energies

Article

Techno-Economic Assessment for the Best Flexible Operation of the CO_2 Removal Section by Potassium Taurate Solvent in a Coal-Fired Power Plant

Stefania Moioli *, Elvira Spatolisano and Laura A. Pellegrini

GASP—Group on Advanced Separation Processes & GAS Processing, Dipartimento di Chimica, Materiali e Ingegneria Chimica "Giulio Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milan, Italy
* Correspondence: stefania.moioli@polimi.it; Tel.: +39-02-2399-4721

Abstract: Alternative solvents based on aqueous solutions of amino acids have been recently developed as possible substitutes for Mono Ethanol Amine (MEA) for CO_2 removal from flue gas streams. The potassium taurate solvent has the advantages of degradation resistance, low toxicity and low energy requirements for its regeneration. With any type of solvent, CO_2 removal applied to a power production plant decreases the revenues obtained from selling electricity because of the energy requirements. Operating the CO_2 removal section in flexible mode avoids significant effects on the profits of the power plant, while accomplishing environmental regulations. This work is the first journal paper focusing on the application in flexible mode of the potassium taurate system for treating a flue gas stream from a 500 MW coal-fired power plant. Techno-economic evaluations are performed to determine the best operating conditions considering the variation in the electricity demand and its price, and different values of carbon tax. In the summer period, with high electricity prices and demands, carbon tax values between 45 EUR/t_{CO2} and 60 EUR/t_{CO2} favor CO_2 absorption in the flexible mode, without periods of full CO_2 emissions during the day.

Keywords: CO_2 removal; potassium taurate solvent; process design; energy requirement

Citation: Moioli, S.; Spatolisano, E.; Pellegrini, L.A. Techno-Economic Assessment for the Best Flexible Operation of the CO_2 Removal Section by Potassium Taurate Solvent in a Coal-Fired Power Plant. *Energies* **2024**, *17*, 1736. https://doi.org/10.3390/en17071736

Academic Editors: Michael Zhengmeng Hou, Hejuan Liu, Cheng Cao, Liehui Zhang and Yulong Zhao

Received: 14 February 2024
Revised: 21 March 2024
Accepted: 26 March 2024
Published: 4 April 2024

1. Introduction

With the aim of reducing the amounts of greenhouse gases (GHGs), mainly CO_2, emitted into the atmosphere due to power and industrial production [1] in order to limit the global temperature increase to 1.5 °C, different technologies can be employed as absorption, mainly with chemical solvents, adsorption, membranes or low-temperature separations [2–5]. The aqueous solution of Mono Ethanol Amine (MEA), generally 30 wt. %, is the benchmark solvent considered in chemical absorption for removing CO_2 from flue gases of power plants, and its thermal requirement can significantly reduce the production of the power plant. The energy consumption is a key parameter for determining the advantages of a process, also taking into account the global energy demand. The latest Monthly Statistics report by the International Energy Agency (IEA) states that in the countries of the Organization for Economic Cooperation and Development (OECD), the production of natural gas increased by 3.9% compared to December 2022, and the imports of natural gas have been 6.4% lower on a year-on-year basis, while total OECD exports have decreased by 2.5% in the same period. The total OECD production of crude oil, NGL and refinery feedstocks increased by 8.7% in December 2023 compared to December 2022.

In addition to the high energy requirement, MEA is characterized by toxicity and degradation, so it cannot be considered a sustainable solvent given its effects on health and the environment, relevant topics for the construction of new industrial plants in general. For this reason, innovative solvents are being taken into account [6], and research on new species and their influence on the CO_2 removal process [7–11] is being carried out. Among the innovative solvents proposed in the last few years, amino acids can be considered environmentally friendly [12], in addition to being advantageous also for their energy requirements. Their salts in aqueous solution have been studied, as in Lerche [13], Majchrowicz [14], Majchrowicz, et al. [15], Sanchez-Fernandez and Goetheer [16], Sanchez Fernandez, et al. [17] and Sanchez Fernandez, et al. [18], who found that amino acids are less corrosive, more stable, and have lower enthalpy in their reactions than the traditional MEA solvent [19]. The potassium taurate (KTau) process, developed by Sanchez-Fernandez et al. [18], can be used for CO_2 removal, with lower energy requirements than MEA. In any case, after an overall study of more than 1000 patents focusing on different technologies by Li et al. [20], it was concluded that no processes have been developed for this purpose that could favor a low added Cost of Electricity (CoE), so the CO_2 removal section of a power plant is always a consuming section of the power plant, representing a cost for the company and, therefore, reducing the profits related to selling the produced electricity.

The flexible operation of the CO_2 removal section makes the plant's profitability improve [21,22], because, during peak demands or when the price of electricity is high, the consumption of the CO_2 removal plant is reduced and the production of electricity is increased. Several studies in the literature, with tests on pilot plants [23], focused on the flexible operation of Carbon Capture and Storage (CCS) power stations, considering MEA as the chemical absorption solvent, and studying the bypass and solvent storage techniques [24–28], the operation at variable capture level [29,30] and the variable solvent regeneration mode [31,32]. Bui et al. [33,34] demonstrated that flexible operation is technically feasible in a large-scale CO_2 capture process via simulations and experimental tests using MEA solvent.

This work was carried out at the Process Design laboratory (PD lab) of GASP of Politecnico di Milano, which is provided with the Process Design and Process Thermodynamics laboratory (PD&PT lab). This paper is the first in the literature aiming at studying the possible operation in flexible mode of the CO_2 removal section of a 500 MW coal-fired power plant with an aqueous solution of potassium taurate (4 M potassium 4 M taurine) to determine the best operating conditions for each hour of key days. It follows previous works in the literature focusing on the same topic applied only to the use of the MEA solvent for CO_2 removal in power plants. Techno-economic evaluations have been carried out, taking into account the price of and demand for electricity in Italy, and the influence of the carbon tax, determining its value of breakeven point.

2. Materials and Methods

2.1. The Electricity Market in Italy

This work was carried out by taking as a basis the price of and the demand for electricity in Italy, for which official detailed values are available.

Terna [35] reports that the electricity market demand in Italy in 2015 was 316.9 TWh and the consumption was equal to 297.2 TWh. In total, 85% of the electricity demand was supplied by Italy and 15% was taken from other countries. The gross national production was about 283.0 TWh. 51% (192 TWh) of the national production was supplied by thermoelectric power plants, 15% (47 TWh) by hydroelectric and 20% (44 TWh) by renewable sources (wind, solar, geothermal and bioenergy). The gross efficient power was 120 GW.

In 2015, the gross thermoelectric production was 198.24 TWh, with geothermal sources accounting for 6.185 TWh. The conventional power production was 192.053 GWh. Natural gas covered provided 110.86 TWh and solid fuel 43.2 TWh, the remaining 37.993 TWh was produced by other fuels (gas derivates, petrochemicals, etc.). Solid fuel accounted for 43.25 TWh of the yearly production of electricity in 2015 [35].

The typical trends of electricity consumption have been detailed in a previous work focusing on chemical absorption using an MEA solvent [36], and the analysis of the electricity price for the year taken as a reference in this work (2015) has been reported by Moioli et al. [28].

Throughout the whole year, the requested power output of fossil-fueled power plants depends on variations in the demand, with peaks occurring hourly and daily. The energy profiles vary every month, with the highest difference between months in Italy being seen during summer, when the price of electricity is higher than 110 EUR/MWh. Lowering the electricity sold to the market because of the steam consumption due to the operation of a CO_2 removal plant during the peak hours in summer would be less advantageous compared to paying a carbon tax.

2.2. Details of the Considered Plant

The gaseous stream to be treated is a flue gas stream from a 500 MW coal-fired power plant, with a flowrate of 19.60 kmol/s and a composition (mole fraction %) of 7% water, 13% CO_2, 75% N_2 and 5% O_2 [37].

The scheme (Figure 1) is similar to the one for traditional amine solvents, with an absorption section wherein the solvent is concurrently contacted with the flue gas and with a regeneration section, where CO_2 is removed from the solvent and is recycled, after cooling, to the absorption columns. Moreover, differently from only liquid amine aqueous solutions, a dissolution heat exchanger is added before the rich solution is fed to the lean–rich heat exchanger for heat recovery. The aim of the additional unit is to dissolve all the precipitated taurine by heating, using condensed water as the service fluid, before entering the regeneration section.

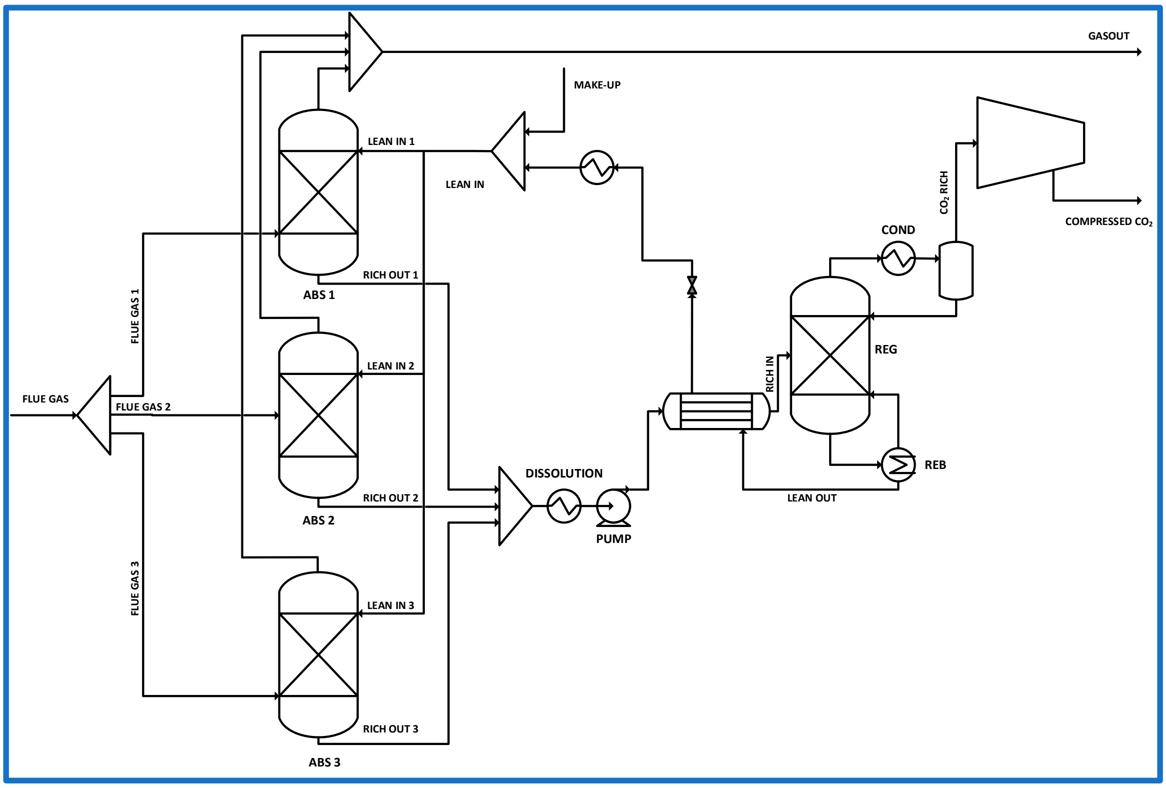


Figure 1. Scheme for the process considered in this work ("*ABS*" refers to the absorption column, "*REG*" refers to the regeneration column, "*COND*" refers to the condenser and "*REB*" refers to the reboiler).

In this work three parallel absorption columns for treating the large flowrate of flue gas are considered [38]. The number of columns has been selected on the basis of the maximum diameter considered at the industrial level [39–41], reported with values up to 15 m, and considering that this choice has already been reported to work in previous literature [42,43] related to the treatment of high flue gas flowrates with chemical absorption for CO_2 removal. The sizes of the absorber and of the regeneration column were selected with the aim of minimizing the total costs [38].

The lean loading has been chosen as done in previous works carried out on this topic [18,37]. The rich loading is a result obtained from simulation, with a value agreeing with common values usually employed for chemical solvents based on amine.

This work does not consider the option of adding a solid–liquid separator, which would allow the bottom products from the absorber to be split into a slurry and a liquid stream (recycled to the absorber) for further lowering the energy requirement.

Table 1 reports the main characteristics of the considered process.

Table 1. Main process parameters for the considered scheme.

Characteristic	Absorber	Regeneration Column
Number of columns	3	1
Diameter (m)	12	12.7
Packed height (m)	30	17.6
Packing type	Mellapak 250X	Mellapak 250X
Lean loading	0.27	
Rich loading	0.44	

The CO_2 obtained from the top of the regeneration column is compressed to 150 bar [44].

2.3. Theory

This paper is the first focusing on the topic of the flexible operation of a CO_2 removal plant applied to a power plant that considers the use of a potassium taurate solvent (no previous analyses of this type applied to Natural Gas Combined Cycle (NGCC) or coal-fired power plants have been found). In this work, both operation for fixed CO_2 removal and operation in flexible mode have been considered. The Capture Level Reduction (CLR) mode is a mode of flexible operation considered to be the best performing mode for coal-fired power plants in previous literature focusing on the MEA solvent. In this work, it has been analyzed for a plant located in Italy. The fixed CO_2 removal operating mode and the no-capture operation have also been considered, with a comparison among all the modes. The degree of removal of CO_2 can be higher or lower in the flexible operation mode than in the fixed configuration, and varies during the day [45] in order to minimize the losses of energy and of revenues. The value of the carbon tax to be paid can influence the process' operation in flexible mode.

This paper analyzes the CLR mode, which involves operating a bypass by splitting part of the rich solvent to be recirculated to the absorption column without being regenerated, and then regenerating the other smaller part of the solvent. The amount of CO_2 that is absorbed is reduced, so a reduction in the thermal power needed at the reboiler is achieved. The CLR mode of operation does not necessitate modifications to the equipment, thus avoiding additional investment costs (for instance, additional tanks and a higher solvent inventory are needed in the case of solvent storage). In particular, in this work, we have considered and compared to the case of no capture the following cases:

- Fixed operation at 90% CO_2 removal;
- Fixed operation at a given % ratio;
- Flexible operation.

In the fixed operation mode, a fixed ratio of 90%, 80%, 70% or 60% of CO_2 removal from the base case has been considered (100% ratio refers to 90% CO_2 removal).

In the CLR mode, CO_2 is vented to the atmosphere over specified time intervals. In this case, the energy required for the regeneration of the solvent and the CO_2 compression decreases as the rich solvent flowrate to be regenerated is lower, with a higher production of electric power. In this period of time, the overall emission of CO_2 is higher than the one at 90% fixed CO_2 removal, and a higher carbon tax must be paid. A minimum value equal to 30% has been set for the % operation ratio, as reported in Cohen et al. [46], to avoid issues in the operation of columns, such as drying out in the regeneration unit.

2.3.1. Profit Minimization

An in-house tool developed by GASP of Politecnico di Milano for economic optimization, on the basis of the assumptions and the methodology detailed in Moioli et al. [36], has been employed. The inputs to the tool are the results of the simulations in ASPEN Plus® V11 that had been previously integrated with new ionic species and has been modified for the thermodynamic model by introducing reactions and values of parameters to represent the vapor–liquid–solid equilibrium of the potassium taurate system. The details of the thermodynamic model, with the comparison to the experimental data, are reported in Moioli et al. [47].

It is assumed that no external sources are employed. Therefore, for each time of the day, the available energy has been calculated on the basis of the electricity needed by the final users.

If needed, a lower amount of electricity is sold to the market to run the CO_2 capture section. In this case, the remaining power needed for the demand of the market should be bought by the final user from another source.

For flexible operation, the objective function is the profit, which must be maximized by operating the capture plant with a varying % ratio. The value of the % ratio that minimizes the profit associated to a power station with a CO_2 capture system is selected on an on hourly basis. The profit is calculated as

$$P = W_{out}C_{energy} - F_{CO_2}C_{CO_2Tax} - F_{fuel}C_{Fuel} - C_{b,O\&M} \quad (1)$$

where the following pertains:

- W_{out}, the net production of electrical power exiting from the power station (MW = MWh/h);
- C_{energy}, the price of electrical energy (EUR/MWh);
- C_{CO2Tax}, the carbon tax (EUR/t_{CO2});
- F_{CO2}, the amount of CO_2 vented in one hour (tCO_2/h);
- F_{fuel}, the fuel consumption (kg/h);
- C_{fuel}, the fuel cost (EUR/kg);
- $C_{b,O\&M}$, the cost of base plant operation and maintenance (EUR/h), excluding the cost of W_{out}.

W_{out} takes into account the reduction in power sold to the users because of the extraction of steam from the turbine to operate the reboiler and because of the electricity needed to operate the CO_2 removal section.

The method employed in this work is suitable for this application, also for other CO_2 removal processes with different solvents.

2.3.2. Assumptions

The assumptions at the basis of this work are:

1. The electricity price is based on Italian historical electricity prices referring to 2015, set out by Gestore dei Mercati Energetici [48] (the methodology could be extended to other electricity markets, and also applied when considering the electricity prices of the following years, when available);
2. The electricity demand was set with reference to the historical data by Terna [35], scaling for the considered power plant production;
3. Carbon tax varies in the range of 5 EUR/t_{CO2} to 200 EUR/t_{CO2}, in steps of 5 EUR/tCO_2;
4. Cold start-up and shut-down costs are neglected;
5. Losses in efficiency due to variations in % ratio are considered with a ramp of 5%/min, as also done by Cohen et al. [49];
6. In cases when additional power is produced in each hour (because of the production set defined on a provision based on the expected trend of electricity consumption) that is not required by the market, it is assumed to be lost;

7. January (generally the coldest month in Italy) and July (when the highest variations in electricity demand and prices occur [50]) have been selected;
8. The time step for the analysis is 1 h, corresponding to the time step at which data on the prices of electricity have been found.

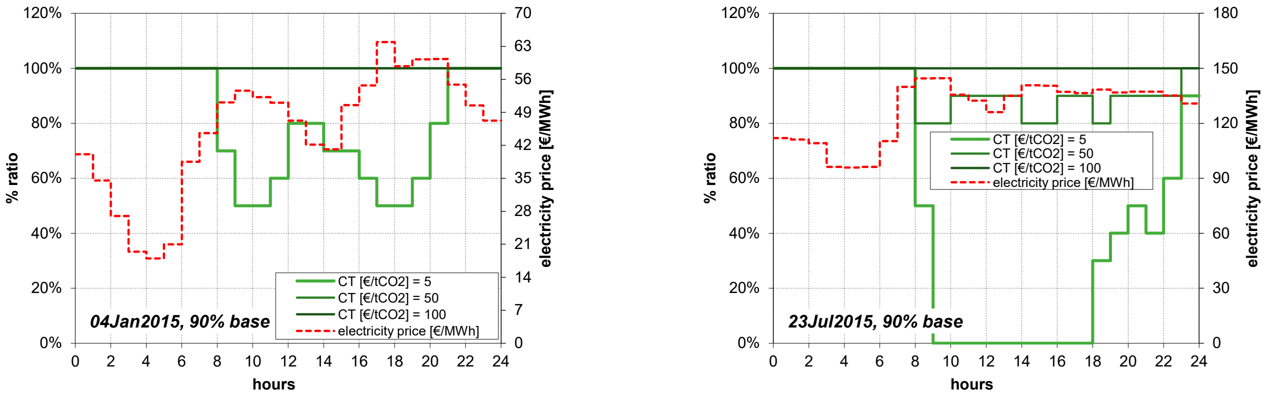
The study considers different modes of operation:

- Base case, i.e., 90% CO_2 removal at fixed operation;
- Fixed capture at 90%, 80%, 70% and 60% of the base case;
- CLR flexible operation;
- No capture.

The characteristics of energy consumption have been considered by taking the whole country as uniform. If detailed data related to each region of Italy become available, an analysis of different regions of Italy may be of interest in order to better understand the influence on the results.

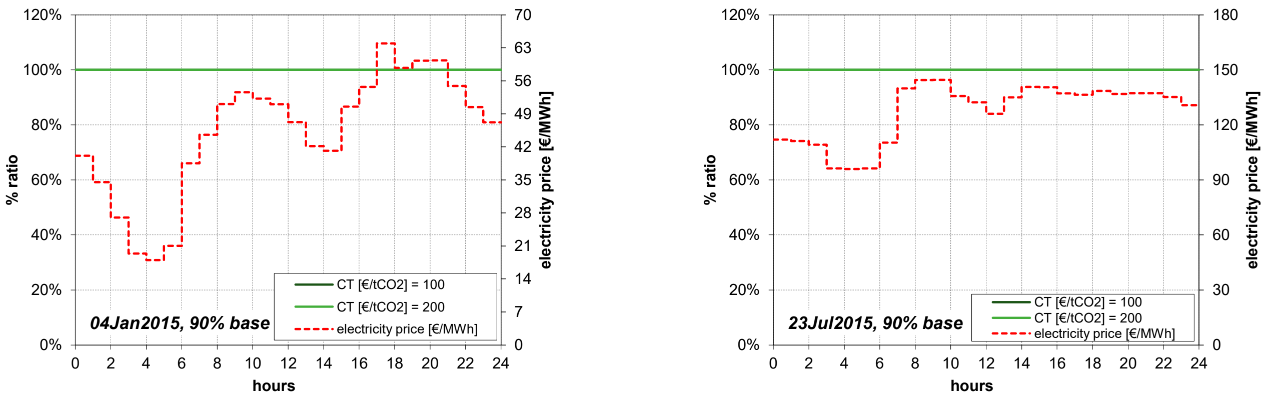
3. Results

In Figures 2–4, the % ratio of operation in CLR mode during the whole day is reported as obtained by the optimization. Figure 5 reports the electric power sold to the market in CLR mode while also considering different carbon taxes, and Figure 6 details the carbon tax paid for emitting CO_2 in the CLR mode, as a function of the carbon tax.



(**a**) (**b**)

Figure 2. Optimal operation with CLR on (**a**) 4 January 2015 and (**b**) 23 July 2015 for values of carbon tax (CT) equal to 5, 50 and 100 EUR/t_{CO2}.



(**a**) (**b**)

Figure 3. Optimal operation with CLR on (**a**) 4 January 2015 and (**b**) 23 July 2015 for values of carbon tax (CT) equal to 100 and 200 EUR/t_{CO2}.

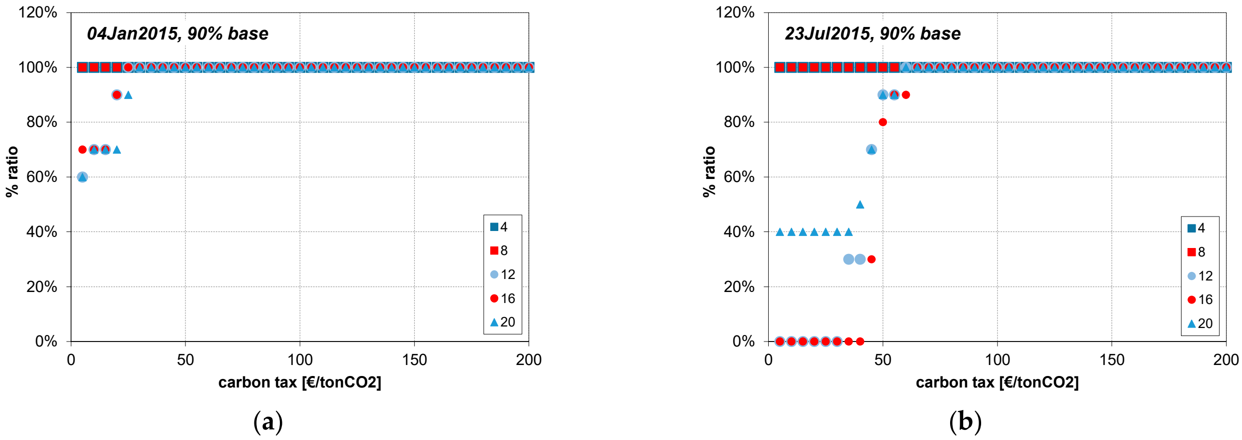


Figure 4. Optimum % ratio as affecting the carbon tax in CLR mode at different hours of the day (8, 12, 16 and 20) on (**a**) January 4th 2015 and (**b**) 23 July 2015.

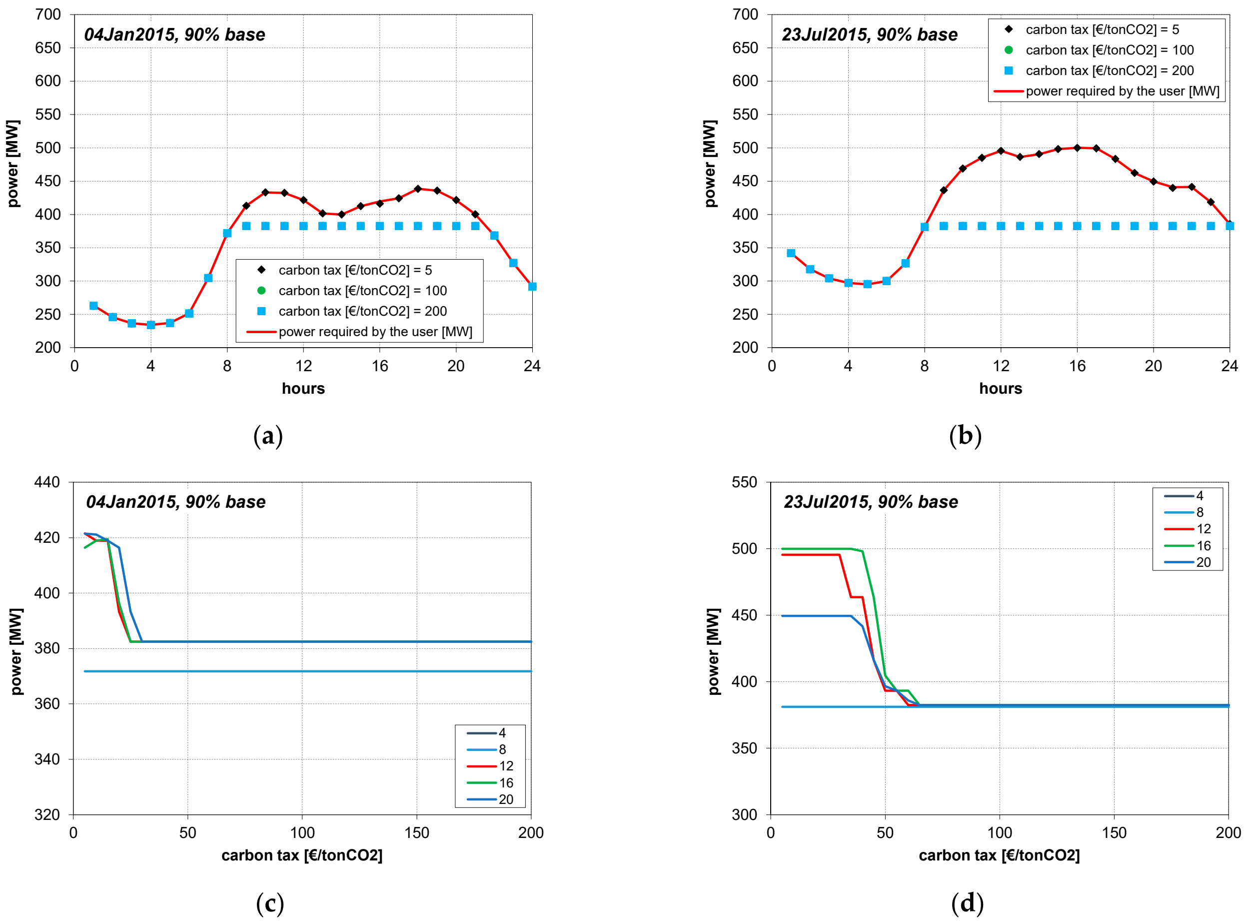


Figure 5. Power (electric) sold to the market in CLR mode for (**a**) 4 January 2015 and (**b**) 23 July 2015, and for different carbon taxes on (**c**) 4 January 2015 and (**d**) 23 July 2015.

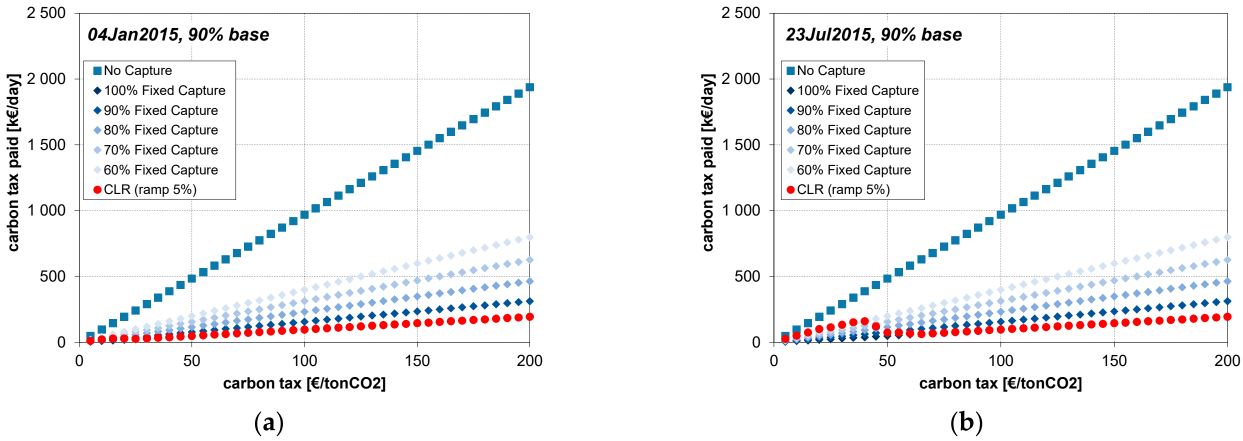


Figure 6. Carbon tax paid for emitting CO_2 in CLR mode as a function of the carbon tax for (**a**) 4 January 2015 and (**b**) 23 July 2015.

4. Discussion

4.1. CLR Mode

The optimal values depend on the electricity's price and demand during the daily period. The % ratio is lower at times of high electricity price and demand, if paying the carbon tax is advantageous. In July, the peaks in the power demand and the high price of electrical energy favor high revenues, meaning that the operation in flexible mode is advantageous (Figures 2b and 3b). In January (Figures 2a and 3a), the level of electricity sold is lower than that produced, and the revenues are lower. Therefore, the expenses related to the payment of the carbon tax due to CO_2 emissions can be avoided, and 90% CO_2 removal is applied (a % ratio equal to 100%). For a carbon tax of 5 EUR/t_{CO2}, emitting into the atmosphere was shown to be advantageous from 9:00 to 21:00 on 4 January 2015 and from 9:00 to the end of the day on 23 July 2015. In summer, CO_2 removal is advantageous for hours with low electricity demand and prices, occurring only in the early mornings and during nights.

The carbon tax influences the optimum % ratio (Figure 4). The threshold value of carbon tax for 4 January 2015 has been shown to be 25 EUR/t_{CO2}, and the one for 23 July 2015 is 65 EUR/t_{CO2}. For higher values, the operation at 90% CO_2 removal is carried out, because the amount of CO_2 emitted would be too expensive in terms of carbon tax to be paid. In winter, the no capture mode is not advantageous, while in summer, with low values of carbon tax, emitting all the CO_2 present in the flue gas stream would seem to be more advantageous than removing it in terms of avoiding the emission of CO_2 into the atmosphere.

For January, the obtained profit decreases with increases in the carbon tax and with reductions in the % ratio in fixed mode. A different trend is obtained for July, due to the high amounts, and high prices, of the electricity sold to the market.

For a carbon tax equal to 5 EUR/t_{CO2}, the electric power remaining after the consumption of steam for CO_2 removal corresponds to the amount of power requested by the market, because CO_2 removal is not in operation (Figure 5). When there are higher carbon taxes, the power sold to the market is decreased, and greater lowering occurs in summer, when much electricity is needed by the user. The power consumed by the CO_2 removal and compression section is provided by significantly reducing the power sold to the market, which case is different from that in winter.

Figure 6 shows that the trend obtained for the CLR mode is different to a monotonic profile, in particular for 23 July 2015, because the carbon tax paid depends on the % ratio at each hour, which is selected on the basis of techno-economic analyses taking into account the variation in the market. In the fixed operation mode, the amount of carbon tax to be paid is constantly increasing with the unitary value of the carbon tax.

This work is the first to focus on the potassium taurate process, and therefore no comparison with other works employing the same solvent can be performed. The obtained trends are in agreement with the trends obtained in previous papers published in the literature referring to the flexible operation mode, although taking into account a different solvent for CO_2 removal, and confirm the validity of the methodology.

4.2. Case of No CO_2 Removal

The no capture case has also been considered. The amount paid in this case is up to one order of magnitude higher (if compared to the CLR mode of operation) than any case of operation for removal (also partial) of carbon dioxide (Figure 6). Treating flue gas is profitable when the cost of the emitted CO_2 is higher than the price of electricity. This work confirms the relevance of policy decisions related to the application of carbon tax, which leads to CO_2 removal being more advantageous than CO_2 emission in economic terms.

The results obtained for the potassium taurate system, though differing in terms of the % ratio and values of carbon tax at which operating the CO_2 removal plant at a 100% ratio is advantageous, are in line with the results obtained in the literature for the MEA solvent used for chemical absorption to treat flue gases produced by coal-fired power plants [24,25,51–54].

4.3. Cases of Fixed Operation

When operating in a fixed operation mode at certain % ratios, if more CO_2 is removed, a lower amount of electric power is available to the final user. In summer, the profit obtained by paying the carbon tax for emitting carbon dioxide could prove to be more advantageous than attempting the absorption of high amounts of CO_2. When the demand for electricity is lower, as in winter, the more CO_2 is absorbed, the better it is for the economics of the plant, because a lower carbon tax is paid. Therefore, the full 90% CO_2 removal must be selected (instead of a lower % ratio of fixed CO_2 removals). It can be concluded that if the operation in fixed mode is preferred, the % ratio could be selected on the basis of the period of the year, and on the required energy. In any case, the CLR operation would ensure lower losses of revenues for the company, because the variation in the % ratio will be optimized for this aim.

5. Conclusions

This paper presents the first techno-economic evaluation in the literature on the application of the potassium taurate process in flexible mode for the treatment of a flue gas stream produced by a 500 MW coal-fired power plant. A process using this type of solvent has been chosen because it is characterized by lower energy requirements than other processes based on the MEA solvent, in addition to employing a solution with reduced toxicity and corrosive effects.

In this paper, the effects of the variation in the electricity demand and price in Italy, and in the value of carbon tax, in the range of 5 EUR/t_{CO2} to 200 EUR/t_{CO2}, have been analyzed in detail for two relevant days in different seasons of the year (winter and summer) for which information was available.

On the basis of the results, it can be concluded, as expected, that the higher the value of the carbon tax, the higher the average % ratio of the CO_2 capture system.

In summer, because of the high energy demand and the high price of electricity, venting CO_2 into the atmosphere and paying a carbon tax as high as 40 EUR/t_{CO2} will be more profitable at given hours because of the high value of electricity, losses in which caused by carbon capture operation heavily affect the economics of the system. With a carbon tax ranging from 45 EUR/t_{CO2} to 60 EUR/t_{CO2}, flexible absorption without any hours of full CO_2 emission is the best option. The obtained results for 4th July 2015 are different, and here, no operation at 0% ratio is needed, thus precluding the emission of the CO_2 present in the flue gas stream at given hours of the day.

Higher carbon tax values lead to the carbon dioxide removal system being operated at higher % ratios, both in winter and in summer.

The demand for and the price of electricity in different periods of the year cause the maximum % ratio (except 0%) to be different in summer and in winter, with the minimum values being 30% in July and 50% in January.

The proposed methodology could be applied to any following year for which detailed data on electricity price and demand are available. A future development of this work could focus on the analysis of the characteristics of energy consumption in different regions of Italy (when detailed data are available) to evaluate the effects on the obtained results.

Author Contributions: Conceptualization, S.M. and L.A.P.; methodology, S.M. and E.S.; software, S.M.; validation, S.M. and E.S.; formal analysis, S.M. and E.S.; investigation, S.M. and E.S.; resources, E.S.; data curation, S.M. and E.S.; writing—original draft preparation, S.M.; writing—review and editing, E.S. and L.A.P.; visualization, S.M., E.S. and L.A.P.; supervision, L.A.P.; project administration, L.A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. IEA. *Putting CO_2 to Use*; IEA: Paris, France, 2019.
2. De Guido, G.; Pellegrini, L.A. Calculation of solid-vapor equilibria for cryogenic carbon capture. *Comp. Chem. Eng.* **2022**, *156*, 107569. [CrossRef]
3. Pellegrini, L.A.; De Guido, G.; Ingrosso, S. Thermodynamic framework for cryogenic carbon capture. *Comput. Aided Chem. Eng.* **2020**, *48*, 475–480.
4. Ebner, A.D.; Ritter, J.A. State-of-the-art Adsorption and Membrane Separation Processes for Carbon Dioxide Production from Carbon Dioxide Emitting Industries. *Sep. Sci. Technol.* **2009**, *44*, 1273–1421. [CrossRef]
5. Feron, P.H.M.; Jansen, A.E.; Klaassen, R. Membrane technology in carbon dioxide removal. *Energy Convers. Manag.* **1992**, *33*, 421–428. [CrossRef]
6. Yang, C.; Li, T.; Tantikhajorngosol, P.; Sema, T.; Xiao, M.; Tontiwachwuthikul, P. Evaluation of novel aqueous piperazine-based physical-chemical solutions as biphasic solvents for CO_2 capture: Initial absorption rate, equilibrium solubility, phase separation and desorption rate. *Chem. Eng. Sci.* **2023**, *277*, 118852. [CrossRef]
7. Pellegrini, L.A.; Gilardi, M.; Giudici, F.; Spatolisano, E. New Solvents for CO_2 and H_2S Removal from Gaseous Streams. *Energies* **2021**, *14*, 6687. [CrossRef]
8. Lu, Y.; Nielsen, P.; Lu, H. Development and Bench Scale Testing of a Novel Biphasic Solvent Enabled Absorption Process for Post Combustion Carbon Capture DE FE0031600. In Proceedings of the 2022 Carbon Management Project Review Meeting, Pittsburgh, PA, USA, 15–19 August 2022.
9. Wanderley, R.R.; Pinto, D.D.D.; Knuutila, H.K. From hybrid solvents to water-lean solvents—A critical and historical review. *Sep. Purif. Technol.* **2021**, *260*, 118193. [CrossRef]
10. Schuur, B.; Brouwer, T.; Smink, D.; Sprakel, L.M.J. Green solvents for sustainable separation processes. *Curr. Opin. Green Sustain. Chem.* **2019**, *18*, 57–65. [CrossRef]
11. Vanderveen, J.R.; Patiny, L.; Chalifoux, C.B.; Jessop, M.J.; Jessop, P.G. A virtual screening approach to identifying the greenest compound for a task: Application to switchable-hydrophilicity solvents. *Green Chem.* **2015**, *17*, 5182–5188. [CrossRef]
12. Ramezani, R.; Mazinani, S.; Di Felice, R. State-of-the-art of CO_2 capture with amino acid salt solutions. *Rev. Chem. Eng.* **2022**, *38*, 273–299. [CrossRef]
13. Lerche, B.M. CO_2 Capture from Flue Gas Using Amino Acid Salt Solutions. Ph.D. Thesis, Technical University of Denmark, Lyngby, Denmark, 2012.
14. Majchrowicz, M.E. Amino Acid Salt Solutions for Carbon Dioxide Capture. Ph.D. Thesis, University of Twente, Twente, The Netherlands, 2014.
15. Majchrowicz, M.E.; Brilman, D.W.F.W.; Groeneved, M.J. Precipitation regime for selected amino acid salts for CO_2 capture from flue gases. *Energy Procedia* **2009**, *1*, 979–984. [CrossRef]
16. Sanchez-Fernandez, E.; Goetheer, E.L.V. DECAB: Process development of a phase change absorption process. *Energy Procedia* **2011**, *4*, 868–875. [CrossRef]
17. Sanchez Fernandez, E.; Goetheer, E.L.V.; Manzolini, G.; Macchi, E.; Rezvani, S.; Vlugt, T.J.H. Thermodynamic assessment of amine based CO_2 capture technologies in power plants based on European Benchmarking Task Force methodology. *Fuel* **2014**, *129*, 318–329. [CrossRef]

18. Sanchez Fernandez, E.; Heffernan, K.; van der Ham, L.V.; Linders, M.J.G.; Eggink, E.; Schrama, F.N.H.; Brilman, D.W.F.; Goetheer, E.L.V.; Vlugt, T.J.H. Conceptual Design of a Novel CO_2 Capture Process Based on Precipitating Amino Acid Solvents. *Ind. Eng. Chem. Res.* **2013**, *52*, 12223–12235. [CrossRef]
19. Brouwer, J.P.; Feron, P.H.M.; ten Asbroek, N.A.M. Amino-Acid Salts for CO_2 Capture from Flue Gases. 2009. Available online: https://www.researchgate.net/publication/228408743_Amino-acid_salts_for_CO2_capture_from_flue_gases (accessed on 15 April 2023).
20. Li, B.; Duan, Y.; Luebke, D.; Morreale, B. Advances in CO_2 capture technology: A patent review. *Appl. Energy* **2013**, *102*, 1439–1447. [CrossRef]
21. Domenichini, R.; Mancuso, L.; Ferrari, N.; Davison, J. Operating Flexibility of Power Plants with Carbon Capture and Storage (CCS). *Enrgy Procedia* **2013**, *37*, 2727–2737. [CrossRef]
22. Bui, M.; Gunawan, I.; Verheyen, V.; Feron, P.; Meuleman, E.; Adeloju, S. Dynamic modelling and optimisation of flexible operation in post-combustion CO_2 capture plants—A review. *Comp. Chem. Eng.* **2014**, *61*, 245–265. [CrossRef]
23. Bui, M.; Tait, P.; Lucquiaud, M.; Mac Dowell, N. Dynamic operation and modelling of amine-based CO_2 capture at pilot scale. *Int. J. Greenh. Gas Control* **2018**, *79*, 134–153. [CrossRef]
24. Chalmers, H.; Gibbins, J. Initial evaluation of the impact of post-combustion capture of carbon dioxide on supercritical pulverised coal power plant part load performance. *Fuel* **2007**, *86*, 2109–2123. [CrossRef]
25. Gibbins, J.R.; Crane, R.I. Scope for reductions in the cost of CO_2 capture using flue gas scrubbing with amine solvents. *Proc. Inst. Mech. Eng. A-J. Power Energy* **2004**, *218*, 231–239. [CrossRef]
26. Delarue, E.; Martens, P.; D'haeseleer, W. Market opportunities for power plants with post-combustion carbon capture. *Int. J. Greenh. Gas Control* **2012**, *6*, 12–20. [CrossRef]
27. Haines, M.R.; Davison, J.E. Designing Carbon Capture power plants to assist in meeting peak power demand. *Greenh. Gas Control Technol.* **2009**, *1*, 1457–1464. [CrossRef]
28. Moioli, S.; Pellegrini, L.A. Operating the CO_2 absorption plant in a post-combustion unit in flexible mode for cost reduction. *Chem. Eng. Res. Des.* **2019**, *147*, 604–614. [CrossRef]
29. Errey, O.; Chalmers, H.; Lucquiaud, M.; Gibbins, J. Valuing Responsive Operation of Post-combustion CCS Power Plants in Low Carbon Electricity Markets. *Energy Procedia* **2014**, *63*, 7471–7484. [CrossRef]
30. Rubin, E.S.; Chen, C.; Rao, A.B. Cost and performance of fossil fuel power plants with CO_2 capture and storage. *Energy Policy* **2007**, *35*, 4444–4454. [CrossRef]
31. Mac Dowell, N.; Shah, N. Optimisation of Post-combustion CO_2 Capture for Flexible Operation. *Energy Procedia* **2014**, *63* (Suppl. C), 1525–1535. [CrossRef]
32. Mechleri, E.; Fennell, P.S.; Dowell, N.M. Flexible Operation Strategies for Coal- and Gas-CCS Power Stations under the UK and USA Markets. *Energy Procedia* **2017**, *114*, 6543–6551. [CrossRef]
33. Bui, M.; Flø, N.E.; de Cazenove, T.; Mac Dowell, N. Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant. *Int. J. Greenh. Gas Control* **2020**, *93*, 102879. [CrossRef]
34. Bui, M.; Gunawan, I.; Verheyen, V.; Feron, P.; Meuleman, E. Flexible operation of CSIRO's post-combustion CO_2 capture pilot plant at the AGL Loy Yang power station. *Int. J. Greenh. Gas Control* **2016**, *48*, 188–203. [CrossRef]
35. Terna, S.p.A. Available online: https://www.terna.it/it (accessed on 15 April 2023).
36. Moioli, S.; Pellegrini, L.A. Fixed and Capture Level Reduction operating modes for carbon dioxide removal in a Natural Gas Combined Cycle power plant. *J. Clean. Prod.* **2020**, *254*, 120016. [CrossRef]
37. Moioli, S.; Ho, M.H.; Wiley, D.E.; Pellegrini, L.A. Assessment of carbon dioxide capture by precipitating potassium taurate solvent. *Int. J. Greenh. Gas Control* **2019**, *87*, 159–169. [CrossRef]
38. Baiguini, N. Flexible Operation in Post-Combustion CO_2 Removal Plants by MEA Solvent and Potassium Taurate Solvent. Master's Thesis, Politecnico di Milano, Milano, Italy, 2018.
39. Fluor. Available online: http://www.fluor.com/econamine/pages/default.aspx (accessed on 15 April 2023).
40. Just, P.-E. Advances in the development of CO_2 capture solvents. *Energy Procedia* **2013**, *37*, 314–324. [CrossRef]
41. Shell CANSOLV Carbon Dioxide (CO2) Capture System. Available online: http://www.shell.com/business-customers/global-solutions/gas-processing-licensing/licensed-technologies/shell-cansolv-gas-absorption-solutions/cansolv-co2-capture-system.html (accessed on 15 April 2023).
42. Biliyok, C.; Canepa, R.; Wang, M.; Yeung, H. Techno-Economic Analysis of a Natural Gas Combined Cycle Power Plant with CO_2 Capture. In *Computer Aided Chemical Engineering*; Kraslawski, A., Turunen, I., Eds.; Elsevier: Amsterdam, The Netherlands, 2013; Volume 32, pp. 187–192.
43. Aromada, S.A.; Eldrup, N.H.; Øi, L.E. Cost and Emissions Reduction in CO_2 Capture Plant Dependent on Heat Exchanger Type and Different Process Configurations: Optimum Temperature Approach Analysis. *Energies* **2022**, *15*, 425. [CrossRef]
44. Fout, T.; Zoelle, A.; Keairns, D.; Turner, M.; Woods, M.; Kuehn, N.; Shah, V.; Chou, V.; Pinkerton, L. *Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3. DOE/NETL-2015/1723*; National Energy Technology Laboratory (NETL): Pittsburgh, PA, USA; Morgantown, WV, USA, 2015.
45. Moioli, S.; Pellegrini, L.A. Comparison of CLR and SS Flexible Systems for Post-Combustion CO_2 Removal in a NGCC Power Plant. *Chem. Eng. Trans.* **2019**, *74*, 829–834.

46. Cohen, S.M.; Rochelle, G.T.; Webber, M.E. Optimal operation of flexible post-combustion CO_2 capture in response to volatile electricity prices. *Energy Procedia* **2011**, *4*, 2604–2611. [CrossRef]
47. Moioli, S.; Ho, M.H.; Wiley, D.E.; Pellegrini, L.A. Thermodynamic Modeling of the System of CO_2 and Potassium Taurate Solution for Simulation of the Process of Carbon Dioxide Removal. *Chem. Eng. Res. Des.* **2018**, *136*, 834–845. [CrossRef]
48. GME Gestore Mercati Energetici. Available online: http://www.mercatoelettrico.org/it/ (accessed on 15 April 2023).
49. Cohen, S.M.; Rochelle, G.T.; Webber, M.E. Optimizing post-combustion CO_2 capture in response to volatile electricity prices. *Int. J. Greenh. Gas Control* **2012**, *8*, 180–195. [CrossRef]
50. Moioli, S.; Pellegrini, L.A. Optimal Operation of a CO_2 Absorption Plant in a Post-Combustion Unit for Cost Reduction. *Chem. Eng. Trans.* **2018**, *69*, 151–156.
51. Chalmers, H.; Leach, M.; Lucquiaud, M.; Gibbins, J. Valuing flexible operation of power plants with CO_2 capture. *Greenh. Gas Control Technol.* **2009**, *1*, 4289–4296. [CrossRef]
52. Chalmers, H.; Lucquiaud, M.; Gibbins, J.; Leach, M. Flexible Operation of Coal Fired Power Plants with Postcombustion Capture of Carbon Dioxide. *J. Environ. Eng.-Asce* **2009**, *135*, 449–458. [CrossRef]
53. Lucquiaud, M.; Chalmers, H.; Gibbins, J. Capture-ready supercritical coal-fired power plants and flexible post-combustion CO_2 capture. *Greenh. Gas Control Technol.* **2009**, *1*, 1411–1418. [CrossRef]
54. Lucquiaud, M.; Fernandez, E.S.; Chalmers, H.; Mac Dowell, N.; Gibbins, J. Enhanced operating flexibility and optimised off-design operation of coal plants with post-combustion capture. *Energy Procedia* **2014**, *63*, 7494–7507. [CrossRef]