This is a repository copy of *Evaluation of life cycle energy, economy and CO2 emissions for biomass chemical looping gasification to power generation*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/174020/

Version: Accepted Version

Article:

Mohamed, U., Zhao, Y.-J., Yi, Q. et al. (3 more authors) (2021) Evaluation of life cycle energy, economy and CO2 emissions for biomass chemical looping gasification to power generation. Renewable Energy, 176. pp. 366-387. ISSN 0960-1481

https://doi.org/10.1016/j.renene.2021.05.067

Article available under the terms of the CC-BY-NC-ND licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).

Reuse

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Evaluation of Life Cycle Energy, Economy and CO_2 Emissions for Biomass Chemical Looping Gasification to Power Generation

Usama Mohamed [a,c], *Ying-jie Zhao* [c], *Qun Yi* [*a,b,c], *Li-juan Shi* [b,c], *Guo-qing Wei* [d], *William Nimmo* [*a]

[a] *Energy 2050 Group, Faculty of Engineering, University of Sheffield, S10 2TN, UK*

[b] *School of Chemical Engineering and Pharmacy, Wuhan Institute of Technology, Wuhan, 430205, P.R. China*

[c] *College of Environmental Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, PR China.*

[d] *Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences (CAS), Guangzhou, 510640, P. R. China*

Abstract:

A life cycle energy use, CO_2 emissions and cost input evaluation of a 650 MW Biomass Chemical Looping Gasification Combined Cycle (BCLGCC) and Biomass/Coal Integrated Gasification Combined Cycle (BIGCC/CIGCC) power generation plants with and without (w/o) CO_2 capture & storage (CCS) are analysed. These were then compared to coal/biomass combustion technologies. The life cycle evaluation covers the whole power generation process including biomass/coal supply chain, electricity generation at the power plant and the CCS process. Gasification power plants showed lower energy input and CO_2 emissions, yet higher costs compared to combustion power plants. Coal power plants illustrated lower energy and cost input; however higher CO_2 emissions compared to biomass power plants. Coal CCS plants can reduce CO_2 emissions to near zero, while BCLGCC and BIGCC plants with CCS resulted in negative 680 kg-CO_2/MWh and 769 kg-CO_2/MWh, respectively, which is due to higher biomass utilization efficiency for BCLGCC compared to BIGCC hence less CO_2 captured and stored. Regarding the total life cycle costs input (TLCCI), BCLGCC with and without CCS equal to 149.3 £/MWh

*Corresponding author. +86351-6018957; +44 7818485631. E-mail addresses: yiqun@tyut.edu.cn; w.nimmo@sheffield.ac.uk

and 199.6 £/MWh, and the total life cycle energy input (TLCEI) for both with and without CCS is equal to 2162 MJ/MWh and 1765 MJ/MWh, respectively.

Key words: Life Cycle, Chemical Looping Gasification, Biomass, CCS, Power Generation

1. Introduction

Fossil fuels are abundant and readily available in many geographical locations over the world therefore considered a cheap and reliable energy source, as a result it contributes towards 86% of the world's total energy demand [1]. The rapidly expanding economies of the world and continuous increase in world population is associated with an increase in energy demands. It was estimated by the U.S Energy Information Administration that the total world energy consumption is to increase by 28% in 2040 relative to 2015 [2]. The energy sector which contributes towards 41% greenhouse gas emissions is expected to have the fastest growth rate [3]. The negative environmental impacts of the increased anthropogenic greenhouse gas emissions in the long and short terms urged for a shift towards sustainable sources of energy through legislations and international agreements. The Paris Agreement aimed to maintain temperature rise well below 2°C by the end of this century relative to per-industrial levels with efforts to further limit the increase to 1.5°C, with a net zero global emissions for the second half of the century [4]. This exhorted nations to set targets to their greenhouse gas emissions. After the Kyoto protocol agreement, the United Kingdom, in a step to reduce emissions, set a target to reduce their greenhouse gas emissions by at least 80% by the year 2050, relative to 1990 levels [5]. Nevertheless, recent changes to its target was to achieve a net zero carbon emission by the year 2050 after the UK House of Commons passes bill [6], hence requiring radical change in the entire UK's economy and power generation to achieve this target. The push towards reducing greenhouse gasses into the atmosphere can be done by either improving power generation efficiencies, employing carbon capture &

storage, or moving towards renewable energy. Drax power plant, one of the largest in the UK will be ending its commercial coal power usage by March 2021, four years ahead of its 2025 deadline [7], with many other coal power plants have already closed or getting closer to their closure [8]. This comes alongside the ban of selling petrol and diesel cars in the UK after 2035 [9]. Coal production and import into the UK have also dropped by 27% and 56% in 2020's first quarter relative to 2019's first quarter, respectively, due to the decrease in demand from power generators [10]. Moreover, in April 2020 11 industry and energy leading companies in the UK has signed an agreement to transform the Humber region into the world's first 'zero-carbon cluster' by 2040 [11]. Furthermore, recently the UK went for a record period of 68 days coal-free [12]**.** Even though the UK are working towards eliminating coal from its power industry, the steel industry still heavily relies on coal, however current research is directed to test the feasibility of replacing coal with biomass [13]. With increased research and development of post- and pre-combustion capture technologies [14], CO_2 capture and storage (CCS) is seen as a promising technology in mitigating CO_2 emissions with its potential to help reduce global emissions by 20% by 2050 [15]. In 2019 the UK obtained 19.8% of its energy demand from low carbon sources with bioenergy accounting for the highest contribution of 37% of it. Since the year 2000, bioenergy experienced the fastest increase in capacity with an increase from 0.9% to 7.3% [16], showing the potential and effectiveness of bioenergy as a renewable and alternative growing source of energy for the UK. Table 1S in the Supporting Information summarizes the currently operating biomass-based thermal power plants in the UK. Nearly all biomass power plants in the UK that use combustion-based technology with a few operating biomass gasification power plants. Combustion is known as the complete burning of the fuel under enriched oxygen atmosphere to generate thermal energy while producing CO_2 and H_2O, whereas gasification is the partial combustion of the fuel under depleted oxygen conditions to produce CO and H_2 (syngas). Even though biomass combustion is a simple process to generate electricity, but its net efficiency (34 – 37%) is lower compared to gasification processes (36 – 40%) [17 – 22].

As a result, biomass gasification is explored in hope to find more effective processes that would improve biomass utilization in power generation. Biomass gasification dates back to the 18th century, where it was developed by a French engineer called Philippe Le Bon. The process was initially used to produce 'wood gas' for gas lighting. The gas used for lighting was known as town gas, which mostly comprised of coal gas. This was used until after World War 2 by natural gas. However, the interest in wood gas during the early 1920's was shifted to be used for transport fuel, which faced several technical issues [23]. During the late 1970's, as the oil crisis began, there was a huge shift in the UK's source of energy towards coal. During that period, several coal gasification technologies developed and became commercialized to produce synthetic fuels using Fischer Tropsch reactor. However, a decrease in oil prices during the following years, resulted in the technology not finding its share in the market. Nevertheless, throughout the last decade research into this area was brought back to life, though directing it towards biomass fuel utilization instead of coal to tackling climate change [24]. Currently the largest waste wood gasification power plant in the UK, Cheshire generates 21.5 MW of electricity, which is expected to reduce GHG emissions by 65,000 tonnes of CO_2 equivalent per year [25], with several smaller plants in operation and in construction/commissioning stage [26].

Recently several technologies have been developed for biomass gasification processes [27, 28]. Conventional gasification processes generally use air or enriched O_2 air with steam as the gasifying agent [29]. However, drawbacks associated with using air or pure oxygen reduces the effectiveness of the process. The use of air as the gasification medium results in a highly N_2 concentrated syngas, reducing its energy density. Whereas, using pure oxygen increases the parasitic energy as well as capital and operational costs of the whole process due to the requirement of an additional energy intensive air separation unit (ASU). Moreover, the high amount of tar formed in conventional gasification reduces the gasification efficiency (due to lower carbon conversion) and can block downstream equipment. Tar formation can be controlled via five different methods including mechanism methods, self-modification, thermal cracking, catalytic cracking, and plasma method. This as a result reduces blockage of downstream equipment and improves biomass utilization, however it comes at an increase in energy penalty and costs [30].

A new emerging gasification technology known as chemical-looping gasification (CLG) offering potentially higher efficiencies and lower costs is presented as an alternative [31, 32]. The difference between CLG technology and conventional gasification methods is the oxygen source, where molecular oxygen is substituted with lattice oxygen in the form of a metal oxide (Me_xO_y) as the oxidizing agent. The process is divided into two stages, the biomass is initially injected into a fuel reactor (FR) where it decomposes, releasing pyrolysis gas which reacts with the oxygen carrier (OC) granules (endothermic). This process breaks down (oxidizes) the pyrolysis gas into mainly CO and H_2 (syngas) with some CH_4, CO_2 and H_2O and reduces the oxygen carrier, Equation (1).

$$C_nH_{2m}O_P + (n-p)Me_xO_y \rightarrow nCO + mH_2 + (n-p)Me_xO_{y-1} \text{ (Reduction)} \tag{1}$$

The reduced oxygen carrier (Me_xO_{y-1}) is then circulated into an air reactor (AR) where it is oxidized into its initial state (Me_xO_y) by reacting with air (exothermic reaction), Equation (2). The oxygen carrier is then circulated back into the FR to start the process all over again.

$$(2n + m - p)Me_xO_{y-1} + (n + 0.5m - 0.5p)O_2 \rightarrow (2n + m - p)Me_xO_y \text{ (Oxidation)} \qquad (2)$$

There are several advantages associated with BCLG compared to conventional gasification:

1) The cost and energy depleting process of O_2 separation can be mitigated and replaced with an OC
2) Using lattice oxygen results in a higher quality syngas due to its weaker oxidizing strength compared to molecular oxygen
3) Enhanced tare cracking due to the oxygen carrier's catalytic effect during biomass pyrolysis, hence increasing overall gasification efficiency [33]
4) Chemical looping processes undergoing moderate flameless gasification compared to conventional thermochemical processes (flamed gasification), hence reduces exergy loss [34]

Research into chemical looping technologies has progressed quite a bit in the recent years, with several demonstration pilot plants being established all over the world. Table 2S in the Supporting Information puts together all the continuous chemical looping pilot plants. OC's play an important role in assessing the feasibility and efficiency of the CLPs. They go through multiple cycles, which can result in a decrease in its physical integrity and chemical strength. Such processes require OC's to possess certain qualities, ensuring process optimization. These qualities are numerous which include long-term stability, environmental friendliness, physical strength, redox reactivity, low production cost, high melting point, resistance to agglomeration and attrition [35, 36] According to the Ellingham diagram which determines the metal oxides thermodynamic restrictions according to the standard Gibbs free energies of several oxygen carriers as a function of temperature, Ni, Co, Mn, Cu and Fe-based oxygen carriers are commonly suggested and being researched into [31].

Comparing between all these materials as oxygen carriers in Table 1, Fe seems to be the most attractive option due to its low cost, ability to withstand conditions inside a combustor (good stability at high temperature), non-toxic in nature and has no negative environmental impact. Even though it has its down sides as a low oxygen transport carrier, it will be used in this process for CLG instead of CLC which gives it a slight advantage. Other oxygen carrier materials do have their strengths; however, this article will focus on iron-based oxygen carriers.

The scope of many previous articles and research on gasification technology focused on conducting techno-economic-environmental analysis of gasification power plants using coal/biomass. This comprised of investigating the cost effectiveness, efficiencies, and internal factors of the plant with and without CCS technologies [18, 19, 38-42]. Others conducted studies on Life Cycle Assessment (LCA) on these power plants which looked at both internal and external factors, including analysing factors that affect economic, energy, and environmental performance through evaluating the feedstock supply chain, the power plant size and CO_2 capture, transport and storage [43-49]. In regard to chemical looping processes some LCA studies have been conducted, some using chemical looping for hydrogen production [50-54] and one for chemical looping technology coupled with a power-to-methane system [55]. However, in particular to chemical looping technology to power generation, only a few papers looked into conducting a life cycle assessment of the entire process.

Table 1. Comparing between the common types of metal oxide oxygen carriers [31, 37]

Metal Based Material	Advantages	Disadvantages
Nickel	• High catalytic reactivity	• Increase in circulation results in a decrease in metallic Ni, hence reducing catalytic performance • Low porosity leads to suppressed reaction rate • Can be poisoned by sulphur • High cost • Toxic
Copper	• High reactivity • High oxygen transfer capacity • Relatively low toxicity • Sulphur in fuel do not affect performance	• Causes agglomeration due to low relatively melting point (1085°C) • Relatively high cost • Low resistance to attrition
Manganese	• Low toxicity • Inexpensive	• Reactivity can be suppressed in the presence of sulphur • Reacts with some typical supporting materials resulting in stable and unreactive materials
Cobalt	• High reactivity • High oxygen transport capacity	• High cost • Environmental concerns • Reacts with some typical supporting materials resulting in complete loss of reactivity • Negative health effects
Iron	• Low cost • High mechanical strength • High melting point • Environmentally benign • No tendency for carbon or sulphide/sulphate formation	• Relatively low oxygen transport capacity • Reactively low reactivity • Agglomeration issues

Navajas et al. [56] conducted an environmental life cycle analysis of a natural gas based chemical looping combustion (CLC) to power generation process. The author investigated the effect on 14 environmental impact factors using Gabi 8.7 pro software on the CLC to power using five different oxygen carriers (2 nickel, 2 iron and 1 copper based) and compared them to a conventional natural gas combustion combined cycle plant with and without amine CO_2 capture. It was concluded that the CLC process did not add much environmental impact compared to the conventional process, since the impact associated with the oxygen carrier is very insignificant in comparison to the rest of the feedstock. When CLC to power process is compared to conventional combustion with CO_2 capture, the CLC process resulted in lower environmental impact values which demonstrates the potential of CLC technology from a life cycle perspective in CO_2 capture. When comparing between the oxygen carriers, NiO-based OC's demonstrated the lowest global warming impact (GWI), however its downside is its toxicity, hence presenting Fe_2O_3 as the best alternative yet requiring some chemical and mechanical improvements. He et al. [57] conducted a life cycle greenhouse gas emission environmental assessment of a polygeneration process consisting of coal-based synthetic natural gas (SNG) production followed by a CLC process to power generation. The author calculated the GWI of each stage of the process and tested the effect of some key parameters on its value. The results of the novel process were then compared to a conventional SNG combustion system with air. Fan et al. [58] examined the GWI of a natural gas based CLC power plant and tested the relationship between GWI and four essential factors. These factors included the type of OC (Fe- and Ni-based), lifetime of the OC, GWP of the OC and the thermodynamic performances of the CLC power facility. The plant was developed, and factors were tested by establishing an Aspen Plus model. Results showed that Ni-based OC power plants favoured a higher plant efficiency compared to Fe-based OC power plant, hence resulting in a lower GWI value. However, Fe-based OC favoured a lifetime of the OC to be less than 2500hr whereas Ni-based OC favours higher longer operating hours. Petrescu et al. [59] compares between a conventional coal gasification power plant, a calcium looping CO_2 capture power plant, and an indirect iron-based coal chemical looping (syngas production followed by chemical looping) power plant. The author developed a Gabi model for each of the processes and compared between 11 different environmental indicators. Chemical looping power generation showed the best values for reducing greenhouse gas emissions, whereas at the same time other factors effecting the environment showed an increase compared to conventional gasification. This was due to the use of additional up-stream processes for the OC and downstream CO_2 capture, transport, and storage. Fan et al. [60] also conducted a life cycle global warming impact analysis of a coal in-situ gasification chemical looping gasification (iG-CLC) power plant using ilmenite and steam as gasification agents with CO_2 capture. A thermodynamic analysis to determine the optimum conditions for the best GWI was conducted, which included testing the effect of steam to carbon ratio, OC to fuel ratio, lifetime of the OC and type of OC. The iG-CLC process was compared to 7 other coal power generation technologies with CO_2 capture technology and resulted in being the 2nd lowest GWI after oxy-fuel combustion power generation plant. Finally, Tagliaferri et al. [61] conducted a LCA of a chemical looping air system (CLAS) for power generation using lignite coal, which uses a chemical looping process to produce oxygen for an oxyfuel combustion system. The LCA was conducted using Gabi software. The results of the CLAS for power generation process was then compared to conventional renewable and non-renewable power generation processes.

From looking at all the previous LCA literature for chemical looping power generation systems, there are no studies that refer to LCA of a biomass direct chemical looping gasification (BCLG) to power plant with and without CCS in the UK. Hence there is a need to provide more data for performance comparisons of lifecycle energy-economy-environment evaluation between conventional power generation systems using coal/biomass and biomass chemical looping gasification combined cycle (BCLGCC) processes.

In our previous work we developed and validated a direct BCLGCC using Fe-based OC Aspen Plus model on experimental study, followed by conducting a techno-economic analysis as well as a sustainability evaluation [41], which proved technical and economic feasibility. This paper will build on our previous work and investigate the life cycle assessment of a BCLGCC power plant. The objectives of this paper are to: (i) conduct a life cycle analysis of energy use, CO_2 emissions and cost input distribution for BCLGCC power plant with and without CCS technologies in the UK; (ii) quantify and compare the results with the energy-economy-CO_2 emissions distribution with biomass/coal based Integrated Gasification Combined Cycle (IGCC), as well as biomass/coal combustion; (iii) determine the key factors that contribute the most to the life cycle performance of the power plants; (iv) conduct a sensitivity analysis to determine the variables that have the most impact on the life cycles, which also allowed for understanding the impact on the supply chain if the plan was located in a different country or area. Based on the findings from this study, scientists and policy makers can decide on appropriate technological improvement measures and policies to promote deployment of gasification technologies with and without CCS technologies in the context to reduce carbon emissions and promoting bio-energy with carbon capture and storage (BECCS).

2. Methodology

The Life Cycle Assessment strategy in this paper is used to assess the Energy-Cost impact-CO_2 emissions associated with each process in the whole lifecycle. It can be used to understand the effect of CCS technology, fuels source and power generation technology on the energy – cost – CO_2 emissions distribution on power plants.

A life cycle assessment was conducted in this paper according to the ISO-14040 and ISO-14044 standards [62, 63] which included the following stages: defining the goal and scope of the study, creating a life cycle inventory (LCI), conducting a life cycle inventory assessment (LCIA) and interpretation.

As part of the first step in defining the goal and scope, we should define the research target, system boundaries, assumptions made, product function and functional unit. The following step is to create the LCI by collecting data from literature and listing the CO_2 emissions, energy required and cost input data for various processes in the plant. LCI allows you to calculate the LCIA which identifies and evaluates the amount and significance of the potential environmental impact of a product system. This is done by identifying the impact categories of the product and evaluating the CO_2 emissions, energy and cost distribution for each system and its product.

The Integrated Environmental Control Model (IECM, version 11.2), a software that presents a complete package to simulate the techno-economic performance of a large-scale biomass/fossil fueled power plants [64] was used to evaluate data of a BIGCC power plant. The IECM was developed by Carnegie Mellon University with the support of the US Department of Energy's National Energy Technology Laboratory (DOE/NETL). It is commonly used as a computer modelling software that uses fundamental mass and energy balances, using both the user specific plant size and conditions alongside empirical relationships and sub models to calculate the performance, emissions and costs of a power plant for either CCS or Non-CCS [65].

The IECM computer model has a number of pre-defined fuel compositions which uses a look-up table to assign the syngas composition. In the BIGCC plant type model, when an arbitrary fuel composition is inputted, it cannot calculate the syngas composition, however the user can manually define a syngas composition for a respective fuel composition. An Aspen Plus model (Figure 1S and Table 5S, Supporting Information) was developed for a conventional oxygen-based biomass gasification plant, validated based on literature [66] (Table 6S, Supporting Information) and used to calculate the syngas composition of biomass, which was consequently inputted in the IECM software to give us the techno-economic results required for conducting a life cycle analysis for the BIGCC power plant. Technical values for the CIGCC were extracted from the IECM software using a pre-defined coal and syngas composition while economic values were taken from literature [39]. Moreover, values for the BCLGCC power plant were taken from our previous study, where a large scale 650MW power plant with and without CCS was simulated and validated followed by conducting a detailed techno-economic analysis [41]. Finally, values of the life cycle analysis of the coal and biomass combustion plants are taken from literature for performance comparison [67].

2.1 Goal & Scope, Calculation Method

Solid fuels with CCS technology have the potential to play a vital role in generating low carbon power in the UK. The goal of this research is to evaluate and compare the life cycle impact of an energy – cost – CO_2 emissions distribution of 10 different gasification power generation technologies. This included evaluating and analyzing 1) BCLGCC with and 2) without CCS, 3) BIGCC with and 4) without CCS, 5) CIGCC with and 6) without CCS, followed by comparing those results with 7) Direct Biomass Combustion (DBC) with and 8) without CCS and 9) Pulverized Coal Combustion (PCC) with and 10) without CCS. Figure 1 shows simple flow diagrams of each of the power generation systems.

These systems of the mentioned technologies are selected from three different groups including, the feedstock (biomass or coal), thermal conversion technology (chemical looping gasification, conventional gasification or combustion), and whether the plant is coupled with or without a CCS process (post combustion using MEA or pre-combustion using selexol).

A detail description of each process and unit for the power generation systems can be found in the Supporting Information in Section 3. In addition, Table 7S in the Supporting Information summarizes the composition in each stream for each process. A comprehensive energy, cost and CO_2 assessment will be achieved by conducting a detailed calculation of each process phase throughout the whole process for the BCLGCC, BIGCC and CIGCC with and without CCS power plants. Values for the CO_2 emissions, energy requirement and cost input distribution of the DBC and PCC plants with and without capture are taken from literature and compared with the other plants [67].

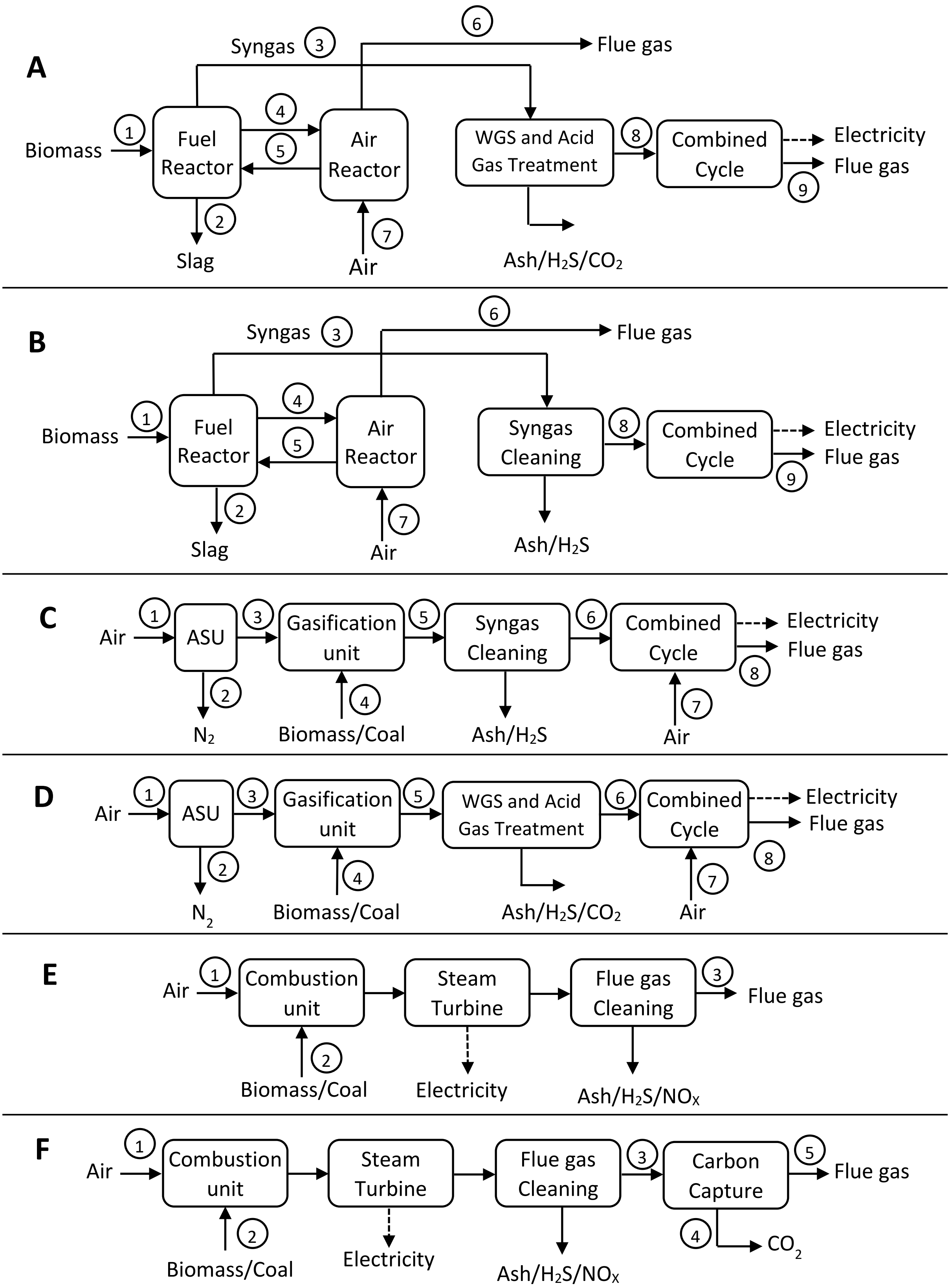


Figure 1. Simple flow diagram of the different power generation systems, where (**A**) BCLGCC with CCS, (**B**) BCLGCC w/o CCS, (**C**) biomass/coal IGCC w/o CCS, (**D**) biomass/coal IGCC with CCS, (**E**) biomass/coal combustion w/o CCS, (**F**) biomass/coal combustion with CCS

Table 2 presents the performance and cost summary of the 10 power plants. The BIGCC and CIGCC data presented in Table 2 are extracted from the reliable IECM software which was developed by Carnegie Mellon University with the support of the US Department of Energy's National Energy Technology Laboratory (DOE/NETL) as well as the "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity" [39] report by the US Department of Energy. Whereas the BCLGCC cost and performance data are extracted from our previously published work [41], where we developed and validated a 650MW Aspen Plus model, followed by conducting a techno-economic analysis. Finally, the PB and PCC power plants cost and performance data, as well as life cycle data was taken from our group's previous work published in [67]. This is then followed by conducting a sensitivity analysis on the life cycle results to ensure the reliability of the results presented.

The system boundary is from cradle to grave, with the scope of the power plants include wood harvesting and transport, wood processing at the pellet plant, pellets transport (via rail, shipment and truck), wood pellets handling and storage, iron mining, iron transport to the power plant, coal mining and washing, coal transport to the power plant, power generation, CO_2 capture and compression, CO_2 pipeline transport, and CO_2 storage. This is summarized in Figure 2. All these process phases are investigated to achieve the proposed goal. The function of the process is to generate electricity and the functional unit (FU) is taken as one MWh for impartial comparison between different power generation technology with and without CCS. Since no other significant co-product is generated during the process, there is no multifunctionality, hence other products can be ignored.

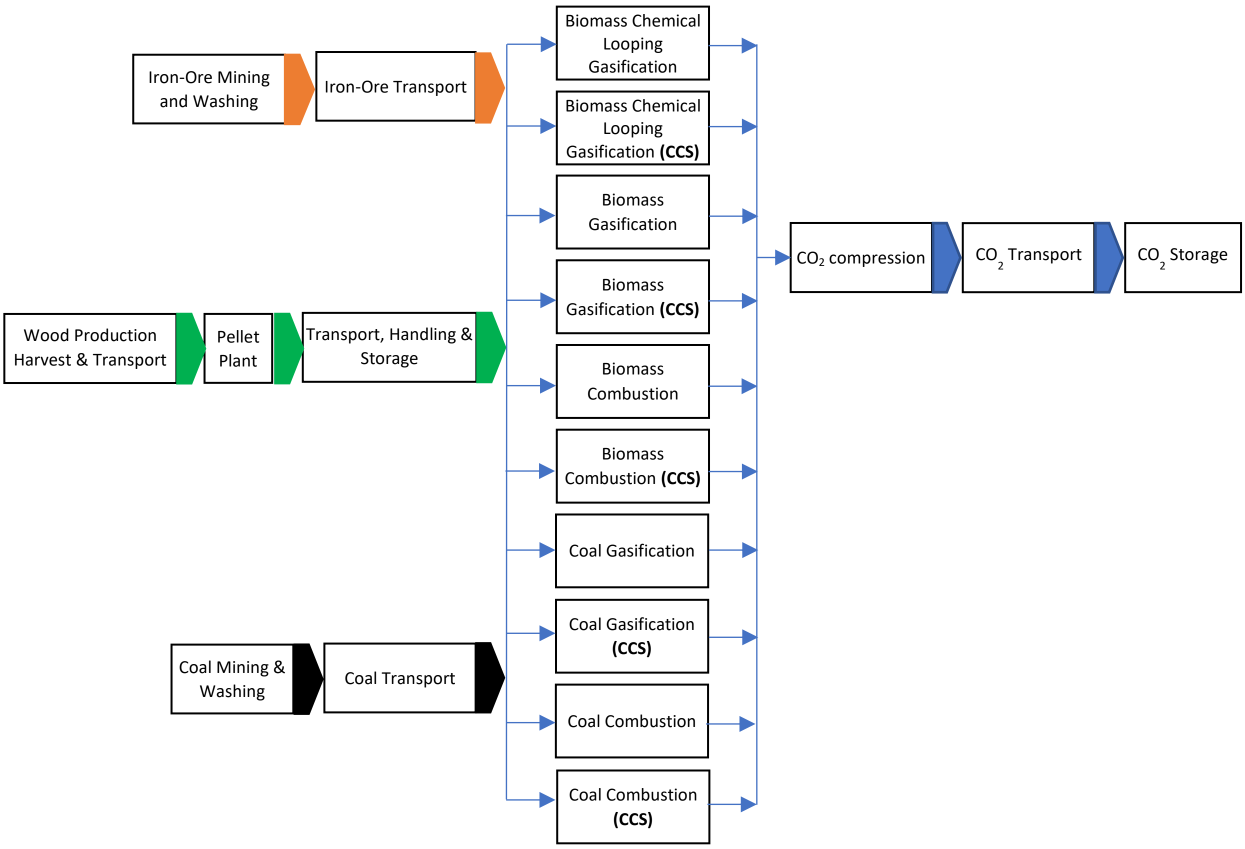


Figure 2. Complete life cycle scope of the biomass/coal gasification plants

Table 2. Cost and performance values for the life cycle analysis. [39, 41, 67]

Power Plant	BCLGCC		BIGCC		CIGCC		PB		PCC	
CCS/Non-CCS	Non-CCS	CCS	Non-CCS	CCS	Non-CCS	CCS	Non-CCS	CCS	Non-CCS	CCS
Fuel Type	Biomass		Biomass		Coal		Biomass		Coal	
Gross Power, MW	650	650	650	650	650	650	650	650	650	650
Net Power, MW	546	504	586	549	559	520	607	500	605	526
Net Efficiency, %	41	36	38.6	32.4	39.5	32.9	37.5	26.4	38.3	28.5
Feedstock Input, t/h	275	270	297	326	195	218	311	364	231	270
Capacity Factor, %	0.8	0.8	0.8	0.8	0.8	0.8	0.62	0.62	0.85	0.85
Plant Life, year	25	25	25	25	25	25	20	20	20	20
Discount ratio, %	10	10	10	10	10	10	10	10	10	10
CO_2 Capture Efficiency, %	0	90	0	90	0	90	0	90	0	90
Plant Capital Cost, £/kW	2101	2966	2268	3240	1970	2800	1212	2302	1184	2236

During the past decade, the UK has been moving away from coal power generation and has been increasing its biomass power generation sourced mainly from the United States which has been a reliable and steadily growing supplier in the past few years [68, 69]. The biomass pellets will be supplied from a pellet manufacturer in America, whereas bituminous coal is domestically mined in the UK or imported from Russian, Colombia, Australia or the US [10], however in this paper coal is assumed to be sourced from UK mines. The elemental composition (on a dry basis wt%, db) of the biomass pellets is 44.4% Carbon, 4.6% Hydrogen, 0.2% Nitrogen, 0.01% Sulphur, 43.5% Oxygen, 7.1% Moisture and 0.2% Ash, with the lower heating value (LHV) equal to 18.7 MJ.kg^{-1}. Whereas the elemental composition (on a dry basis wt%, db) of coal is 59.6% Carbon, 3.8% Hydrogen, 1.5% Nitrogen, 1.8% Sulphur, 5.5% Oxygen, 0.2% Chlorine, 12.0% Moisture and 15.6% Ash, with the lower heating value (LHV) equal to 24.61 MJ.kg^{-1}.

The equation to calculate the total life cycle energy input (TLCEI) per MWh electricity (MJ/MWh) of a power plant is expressed by Equation [3] shown below:

$$TLCEI = \frac{\sum_{i=1}^{n} E_i}{Total\ no.of\ hrs/yr \times Net\ Power\ Output\ (MW)} \qquad [3]$$

where $\sum_{i=1}^{n} E_i$ is the energy consumption in the i_{th} sub process.

The equation to calculate the total life cycle CO_2 emissions (TLCCE) per MWh electricity ($kgCO_2$/MWh) of a power plant is expressed by Equation [4] shown below;

$$TLCCE = \frac{\sum_{i=1}^{n} CE_i + CE_{pp} + \sum_{j=1}^{n} CE_j}{Total\ no.of \frac{hrs}{yr} \times Net\ Power\ Output\ (MW)} \qquad [4]$$

where CE_i and CE_j are the CO_2 emissions of the i_{th} sub process in feedstock supply chain and j_{th} sub process in CO_2 compression, transport and storage, respectively. CE_{PP} is the emissions at the power plant during electricity generation.

Similarly, the total life cycle cost input (TLCCI) per MWh electricity (£/MWh) of a power plant can be calculated using Equation [5];

$$TLCCI = \frac{\sum_{i=1}^{n} C_i + C_{pp} + V_{pp}}{Total\ no.of \frac{hrs}{yr} \times Net\ Power\ Output\ (MW)} \quad [5]$$

Where $\sum_{i=1}^{n} C_i$ is the total cost input (£/yr) of the i_{th} sub process from the feedstock supply chain as well as CO_2 transport and storage, C_{pp} is the total annual capital cost of the power plant (£/yr), and V_{pp} is the variable cost (£/yr).

The annual capital cost (ACC, £/yr) can be calculated using Equation [6];

$$\mathrm{ACC} = \frac{Capital\ Cost \times i}{1-(1+i)^{-N}} \quad [6]$$

where i is the discount rate, 10% and the N is the plant lifetime in years (25 years) [17].

2.2 Life Cycle Inventory

Woody biomass is initially harvested and often chipped then transported to the pelleting plant via trucks or railways, most common methods for inland transport. Since the pellet plant is usually close to the harvesting ground the input cost, CO_2 emissions and energy input for the transport to pellet plant stage is assumed to be very negligible and taken part of the wood harvesting values. At the pellet plant, the untreated biomass chips are taken through the process of drying, size reduction and pelletization to make them suitable for transportation [70].

In this paper it is assumed that the power plants are located in the same region as the Keadby power station, United Kingdom. This is because it already has a large combined cycle gas turbine (CCGT) power stations in operation with current discussions regarding a Keadby 3 station which uses hydrogen energy is being proposed [71]. The region has a potential to play a vital role in supplying the UK's energy demands in the future as it is being transformed into the world's first 'zero-carbon cluster' by 2040. The first stage of biomass transportation is via rail for 149 km from Tifton [72], Georgia in the US to the port in Savannah. The biomass feedstock is stored, handled, and loaded onto a Handymax ship (45,000-ton capacity [72]) and transshipped to the port of Hull, UK, covering 7,500 km [73]. From the port the biomass feedstock is transported via trucks to the power plant covering 63 km [74]. In regard to coal supply chain, all coal mines in the UK are opencast due to the closure of deep coal mines in recent years. The opencast mines are found to be distributed not far from the Keadby power plant at a range of 50 – 150 km. The coal supply chain to the power plant includes mining, washing and transport via rail (100km). According to the distribution of iron mines in the UK [75], they are approximately 200 km away from the location of the power plant. The supply chain process for iron ores is essentially iron mining and transport.

Table 3. Life cycle inventory data for the life cycle analysis.

Energy Consumption	**Value**	**Unit**	**References**
Coal mining and washing	1.8	MJ/kg	[76, 77]
Coal Transport (100 km)	0.281	MJ/t km	[77]
Wood Harvesting & Transport	9.9	$MJ/MWh_{(biomass)}$	[72]
Wood Processing	573.3	$MJ/MWh_{(biomass)}$	[72]
Pellet Handling & Storage	3.8	$MJ/MWh_{(biomass)}$	[72]
Transport to port (by rail) - 145 km	11.1	$MJ/MWh_{(biomass)}$	[72]
Ocean Transport - 7500 km	0.03	MJ/t km	[72]
Transport to power plant (by truck) - 50 km	2.3	MJ/t km	[72]
Iron mining	124.4	MJ/t	[78]
Iron Transport (200 - 300km)	20.9	MJ/t km	[78]
CO_2 Capture		Calculated	
CO_2 storage (Injection compression)	7	kWh/t CO_2	[79]
CO_2 transport	2.4	kWh/t CO_2	[80]
CO_2 Emissions			
Coal mining and washing	49.74	kg/t	[67]
Coal transport (by rail)	0.0830	kg/t km	[77]
Wood production harvest and transport	1.6	$kgCO_2/t$	[72]
Wood processing in pellet plant	12.2	$kgCO_2/MWh_{(biomass)}$	[72]
Handling and storage	0.28	$kgCO_2/MWh_{(biomass)}$	[72]
Wood pellets transport to port (by rail)	0.01	$kgCO_2$/t km	[72]
Wood pellets ocean transport	0.004	$kgCO_2$/t km	[72]
Wood pellets transport to power plant (by truck)	0.12	$kgCO_2$/t km	[72]
CO_2 compression (fugitive CO_2 emission compressor)	23.2	tCO_2/MW/yr	[79]
CO_2 transport (fugitive CO_2 emissions pipeline)	2.32	tCO_2/km/yr	[79]
Fugitive CO_2 emission from CO_2 storage	7.01	$kgCO_2/tCO_2$	[81]
Iron mining	9.8	$kgCO_2$/t ore	[78]
Iron Transport (200 - 300km)	1.3	$kgCO_2$/t ore	[78]
Cost			
Coal mining and washing	52	£/t	[67]
Coal transport (by rail)	5.93	£/t	[82]
Wood production harvest and transport	10.97	$£/MWh_{(biomass)}$	[72]
Wood processing in pellet plant	8.47	$£/MWh_{(biomass)}$	[72]
Loading port handling and storage	4.5	£/t	[70]
Wood pellets transport to port (by rail)	2.19	$£/MWh_{(biomass)}$	[72]
Wood pellets ocean transport	0.00036	£/MWh km	[72]
Wood pellets transport to power plant (by truck)	2.9	$£/MWh_{(biomass)}$	[72]
Receiving port handling and storage	4.5	£/t CO_2	[70]
Iron mining	75	£/t CO_2	[83]
Iron Transport (200 - 300km)	10	£/t CO_2	[84]
CO_2 transport & storage	25.275	$£/tCO_2$	[17]

Finally, since the power plants are gasification based, hence produce syngas with a higher CO_2 concentration, a pre-combustion capture technology is used, i.e selexol process using polyethylene glycol dimethyl ether. The CO_2 is compressed to 11 MPa (sub-critical state) for transportation using pipelines, due to them being the cheapest and most commonly used method for long distance CO_2 transport. Out of all the different geological CO_2 storage sites saline aquifers are used due to their large storage capacity. The CO_2 is then recompressed from 10.76 MPa to 15 MPa, the pressure used by most existing CCS projects before injection. Additionally, the CO_2 released during transportation and compression is also considered in the life cycle assessment according to the methodology developed by the IPCC report [85]. It was assumed that the storage site is 150 km [86] away from the power plant since storage sites are scattered around that distance.

All the data for each stage during the supply chain process for cost input, CO_2 emission and energy input is listed in Table 3. The data used for the life cycle calculation of each section was taken from government bodies, the IPCC reports and the International Energy Agency (IEA) as shown in references [70, 72, 76 - 84]. Those are all reliable and accurate sources with peer reviewed work (almost all the data are from the official authoritative data) showing that the data (in Tables 2 and 3) used in this paper is reliable and acceptable.

3. Results and Discussion

3.1 Life cycle assessment of energy distribution

Figure 3 illustrates the energy input distribution of both a BCLGCC with and without CCS power plants, generating a gross power of 650 MW. BCLGCC (1429.2 MW) requires 26 MW more biomass than BCLGCC with CCS (1403.2 MW). This implies that the WGS and carbon capture units increases the energy density of the syngas, hence increasing the gross power by 26 MW. However, this decreases the overall net power of the CCS plant by 42 MW (Energy for carbon capture: 45.5 MW). Both CCS and non-CCS plants requires a TLCEI of 2160.3 MJ/MWh and 1764.5 MJ/MWh, respectively. The most energy intensive stage is the drying and pelletization stage, which require 1596.2 MJ/MWh and 1500.7 MJ/MWh for CCS and non-CCS plant, respectively, accounting for 73.9% and 85.0% of the TLCEI. The second most energy intensive stage is the CCS process which requires an energy input of 259.9 MJ/MWh. The biomass transport supply chain process also accounts for a high energy input of 239.6 MJ/MWh and 227.6 MJ/MWh for CCS and non-CCS, respectively. The overall lifecycle net power of the CCS and non-CCS plant is equal to 242.7 MW and 279.9 MW, respectively. Figure 4 illustrates the life cycle energy input distribution of a BIGCC power plant with and without CCS, with both power plants set at a gross power equal to 650MW. The total life cycle energy input required for the CCS power plant is equal to 2482.6 MJ/MWh whereas non-CCS power plant is 1775.1 MJ/MWh. The CCS power plant biomass feedstock (1694.5 MW) requirement 177.7 MW higher compared to non-CCS (1516.8 MW). The most energy intensive process is the wood processing stage, accounting for 71.3% and 85.2% of the CCS and non-CCS power plant, respectively. The CO_2 capture, transport and storage added a 403.2 MJ/MWh to the CCS power plant. Figure 5 illustrates the life cycle energy input distribution of a CIGCC power plant with and without CCS. The gross power for both CCS and non-CCS power plants is equal to 650 MW. The percentage coal mining and washing energy input for both the CCS and non-CCS power plants is equal to 98.5% (628.1 MJ/MWh) and 65.7% (755.3 MJ/MWh). The total life cycle energy input required for the coal supply chain for the CCS power plant is equal to 1149.1 MJ/MWh whereas non-CCS power plant is 637.9 MJ/MWh. The CCS power plant consumes an additional 382.0 MJ/MWh (33.2%) for CO_2 compression, transport, and storage.

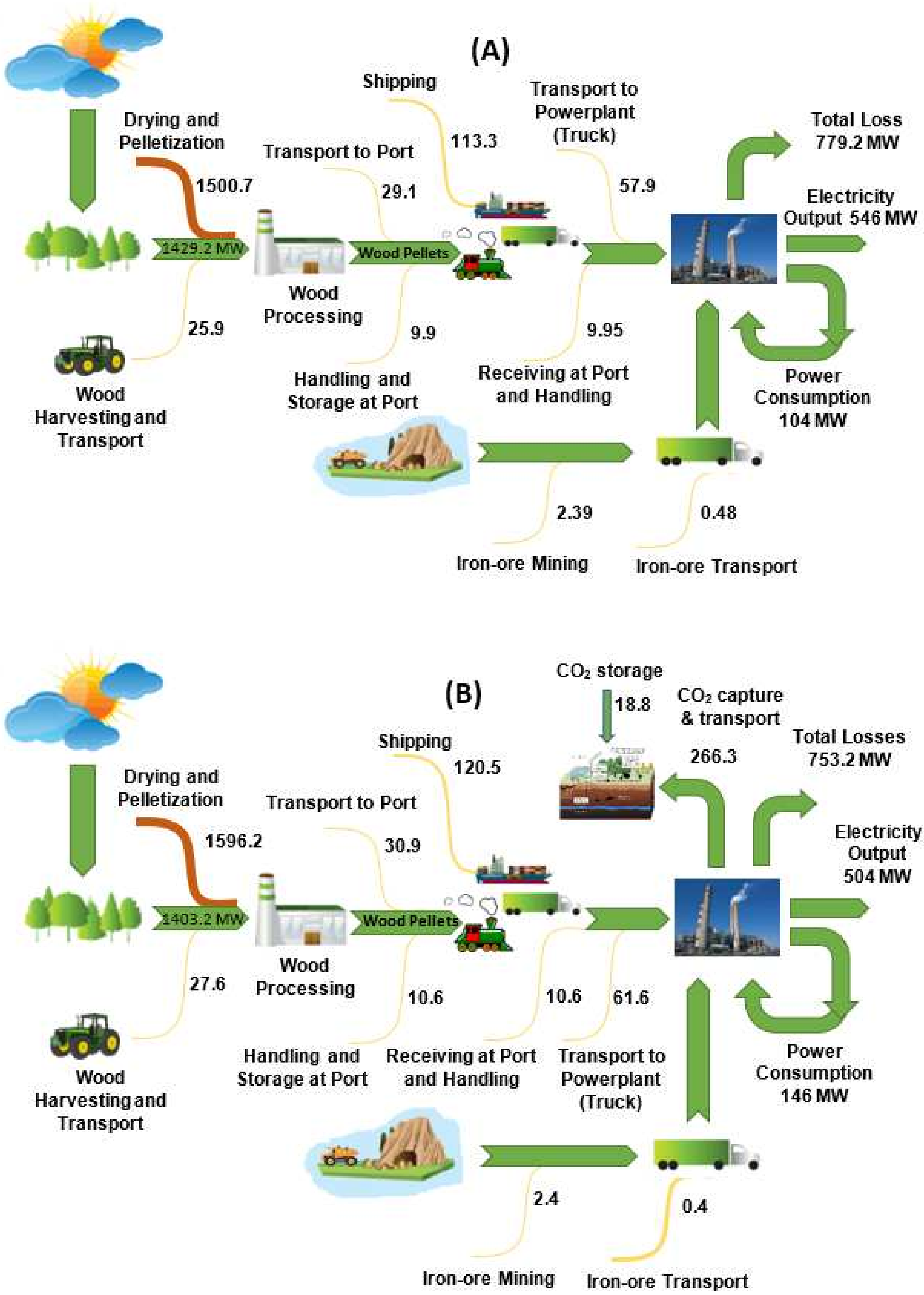


Figure 3. Life cycle energy input distribution for a BCLGCC power plant w/o (**A**) and with (**B**) CCS. Unit: MJ/MWh unless shown.

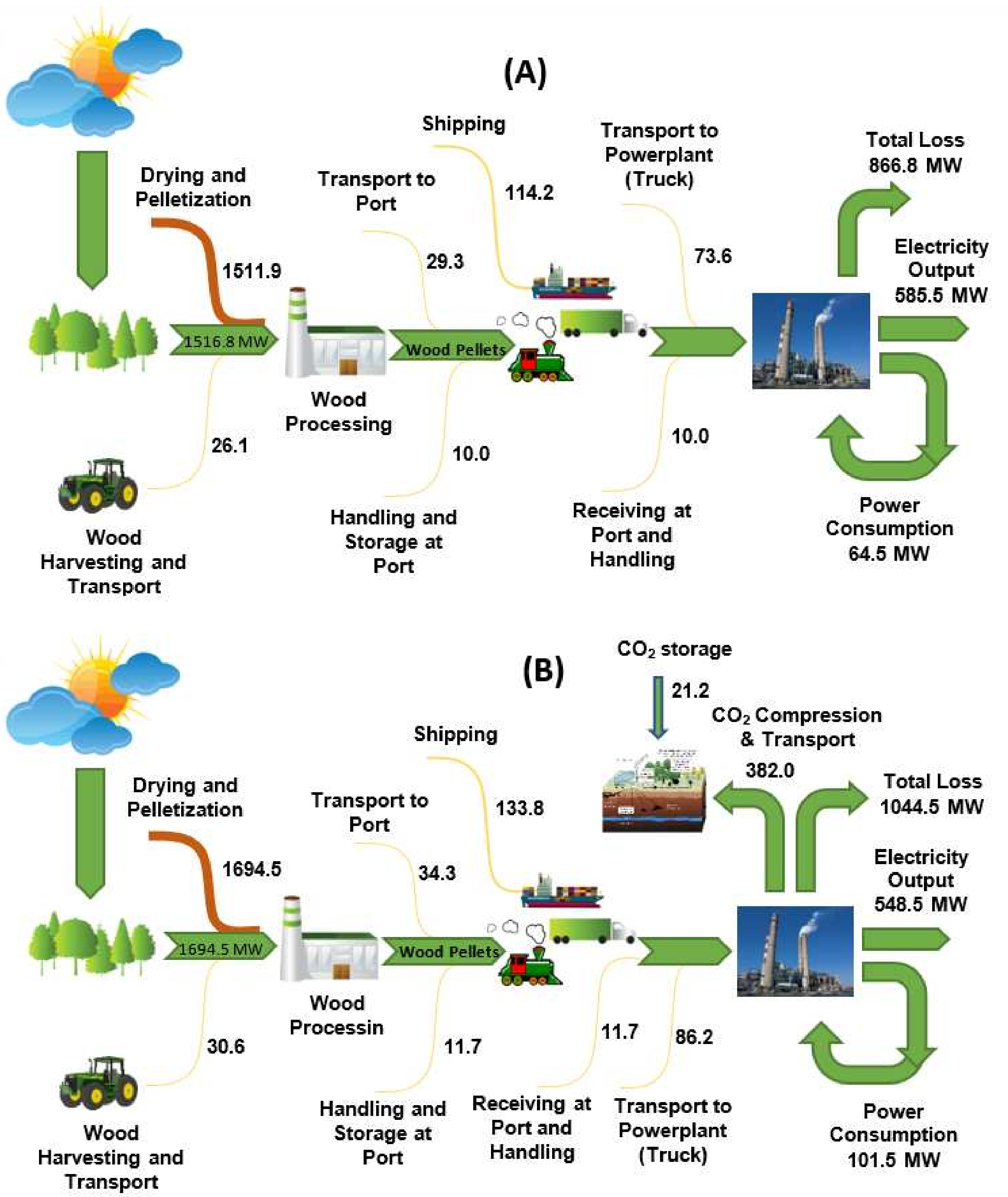


Figure 4. Life cycle energy input distribution for a biomass IGCC power plant w/o (A) and with (B) CCS. Unit: MJ/MWh unless shown.

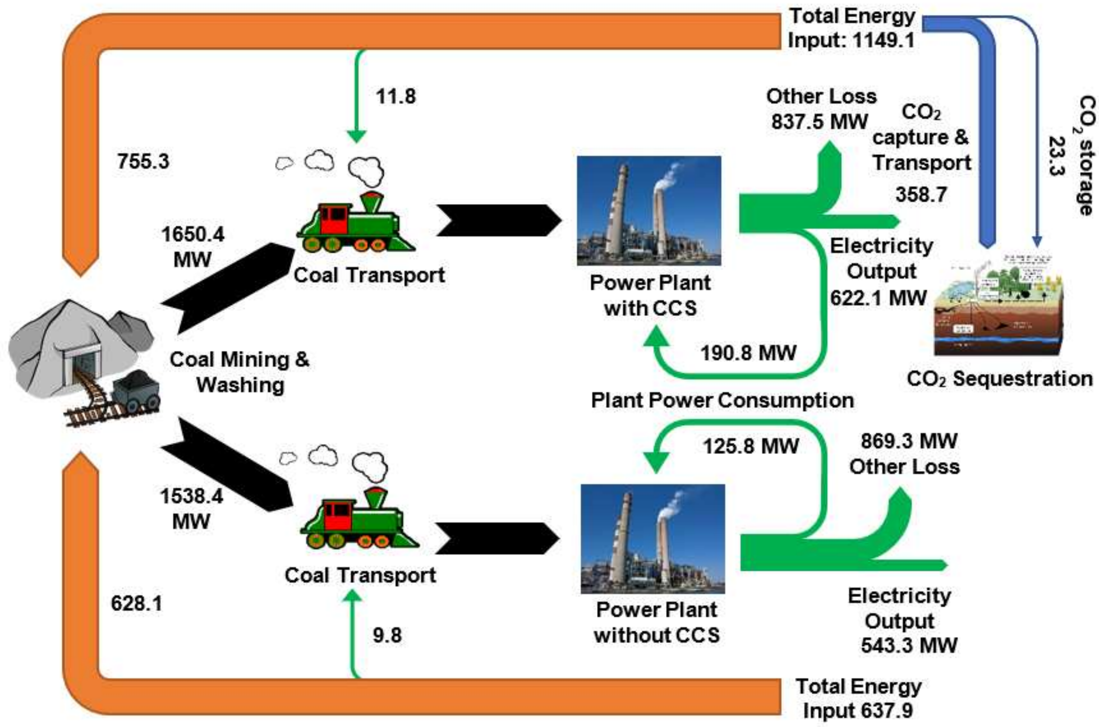


Figure 5. Life cycle energy input distribution for a CIGCC power plant with and w/o CCS. Unit: MJ/MWh unless shown.

3.2 Life cycle assessment of CO_2 emissions distribution

Figure 6 demonstrates the total estimated life cycle CO_2 emissions for the BCLGCC power plant with and without CCS, respectively. The TLCCE is equal to 874.0 kg CO_2/MWh, of which 32.7 kg-CO_2/MWh (34.9 kg-CO_2/MWh for the CCS power plant) is released from wood harvesting, transport and processing accounting for the highest emissions for both CCS and non-CCS plants, followed by 20.4 kg-CO_2/MWh (22.5 kg-CO_2/MWh for the CCS power plant) from the pellets transportation and 0.2 kg-CO_2/MWh (0.22 kg-CO_2/MWh for the CCS power plant) from the iron-ore supply chain. The total emissions from fossil-based fuel during the feedstock supply chain process is 54.1 kg-CO_2/MWh. The other 820.0 kg-CO_2/MWh is released from the biomass power generation process which is released to the atmosphere and absorb by plants during photosynthesis to regrow biomass. The BCLGCC-CCS power plant has a total life cycle CO_2 emission of 921.8 kg-CO_2/MWh (47.8 kg-CO_2/MWh more than the non-CCS process) of which 744.0 kg-CO_2/MWh is captured. The remaining 115.1 kg-CO_2/MWh is emissions from the power plant (from both fuel and air reactors) and 62.7 kg-CO_2/MWh is emitted from fossil-based fuel during the supply chain and CCS processes. This results in a net CO_2 emission of 54.1 kg-CO_2/MWh and a negative emission of 680.1 kg-CO_2/MWh for the non-CCS and CCS plants, respectively. The total life cycle CO_2 emissions for the BIGCC power plants with and without CCS are illustrated in Figure 7, respectively. The CCS power plant (1033.7 kg-CO_2/MWh) released 192.6 kg-CO_2/MWh more than the non-CCS plant (841.1 kg-CO_2/MWh). The non-CCS power plant emits into the atmosphere from the flue gas 93.5% (786.8 kg-CO_2/MWh) of its TLCCE, whereas the CCS plant emissions emits 11.9% (122.8 kg-CO_2/MWh) into the atmosphere while 81.2% (839.9 kg-CO_2/MWh) is stored. Nevertheless, indirect emissions from CO_2 compression, transport, and storage accounts to 7.5 kg-CO_2/MWh. Looking at the life cycle CO_2 emissions of a CIGCC power plant, the CCS power plant (867.0 kg-CO_2/MWh) released 254.3 kg-CO_2/MWh more than the non-CCS plant (1056.1 kg-CO_2/MWh). The non-CCS power plant emits into the atmosphere from the flue gas 97.7% (846.7 kg-CO_2/MWh) of its total cycle CO_2 emissions, whereas the CCS plant emits 9.3% (98.6 kg-CO_2/MWh) and 87.6% (925.1 kg-CO_2/MWh) stored. Nevertheless, indirect emissions from CO_2 compression, transport, and storage accounts to 6.5 kg-CO_2/MWh. The life cycle CO_2 emission distribution diagram of a CIGCC plant is summarized in Figure 8.

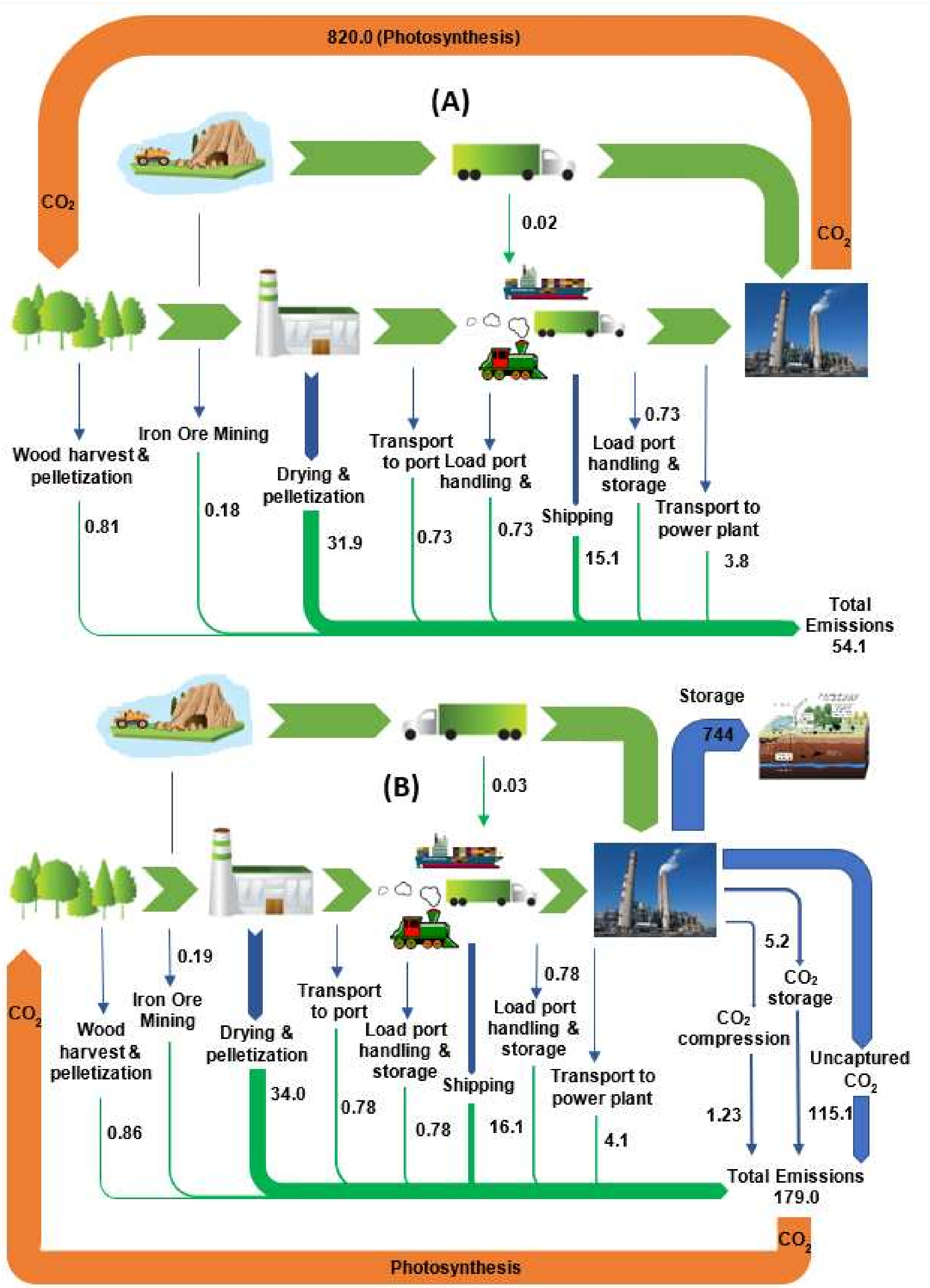


Figure 6. Life cycle CO_2 emission distribution for a BCLGCC power plant w/o (**A**) and with (**B**) CCS. Unit: kg-CO_2/MWh unless shown.

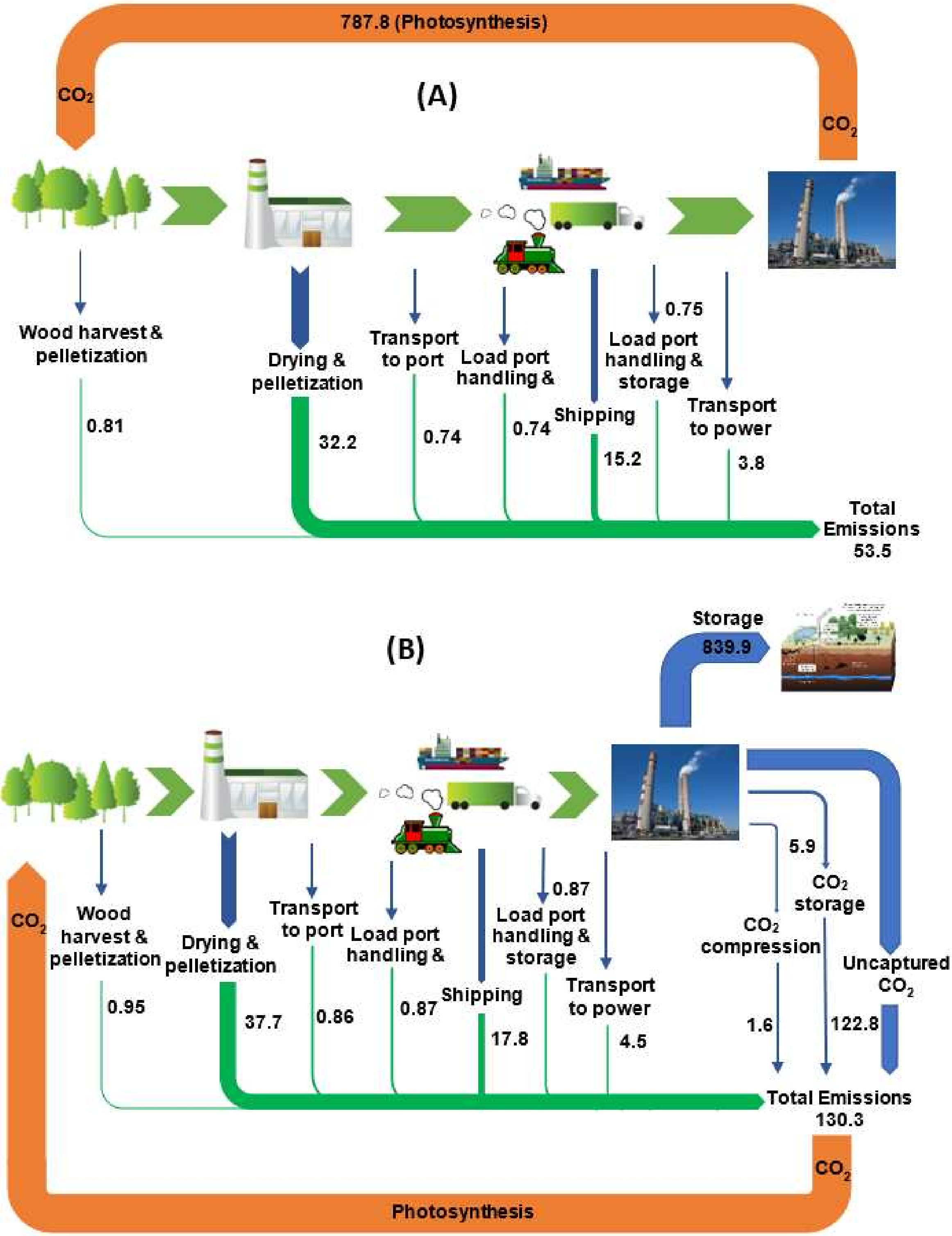


Figure 7. Life cycle CO_2 emission distribution diagram for a IGCC power plant w/o (A) and with (B) CCS. Unit: kg-CO_2/MWh unless shown.

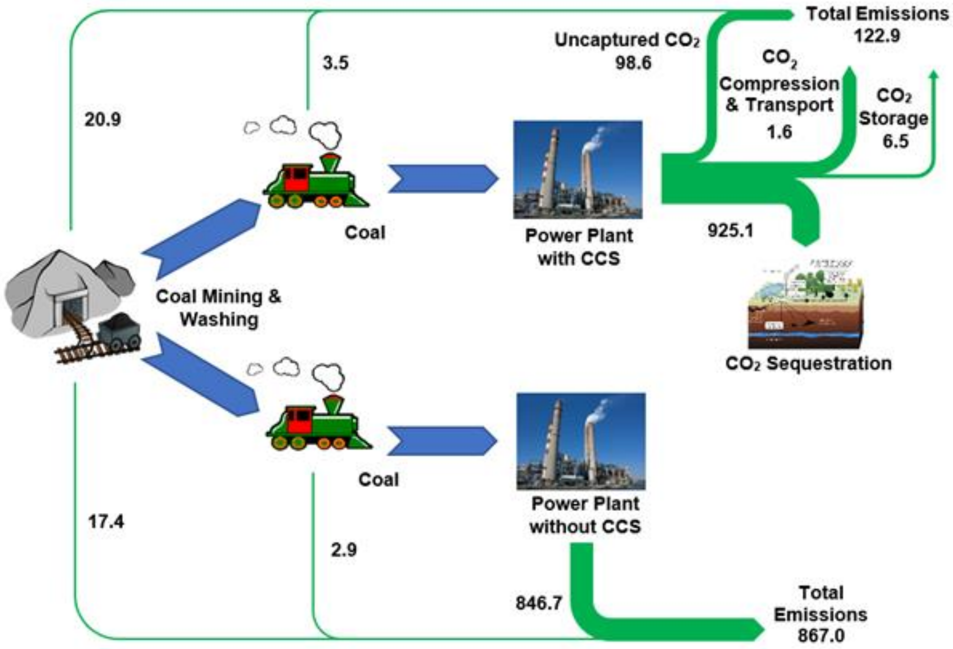


Figure 8. Life cycle CO_2 emission distribution diagram for a CIGCC power plant with and w/o CCS. Unit: kg-CO_2/MWh unless shown.

3.3 Life cycle assessment of cost input distribution

The life cycle cost input of both BCLGCC with and without CCS are equal to 200.5 £/MWh and 150.1 £/MWh, respectively, as shown in Figure 9. The two most cost intensive processes in the whole process is within the biomass supply chain process; wood harvesting & processing (84.6 £/MWh and 79.5 £/MWh for CCS and non-CCS) and wood transport (41.4 £/MWh and 38.9 £/MWh for CCS and non-CCS), accounting for 62.8% and 78.9% of the cost of electricity for CCS and non-CCS, respectively. From the cost required during the biomass supply chain the cost of biomass can be estimated to be equal to 10 £/GJ$_{(Biomass)}$. The annual capital cost and O&M labour cost of the BCLGCC with CCS power plant is 17.1 £/MWh and 3.6 £/MWh higher than the non-CCS power plant. Furthermore, CO_2 transport and storage contributes to 18.8 £/MWh to the electric cost of the CCS power plant. Figure 10 illustrates the life cycle cost input of both BIGCC with and without CCS are equal to 212.2 £/MWh and 159.5 £/MWh, respectively. The complete biomass supply chain process contributed the most to the total cost with 111.8 £/MWh for CCS and 95.4 £/MWh to non-CCS. The annual cost and O&M labour cost for CCS is equal to 57.0 £/MWh and 22.2 £/MWh respectively (47.9 £/MWh and 16.2 £/MWh higher than the non-CCS plant), with an additional cost of 21.2 £/MWh for the CO_2 transport and storage. The life cycle cost input of both CIGCC with and without CCS are equal to 119.9 £/MWh and 72.5 £/MWh, respectively, as shown in Figure 11. The annual cost contributed the highest to the cost with 54.1 £/MWh and 38.1 £/MWh for CCS and non-CCS plants. The complete coal supply chain process (mining, washing and transport) contributed the second highest cost to the total electric cost with 27.3 £/MWh for CCS and 22.7 £/MWh for non-CCS. This resulted for the price of coal to be equal to 1.78 £/GJ. Finally, the CCS plant adds an additional cost of 23.4 £/MWh for the CO_2 transport and storage.

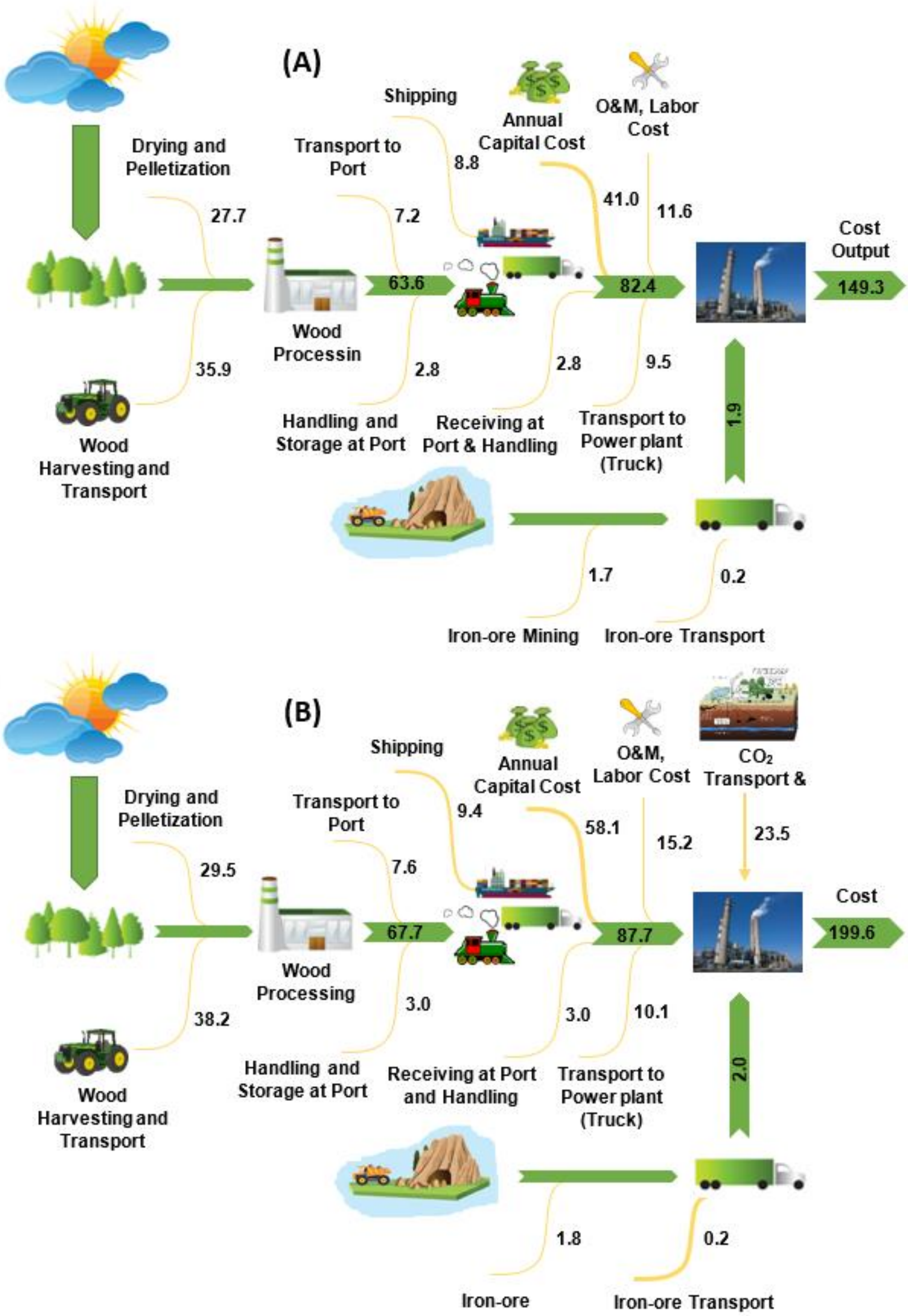


Figure 9. Life cycle cost input distribution diagram for a BCLGCC power plant w/o (**A**) and with (**B**) CCS. Unit: £/MWh unless shown.

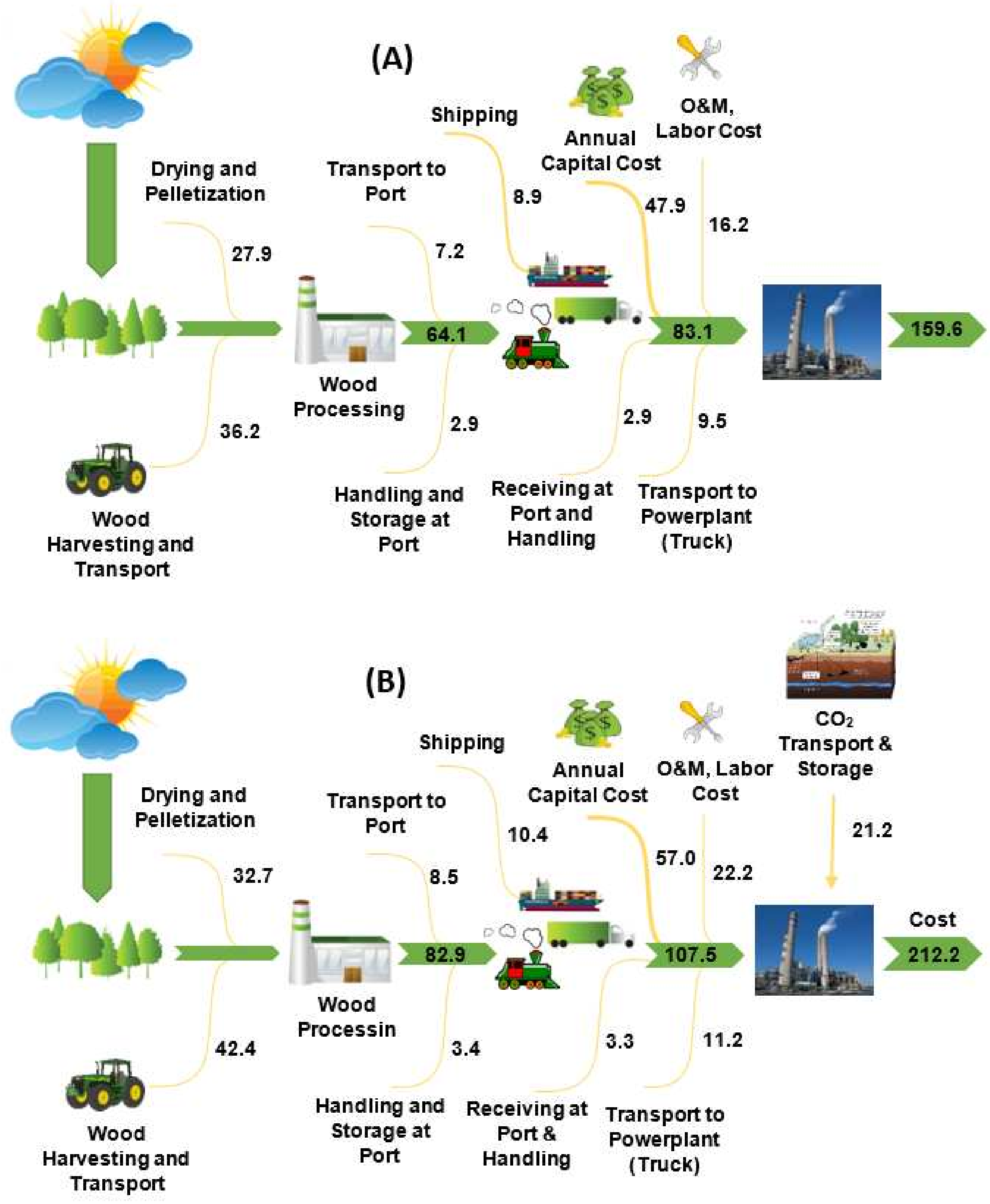


Figure 10. Life cycle cost input distribution diagram for a biomass IGCC power plant w/o (A) and with (B) CCS. Unit: £/MWh unless shown.

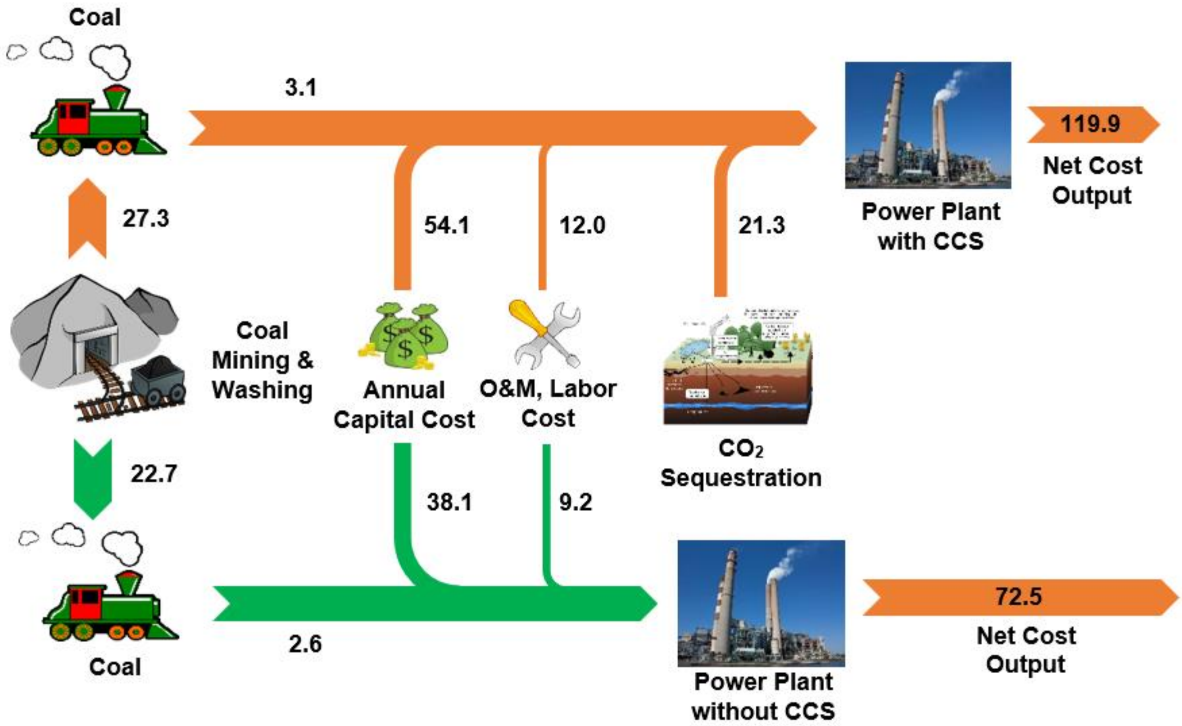


Figure 11. Life cycle cost input distribution diagram for a coal IGCC power plant with and w/o CCS. Unit: £/MWh unless shown.

3.4 Performance comparison among the different types of power generation technologies

The BCLGCC, BIGCC and CIGCC power generation technology were analysed with respect to energy, economic, and CO_2 emission aspect (presented in Figure 3 – Figure 11). The results of these technologies are then compared with each other and with direct biomass combustion as well as coal combustion technology based on the same gross power plant scale (650MW). Figure 12 presents a result summary of the life cycle energy input (a), CO_2 emissions (b) and cost distribution (c) in a stacked bar chart, which also included results of a BDC, and a PCC power plants with and without CCS [67]. To sum up in terms of efficiency, combustion power generation is lower than gasification power generation technology, which is mainly due to the low efficiency of heat transfer in combustion process and the high efficiency of gasification-combined cycle. However, the low energy density of biomass, as well as the transportation and pre-treatment of biomass results in higher energy consumption, while at the same time results in an increase in production cost. Therefore, the advantage of biomass gasification power generation technology in energy efficiency and cost is not obvious compared with that of coal gasification power generation technology.

Comparing between the gasification and combustion technology we can see that gasification technology has a higher thermal efficiency compared to direct combustion. This is due to the combustion process experiences a higher energy loss during the conversion of the solid fuel into heat, whereas gasification controls the dispersion of the thermal energy, hence reducing the overall loss when converting the biomass into syngas. Moreover, syngas can combust at higher temperatures compared to the combustion of solid fuels, hence increasing its thermodynamic upper limit as stated by Carnot's theorem. Furthermore, combustion technology is coupled with a steam turbine to generate electricity, whereas gasification technology is coupled with combined gas and steam turbines which result in higher efficiency due to better utilisation of waste heat. This results in less fuel to be consumed for gasification processes compared to combustion due to better fuel utilization for the same power output. As a result, Figure 12 demonstrates that the CIGCC power plant requires a lower TLCEI per net power, 637.9 MJ/MWh and 1149.1 MJ/MWh, compared to the PCC power plant, 730.7 MJ/MWh and 1420.4 MJ/MWh, for non-CCS and CCS, respectively. However, when comparing between the non-CCS biomass power plants there doesn't seem to be much difference in terms of the TLCEI per net power. Even though gasification technology (BIGCC and BCLGCC) utilizes less biomass feedstock compared to BDC to produce the same gross power (650 MW), it consumes a lot more power within the power plant hence reducing its net power, which consequently increases its TLCEI per net power. However, when comparing between the gasification technologies (BCLGCC and BIGCC) with CCS to combustion technology (DBC) with CCS, they required 825.6 MJ/MWh and 488.9 MJ/MWh less TLCEI, respectively. This is due to BCLGCC and BIGCC power plants resulting in less CO_2 captured for storage (744 kg-CO_2/MWh and 925.1 kg-CO_2/MWh, respectively) compared to DBC (1081.3 kg-CO_2/MWh) which is as a result of less biomass feedstock processed. Therefore, requiring less energy for CO_2 capture, transport, and storage compared to the DBC (459.3 MJ/MW) power plant. This increases the amount of energy consumed by the power plant by combustion, therefore significantly reducing its net power compared to gasification. This hence results in the TLCEI by the BIGCC and BCLGCC with CCS (285.1 MJ/MW and 403.2 MJ/MW, respectively) to be less than combustion (DBC) with CCS (459.3 MJ/MW) power plant, therefore increasing the cost requirements. Comparing between the TLCCI between gasification and combustion technology, combustion with non-CCS seems to require a lower cost compared to gasification. PCC and BDC require 57.8 £/MWh and 116.7 £/MWh whereas CIGCC, BIGCC and BCLGCC require 72.5 £/MWh, 159.5 £/MWh and 149.3 £/MWh. One of the main reasons for the difference in the TLCCI is the cost depleting steps within gasification power generation processes is the initial capital cost. Combustion is an already proven and well-established commercial technology in large scales which reduces its capital cost. Moreover, compared to combustion technology, gasification is a more complex process, resulting in more capital investment and operational costs. As a result, gasification power plants require higher annual capital and operational costs, hence higher TLCCI. When comparing between gasification and combustion CCS power plants, combustion is still cheaper however the gap between both technologies narrows owing to less biomass pre-treatment for gasification and the higher cost required for CO_2 handling for combustion.

When comparing between BIGCC and BCLGCC, we observe that a lower energy input is required by the BCLGCC process which is due to less biomass feedstock required to generate the same power output which is attributed to the more efficient biomass utilization in BCLG technology. This is due to BCLGCC having a higher efficiency compared to conventional BIGCC. This is attributed to the flameless gasification process resulting in less exergy loss during the thermal conversion process. In addition, the tar catalytic cracking ability of the OC in BCLGCC process increases by converting more tar and char into syngas, hence biomass utilization ability increases compared to BIGCC. Therefore, reducing the amount of biomass feedstock for BCLGCC power plant to generate the same output (650 MW). Furthermore, BCLGCC can avoid the cost and energy depleting step of air separation to produce oxygen. Finally, looking at the TLCCI for both gasification technologies, BCLGCC requires less TLCCI due to its high energy efficiency, hence requiring less biomass to be processed within the system, hence reducing the feedstock cost. Additionally, this decreases the physical size of the plant, therefore decreasing its annual capital cost. On the other hand, BCLG technology is more complex than conventional gasification which should slightly increase its cost, yet the TLCCI remains less than the BIGCC process.

Comparing between coal and biomass power plants, on average wood harvesting, processing, and transport (biomass supply chain) consumes approximately 3 and 2.5 times the energy required for coal mining, washing and transport (coal supply chain) per MWh for IGCC and combustion power plants, respectively, with wood processing being the most energy demanding step. This is due to coal being more energy dense compared to biomass hence less coal feedstock processing is required. In addition, coal transport distance is less compared to biomass, which is sourced from North America, hence requiring more energy throughout its supply chain. It was calculated that the life cycle costs of biomass and coal is equal to 10.0 £/GJ and 1.78 £/GJ, respectively, which is in line with the prices in the UK. The TLCCI for coal power plants are much cheaper than biomass power plants due to less amount of feedstock required as well as due to the higher cost of biomass transport. The second most cost intensive process is wood harvesting and transport process. Even though coal powered plants produce cheaper electricity, but government renewable energy incentives and carbon tax schemes (discussed in section 3.6) will reduce cost of biomass power plants making them suitable towards achieving a net-zero carbon emissions by 2050.

The energy (cost) required by CCS accounts for approximately 15.0% (11.7%) of the TLCEI (TLCCI) for biomass power plants and 32.0% (2.2%) for coal power plants. The higher percentage in the coal power plant is due to their lower TLCEI. The flue gas CO_2 emissions from the non-CCS plants ranges from 841 – 899 kg-CO_2/MWh, with DBC having the highest emissions (899 kg-CO_2/MWh), however since biomass is the fuel source, it can be assumed to be carbon neutral. Whereas the CIGCC plant releases the most CO_2 (867 kg-CO_2/MWh) from a non-renewable source. Even though biomass-based power plants can be assumed to be carbon neutral, fossil fuel-based CO_2 is released during the supply chain process, hence increasing the net CO_2 emissions by approximately 54 – 85 kg-CO_2/MWh. Regarding coal power plants, the coal supply chain emits between 20 - 36 kg-CO_2/MWh. The highest net total life cycle CO_2 emitter was the PCC with CCS (147.9 kg-CO_2/MWh) power plant, followed by CIGCC with CCS (131.0 kg-CO_2/MWh), then BIGCC with CCS (negative 854.1 kg-CO_2/MWh) and finally DBC with CCS power plant (negative 996.2 kg-CO_2/MWh).

3.5 Future Technological Development

After a thorough energy, cost, and CO_2 emission comparison between the thermal conversion technologies in the previous section. It concluded that from an energy efficiency perspective, biomass/coal gasification power generation technology is more efficient than combustion power generation due to the step-by-step chemical energy utilized and high thermal conversion efficiency (gas turbine combined cycle). From the perspective of clean and efficient utilization of energy, the future development of biomass/coal gasification power generation technology is the primary technology to be considered. However, there is a high investment in biomass/coal gasification, and some key core technologies (such as tar cracking, high temperature desulfurization, air separation unit, etc.) need a breakthrough. BCLGCC with and w/o CCS demonstrates itself to be a potential alternative which is due to its efficient fuel utilization and carbon neutral and carbon negative emissions. Moreover, in line with the UK policies, BCLGCC shows better results than BDC and BIGCC coupled with a CCS process which can support the push towards establishing bioenergy with carbon capture and storage (BECCS) technology for a net zero 2050. However, there are a few drawbacks associated with the technology which can be researched into and improved to reduce the cost, energy input and CO_2 emission. These include researching into finding a suitable and effective oxygen carrier, developing and enhancing the design of two-stage fluidized bed reactor and looking into integrating the system by energy matching and incorporating waste heat recovery technology.

Looking at the life cycle energy input and CO_2 emissions stages in details, wood processing and pelletization stage consumes the most amount of energy, hence should be researched into developing low energy consuming and low-cost biomass pre-treatment and biomass moulding technology to reduce the high energy requirement and CO_2 emissions. Moreover, the second most cost intensive process within the life cycle of the power plant is biomass harvesting and transport to the wood pellet plant. This could be reduced if biomass is sourced from a different country with cheaper costs and an abundant source of biomass. It could also have an effect on the supply chain process depending on how far the country the biomass is sourced from, which could also affect the energy input and CO_2 emission. This is one of the main reasons delaying biomass technology from fast commercialization. Moreover, BCLGCC consumes a large amount of the gross power produced within the plant hence reduces the net power. Most of the power is consumed in compressing the syngas before the combined cycle process, hence researching into reducing the energy consumption within the plant is essential to further improve overall efficiency of the technology. This effect can be minimized by developing high temperature and pressure syngas cleaning technology.

In terms of the TLCCI, the annual capital cost consumes the highest cost throughout the life cycle cost input. It is not expected for combustion technology to reduce in capital cost in the near future as it has significantly developed and commercialized, however BIGCC and BCLGCC are still commercializing hence are expected to reduce in costs with further research, especially with BCLGCC. Even though coal is much cheaper compared to biomass in the UK, the UK is planning on closing all coal power plants by 2025, hence the idea of building CIGCC and PCC power plants in the UK will not be applicable, however it could be suitable for other countries that carry on using coal or are interested in coal power plants with CCS. This would have an effect on the fuel supply chain, which will be considered in the following section. Moreover, biomass gasification not only can it generate syngas to power generation but can also be used as an alternative to simultaneously produce hydrogen for hydrogen powered cars since after the year 2035 when selling petrol and diesel cars ban come to effect, or even for MIDREX Direct Reduction Plant process instead of conventional coking process to steel making (coking-steel making causing large amount of carbon emission and pollution) [87]. In conclusion, BCLGCC/BIGCC presents a promising alternative, however further research into this technology can be very much effective in presenting a pathway towards a carbon neutral 2050 from the perfective of life cycle energy input, economy, and CO_2 emissions.

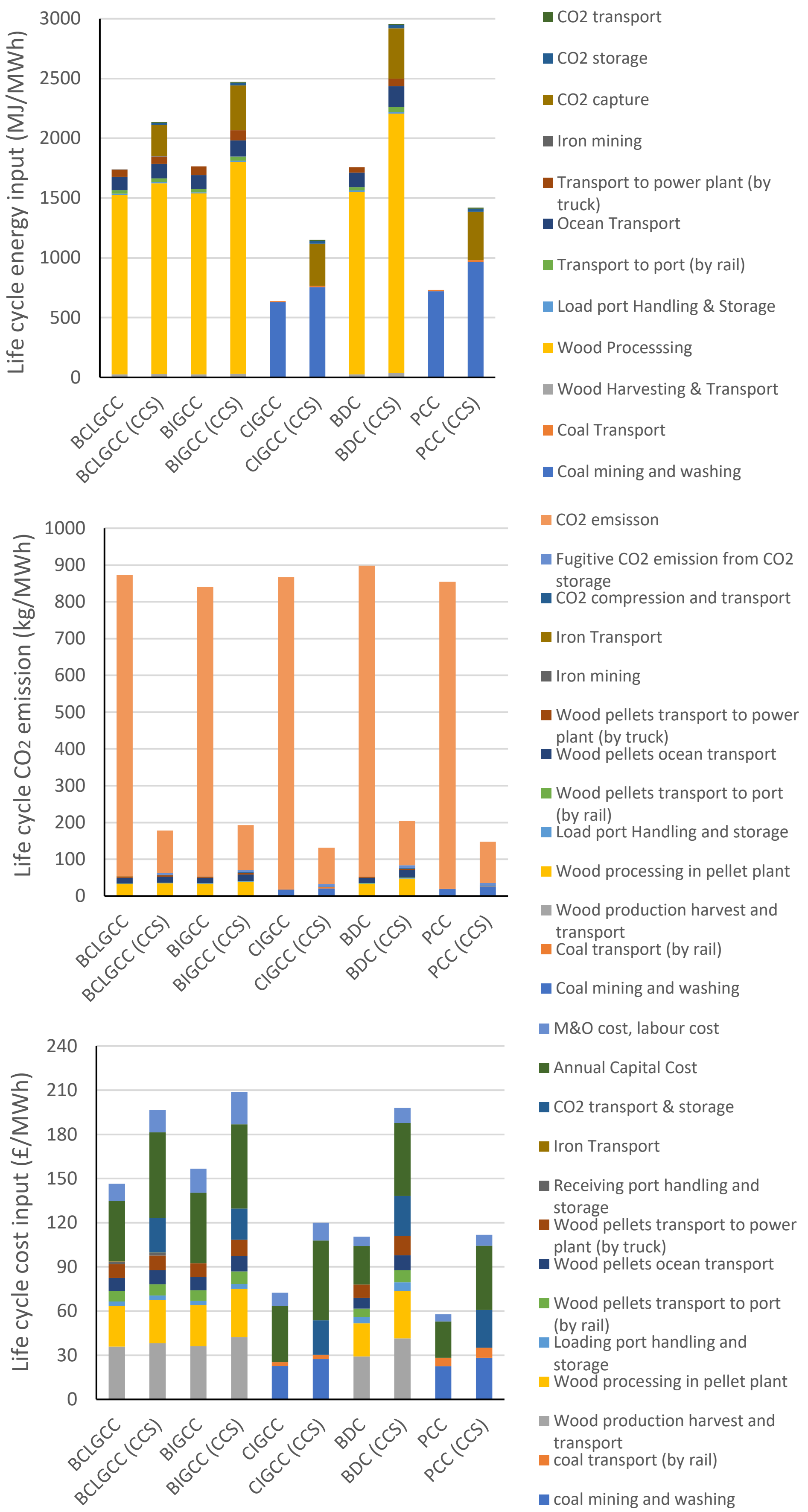
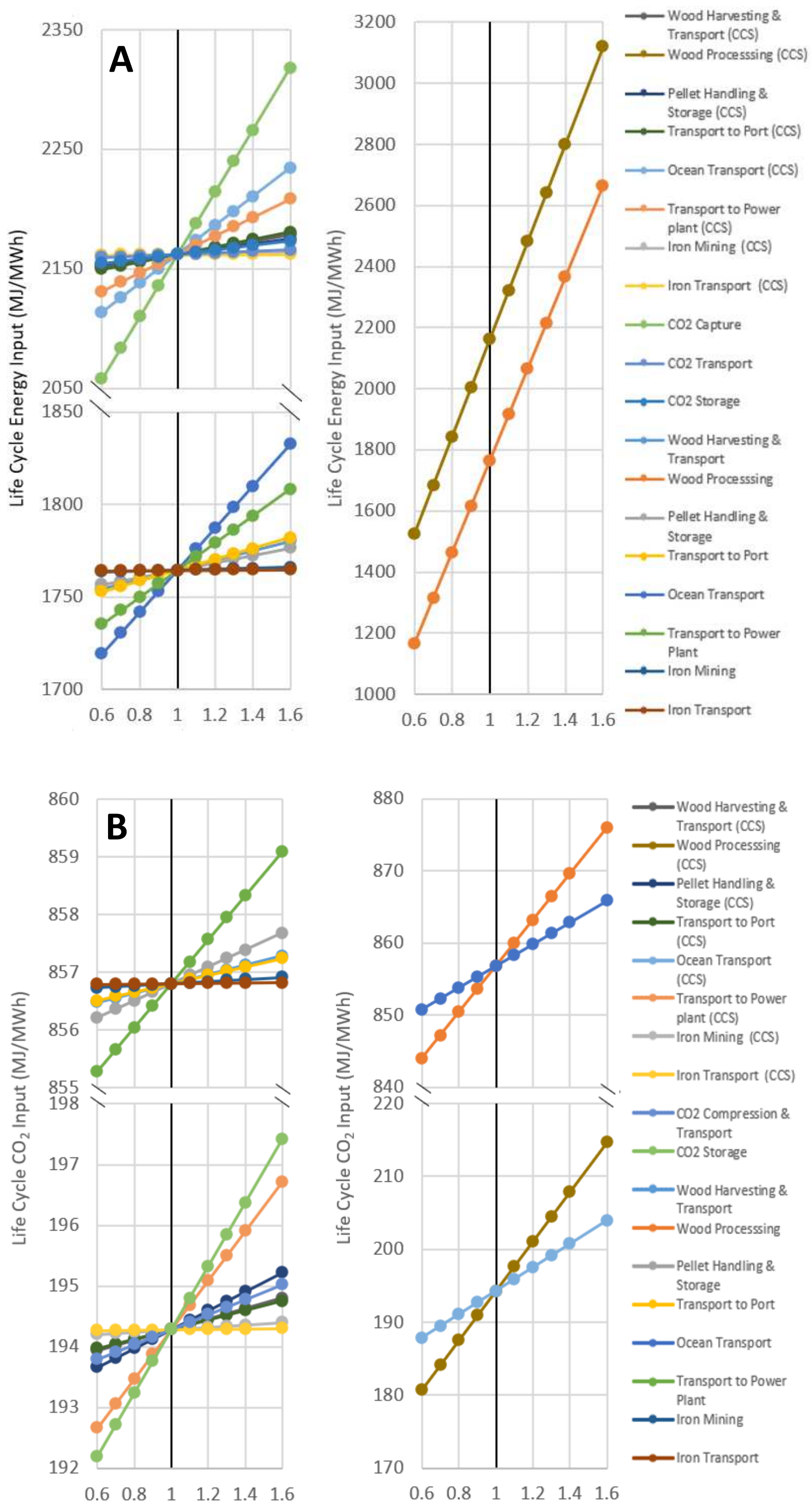


Figure 12. Comparing life cycle energy-CO_2 emission-cost input of eight power plants

3.6 Sensitivity Analysis

Since the values used in this research could change with time, location, technological development or could have a percentage uncertainty, a sensitivity analysis has been performed to identify parameters that would have the most significant impact on the life cycle assessment, Figures 13, 2S & 3S (in Supporting Information). The supply chain processes of all feedstocks as well as the CO_2 capture, transport and storage have been used as the base parameters for the sensitivity analysis to measure their effect on the total life cycle energy input, CO_2 emissions and cost input. Additionally, to further measure the effect of the total life cycle cost input, the variable cost, capital cost and plant life were tested. This has been performed on a BCLGCC, BIGCC and CIGCC plants with and w/o CCS. The parameters that had the highest impact on the TLCEI and consequently TLCCE are the wood processing, coal mining and washing, CO_2 capture, and biomass transport. However, out of the biomass transport process, ocean transport resulted in the highest impact on the life cycle values. The biomass transport process varies the TLCEI by approximately 8.0% and 6.8% for both CCS and non-CCS power generation systems, respectively, as the biomass transport energy input varies by 60%. This also results in the TLCCE to vary by around 1.4% and 7.6% for biomass non-CCS and CCS power plants, respectively. Since coal power plants are not expected to be invested into in the near future in the UK, the values can be applied in other countries (e.g. China, USA, India) that still heavily invest in coal power station. Changing the geographical location of the plant will have an effect on the coal transport for the CIGCC plant. Increasing the coal transport energy by 60% increases the TLCEI and TLCCE by 0.9% (0.6% for CCS) and 0.2% (1.7% for CCS), respectively. Establishing the power plant in other geographical locations could reduce the fuel supply chain energy input, CO_2 emission and cost input depending on the abundance of the fuel (biomass or coal), however coal would still be preferred due to its lower overall cost unless government subsidies and policies are put in place to encourage using biomass fuel, which in the UK is the Renewable Obligation Certificate (ROC)'s requiring 100% renewable electricity to be producing giving a value of 50.05 £/MWh [88]. Another factor from the fuel supply chain that heavily influences the TLCEI and TLCCE are wood processing for biomass and mining & washing for coal. As wood processing varies value by 60%, the overall TLCEI varies by approximately 51% for non-CCS (43% for CCS), while the overall TLCCE varies by approximately 2.1% for non-CCS (11.9% for CCS). This shows that wood processing has a higher sensitivity impact on TLCEI compared to the TLCCE, with it having a greater impact on CCS plants compared to non-CCS for the TLCCE. Similarly, with the CIGCC power plant, a 60% increase in coal mining and washing increases the TLCEE by 59.1% for non-CCS (39.4% for CCS) and increases the TLCCE by 19.4% for non-CCS (13.9% for CCS). Regarding CCS, it also has a higher sensitivity on TLCEI compared to TLCCE. In terms of cost, the annual cost, wood harvesting, wood processing and coal mining & washing cause the highest sensitivity to the TLCCI. A 60% change in annual capital cost will result in approximately 17.0% change in the TLCCI for the biomass power plants (CCS and non-CCS) and 30.5% for the CIGCC plant (24.4% for CIGCC with CCS). Looking at the supply chain of the fuel feedstock which depends on the location of the power plant, increasing the biomass supply chain by 60% increases the TLCCI by approximately 10 – 13%, and increasing the coal supply chain by 60% increases the TLCCI by 2 – 4%. Therefore, establishing a biomass-based power plant in a geographic location surrounded by an abundant source of biomass would significantly reduce the costs. Additionally, the cost of CO_2 capture and storage varies TLCCI by 7.1% for BCLGCC, 6.6% for BIGCC and 13.9% for CIGCC when its cost varies by 60%. Taking into consideration the 50.05 £/MWh ROC government subsidy in the TLECI values, this will reduce the TLECI of BCLGCC, BIGCC and BDC to 99.2 £/MWh (149.6 £/MWh with CCS), 109.5 £/MWh (162.2 £/MWh with

CCS) and 66.7 £/MWh (156.6 MWh with CCS), respectively. A comparison between the TLCCI of all the 10 difference power generation technologies with and without CCS including the ROC government subsidies is summarized in Figure 14.



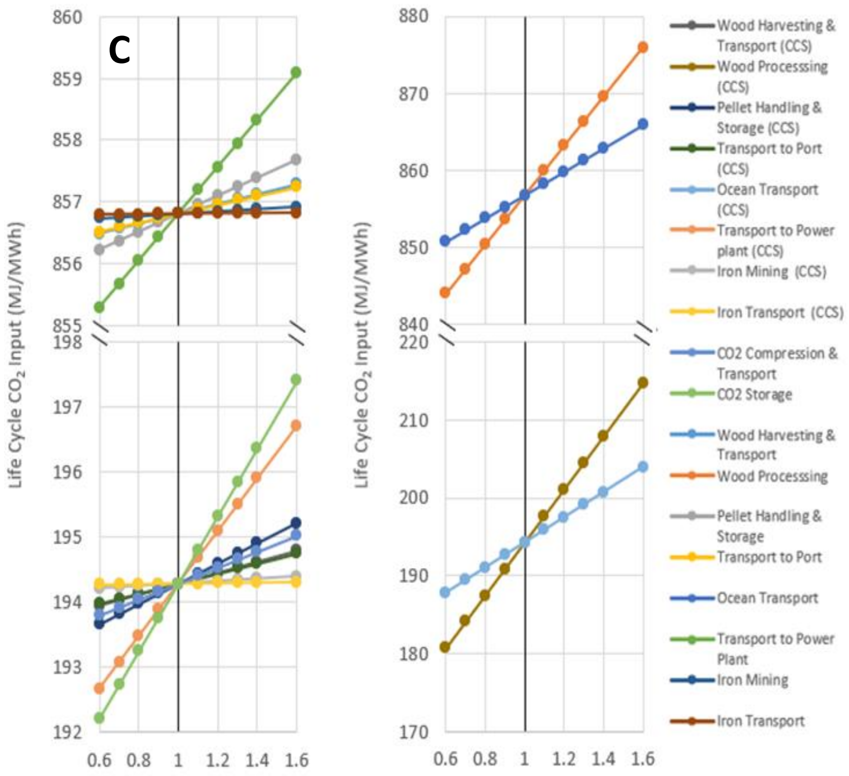


Figure 13. Sensitivity analysis of life cycle (**A**) energy input, (**B**) CO_2 emissions and (**C**) cost input of a BCLGCC power plant

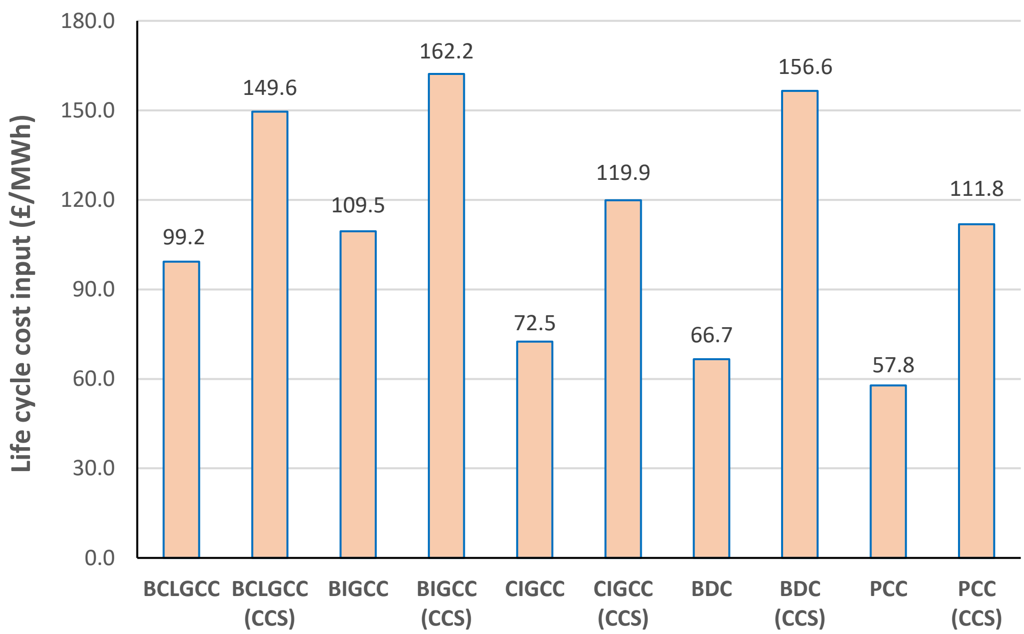


Figure 14. Comparison of TLCCI when taking into consideration the UK's ROC subsides

4. Conclusions

As a push towards more efficient and renewable technology, research in gasification to power technology has become more prominent during the past decades. This study presented a life cycle energy – economy – CO_2 emissions analysis of the BCLGCC power plant and compared it to conventional coal/biomass gasification as well as biomass direct combustion. Major conclusions are as follows:

1) Coal power plants illustrated the least energy and cost input compared to biomass power plants, however resulted in higher net CO_2 emissions, since biomass power plants can be assumed to be near carbon neutral. Coal CCS plants can reduce CO_2 emissions to near zero, with BCLGCC and BIGCC plants with CCS can result in negative 680 kg-CO_2/MWh and 768.9 kg-CO_2/MWh, respectively, yet BIGCC requires more TLCEI for the same power output due to more energy required for the CCS due to more CO_2 emission.
2) CIGCC without CCS plant requires the lowest amount of TLCEI (637.9 MJ/MWh) whereas BDC with CCS requires the most (2971.5 MJ/MWh). However, out of the biomass power plants BCLGCC requires the lowest energy requirement, were BCLGCC with CCS required 336.7 MJ/MWh and 827.3 MJ/MWh less energy input than BIGCC and BDC both with CCS technology.
3) In terms of TLCCI, PCC plant demonstrates the lowest value (57.8 £/MWh) and BIGCC showing the highest (159.5 £/MWh) out of the non-CCS processes, and similarly with the CCS power plants (212.2 £/MWh for BIGCC and 111.8 £/MWh for PCC), with BCLGCC having a higher TLCCI compared to BDC which is due to the higher capital cost of the plant as it is still in its development stage, hence higher process and project contingencies.

4) The biomass supply chain process accounted for approximately 85% of energy input 31% of CO_2 emissions, 50% of cost input for CCS power plants. BCLGCC plant required 14.3% and 11.6% (23.0 & 25.8% with CCS) less biomass compared to BIGGCC and DBC power plants to generate the same amount of power, respectively. Wood processing & pelletization stage should be improved to reduce the high energy requirement and CO_2 emissions. This will result in a reduction in the cost of the process, hence reducing the overall cost of biomass.
5) The parameters that had the highest effects on the TLCEI and TLCCE are the wood processing, coal mining and washing, CO_2 capture, and biomass transport. Whereas in terms of cost, the annual cost, wood harvesting, wood processing and coal mining & washing caused the highest influence on the TLCCI. Regarding the CCS power plants, the carbon capture and storage section had the highest impact of TLCCI followed by TLCCE and finally TLCEI.

Moreover, in line with the UK policies, BCLGCC shows better results than BDC and BIGCC coupled with CCS technology to help drive bioenergy with carbon capture and storage (BECCS) technology towards a net zero 2050. Government subsidies and negative emissions incentives are essential for project feasibility. These results can be a guide for comprehensive comparison between BCLGCC and conventional thermochemical power generation technology with and w/o CCS in a move towards a carbon neural 2050 via BECCS technology.

Acknowledgements

The authors gratefully acknowledge the financial support from the UK EPSRC and the National Natural Science Foundation of China (U1810125, 51776133), and the Key R&D Program of Shanxi Province (201903D121031).

References

[1] Agbor, E., Oyedun, A., Zhang, X. and Kumar, A. (2016). Integrated techno-economic and environmental assessments of sixty scenarios for co-firing biomass with coal and natural gas. *Applied Energy*, 169, pp.433-449.

[2] EIA (2017). *International Energy Outlook 2017*. U.S: U.S Energy Information Administration.

[3] World Energy Resources. (2017). 24th ed. [ebook] London: World Energy Council - Executive Summary, p.3. Available at: http://www.worldenergy.org/wp-content/uploads/2016/10/World-Energy-Resources_ExecutiveSummary_2016.pdf [Accessed 13 Aug. 2019].

[4] Paris Agreement, (2015), United Nations Framework Convention on Climate Change.

[5] UK Climate action following the Paris Agreement. In: Change CoC, 2016.

[6] Committee on Climate Change (2019). Net Zero: The UK's contribution to stopping global warming.

[7] Drax. 2020. *End of Coal Generation at Drax Power Station - Drax*. [online] Available at: <https://www.drax.com/investors/end-of-coal-generation-at-drax-power-station/> [Accessed 26 June 2020].

[8] Nsenergybusiness.com. 2020. *UK Coal: What Will Happen To Britain's Power Stations After 2025 Deadline?*. [online] Available at: <https://www.nsenergybusiness.com/features/uk-coal-power-stations> [Accessed 26 June 2020].

[9] BBC News. 2020. *Ban on Petrol And Diesel Car Sales Brought Forward*. [online] Available at: <https://www.bbc.co.uk/news/science-environment-51366123> [Accessed 26 June 2020].

[10] Department for Business, Energy & Industrial Strategy, 2020. *Section 2 – UK Solid Fuels and Derived Gases January To March 2020*.

[11] Ukconstructionmedia.co.uk. 2020. *World'S First Zero Carbon Cluster - UK Construction Online*. [online] Available at: <https://www.ukconstructionmedia.co.uk/news/first-zero-carbon-cluster/> [Accessed 26 June 2020].

[12] The Independent. 2020. *UK's Record Coal-Free Power Run Comes to An End*. [online] Available at: <https://www.independent.co.uk/environment/coal-free-power-uk-record-time-2020-how-long-renewable-energy-a9570891.html> [Accessed 26 June 2020].

[13] Mandova, H., Gale, W.F., Williams, A., Heyes, A.L., Hodgson, P. and Miah, K.H., 2018. Global assessment of biomass suitability for ironmaking–opportunities for co-location of sustainable biomass, iron and steel production and supportive policies. *Sustainable Energy Technologies and Assessments*, *27*, pp.23-39.

[14] Leung, D.Y., Caramanna, G. and Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, *39*, pp.426-443.

[15] Platform, E.B.T., 2012. Biomass with CO2 capture and storage (Bio-CCS)-The way forward for Europe.

[16] Department for Business, Energy and Industrial Strategy, 2020. *UK ENERGY IN BRIEF*.

[17] Al-Qayim, K., Nimmo, W. and Pourkashanian, M., 2015. Comparative techno-economic assessment of biomass and coal with CCS technologies in a pulverized combustion power plant in the United Kingdom. International Journal of Greenhouse Gas Control, 43, pp.82-92.

[18] Oreggioni, G.D., Friedrich, D., Brandani, S. and Ahn, H., 2014. Techno-economic study of adsorption processes for pre-combustion carbon capture at a biomass CHP plant. *Energy Procedia*, *63*, pp.6738-6744.

[19] Zang, G., Jia, J., Tejasvi, S., Ratner, A. and Lora, E.S., 2018. Techno-economic comparative analysis of biomass integrated gasification combined cycles with and without CO_2 capture. *International Journal of Greenhouse Gas Control*, 78, pp.73-84.

[20] Domenichini, R., Gasparini, F., Cotone, P. and Santos, S., 2011. Techno-economic evaluation of biomass fired or co-fired power plants with post combustion CO2 capture. *Energy Procedia*, *4*, pp.1851-1860.

[21] Do, T.X., Lim, Y.I., Yeo, H., Choi, Y.T. and Song, J.H., 2014. Techno-economic analysis of power plant via circulating fluidized-bed gasification from woodchips. *Energy*, *70*, pp.547-560.

[22] McIlveen-Wright, D.R., Huang, Y., Rezvani, S., Redpath, D., Anderson, M., Dave, A. and Hewitt, N.J., 2013. A technical and economic analysis of three large scale biomass combustion plants in the UK. *Applied energy*, *112*, pp.396-404.

[23] Ernsting, A., 2015. *Biomass Gasification & Pyrolysis*. Biofuelwatch.

[24] Prins, M.J., Ptasinski, K.J. and Janssen, F.J., 2007. From coal to biomass gasification: Comparison of thermodynamic efficiency. *Energy*, *32*(7), pp.1248-1259.

[25] Shrestha, P., 2019. *UK'S 'Largest' Waste Wood Gasification Plant Fired Up in Cheshire - Energy Live News*. [online] Energy Live News. Available at: <https://www.energylivenews.com/2019/03/26/uks-largest-waste-wood-gasification-plant-fired-up-in-cheshire/> [Accessed 26 June 2020].

[26] Cooper, S., Blanco-Sanchez, P., Welfle, A. and McManus, M., 2019. *Bioenergy And Waste Gasification In The UK: Barriers And Research Needs*. Bath: Supergen Bioenergy Hub.

[27] Sikarwar, V., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M., Shah, N., Anthony, E. and Fennell, P. (2016). An overview of advances in biomass gasification. *Energy & Environmental Science*, 9(10), pp.2939-2977.

[28] Maniatis, K., 2008. Progress in biomass gasification: an overview. Progress in thermochemical biomass conversion.

[29] National Energy Technology Laboratory. (2018). Fluidized bed gasifiers. https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/ugas [Accessed 10 Jun. 2018].

[30] Han, J. and Kim, H., 2008. The reduction and control technology of tar during biomass gasification/pyrolysis: an overview. *Renewable and sustainable energy reviews*, *12*(2), pp.397-416.

[31] Zhao, X., Zhou, H., Sikarwar, V., Zhao, M., Park, A., Fennell, P., Shen, L. and Fan, L. (2017). Biomass-based chemical looping technologies: the good, the bad and the future. *Energy & environmental Science*, 10(9), pp.1885-1910.

[32] Kobayashi, N. and Fan, L. (2011). Biomass direct chemical looping process: A perspective. *Biomass and Bioenergy*, 35(3), pp.1252-1262.

[33] Virginie, M., Adánez, J., Courson, C., de Diego, L., García-Labiano, F., Niznansky, D., Kiennemann, A., Gayán, P. and Abad, A. (2012). Effect of Fe-olivine on the tar content during biomass gasification in a dual fluidized bed. *Applied Catalysis B: Environmental*, 121, pp.214-222.

[34] Jin, H., Hong, H. and Han, T. (2009). Progress of energy system with chemical-looping combustion. *Science Bulletin*, 54(6), pp.906-919.

[35] Matzen, M., Pinkerton, J., Wang, X. and Demirel, Y., 2017. Use of natural ores as oxygen carriers in chemical looping combustion: A review. *International Journal of Greenhouse Gas Control*, *65*, pp.1-14.

[36] Cho, P., Mattisson, T. and Lyngfelt, A. (2004). Comparison of iron-, nickel-, copper- and manganese-based oxygen carriers for chemical-looping combustion. Fuel, 83(9), pp.1215-1225.

[37] Luo, S., Zeng, L. and Fan, L. (2015). Chemical Looping Technology: Oxygen Carrier Characteristics. *Annual Review of Chemical and Biomolecular Engineering*, 6(1), pp.53-75.

[38] Shabani, S., Delavar, M.A. and Azmi, M., 2013. Investigation of biomass gasification hydrogen and electricity co-production with carbon dioxide capture and storage. *International journal of hydrogen energy*, *38*(9), pp.3630-3639.

[39] National Energy Technology Laboratory (2010). Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity.

[40] Hoffmann, B.S. and Szklo, A., 2011. Integrated gasification combined cycle and carbon capture: a risky option to mitigate CO2 emissions of coal-fired power plants. *Applied Energy*, *88*(11), pp.3917-3929.

[41] Mohamed, U., Zhao, Y., Huang, Y., Cui, Y., Shi, L., Li, C., Mohamed, P., Wei, G., Yi, Q. and Nimmo, W., 2020. Sustainability evaluation of biomass direct gasification using chemical looping technology for power generation with and w/o CO2 capture. Energy, p.117904.

[42] Hammond, G.P. and Spargo, J., 2014. The prospects for coal-fired power plants with carbon capture and storage: A UK perspective. *Energy Conversion and Management*, *86*, pp.476-489.

[43] Liang, X., Wang, Z., Zhou, Z., Huang, Z., Zhou, J. and Cen, K., 2013. Up-to-date life cycle assessment and comparison study of clean coal power generation technologies in China. *Journal of cleaner production*, *39*, pp.24-31.

[44] Yang, K., Zhu, N. and Yuan, T., 2017. Analysis of optimum scale of biomass gasification combined cooling heating and power (CCHP) system based on life cycle assessment (LCA). *Procedia Engineering*, *205*, pp.145-152.

[45] Mann, M.K. and Spath, P.L., 1997. *Life cycle assessment of a biomass gasification combined-cycle power system* (No. NREL/TP-430-23076; ON: DE98002709). National Renewable Energy Lab., Golden, CO (US).

[46] Zang, G., Zhang, J., Jia, J., Lora, E.S. and Ratner, A., 2020. Life cycle assessment of power-generation systems based on biomass integrated gasification combined cycles. *Renewable Energy*, *149*, pp.336-346.

[47] Carpentieri, M., Corti, A. and Lombardi, L., 2005. Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO2 removal. *Energy Conversion and Management*, *46*(11-12), pp.1790-1808.

[48] Odeh, N.A. and Cockerill, T.T., 2008. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy*, *36*(1), pp.367-380.

[49] Stamford, L. and Azapagic, A., 2014. Life cycle sustainability assessment of UK electricity scenarios to 2070. *Energy for Sustainable Development*, *23*, pp.194-211.

[50] Wang, Z., Li, L. and Zhang, G., 2018. Life cycle greenhouse gas assessment of hydrogen production via chemical looping combustion thermally coupled steam reforming. *Journal of Cleaner Production*, *179*, pp.335-346.

[51] Li, G., Liu, F., Liu, T., Yu, Z., Liu, Z. and Fang, Y., 2019. Life cycle assessment of coal direct chemical looping hydrogen generation with Fe_2O_3 oxygen carrier. *Journal of Cleaner Production*, *239*, p.118118.

[52] Heng, L., Xiao, R. and Zhang, H., 2018. Life cycle assessment of hydrogen production via iron-based chemical-looping process using non-aqueous phase bio-oil as fuel. *International Journal of Greenhouse Gas Control*, *76*, pp.78-84.

[53] Petrescu, L., Müller, C.R. and Cormos, C.C., 2014. Life cycle assessment of natural gas-based chemical looping for hydrogen production. *Energy Procedia*, *63*, pp.7408-7420.

[54] Salkuyeh, Y.K., Saville, B.A. and MacLean, H.L., 2017. Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies. *International Journal of hydrogen energy*, *42*(30), pp.18894-18909.

[55] Bareschino, P., Mancusi, E., Urciuolo, M., Paulillo, A., Chirone, R. and Pepe, F., 2020. Life cycle assessment and feasibility analysis of a combined chemical looping combustion and power-to-methane system for CO2 capture and utilization. *Renewable and Sustainable Energy Reviews*, *130*, p.109962.

[56] Navajas, A., Mendiara, T., Goñi, V., Jiménez, A., Gandía, L.M., Abad, A., García-Labiano, F. and Luis, F., 2019. Life cycle assessment of natural gas fuelled power plants based on chemical looping combustion technology. *Energy Conversion and Management*, *198*, p.111856.

[57] He, Y., Zhu, L., Li, L. and Rao, D., 2019. Life-cycle assessment of SNG and power generation: The role of implement of chemical looping combustion for carbon capture. *Energy*, *172*, pp.777-786.

[58] Fan, J., Hong, H. and Jin, H., 2018. Power generation based on chemical looping combustion: will it qualify to reduce greenhouse gas emissions from life-cycle assessment?. *ACS Sustainable Chemistry & Engineering*, *6*(5), pp.6730-6737.

[59] Petrescu, L. and Cormos, C.C., 2017. Environmental assessment of IGCC power plants with pre-combustion CO2 capture by chemical & calcium looping methods. *Journal of Cleaner Production*, *158*, pp.233-244.

[60] Fan, J., Hong, H. and Jin, H., 2019. Life cycle global warming impact of CO2 capture by in-situ gasification chemical looping combustion using ilmenite oxygen carriers. *Journal of Cleaner Production*, *234*, pp.568-578.

[61] Tagliaferri, C., Görke, R., Scott, S., Dennis, J. and Lettieri, P., 2018. Life cycle assessment of optimised chemical looping air separation systems for electricity production. *Chemical Engineering Research and Design*, *131*, pp.686-698.

[62] International Organisation for Standardisation (ISO), 2006. Environmental Management–Life Cycle Assessment–Requirements and Guidelines (ISO 14044).

[63] International Organization for Standardization, 2006. *Environmental Management: Life Cycle Assessment; Principles and Framework* (No. 2006). ISO.

[64] Cmu.edu. 2020. *Integrated Environmental Control Model - About*. [online] Available at: <https://www.cmu.edu/epp/iecm/about.html> [Accessed 27 June 2020].

[65] Rubin, E.S., Berkenpas, M.B., Kietzke, K., Diwekar, U., Frey, H.C., Kalagnanam, J. and Fry, J.J., 1999. *IECM. Integrated Environmental Control Model* (No. ESTSC--001311IBMPC00). Carnegie-Mellon Inst. of Research, Pittsburgh, PA (United States).

[66] Barisano, D., Canneto, G., Nanna, F., Alvino, E., Pinto, G., Villone, A., Carnevale, M., Valerio, V., Battafarano, A. and Braccio, G. (2016). Steam/oxygen biomass gasification at pilot scale in an internally circulating bubbling fluidized bed reactor. *Fuel Processing Technology*, 141, pp.74-81.

[67] Yi, Q., Zhao, Y., Huang, Y., Wei, G., Hao, Y., Feng, J., Mohamed, U., Pourkashanian, M., Nimmo, W. and Li, W., 2018. Life cycle energy-economic-CO2 emissions evaluation of biomass/coal, with and without CO2 capture and storage, in a pulverized fuel combustion power plant in the United Kingdom. Applied energy, 225, pp.258-272.

[68] Carolyn Beeler, J., 2020. *The UK'S Move Away from Coal Means They're Burning Wood From The US*. [online] Keranews.org. Available at: <https://www.keranews.org/post/uk-s-move-away-coal-means-they-re-burning-wood-us> [Accessed 12 May 2020].

[69] Ricardo Energy & Environment, 2018. *Global Biomass Markets*. Department for Business, Energy and Industrial Strategy.

[70] Beets, M.D.A., 2017. *A Torrefied Wood Pellet Supply Chain. A detailed cost analysis of the comptetitiveness of torrefied wood pellets compared to white wood pellets* (Master's thesis).

[71] Ssethermal.com. 2020. *SSE Thermal Opens Consultation for Proposed Keadby 3 Low-Carbon Power Station | SSE Thermal*. [online] Available at: <https://www.ssethermal.com/news-and-views/2020/06/sse-thermal-opens-consultation-for-proposed-keadby-3-low-carbon-power-station/> [Accessed 29 June 2020].

[72] Gårdbro, G., 2014. Techno-economic modeling of the supply chain for torrefied biomass (Master's thesis).

[73] Sea-distances.org. 2020. *SEA-DISTANCES*. [online] Available at: <https://sea-distances.org/> [Accessed 18 October 2020].

[74] Google Maps. 2020. *Google Maps*. [online] Available at: <https://www.google.co.uk/maps/> [Accessed 18 October 2020].

[75] Aditnow.co.uk. 2020. *Lists And Maps Of UK And International Mines And Quarries*. [online] Available at: <https://www.aditnow.co.uk/Database/> [Accessed 27 June 2020].

[76] Li, S., Gao, L. and Jin, H., 2016. Life cycle energy use and GHG emission assessment of coal-based SNG and power cogeneration technology in China. Energy Conversion and Management, 112, pp.91-100

[77] IEA-ETSAP. 2014. Coal mining and logistics.

[78] Norgate, T. and Haque, N., 2010. Energy and greenhouse gas impacts of mining and mineral processing operations. Journal of Cleaner Production, 18(3), pp.266-274.

[79] Koornneef, J., van Keulen, T., Faaij, A. and Turkenburg, W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. International journal of greenhouse gas control, 2(4), pp.448-467.

[80] Yang, B., Wei, Y.M., Hou, Y., Li, H. and Wang, P., 2019. Life cycle environmental impact assessment of fuel mix-based biomass co-firing plants with CO2 capture and storage. Applied Energy, 252, p.113483.

[81] Yujia, W., Zhaofeng, X. and Zheng, L., 2014. Lifecycle analysis of coal-fired power plants with CCS in China. Energy Procedia, 63, pp.7444-7451.

[82] Analysis of road and rail costs between coal mines and power stations. MDS transmodal; 2012.

[83] GmbH, f., 2020. *Iron Ore PRICE Today | Iron Ore Spot Price Chart | Live Price Of Iron Ore Per Ounce | Markets Insider*. [online] markets.businessinsider.com. Available at: <https://markets.businessinsider.com/commodities/iron-ore-price> [Accessed 16 September 2020].

[84] Government Office for Science, 2019. *Understanding The UK Freight Transport System*. Future of Mobility: Evidence Review.

[85] Holloway, S., Karimjee, A., Akai, M., Pipatti, R. and Rypdal, K., 2006. Carbon dioxide transport, injection and geological storage. *In: IPCC guidelines for national greenhouse gas inventories/edited by Intergovernmental Panel on Climate Change [IPCC]. Paris, France: OECD. p.*, *5*, pp.5-1.

[86] Energy Technologies Institute, 2020. *A Picture Of CO2 Storage In The UK - Learnings From The ETI'S UKSAP And Derived Projects*.

[87] Rectisol, L., 2010. Coal gasification for DRI production–An Indian solution. *Steel Times International*.

[88] Ofgem, 2020. *Renewables Obligation: Guidance For Suppliers*.