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Comparative Techno-Economic Analysis of Carbon Capture Processes: Pre-Combustion, Post-Combustion, and Oxy-Fuel Combustion Operations

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Abstract: Evaluation of economic aspects is one of the main milestones that affect taking rapid actions in dealing with GHGs mitigation; in particular, avoiding CO_2 emissions from large source points, such as power plants. In the present study, three kinds of capturing solutions for coal power plants as the most common source of electricity generation have been studied from technical and economic standpoints. Aspen HYSYS (ver.11) has been used to simulate the overall processes, calculate the battery limit, and assess required equipment. The Taylor scoring method has been utilized to calculate the costliness indexes, assessing the capital and investment costs of a 230 MW power plant using anthracite coal with and without post-combustion, pre-combustion, and oxy-fuel combustion CO_2 capture technologies. Comparing the costs and the levelized cost of electricity, it was found that pre-combustion is more costly, to the extent that the total investment for it is approximately 1.6 times higher than the oxy-fuel process. Finally, post-combustion, in terms of maturity and cost-effectiveness, seems to be more attractive, since the capital cost and indirect costs are less. Most importantly, this can be applied to the existing plants without major disruption to the current operation of the plants.

Keywords: carbon capture; CCS; post-combustion; pre-combustion; oxy-fuel combustion; cost evaluation; total investments; Taylor scoring method; Aspen HYSYS; power plants; levelized cost of electricity

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1. Introduction

Reducing the carbon emission rate in 2020 due to the COVID-19 pandemic's lockdown and co-occurring increase in greenhouse gases (GHGs) and global temperature trends confirm that the anthropogenic produced CO_2 is mainly to blame for the recent global warming [1,2]. Power plants in general and coal-fired power plants, in particular, have been specifically reported to be the largest and heaviest source of GHGs emissions, which are mainly CO_2. It has been predicted that, due to the global emission, the average global temperature will grow up to 3 °C by the end of the 21st century [3]. Therefore, a trade-off between energy demand and GHGs mitigation is required to be obtained.

Regardless of other factors influencing the economics and operations of production, several options were introduced to lower the emission rate of power plants, ranging from switching to cleaner coals to shutting down the plant, or retrofitting or rebuilding it with the utilization of other types of fuel, such as natural gas.

Alternatively, several carbon capture and storage CCS technologies have been employed to benefit from GHGs abatement without a basic intervention of the main process [4].

As the name suggests, CCS technologies are divided into three parts. The carbon capture process is the most expensive element of CCS technology, and accounts for 50% of the total costs, and, with CO_2 compression, the costs can make up to 90% of the total costs. The second part of CCS technologies, which requires the transportation of CO_2 as a link between capture, and the third part, which is storage, are both the lowest cost-intensive parts, but could be the most demanding in their planning and implementation [5].

All of the capturing approaches are categorized into three general processes, namely pre-combustion, oxy-fuel-combustion, and post-combustion. Other industrial approaches, regardless of whether they use a low amount of carbon or are carbon-free, are based on one or a mix of these main methods.

The capture cost can escalate the price of electricity production up to 90%. In addition, taking into account the current technology, retrofitting the existing power plant is more cost-effective than building new plants with CCS [6]. However, there is no general rule, and it could be completely case-dependent. Some other factors, such as the availability of fuel, penalties and taxes, and renewable energies, will play an important role in the future of GHGs abatement. A.Ficher and R.Volpe utilized four indicators (LCOE, LACE, cost of CO_2 avoided, and cost of CO_2 captured) for a techno-economic assessment of different technologies in Italian power plants. Based on their achievements, which compare USC, NGCC, IGCC, and wind power, CCS investment is suitable for USC and IGCC plants without CCS, but the carbon tax for IGCC is lower, while the unavailability of natural gas is an important drawback, and retrofitting none of the mentioned technologies shows viability [7]. Additionally, oxy-fuel combustion is highly dependent on the air separation unit (ASU) and its technology. The cryogenic separation unit is the most common separation method, whereas the other technologies, such as adsorption and membrane air separation, are less favorable and common due to the higher fabrication, integration, maintenance, and energy footprint that lead to the higher cost of O_2 production [8].

Among the above mentioned post-combustion CCS methods, amine chemical absorption is the most commercialized technology, with a well-developed background in natural gas sweetening and petrochemical industries, but some practical problems, such as the degradation and formation of heat-stable salts due to the presence of impurities, or intensifying the corrosion rate because of the presence of oxygen, are the main drawbacks nonetheless. Thus, reducing the impurities from the flue gas stream is of paramount importance before contacting with a solvent, such as amines. MEA solvent has been reported as one of the foremost single amine types in terms of its selectivity toward CO_2 and low regeneration cost. On the other hand, the high energy penalty toward utilizing CCS technology is another major challenge that should be considered, since it can be very costly, both in terms of its capital and operational cost [9,10].

The estimation methods can be categorized into four classes (simplified, preliminary, detailed, and finalized) based on the provided detailed information. Rubin reviewed and compared the significance of the consistency and unity of fossil fuel power plant CCS cost estimation basics and metrics in both technical and economic aspects. Rubin discussed how the same units (USD/tCO_2) of similar concepts, such as the cost of CO_2 avoided, cost of CO_2 captured, and cost of CO_2 abated, can confuse an unfamiliar audience. Based on the comparison of the assumption of different work (NETL 2007, NETL 2010, EPRI 2009, IEAGHG 2009, DECC 2010), such as owner's costs, the average annual capacity factor as an indicator for the riskiness of technology, usually being the ''first-of-a-kind" (FOAK) or the ''Nth-of-a-kind" (NOKA), is not considered by the cost estimator model. The annual average capacity factor would have an impact on the cost of electricity and financial riskiness, but it is not always equal to the plant availability. He reported 0.85 and 0.8 for the DOE/NETL pulverized coal plant and NETL 2010 IGCC, respectively. However, anticipating and taking into account all factors, such as the project contingency range, equipment amortization, or, in the case of retrofitting the plant, the capital cost "retrofitting factor", is difficult, and, most of the time, contains errors [11].

The utility supplier scenario is another parameter that should take into account the cost estimation, especially for the retrofitting cases. Roussanaly et al. discussed and suggested a developed guideline for the estimation of the CCS cost, and introduced some elements that have a large impact on the cost estimation. They showed that heat and power supply strategies may affect the outcome in very different CO_2-avoided costs. Furthermore, in some cases, particularly where the core process needs to be modified, the associated costs due to the disruption and possible shut down of the plant are noticeable and must not be overlooked. Maintaining the product quality could be another noticeable element in retrofitting; for example, clinker production in cement industries will be highly affected by selecting the oxy-fuel abatement process. Space and land requirements, along with impurities, are also important factors in retrofitting [12].

Generally, the estimation methods do not consider future costs. Rubin et al. focused on the hybrid method for predicting the future cost of the process, combining the conventional engineering–economic method and the experience curve model. Technologies that are at their earlier stage are more costly because of related items for ensuring their reliable operation, such as redundant equipment and oversized vessels. These costs and risks are more important in the case of (FOAK) plants, as they may get involved with operational and safety issues, such as startup and shutdown, control, and protection systems. In addition, contingency has played a great role based on the technology readiness level (TRL) of the proposed technology, varying the percentage of the associated process capital from 40% to 0–10% for the TRL 3 to 9, respectively. Utilizing chemical reagents, sorbents, and other materials that are not produced on a commercial scale is all in the context of variable operation and maintenance (O&M). O&M costs for FOAK technologies are generally higher than in (NOAK).

Besides, the capacity factor as another effective factor that leads to a low estimation of LCOE, financial factors, and project lifetime should be considered carefully, since it affects the LCOE, particularly in FOAK plants [13].

An assessment of the CO_2 capture cost has been conducted by Edvard. S. Rubin et.al based on the IPCC Special Report on Carbon Dioxide Capture and Storage 2005 (SRCCS). After 10 years, he concluded that, not only has the capital cost of CCS grown, but also that, despite increasing the capital and fuel cost, the levelized cost of electricity power plants with and without CCS has a slight variation. According to their conclusion, when comparing between post-combustion CO_2 capture at supercritical pulverized coal (SCPC), natural gas combined cycle (NGCC) power plants, and pre-combustion capture at coal-based integrated gasification combined cycle (IGCC) power plants, no superiority was suggested. However, it has been found that oxy-combustion could be a competitive choice with post-combustion (SCPC) capture [14]. The levelized cost of electricity (LCOE), cost of CO_2 avoided, and the cost of CO_2 capture has been proposed to assess the CCS technology in order to support the decision on technology selection, R&D priorities, and the marketing strategy, regulatory, and legislative policy-related activities. LCOE specifically concentrates on CCS instalment in power technology while avoiding costs by considering the whole cost of the CCS technology [14,15].

Currently, there are 65 ongoing industrial CCS projects across the world: 26 are operating, whereas 3 are currently close to being constructed and 34 are in early development or in advanced development, reaching front-end engineering design stages [16]. These CCS projects capture approximately 40 Gt/year of CO_2, which only accounts for 0.1% of the total emissions across the world [17]. Nevertheless, the deployment of these projects needs to be accelerated.

There are some unsuccessful or underestimated cost examples of implementing CCS projects. The Kemper power plant is a clear example of how expensive it can be to implement pre-combustion technology, as the cost of the power plant totaled USD 7.5 billion, where, initially, it was proposed to cost USD 2.4 billion (three times less). It is worth noting that the Schwarze Pumpe plant operated at 30 MW by Vattenfall; however, when it came to commercializing the project and increasing its productivity, the company decided against it because they believed that the costs and required energy for the commercialization of the project resulted in the technology being financially unviable. Thus, this study investigates predicting the cost of CCS technology in the power plant sector in order to fill the gap of cost assessment comparisons regarding common CCS technologies. This is based on standard metrics and indicators to help decision-makers, from techno-economic points of view, to select the right process among post, pre, and oxy-fuel combustion operations.

2. Methodology

The power plant of the subject of this study was 230 MW. Before carrying out any simulations for each of the capturing processes for a power plant with any capacity, it is important to ensure that the fuel type is the same for each process to certify that there is a level of consistency when comparing the results. The differences in the fuel compositions can have a significant impact on the amount of CO_2 produced and can result in lower/higher costs. For example, if sulfur is present, then a sulfur processor should operate to remove impurities and undesired components. Thus, for all three simulations conducted to analyze the techno-economic analysis of carbon capture processes, anthracite coal was chosen and the properties entered in Aspen HYSYS are shown in Table 1. The sulfur content in anthracite coal is extremely small, and so it was considered negligible. Furthermore, the fixed carbon content of coals, not including the moisture and ash, ranges from 50% to approximately 98%. Although the ignition of anthracites is difficult, it is often burned steadily for a long time with a short, clean flame, and contains a high proportion of fixed carbon. Ash is another by-product, can be captured by various technologies, such as cyclones, etc., and was not included in the core of this work.

Furthermore, the "Taylor scoring method" has been used to calculate the costliness index used for calculating the capital cost. This method just needs to outline information about the process, with an accuracy of approximately 95% confidence limits of +36% to −26%. Taylor explained his method step by step and showed how the complexity score can be calculated by considering factors such as the throughput and reaction time [18]

Table 1. Composition of different coal types and the corresponding prices. Adapted from [19].

Coal Type	Lignite	Sub-Bituminous	Bituminous	Anthracite
Carbon (wt. %)	65–72	72–76	76–90	90–95
Hydrogen (wt. %)	~5	~3	~2	~2
Oxygen (wt. %)	~30	10–15	~10	1
Sulfur (wt. %)	0	~2	4	~0
Nitrogen (wt. %)	~0	~1	~1	1–2
Moisture	70–30	30–10	10–15	~5
Price (GBP/ton)	GBP 14.29	GBP 10.08	GBP 42.39	GBP 73.53

3. Aspen HYSYS Simulations

3.1. IGCC Power Plant with Pre-Combustion Carbon Capture

For the IGCC pre-combustion power plant, several operation units were required for successful operation. Figure 1 shows the process flow sheet extracted from Aspen HYSYS for this specific simulation. For this system, the two major operating units were the gasifier and the water-gas shift reactor.

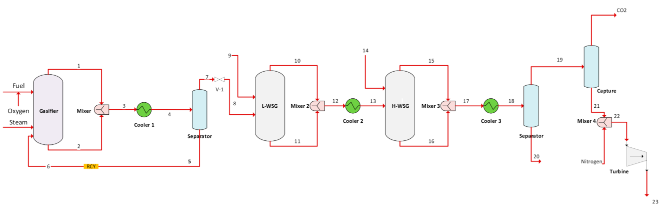

Figure 1. Pre-combustion carbon capture combined with an IGCC power plant.

The gasifier operates at 1200–1482 °C and 41 bars and is used to react the coal with limited O_2 and H_2O to produce syngas and small amounts of unwanted gases. The next step involved cooling the syngas mixture and recycling the unreacted carbon back into the gasifier, which helps to improve the overall efficiency of the process. To improve the efficiency and remove a higher amount of carbon dioxide, two water-gas shift (WGS) reactors are used instead of one, with the latter operating at a lower temperature. Water is used to initiate the water gas shift reaction, which helps to increase the amount of CO_2 and H_2 while reducing CO and H_2O.

Before the WGS reactor, the unwanted gases can be classified as untreated syngas, and progress through various gas treatment steps. A sulfur processor separates this substance, since it is a highly desired component in several industries. However, due to the composition of the initial feed, a sulfur processor is not needed.

The treated syngas, if needed, can be fed into a gas processor to ensure that the syngas mixture is free of any undesired components. Finally, CO_2 is captured and compressed, with the possibility of using it for an enhanced oil recovery in oil fields, or it can be stored via carbon sequestration. The hydrogen can be used in a gas turbine to generate electricity.

3.2. PC Power Plant with Post-Combustion Carbon Capture

Figure 2 shows the process flow diagram for the PC power plant with the post-combustion technology. For this system, anthracite coal enters the steam boiler, along with excess air, and complete combustion occurs, producing flue gas with low concentrations of CO_2 (10–15%). The produced flue gas (232 °C) needs to be cooled; therefore, a cooler is used to reduce the temperature to 40 °C. The flue gas enters from the bottom of the absorber, while the MEA solvent flows from the top of the absorber in the down direction, which results in contact between the two components. The MEA/flue gas solution then enters the stripper, which operates at 120, and is used to remove the unwanted acid gases. After this, the recovered CO_2 from the stripper progresses through a condenser and reflux drum to reduce the temperature and also to remove the water before the compression of the gas and storage. Simultaneously, at the beginning of the process, during the combustion of coal, a large amount of steam is produced. The steam is used to power a steam turbine and then, later, to power a generator in order to produce electricity.

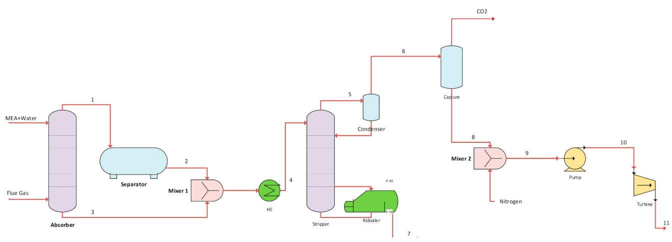

Figure 2. Post-combustion carbon capture with a PC plant.

3.3. PC Power Plant with Oxy-Fuel Carbon Capture

From the three processes, the oxy-fuel system was the easiest to model due to its simplicity. The process flow diagram for the PC power plant with the oxy-fuel technology is shown in Figure 3. Initially, air enters an ASU (not included in the flowsheet) to obtain the desired gas component (oxygen), with a high purity of 95–97%. Anthracite coal is fed into the boiler, along with oxygen, which results in combustion occurring. As a result of the combustion reaction, flue gas is produced, which consists of carbon dioxide and water, along with contaminants (SO_x, HCL, HF, and fly ash). However, due to relatively low amounts of sulfur in this type of coal, sulfur components are produced in extremely small amounts and, therefore, are counted as negligible. The fuel gas is then subjected to several treatment processes to remove unwanted contaminants. A total of 80% of the flue gas is recirculated into the boiler to control the temperature of the reactor and aid in increasing the CO_2 concentration in the flue gas, which results in a higher CO_2 capture. The steam produced as a result of the combustion reaction can be used for power production. The mixture of CO_2 and H_2O progresses through several purification units that aid in removing water by dehydration, and finally leaves the captured CO_2. The final step is the compression, transportation, and storage of the CO_2.

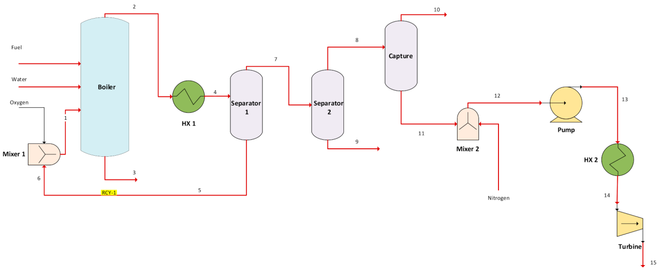

Figure 3. Oxy-fuel carbon capture combined with a PC plant.

4. Economic Assessment

It is important to carry out preliminary calculations, which are substantial in assessing the economic feasibility of carbon capture processes. Taylor proposed a method of estimating the costs of chemical plants using "Process Step Scoring" between 1972–1975 [20]. The method includes assigning a complexity score (0, 1, 2, or 3) to each significant step based on several parameters, such as the storage time, material and relative throughput, etc. The next step involves the calculation of the costliness index, which can be used to calculate the capital and operating costs for each process [18]. Using this information, an overall economic assessment can be carried out based on the simulations. The Taylor scoring method is shown in Tables 2–4 for the pre-combustion process combined with the IGCC plant, post-combustion process combined with PC, and oxy-fuel process combined with PC, respectively.

Table 2. Taylor step scoring for the pre-combustion process combined with IGCC plant.

Equipment	Relative Throughput	Temperature	Pressure	Material	Storage	Other	Total	Costliness Index
Air Separation Unit	1.5	0	0	1	2	0	4.5	3.26
Gasifier (FBR)	2.5	2.5	2	1	0	0	8	8.16
Cooler	1	1.5	0	1	0	0	3.5	2.50
Separator	1	0	0	1	0	0	2	1.69
Shift Reactor	2	1.5	1	1	0	0	5.5	4.23
Cooler	1	1	0	1	0	0	3	2.20
Shift Reactor	2	1	1	1	0	0	5	3.71
Cooler	1	1	0	1	0	0	3	2.20
Separator	1	0	0	1	0	0	2	1.69
Carbon Capture	1.5	0.5	0	1	1	0	4	2.86
Turbine	1	0.5	2.5	1	0	0	5	3.71
Compressor	1	0	1	1	0	0	3	2.20
Sum								38.41

Table 3. Taylor step scoring for the post-combustion process combined with PC.

Equipment	Relative Throughput	Temperature	Pressure	Material	Storage	Other	Total	Costliness Index
Boiler	2	1.5	1	1	2	0	7.5	7.15
Separator	1	0	0	1	0	0	2	1.69

Table 3. *Cont.*

Equipment	Relative Throughput	Temperature	Pressure	Material	Storage	Other	Total	Costliness Index
Cooler	1	1.5	0	1	0	0	3.5	2.50
Separator	1	0	0	1	0	0	2	1.69
Cooler	1	1	0	1	0	0	3	2.20
Absorber	1.5	0.5	0	1	0	0	3	2.20
Separator	1	0	0	1	0	0	2	1.69
Pump	1	0	1	1	0	0	3	2.20
Heat Exchanger	1	1.2	0	1	0	0	3.2	2.32
Stripper	1	1.5	1.5	1	0	0	5	3.71
Separator	1	0	0	1	0	0	2	1.69
Carbon Capture	1.5	0	0	1	1	0	3.5	2.50
Pump	1	0	3	1	0	0	5	3.71
Compressor	1	0	1	1	0	0	3	2.20
Turbine	1	0	0	1	0	0	2	1.69
Sum								39.14

Table 4. Taylor step scoring for the oxy-fuel process combined with PC.

Process	Relative Throughput	Temperature	Pressure	Material	Storage	Other	Total	Costliness Index
Air SeparationUnit	1.5	0	0	1	2	0	4.5	3.26
Boiler	1.5	2	2	1	0	0	6.5	5.50
Cooler	1	1	0	1	0	0	3	2.20
Separator	1	0	0	1	0	0	2	1.69
Separator	1	0	0	1	0	0	2	1.69
Carbon Capture	1.5	0.5	0	1	1	0	4	2.86
Pump	1	0	3	1	0	0	5	3.71
Heat Exchanger	1	1.5	0	1	0	0	3.5	2.50
Compressor	1	0	1	1	0	0	3	2.20
Turbine	1	0	0	1	0	0	2	1.69
								27.30

Equation (1) has been used to calculate the overall costliness index of each process. The equation entailed calculating the individual costliness index of each significant step and then adding up the values to obtain the total value of the costliness index [18].

$$I = \sum_{1}^{n} (1.3)^{S} \quad (1)$$

5. Results and Discussion

The costliness index is a key component for conducting an economic analysis because it allows for the calculation of the capital costs involved. Table 5 shows the calculated costliness index of each power plant with and without the associated CCS technologies. The total complexity index describes the complexity of all of the significant steps involved in each process and was integral to calculations carried out later in the report.

Table 5. Costliness index of the different power plants (excluding CCS technology).

Costliness Index	IGCC Power Plant Pre-Combustion	PC Power Plant Post-Combustion	PC Power Plant Oxy-Fuel
With CCS	38.41	39.14	27.3
Without CCS	29.64	29.04	14.34

The next step is to calculate the capital cost of the chemical plant combined with the appropriate CCS technology, which is also commonly known as the battery limit. However, before the calculation is carried out, the total costliness index and plant capacity have to be known. For the plant capacity, the CO_2 produced in each plant was used, as this was the focal point for this project. Table 6 shows the amount of carbon dioxide produced for each power plant, with the information extracted from the Aspen simulations.

Table 6. Produced CO_2 from power plants combined with CCS.

Process Type	Pre-Combustion	Post-Combustion	Oxy-Fuel
CO_2 Produced (t/year) (plant capacity)	561,954	485,392	406,114

Equation (2) is used to calculate the total capital cost [18]:

$$\frac{\text{Capital in k€}}{\text{Costliness Index}} = 42 \times (\text{amount of produced carbon dioxide})^{0.39} \quad (2)$$

5.1. Power Plants with and without CCS Technologies

5.1.1. Power Plants with CCS

Using Equation (3), the capital cost calculations were carried out, having been tabulated in Table 7.

Table 7. Capital costs of different CCS power plants.

Costs	IGCC Power Plant Pre-Combustion	PC Power Plant Post-Combustion	PC Power Plant Oxy-Fuel	Index
Capital Cost 1977	GBP 16,412,256	GBP 15,795,650	GBP 10,277,226	182
Modified Capital cost 2020	GBP 104,244,879	GBP 100,328,414	GBP 65,277,325	1156

The Taylor scoring method was devised in 1977; therefore, the capital cost above needs to be modified in order to take into account inflation [21].

$$\text{Capital}_{\text{selectedyear}} = \frac{\text{Capital}_{1977}}{\frac{\text{Index}_{1977}}{\text{Index}_{\text{selectedyear(2020)}}}} \quad (3)$$

5.1.2. Power Plants without CCS

The calculation of the capital costs for the power plants, which excluded any operation units required for CCS technologies, has been carried out and presented in Table 8.

Table 8. Capital costs of different power plants, excluding CCS.

Costs	IGCC Power Plant (without Pre-Combustion)	PC Power Plant (without Post-Combustion)	PC Power Plant (without Oxy-Fuel)
Capital Cost 1977	GBP 14,706,549	GBP 11,719,613	GBP 5,398,367
Capital Cost 2020	GBP 93,410,828	GBP 74,438,860	GBP 34,288,529

5.2. Operating Costs and Economic Assessment

Assessing the economic feasibility analysis of different processes is essential to help decision-makers choose the superior process. Based on Figure 4, the costs associated with the three mentioned processes were obtained.

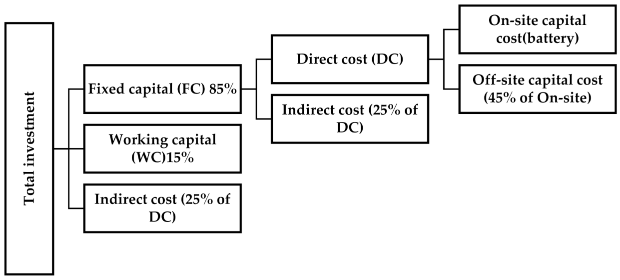

Figure 4. Cost flow chart.

The flowchart shown in Figure 4 demonstrates the several costs involved in the construction and operation of chemical plants. For the techno-economic feasibility analysis of pre-combustion, post-combustion, and oxy-fuel, it is important to calculate the cost of the operating chemical plant, along with the CCS technology. Therefore, several factors, such as the total expenditure (initial building cost, maintenance, and operational costs) and fixed capital costs (initial feed, vessel/reactors, heat exchangers, and separators), are taken into account. Table 9 summarizes the costs involved, whereas Figure 5 shows a graphical representation that clearly shows that the pre-combustion power plant was consistently the most expensive in all of the costs analyzed.

Table 9. Operating costs and total investment for different power plants using CCS technologies.

Parameters	**Costs**		
	IGCC—Pre Combustion	**PC—Post Combustion**	**PC—Oxy-Fuel**
On-site	GBP 104,244,879	GBP 100,328,414	GBP 65,277,326
Off-site	GBP 46,910,195	GBP 45,147,786	GBP 29,374,796
Direct	GBP 151,155,081	GBP 145,476,200	GBP 94,652,122
Indirect	GBP 37,788,770	GBP 36,369,050	GBP 23,663,031
Fixed capital	GBP 188,943,851	GBP 181,845,250	GBP118,315,043
Start-up	GBP 18,894,385	GBP 18,184,525	GBP 11,831,504
Investment	GBP 244,515,571	GBP 235,329,147	GBP 153,113,585

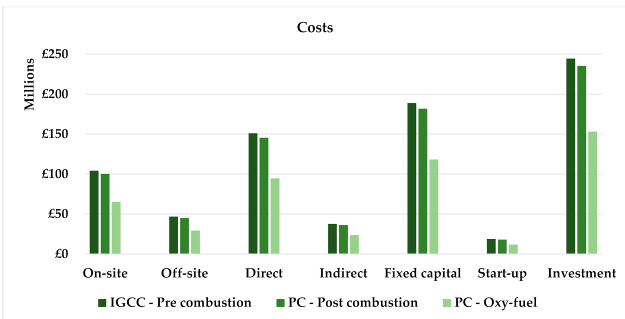

Figure 5. Graphical representation of costs.

Table 10 represents the operating costs and total investment for power plants, excluding CCS technology, and Figure 6 compared the total investment of the power plants, including and excluding CCS technology.

Table 10. Operating costs and total investment for power plants, excluding CCS.

Parameters	Cost		
	IGCC Power Plant Without CCS	**PC Power Plant Without CCS**	**PC Oxy-Fuel Power Plant Without CCS**
On-site	GBP 93,410,831	GBP 74,438,865	GBP 34,288,527
Off-site	GBP 42,034,874	GBP 33,497,488	GBP 15,429,838
Direct	GBP 135,445,705	GBP 107,936,352	GBP 49,718,365
Indirect	GBP 33,861,426	GBP 26,984,088	GBP 12,429,591
Fixed capital	GBP 169,307,131	GBP 134,920,441	GBP 62,147,956
Start-up	GBP 16,930,713	GBP 13,492,044	GBP 6,214,795
Investment	GBP 219,103,346	GBP 174,602,923	GBP 80,426,766

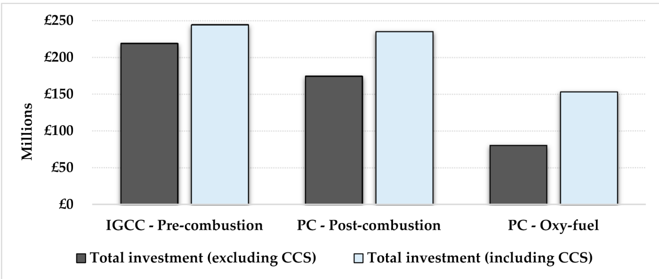

Figure 6. Total investment (including and excluding CCS).

5.3. Material Balance Cost Analysis

After the successful completion of the material balances for the three processes, several important variables, such as the carbon capture rate and the amount of fuel required, were extracted. These results are shown in Table 11. Another important factor is the price of anthracite coal, which was extracted from [22,23], and was GBP 73.68 per tonne.

Table 11. Important parameters extracted from the material balance calculations.

Parameter	Pre-Combustion	Post-Combustion	Oxy-Fuel
Carbon Capture	90%	92%	90%
Amount of Fuel Required	24,820 kg/h 217,432 t/year	22,340 kg/h 195,698 t/year	21,100 kg/h 184,836 t/year
Cost of Fuel (GBP/year)	GBP 16,020,390	GBP 14,419,029	GBP 13,618,716

For the pre-combustion carbon capture simulation, one WGS was initially used to increase the amount of carbon dioxide and hydrogen in the product stream. However, due to relatively low yields and a low carbon capture, a second WGS reactor was used, which resulted in an accepted carbon capture of 90%. The power produced is 230 MW or 2,014,800 MW/year. The power generated has been considered as consistent for all three processes to ensure both a high level of consistency and the possibility of accurate comparisons.

Furthermore, the costs for ASU added an approximately 3–4% additional energy penalty, with the capital cost of the cryogenic-air-separation-unit-based system accounting for 14% of the total oxy-combustion plant, which must be considered in decision making [8].

5.4. Levelized Cost of Electricity Calculations

The levelized cost of electricity is an important parameter when carrying out an economic evaluation of CCS technologies. It allows for a company to identify how much money is required per MWh of electricity to recoup the lifetime costs involved in constructing and operating a power plant. Equation (4) shows the formula for calculating LCOE.

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (4)$$

where: LCOE = average lifetime levelized cost of electricity; I_t = investment cost; M_t = operation and maintenance cost (indirect cost); F_t = fuel cost; E_t = electricity generation (MW/year); r = discount rate (20%); n = life cycle of the plant (25 years). In using this LCOE formula, it should be noted that taxes, inflation, and the potential of the profitability of produced CO_2 in the trading market have been neglected. Moreover, operating and maintenance costs are calculated based on Figure 4, and are the same, as fuel costs are not directly inflation inclusive.

Table 12 shows the LCOE values obtained via the calculations carried out and the results from [24]. Many technical and economic assumptions, such as taxes, the type of fuel, the life cycle of the plants, etc., are employed to calculate the LCOE. However, there is no unique method to assess this metric. As can be seen from Table 12, three important references reported these amounts for 90% capture (costs have been modified by the 2020 cost index). There is a level of consistency between their result and the obtained result of the presented study. As listed in Table 12, when the CCS technologies are not utilized, the LCOE was lower for all three power plants, which is predictable, because employing the capture technology requires additional costs to implement and operate. Companies need to find the optimal process by taking all factors involved into consideration. However, LCOE calculations are standardized, and the cost throughout the lifespan of a power plant is a function of some factors, such as the coal market supplier, transportation costs, inflation, and plant downtime, which makes an accurate assessment difficult.

Table 12. LCOE values obtained via the calculations and the results from other references.

LCOE (GBP/MWh)	EIA		NETL		Lazard		Calculated
Technology	**Low**	**High**	**Low**	**High**	**Low**	**High**	
PC (Post-combustion)	-	-	92.07	122.24	-	-	142
PC (excluding CCS)	46.31	82.41	54.93	77.26	44.39	65.86	107.2
IGCC (Pre-combustion)	88.73	164	84.47	124.45	87.71	172.52	148.06
IGCC (excluding CCS)	58.19	106.04	63.95	124.45	58.70	125.89	133.5

The amount of calculated LCOE for oxy-fuel combustion with and without CCS are 94.5 (GBP/MWh) and 52.84 (GBP/MWh), respectively, and can be increased in the case of considering ASU.

The differences between the data could be due to several technical and economic reasons, such as:

- A higher/lower discount rate in different cases;
- The chemical plant operating for a longer/shorter period;
- The difference in productivity between both plants causes an associated costs variation, e.g., investment and indirect costs, which have a significant impact on the LCOE;
- The fuel cost has a significant impact on LCOE, since anthracite is high-value coal that would cause higher LCOE, but using such a coal would have other advantages, such as decreasing the capital cost and operational cost because of a lower impurity content level.

5.5. Cost of Avoiding CO_2

The techno-economic feasibility of carbon capture processes consists of analyzing several different economic measures to produce an overall assessment. A vital component of the overall economic assessment of CCS chemical plants involves calculating the cost of capturing one ton of atmospheric carbon dioxide emissions while producing one MWh of electricity. The following equation was extracted from Qayim et al. [25]. Table 13 depicts the cost of captured CO_2 for the mentioned process types, with the oxy-fuel combustion having the highest cost of captured CO_2 compared with the others.

$$\text{Cost}_{(CO_2)\text{captured}} = \left(\text{GBP}(\text{tco}_2)^{-1}\right) = \frac{\text{COE}_{\text{CCS}} - \text{COE}_{\text{Ref}}}{\left(\frac{\text{tCO}_2}{\text{MWh}}\right)_{\text{Ref}} - \frac{\text{tCO}_2}{\text{MWh}_{\text{CCS}}}} \quad (5)$$

where:

$$\text{COE} = \text{electricity generation cost}$$

and

$$\frac{\text{tCO}_2}{\text{MWh}} = \text{rate of mass emission to the atmosphere}$$

Table 13. The cost of avoiding CO_2 $\left(\text{GBP}(\text{tco}_2)^{-1}\right)$.

Costs	IGCC Power Plant (Pre-Combustion)	PC Power Plant (Post-Combustion)	PC Power Plant (Oxy-Fuel)
Cost of captured	60.4	124.7	206.6

6. Conclusions

The main objective of this research is the techno-economic analysis of three major technologies—pre-combustion, post-combustion, and oxy-fuel—in order to investigate which capture technology is the superior process.

Pre-combustion resulted in being the most expensive process to implement and operate over its life span, as it requires considerably more overall investment than the PC power plant with oxy-fuel CCS technology (≈1.6 times more). This is mainly due to the complexity of the process and the several major operation units required for the successful implementation of capture technology.

Several processes, including the power plants with the combined CCS technologies, have been carried out to obtain important parameters, such as the amount of fuel and cost of fuel per year, as well as the cost of electricity, for each of these three processes. The amount of fuel required for the IGCC power plant (pre-combustion) was slightly more than the PC power plant with the post-combustion and oxy-fuel, which, again, validates the initial point made that, from a financial perspective, the pre-combustion power plant requires a significantly higher cost to construct and operate. The Kemper power plant is a clear example of how pre-combustion technology could be expensive to implement.

Although the oxy-fuel process proved to be more economic in terms of LCOE, capital, and investment costs, it has failed to operate on a commercial scale. It is worth noting that this current study was made without considering the operational challenges, such as oxygen corrosion in the oxy-fuel process or the issue of corrosion in the post-combustion process, in the rich amine circulation system. The standard carbon steel material was used for all three processes to make a reasonable comparison. Corrosion is considered a long-term issue and, of course, can be prevented by anti-corrosion or enhancing the grade of material. One example is the Schwarze Pumpe plant, which faces financial problems in the case of an increase in productivity and commercialization. Therefore, further research needs to be conducted to analyze and develop oxy-fuel technology.

Finally, if a company is looking to implement one of the three CCS technologies to the existing operational plants, post-combustion technology could be the most attractive process. This will cause less disruption to the existing operation and a lower loss of revenue due to shutting down and revamping plants. It requires less total investment and indirect costs, including utilities and salaries. Moreover, due to the maturity of such a technology compared with other technologies, such as pre-combustion, it would be safer. Therefore from a financial standpoint, post-combustion stands as a better option.

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