-1}$ on a dry basis (wt%, db). The total coal consumption (2016) of the UK was estimated about 12.7 million tonnes, 1/3 of which was from domestic production, and 12.1 million tonnes coal were used for power generation. Bituminous coal, mainly used by power stations, accounted for 90 per cent of total coal production and 99 per cent of total coal import in the UK [21]. The properties of the coal are as follows: C, 59.6; H, 3.8; N, 1.5; S, 1.8; O, 5.5; Cl, 0.2 and ash, 15.6 (wt%, db), and moisture content, 12 wt% and HHV, 24.61 $MJ \cdot kg^{-1}$ (db). In the PCB and PCB-CCS plant, the blend feedstock is composed of 75% coal and 25% wood pellets on a weight basis. Amine method is used for CO_2 capture in CO_2 captured power plants. The scopes of the life cycle analysis of the above power plants includes the following processes: wood harvest & transport, wood processing at pellets plant, wood pellets transport, port handling & storage, coal mining and washing, coal transport, power generation, CO_2 capture and compression, CO_2 transport and CO_2 sequestration (see **Fig.1**). The basic information of the six plants is presented in **Table 1**.

The method for calculating the total life cycle energy input (TLCEI) per MWh electricity (MJ/MWh) is expressed by Eq. (1).

$$\text{TLCEI} = \frac{\sum_{i=1}^{n} E_i}{\text{Total no. of hrs/yr} * \text{Net electrical output MW}} \qquad (1)$$

where E_i is the energy consumption in the i_{th} sub process.

The total life cycle of CO_2 emissions (TLCCE) per MWh electricity (kg/MWh) is calculated using Eq. (2) based on [46]. This includes CO_2 emissions arising from fuel combustion and during fuel production & transportation.

$$\text{TLCCE} = \frac{\sum_{i=1}^{n} CE_i + CE_{pp} + \sum_{j=1}^{n} CE_j}{\text{Total no. of hrs/yr} * \text{Net electrical output MW}} \qquad (2)$$

where the first term and the third term in Eq. (2) represent the fugitive CO_2 emissions, and CE_{pp} refers to the emissions from fuel combustion. CE_i is the CO_2 emission of the i_{th} sub process in feedstock supply chain, and CE_j is the CO_2 emission of the j_{th} sub process in CO_2 compression, transport and storage.

Accordingly, the total life cycle cost input (TLCCI) per MWh electricity (kg/MWh) can be written by Eq. (3).

$$\text{TLCCI} = \frac{\sum_{i=1}^{n} C_i + C_{pp} + V_{pp}}{\text{Total no. of hrs/yr} * \text{Net electrical output MW}} \qquad (3)$$

where $\sum_{i=1}^{n} C_i$ is the total cost input of the i_{th} sub process from coal/biomass supply chain and CO_2 transport and storage, £/yr. The second item is the annualized capital cost of power plant and the last item is annual variable cost, £/yr. Herein, the total life cycle cost input can also be regarded as the cost of electricity (COE) for power plants based on the previous study [13]. It is worth note that the life cycle energy consumption and CO_2 emissions are limited in fuel production and transport, and those during equipment manufacturing and infrastructure construction are not included.

The annual capital cost (ACC) (£) is annualized through formula (4).

$$\text{ACC} = \frac{\text{Capital cost}}{1 - (\text{DR\%} + 1)^{-\text{lifetime}}} \qquad (4)$$

where DR% is discount rate percentage, 10% [47]; lifetime represents the plant life (20 years) [13]. Annual variable cost is the sum of O&M costs and labour costs, and 4% of capital cost is added as O&M costs, and labour costs is dependent on the number of staffs [48], and the labour rate is set as 30.25 £/h [13].

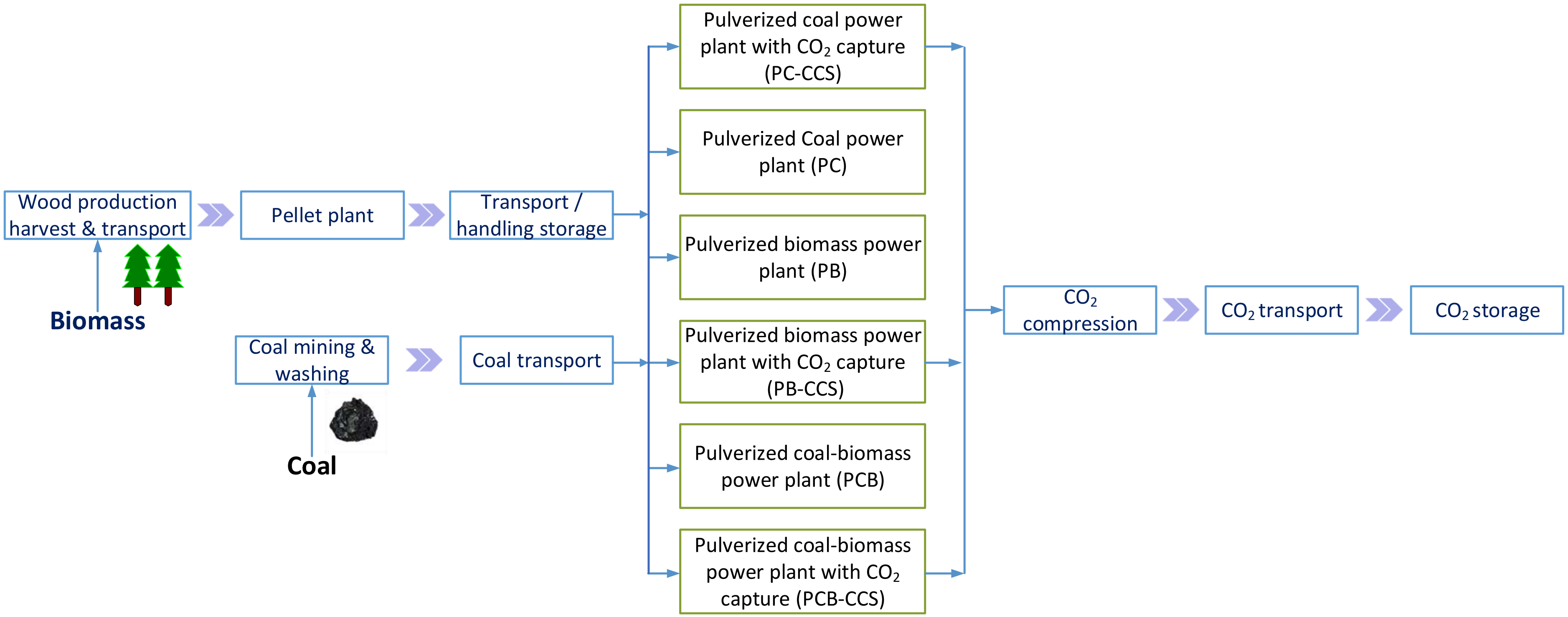


Fig. 1. Life cycle scope of coal/biomass power plants w/o CCS

Table 1 Key parameters and plant configuration for life cycle analysis

Parameter	PC	PC-CCS	PB	PB-CCS	PCB	PCB-CCS
Feedstock type	Bituminous coal		Wood pellets		Bituminous coal +25 wt% wood pellets	
Gross plant size, MW	650	650	650	650	650	650
Net power output, MW [13, 28]	605	526	607.4	500	605.5	520.8
Plant life, y	20	20	20	20	20	20
Capacity factor, % [13,28]	85	85	62.3	62.3	85	85
Feedstock input, t/h	231.1	270	311.3	364.1	246.2	302.5
Net plant efficiency, HHV% [13,28]	38.3	28.5	37.56	26.44	38.27	26.8
CO_2 capture efficiency, %	90	90	90	90	90	90
Capital cost required, £/kW [13,28]	1184	2236	1132	1171	1187	2244

2.2 Life cycle inventory analysis

LCI is a tool used to collected resource and material use, energy input, and air pollutant emissions for each stage of LCA, in which the data show corresponding quantities per functional unit.

Wood biomass is harvested and often chipped, before it is transported to pellets plant. The transportation of the harvested biomass is usually done by truck or by railway, the most common methods for inland transporting of pellets [49]. The transporting stage is however not considered individually in this study, since these costs are limited due to harvesting ground being relatively close to the pellet factory and included in the feedstock price [50]. At the pellets plant, the untreated biomass is refined through drying, size reduction and pelletization etc. to increase its' energy density and make it more suitable for transport [50]. After being upgraded, the biomass is distributed to consumers. The distribution can be composed of several stages of transport with transhipment and storage between them depending on the distance and the conditions. Taking transatlantic exports as an example, includes transport to a port, ocean shipping and finally delivering to end users in the importing country. When delivered, the biomass is stored then consumed after milling. According to the application of the end user, biomass handling would differ. The application also has significant effects on the implementation of biomass, for example co-firing with coal process.

The actual first stage is transportation of the pellets from the pellets plant to a loading port, the second is ocean shipping and the last is from the receiving port to the end user. A summary of biomass or coal+biomass power plants in England are listed in **Table 2** [51-52]. It is clear that both Drax and Drax Ouse are the largest power stations with blend feedstocks or biomass in the UK, and have huge potential in utilization of biomass in the near future. Hence, Drax power station as a typical case will be investigated in the following. In this study, this means the pellets are transported by rail

149 km from Tifton, Georgia (U.S.), to the port of loading in Savannah where it is transhipped to a Handymax ship with 45,000 ton capacity [53]. It is shipped about 7500 km to the port of Hull, UK, from where it is transported by trucks the last 50 km to

Table 2 The typical coal+biomass or biomass power plants in England

Name	Location	County	Region	Type	Total net capacity (MW)	Opened	Steam parameters	Feedstocks
Didcot A	Didcot	Oxfordshire	South East	Coal + Biomass	2109	1968 (2013 closed)		
Drax	Selby	North Yorkshire	Yorkshire and the Humber	Coal + Biomass	3906	1974	565 ^oC,166 bar	Coal, wood and petcoke
Fiddlers Ferry	Widnes– Warrington	Cheshire	North West	Coal + Biomass	1989	1971		
Lynemouth	Lynemouth	Northumberland	North East	Coal + Biomass	420	1972		Coal, sawdust and Wood pellets
Drax Ouse	Selby	North Yorkshire	Yorkshire and the Humber	Biomass	300	Plan		
Wilton 10	Wilton	Redcar and Cleveland	North East	Biomass	30	2007	SST 400 steam turbine/generator set	Sawmill waste and wood
Stallingborough Biomass	Stallingborough	North East Lincolnshire	Yorkshire and the Humber	Biomass	65			Wood-based material
Teesport	Teesport	Redcar and Cleveland	North East	Biomass	300	2013	540 ^oC, 112 bar	Wood pellets and chips
Immingham Heron	Immingham Docks	North East Lincolnshire	Yorkshire and the Humber	Biomass	290	Plan		
Brigg Biomass	Brigg	North Lincolnshire	Yorkshire and the Humber	Biomass	40	2012	540 ^oC, 112 bar	Straw
Glanford	Scunthorpe	North Lincolnshire	Yorkshire and the Humber	Biomass	13.5	1993	450^oC, 67 bar	
Blackburn Meadows Biomass	Blackburn Meadows	Sheffield	Yorkshire and the Humber	Biomass	25	2014		Waste wood
Barton-upon-Irwell				Biomass	20	TBD		
Steven's Croft	Dumfries and Galloway	Scotland	Southwest Pacific	Biomass	44	2008	537 ^oC, 137 bar	60% sawmill coproducts and small round wood; 20% short rotation coppice (willow); 20% recycled fibre
Sleaford	Sleaford	Lincolnshire	East Midlands	Biomass	40	2014	540 ^oC, 112 bar	Straw

a combined coal/biomass plant (Drax power plant). The storage and handling costs at the port of Savannah are were indicated to be £ 4.5 per tonne [50]. Once onshore in the UK, imported biomass may be transferred to store a short distance from the dock, with an additional £ 6.5/t for handling & storage [54].

Currently, only opencast mining of coal takes place in the UK due to the closure of all the deep, coal mines in recent years. It is unlikely that these will be re-opened in the foreseeable future. According to the distribution of coal mines in the UK, it is found that several opencast mines such as Northumberland, Kirklees, Derbyshire and Telford & Wrekin etc. are located beside the Drax power station and coal is transported by rail to the power plant at the range of 50-150 km [55]. The average energy consumption for mining and washing is estimated at 0.9 MJ/MWh based on [46,56]. As for coal transportation, energy use is similar to any other commodity and largely depends on the transportation mode, the type of fuel used and the fuel efficiency. The average energy consumption is 203 kJ/t/km diesel oil and 78 kJ/t/km electricity for typical railway coal transportation [46]. The fugitive CO_2 emissions during coal (mining & washing) and transport are also considered in this paper, which are reported to be 19 g/kWh and 1 g/kWh, respectively, for coal power plant in the UK [40]. Mining and washing cost (including the coal feedstock price) is estimated to be £52 per tonne. According to the research inquiry held by the Energy and Climate Change Committee, evidence was provided that UK coal operators required a coal selling price of between £52.50 and £55 per tonne in Europe to be profitable [57]. Rail costs for coal transport (the study showed that using rail is a cheaper method compared to road transportation) is estimated £ 2.12 per tonne within 100 km in the UK [58].

CO_2 captured from the amine process will be compressed to supercritical state (11 MPa) for transportation. Generally, saline aquifers, enhance oil recovery (EOR), enhance coal bed methane (ECBM), and enhance gas recovery (EGR), etc. are common methods for CCS or CCUS. CO_2 storage in aquifers is considered in this study duo to its huge capacity for CO_2 storage. Pipeline is regarded as one of the cheapest and most commonly used methods for large scale and long distance CO_2 transportation [46]. Furthermore, the captured CO_2 emissions during compression pipeline transportation and sequestration are also considered. According to the methodology developed by the IPCC report, the captured CO_2 emissions is 7.0-116.1 t CO_2/MW/y from compressor and 0.2-23.2 t/km/y from pipeline transportation [59]. CO_2 is assumed to be recompressed from 10.76 to 15 MPa, a typical value for geological storage in some existing operational projects, before injection into the underground. Electricity use for recompression calculated to be 7 kWh electricity consumption per 1 ton of CO_2. The total CO_2 emission factor of aquifer storage is 7.01 kg CO_2 /t CO_2 [60]. Besides, it is assumed that 50 km pipeline is recommended since most CO_2 capture plant matched to its nearby storage site. All the basic information involved with energy consumption, CO_2 emissions and cost input for life cycle different stages of coal/biomass plants based on the literatures are calculated and summarized in **Table 3**.

Table 3 Input data for energy input, CO_2 emissions and cost input

Parameter	Unit	Value
Energy consumption		
Coal mining & washing [46,56]	MJ/MWhe	0.9
Coal transport (by rail) [46]	MJ/ t*km	0.281 (100km)
Wood production harvest & transport [53]	$MJ/MWh_{-biomass}$	9.9
Wood processing in pellets plant[53]	$MJ/MWh_{-biomass}$	573.3
Handling & storage[53]	$MJ/MWh_{-biomass}$	3.8
Wood pellets transport to port (by rail)[53]	$MJ/MWh_{-biomass}$	11.1
Wood pellets ocean transport [53]	MJ/t*km	0.03
Wood pellets transport to power plant (by truck)[53]	MJ/t*km	2.3
CO_2 compression[39]	kWh/tCO_2	111
CO_2 storage (injection compression)[39]	kWh/tCO_2	7
CO_2 emissions		
Coal mining & washing [40]	g/kWh	19
Coal transport (by rail) [40]	g/kWh	1
Wood production harvest & transport [53]	$kgCO_2/t$	1.6
Wood processing in pellets plant [53]	$kgCO_2/MWh_{-biomass}$	12.2
Handling & storage [53]	$kgCO_2/MWh_{-biomass}$	0.28
Wood pellets transport to port (by rail) [53]	$kgCO_2/t*km$	0.01
Wood pellets ocean transport [53]	$kgCO_2/t*km$	0.004
Wood pellets transport to power plant (by truck) [53]	$kgCO_2$ /t*km	0.12
CO_2 compression (fugitive CO_2 emission compressor) [39]	$tCO_2/MW/yr$	23.2(7.0-116.1)
CO_2 transport (fugitive CO_2 emission pipeline) [39]	$tCO_2/MW/yr$	2.32(0.2-23.2)
Fugitive CO_2 emission from CO_2 storage [60]	kg CO_2 /t CO_2	7.01
Cost input		
Coal mining & washing	£/t	52
Coal transport (by rail) [58]	£/t	2.12
Wood production harvest & transport [53]	$£/MWh_{-biomass}$	10.97
Wood processing in pellets plant [53]	$£/MWh_{-biomass}$	8.47
Wood pellets transport to port (by rail) [53]	$£/MWh_{-biomass}$	2.19
Load port handling & storage [50]	£/t	4.5
Wood pellets ocean transport [53]	£/MWh*km	0.00036
Receiving port handling & storage [51]	£/t	6.5
Wood pellets transport to power plant (by truck) [54]	£/t*km	0.46
CO_2 transport & storage [13]	£/t-CO_2	25.275

3. Results and discussion

3.1 Life cycle inventory

On the basis of scope range and data input, the life cycle energy input, CO_2 emissions and cost input of the different biomass/coal–fired power plants are calculated, compared and discussed below.

3.1.1 Life cycle analysis of biomass fired power plants

Fig.2 shows the energy input required by the whole production chain for power plant using wood pellets feedstock. With the same gross power output (650 MW), PCB-CCS requires 273.9 MW more wood biomass feedstock compared to PCB. The most energy intensive sub-process during biomass production is wood drying and pelletization at the pellets plant, which shares 1526.4 MJ/MWh and 2168.4 MJ/MWh for PCB and PCB-CCS, respectively. Besides, CO_2 compression and transport also contributes a large part of energy consumption in PCB-CCS, reaching up to 432.1 MJ/MWh.

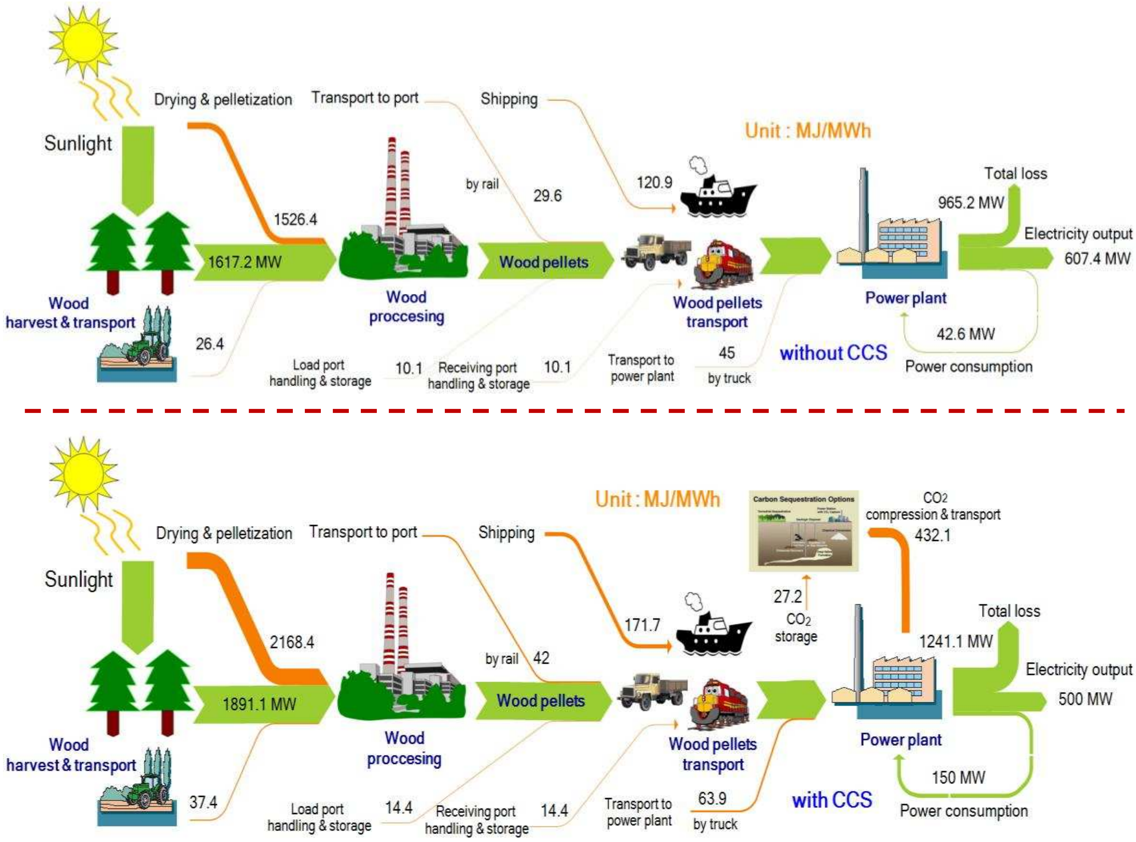


Fig.2 Energy input distributuion in life cycle subprocess of the PB/PB-CCS plants

The estimated total life cycle CO_2 emissions of PB is 898.85 kg CO_2/MWh, of which 53.15 kg CO_2/MWh is released from wood biomass harvesting, processing and transportation processes (see **Fig.3**). The remaining 845.7 kg CO_2/MWh is released in the form of flue gas which can be absorbed by biomass during its growth. Clearly, the major CO_2 emission is from wood processing (32.5 and 46.1 kg CO_2/ MWh) at the pellets plant for both power plants. Regarding the PB-CCS plant, the total CO_2 emission from biomass combustion is 1201.4 kg CO_2/MWh, of which 1081.3 kg CO_2/MWh is captured. CO_2 emission during the biomass supply chain process is 75.5 kg CO_2/MWh, whereas CO_2 compression, transport and storage account towards 9.6 kg CO_2/MWh, and uncaptured CO_2 also contributes emission of 120.1 kg CO_2/MWh. The net CO_2 emission of PB-CCS is 205.2 kg CO_2/MWh, which is lower than that consumed during biomass growth. Hence, PB-CCS power plant can be regarded as a CO_2 negative emission power generation technology from a lifecycle viewpoint.

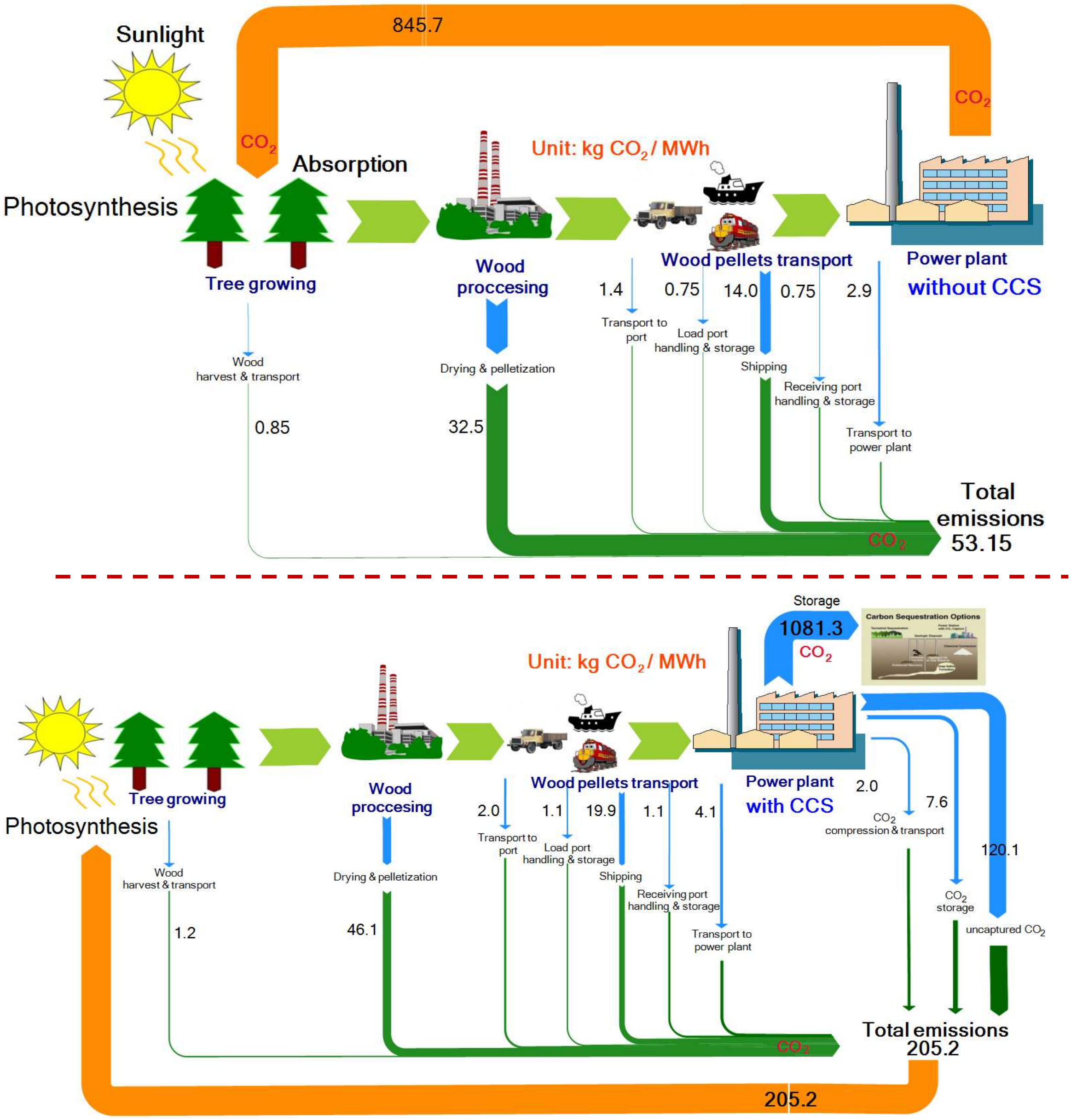


Fig.3 CO_2 emissions in life cycle subprocess of the PB/PB-CCS plants

The life cycle cost input of PB and PB-CCS are 116.7 and 206.6 £/MWh (see **Fig.4**), respectively. The two largest costs depleting processes in biomass supply chain are wood production & transport and wood processing which accounts for about 30-45% of the electric cost. Besides, annual capital cost is another significant component of COE, costing 26.2 £/MWh for PB and 49.7 £/MWh for PB-CCS. Compared to PB, the cost of wood biomass from harvest to user increases by 35.4 £/MWh, the annual capital cost increases by 23.5 £/MWh and O&M and labour costs increase by 3.7 £/MWh in PB-CCS. In addition, CO_2 capture, transport and sequestration also brings about the cost increase of 27.3 £/MWh.

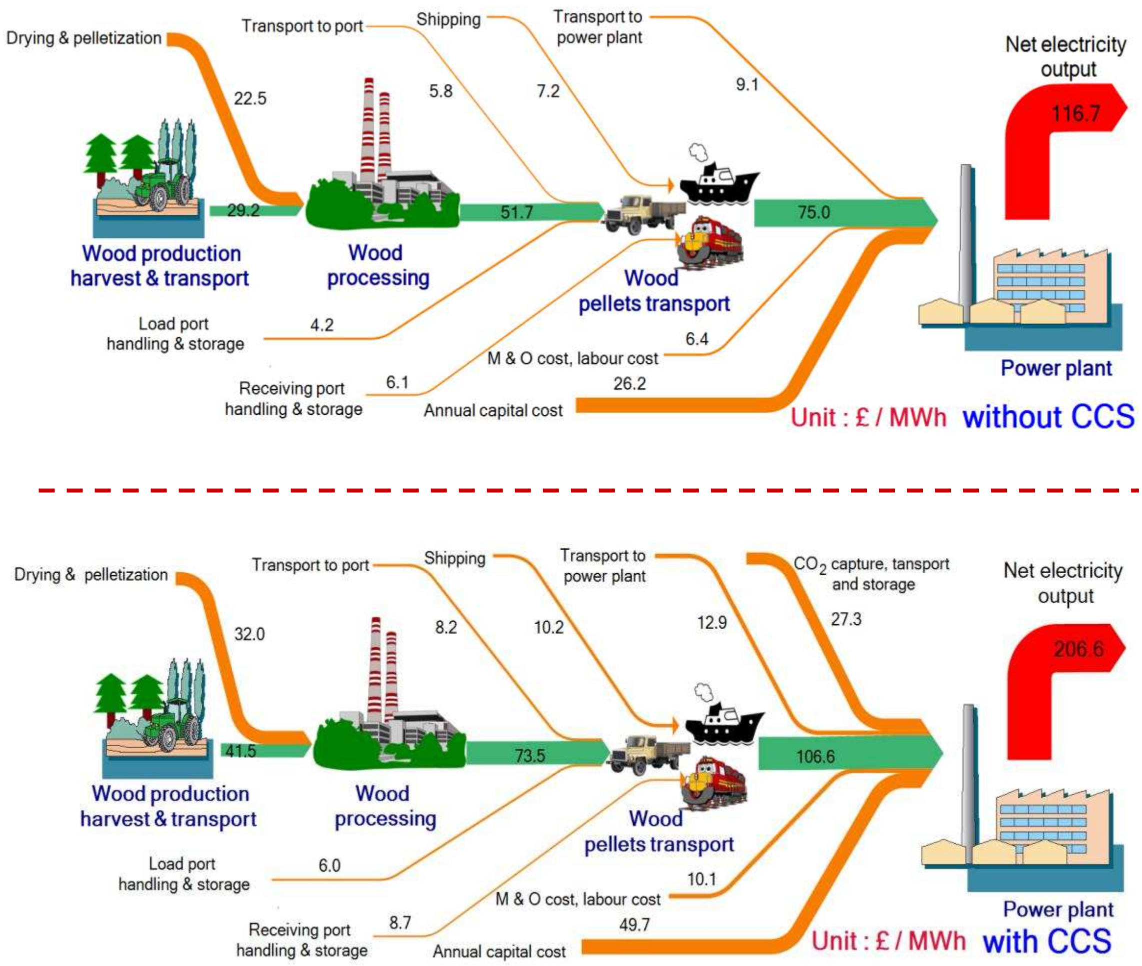


Fig.4 Cost input in life cycle subprocess of the PB/PB-CCS plants

3.1.2 Life cycle analysis of coal fired power plants

Fig.5 shows the life cycle energy input, CO_2 emissions and cost input of PC/PC-CCS plants. With the same gross power output (650 MW), the total energy input is 730.7 MJ/MWh for PC and 1411.7 MJ/MWh for PC-CCS. Coal feedstock required for PC and PCB-CCS are 1579.6 and 1845.6 MW, respectively. The energy input mainly comes from coal mining and washing. However, CO_2 compression, transport and storage lead to extra energy consumption of 429.8 MJ/MWh for PCB-CCS. Flue gas from PC is the major contributor towards CO_2 release sharing about 97% (834.7 kg CO_2/ MWh) of the total CO_2 emissions (854.7 kg CO_2/ MWh). However, 90% of CO_2 is captured at the plant while allowing only 112.2 kg CO_2/ MWh to be released into the atmosphere. Nevertheless, CO_2 compression, transport and storage will give rise to indirect CO_2 emissions of 8.9 kg/MWh. Coal mining & washing cost, CO_2 transportation & sequestration cost and the annual capital cost are the main components of the total cost input in PC/PC-CCS. The life cycle cost input is 57.8 £/MWh for PC and 111.8 £/MWh for PC-CCS. Obviously, PC-CCS leads to extra cost of 25.5 £/MWh caused by CO_2 transportation & sequestration, and an additional 19.1 £/MWh annual capital cost compared to PC.

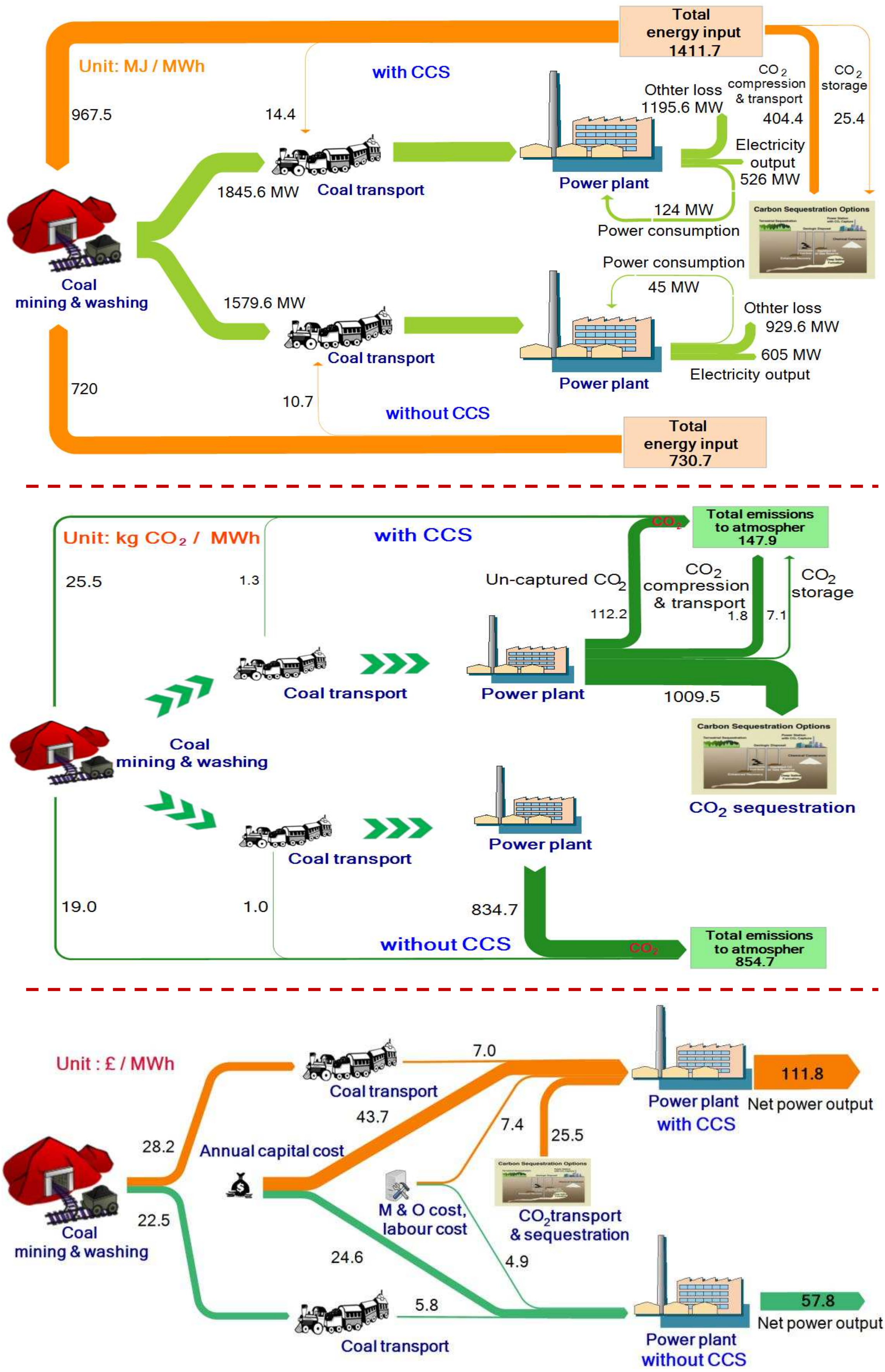


Fig.5 Life cycle energy input, CO_2 emissions and cost input of the PC/PC-CCS plants

3.1.3 Life cycle analysis of coal+biomass-fired power plants

The life cycle energy input, CO_2 emissions and cost input of PCB/PCB-CCS are presented in **Fig.6**. The blend feedstock is composed of coal (75 wt.%) and wood pellets (25 wt.%). The blend feedstock input into the PCB and PCB-CCS plants are 1582.3 and 1943.5 MW, respectively. The total energy input, CO_2 emissions and cost input per MWh electricity are 840.5 MJ/MWh, 829.8 kg CO_2/MWh and 65.4 £/MWh for PCB and 1632.3 MJ/MWh, 155.6 kg CO_2/MWh and 130.4 £/MWh for PCB-CCS, respectively. The net power output of PCB (605.5 MW) is nearly the same as PC (605 MW). However, the total energy input of PCB (840.5 MJ/MWh) is higher than that of PC (730.7 MJ/MWh) due to higher energy consumption during the biomass supply chain process compared to coal supply chain. Besides, the low heat value and carbon content of biomass leads to an increase in feedstock input flowrate and a decrease in CO_2 content in the flue gas, therefore the PCB-CCS plant consume more energy to capture CO_2 in comparison to the PC-CCS. Accordingly, the CO_2 emission life cycle and cost input of PCB/PCB-CCS are higher than that of PC/PC-CCS with pure coal feedstock.

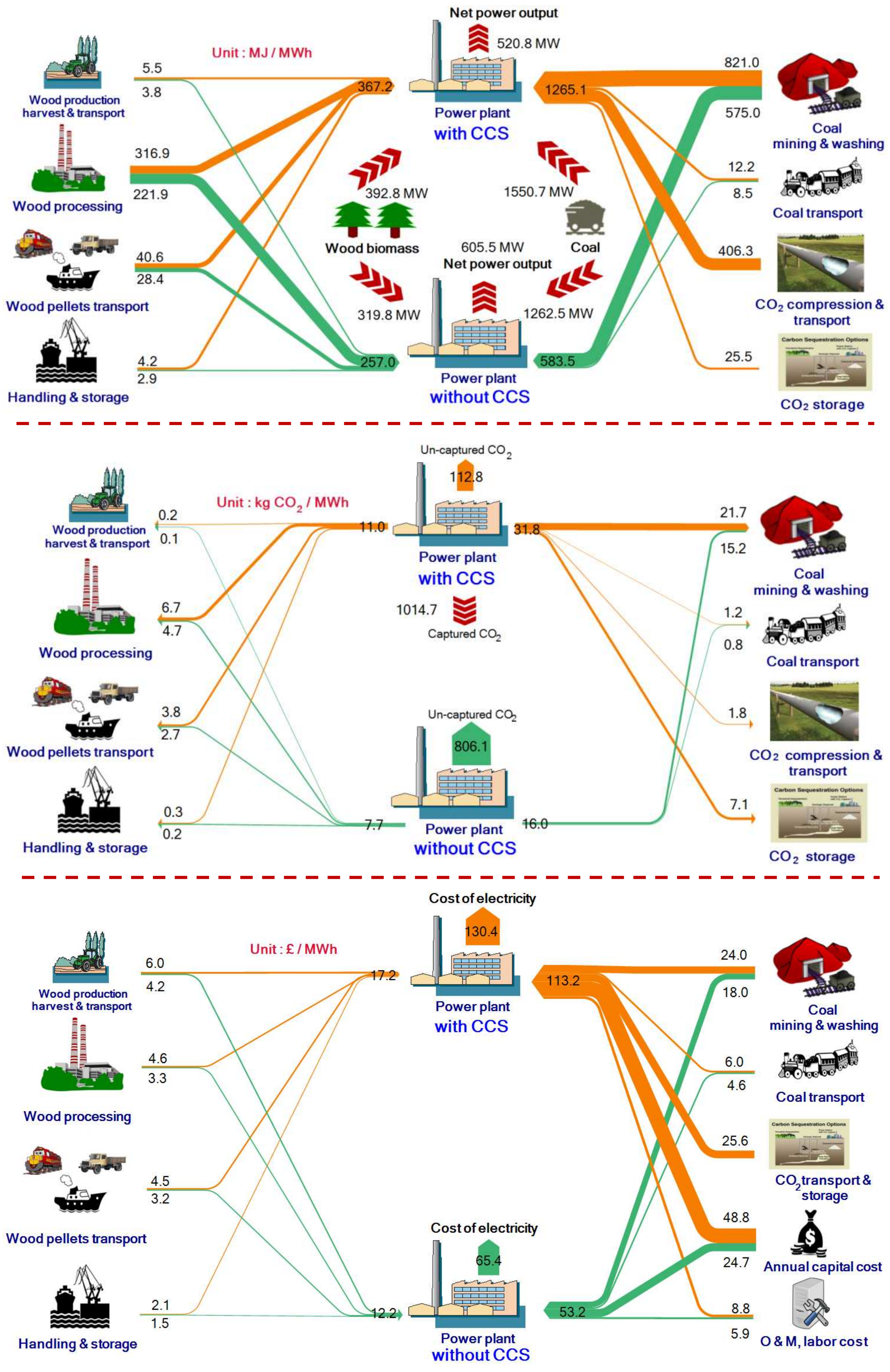


Fig.6 Life cycle energy input, CO_2 emissions and cost input of the PCB/PCB-CCS plants

3.1.4 Summary and comparison of life cycle analysis of coal/biomass w/o CCS

A summary of the results is presented in **Fig 7**. **Fig.7a** presents the total energy input, **Fig.7b** the CO_2 emissions and **Fig.7c** the costs input. PC demonstrates the lowest total life cycle energy input compared to the other five power plants. The life cycle energy input of PB and PB-CCS are higher than those of PC and PCB w/o CCS power pathways mainly due to high energy consumption from wood processing at pellets plant in biomass supply chain. CO_2 compression, transport and storage accounts for nearly 1/3 of the total energy input of the CO_2 capture plant.

The life cycle CO_2 emissions of power plants without CO_2 capture range from 830 to 900 kgCO_2/MWh. Less CO_2 is released to the atmosphere using PC-CCS/PB-CCS/PCB-CCS due to 90% of CO_2 captured, and it is estimated to be below 210 kg CO_2 per MWh net electricity output. The carbon emissions mainly come from uncaptured CO_2 in the exhaust gas. However, as to power plants with biomass or blend feedstock, the emitted CO_2 from biomass combustion can be consumed during biomass growth. Therefore, the CO_2 emissions are lower than the actual discharge from a lifecycle viewpoint. For instance, the life cycle CO_2 emissions of the PB and PB-CCS are 900 and 205 kg CO_2 /MWh respectively, as presented in the **Fig.7b**. Nevertheless, the life cycle CO_2 emission also can be estimated to be 53.15 kg CO_2 /MWh for PB and negative emission for PB-CCS when CO_2-neutral cycle in ecological system is considered in life cycle. In this case, PB will be the better power generation pathway, as it simultaneously considers energy use and CO_2 emissions.

PB-CCS shows the highest total life cycle cost input of 206.6 £/MWh, while PC presents the lowest cost input of 57.8 £/MWh. The cost mainly comes from biomass supply chain for PB and PB-CCS plants. As for CO_2 captured power plants, CO_2 transport & storage contributes to about 25-30 £/MWh increase of cost input. Besides, the capital cost for power plants including CO_2 captured increases to approximate two times compared to the power plants without CCS. On the basis of the above analysis, biomass power plants have no obvious advantages in both energy use and cost saving in comparison with PC and PCB w/o CCS. Seeking an efficient and low-cost biomass supply chain will be an effective solution to promote biomass power plant application.

In addition, carbon tax policy and the specific subsidy on captured emissions from BECCS (Renewable Obligation Certificates (ROCs) price) will be the significant incentives for boosting the commercialization of PB /PCB -CCS power generation technologies based on the investigation of our previous work [13, 61-62].

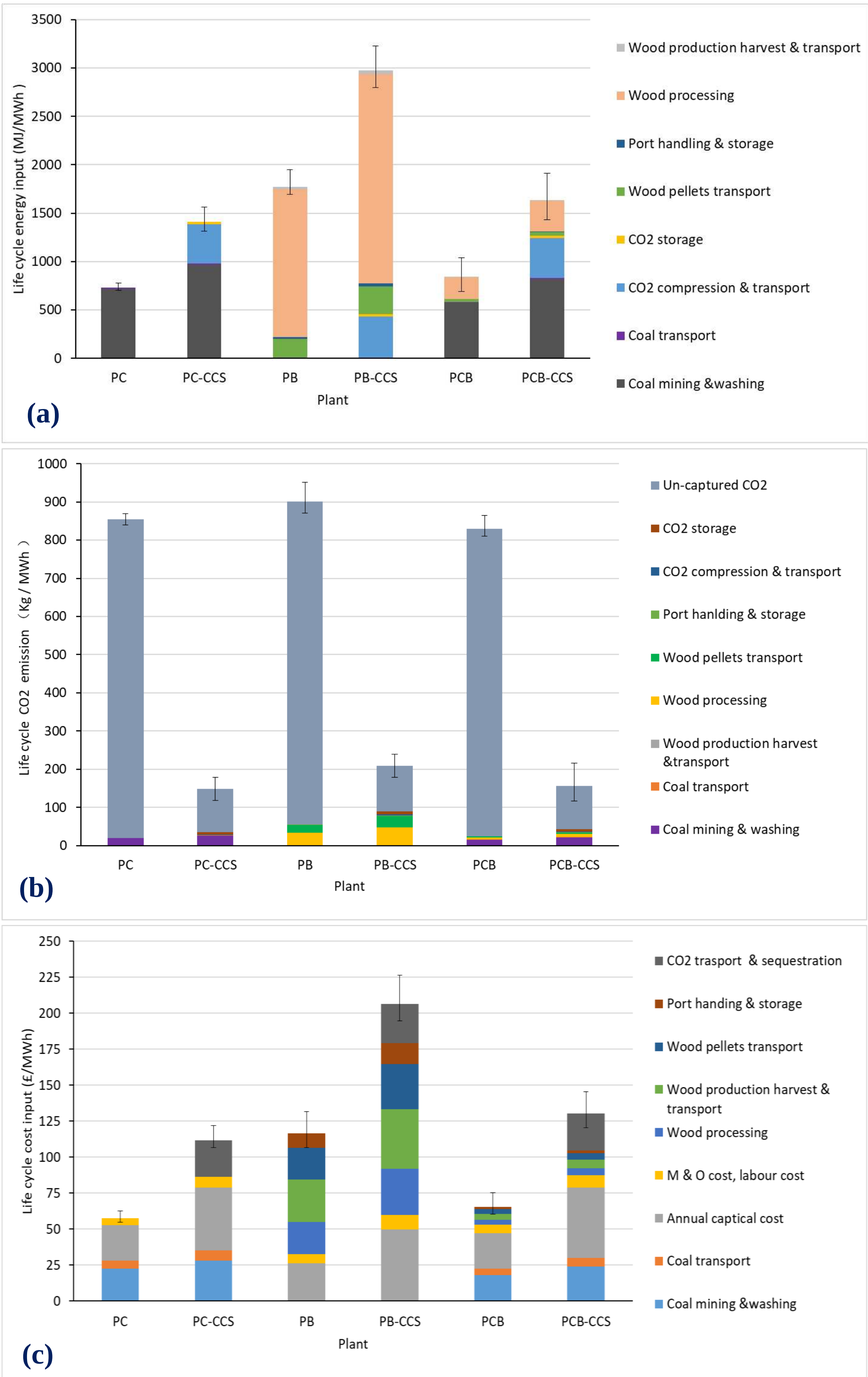
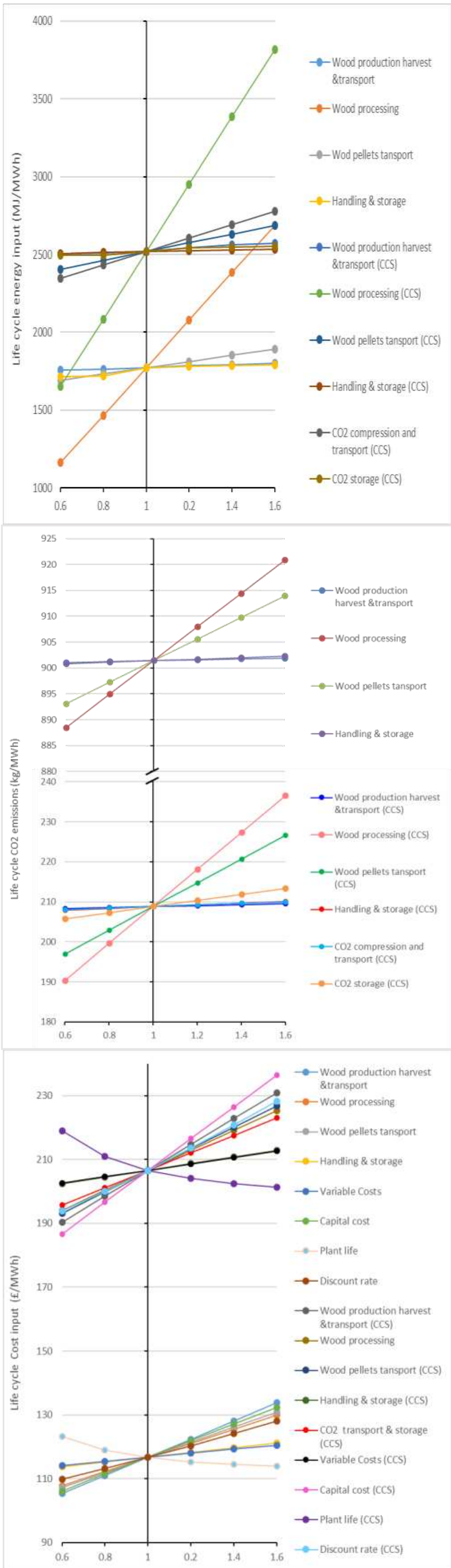


Fig. 7 Comparison of life cycle energy input-CO_2 emissions-cost input

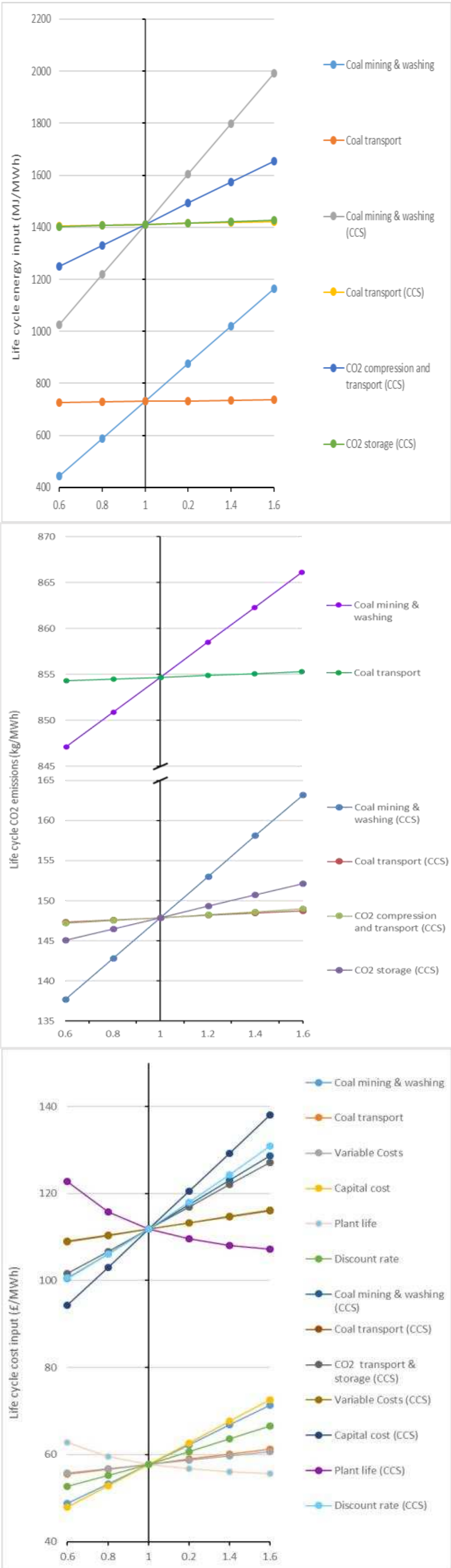
3.2. Life cycle impact assessment

3.2.1 Sensitivity or uncertainty analysis

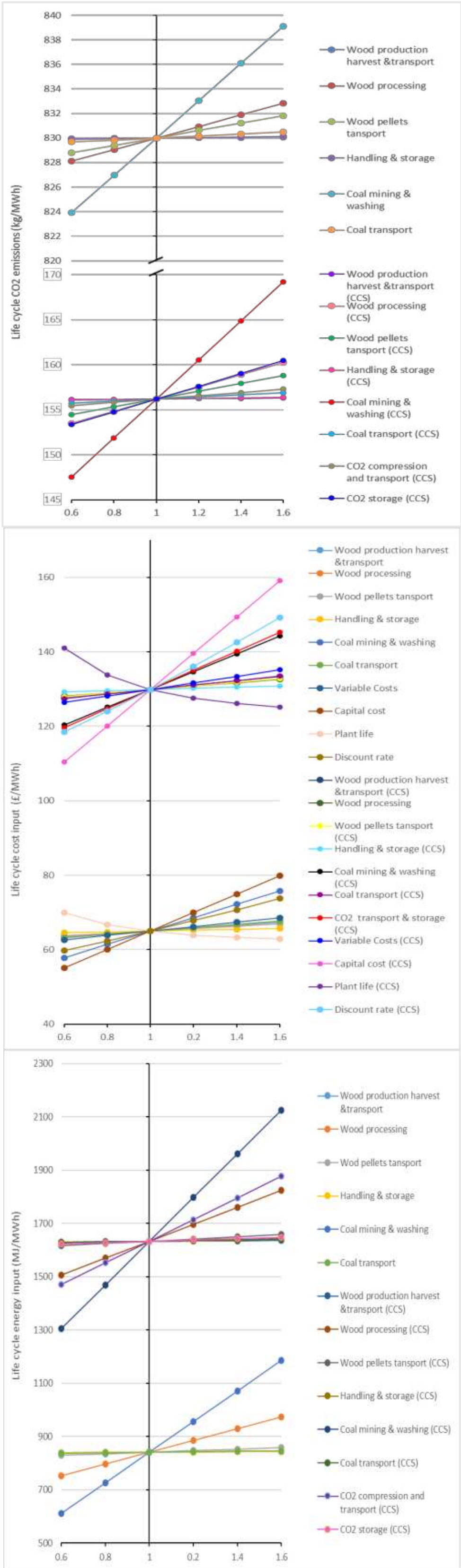
It is noted that some outdated data are used for the life cycle analysis, since it is very difficult to obtain all the latest figures. Besides, these data will also change as time passes and technologies develop. Therefore, a sensitivity or uncertainty analysis has been performed to find which parameters have a significant effect on the final results. The basis data of energy input, CO_2 emissions and cost input involved for coal and the biomass supply chain as well as CO_2 compression, transport and storage process have been selected for the sensitivity analysis over the expected range of parameters variation for PC/PB/PCB power plants w/o CCS as presented in **Fig.8**. In addition, the parameters related to the economic evaluation such as capital cost, variable cost, plant life and discount rate are also considered in sensitivity analysis. The total life cycle energy input is most sensitive to the energy required during wood processing for PB w/o CCS, and coal mining & washing and CO_2 compression & transport for PC/PCB w/o CCS. Accordingly, wood processing for pellets production has the greatest impact on total CO_2 emissions for PB plants, and can bring about 10 % variation in total CO_2 emission when CO_2 emissions of wood processing rises up or drops by 40%. Moreover, CO_2 emissions of PC/PCB power plants are very sensitive to coal mining & washing. Regarding the PC/PB/PCB power plants, feedstock cost (the cost of biomass harvest & transport and coal mining & washing) is a significant factor on the total cost input; as for the PC/PB/PCB-CCS power plants, capital cost become the dominant factor, varying it by 40% leads to cost input changing by about 15 £/MWh. Besides, reducing the biomass transport distance is also worth a mention. At the same time, the total cost input of all investigated power plants decreases with increasing plant life, and 30 years for the plant life will be a better index in reduction of cost. The results imply that technology reforming and improving to reduce energy consumption in processes of wood pellets production, coal mining & washing as well as CCS process is the main challenge for cutting down life cycle energy input and CO_2 emissions of power plants. Additionally, using cheap biomass resource and reducing capital cost (especially for CCS power plants) are the most effective ways to enhance the economic performance of power plants.



(a) Pulverized biomass power plant



(b) Pulverized coal power plant



(c) Pulverized coal/biomass co-firing power plant

Fig. 8 Sensitivity of life cycle energy input, CO_2 emissions and cost input of coal/biomass power plants w/o CCS

4. Conclusions

In the past, coal as a main energy source has played an important role supplying electricity in the UK due to its wide availability, stability of supply and cost. Nevertheless, utilization of coal leads to high CO_2 emissions. Biomass to power as an alternative technology has received extensive attention recently due to its sustainability and being carbon neutral. On the basis of commercialized coal-biomass combined pulverized power plants in the UK, this study presented an analysis on energy-economy-CO_2 emission performance of coal/biomass power plants w/o CCS technology, including the feasibility, economics and environmental impacts of these power plants from the life cycle viewpoint in the UK. Significant conclusions drawn from the analysed results are presented as follows:

1) From a life cycle viewpoint, the CO_2 released due to power generation dominates the total lifecycle CO_2 emission. PB can produce electricity with near carbon-neutral with relatively little CO_2 emissions are from biomass supply chain, while PB-CCS can produce negative-emissions of CO_2. Using CCS can reduce CO_2 emissions during generation to a level that can meet the targets applied in the UK. However, the emissions from upstream processes (coal and biomass supply chain) become dominant especially for PB-CCS, of which CO_2 emissions from biomass supply chain reach up to 90 kg/MWh, accounting for near 50% of the total life cycle CO_2 emissions. Biomass/coal feedstock source, wood pellets processing technology and coal mining & washing methods will play a significant role in determining the final CO_2 emission.
2) In regards to the energy use, power plants with coal feedstock showed advantages compared to wood pellets. The total energy input of coal during the supply chain is lower than that of biomass feedstock, as a large amount of energy consumption from wood transport and wood processing involved with drying, size reduction,

palletization and cooling etc. at pellets plant. CO_2 compression, transport and storage also give rise to an extra energy consumption of 500 MJ per MWh electricity production which accounts for nearly 30% of the total life cycle energy input. This means that energy-effective wood pellets processing and CCS technologies are urgent to develop in the near future.

3) The economic performance of biomass power plants is inferior to that of coal power plants. The high cost input from biomass supply chain is the dominant reason. In addition, using CCS will lead to about 100% increment of capital cost as well as extra 25-30 £/MWh from CO_2 transport & storage compared to power plants without CCS.

4) To reduce the total life cycle energy input and CO_2 emissions, it is imperative to cut down energy consumption in the key processes related to wood pellets processing, coal mining & washing as well as CCS process by technology upgrading. Biomass power plants at present time do not show advantages over coal power pathways in terms of life cycle energy use and cost effectiveness, yet, with the technology still progressing, lower life cycle energy input and lower costs are possible. When energy security, environmental protection and its energy efficiency improvement potentials are all considered, biomass power generation will still be a promising pathway. Development and utilization of advanced technologies to reduce capital cost and seeking low-cost biomass resource (such as the local industrial biomass waste, agricultural biomass and forest biomass etc.) will be the most effective way to boost the economic performance of power plants.

5) The results showed that coal or coal and biomass co-firing power plants with CCS presented disadvantage in economy feasibility at current status. However, in a scenario with new coal power plant and CCS technology deployment in the UK, local coal will be insufficient to meet the requirements of the power sector and a

large quantity of coal will be imported from the neighboring countries in Europe or wider afield on the open market. In that case, the cost of electricity of coal-based power plant will be significantly reduced due to cheap coal feedstock from the imported countries. By then, coal power plant with CCS can be a low carbon, economic pathway of power generation, and biomass (from local cheap biomass resources) combined with coal as feedstocks will be a better scheme for power generation both considering sustainability and economic feasibility.

At present, the specific policy and economic support from the government (such as carbon tax policy and ROCs price) is necessary for facilitating the commercialization of power generation with CCS technologies. Nevertheless, technological progress is the final driving force for wide application and industrialization of coal/biomass power generation coupled with CCS in the long-term future.

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Nomenclature

Abbreviations

C_i = cost input of the i_{th} sub process in feedstock supply chain and CO_2 transport and storage

CE_i = CO_2 emissions of the i_{th} sub process in feedstock supply chain

CE_j = CO_2 emissions of the j_{th} sub process in CO_2 compression, transport and storage

CE_{pp} = CO_2 emissions from fuel combustion

C_{pp} = annual capital cost

E_i = energy consumption in the i_{th} sub process

db= dry basis

hrs = hours

V_{pp} = annual variable cost

yr = year

Acronyms

ACC= annual capital cost

BECCS= bio energy with carbon capture and storage

CCS= carbon capture and storage

CCUS= carbon capture use and storage

COE = cost of electricity

DOE/NETL= Department of Energy's National Energy Technology Laboratory

DR= discount rate

EOR= enhance oil recovery

ECBM= enhance coal bed methane

EGR= enhance gas recovery

GHG = greenhouse gas

HHV = high heat value

IECM= Integrated Environmental Control Model

LCA= life cycle assessment

LCI= life cycle inventory

LCIA=life cycle impact assessment

MEA= monoethanolamine

O&M= management and operation

PC= pulverized coal power plant

PCC= post combustion capture

PC-CCS= pulverized coal power plant with post-combustion CO_2 capture

PB= pulverized biomass power plant

PB-CCS= pulverized biomass power plant with post-combustion CO_2 capture

PCB= pulverized coal/biomass co-firing power plant

PCB-CCS= pulverized coal/biomass co-firing power plant with post-combustion CO_2 capture

ROCs= Renewable Obligation Certificates

TLCCE= total life cycle of CO_2 emissions

TLCCI= total life cycle cost input

TLCEI= total life cycle energy input

UK= United Kingdom

WWP= white wood pellets

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