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Techno-economic Assessment of Flexible Solvent Regeneration & Storage for Base Load Coal-Fired Power Generation with Post Combustion CO_2 Capture

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Abstract

CO_2 capture and storage has the potential to significantly reduce man made CO_2 emissions from large point sources consuming carbon containing fuels. The share of fossil fuels is expected to remain significant in future global energy mix, driven by the energy consumption of power generation facilities. At the same time, an increased demand for flexible electricity supply is expected as a result of more intermittent renewable sources of power generation. In this work the concept of flexibility and associated plant operation parameters are evaluated on an economic basis by performing analysis on the effect of flexible solvent regeneration and storage for a base load coal fired power plant with post combustion CO_2 capture in a market with cyclical electricity price patterns. An MILP model for generating the optimum operating strategy by maximizing weekly profit was developed and results presented. The model and subsequent analysis highlights the potential value of flexible solvent regeneration and storage. The work also shows a positive correlation between weekly profits and electricity price volatility.

Keywords: Post Combustion; CO_2 Capture; Flexible Solvent Regeneration and Storage; Techno-economic; Optimization

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1. Introduction

A large-scale decarbonisation of future energy systems is a possible scenario, moving towards more sustainable energy consumption and conversion. Non-renewable fossil fuels account for over 80% of the global total primary energy consumption. CO_2 emissions from energy use (conversion), where power generation is the single largest contributor [1], amount to about 60% of global manmade greenhouse gas (GHG) emissions [2]. Hence improving energy efficiency and substituting non-renewable fossil fuel technologies with renewables are important measures in developing a more sustainable energy future. Despite increased focus on and development within these technologies, global supply of energy will continue to rely on fossil fuels in the foreseeable future.

CO_2 capture and storage (CCS) is a collective term for different technologies employed to capture, transport and permanently store CO_2, emitted from large industrial sources, in underground geological formations. CCS has a

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potential of reducing CO_2 emissions from large point sources consuming carbon containing fuels, such as fossil fuel power plants, steel production, cement industry etc. CCS investments are associated with substantial capital expenditures, operational expenditures dominated by high energy use and potential operational restrictions on the underlying industrial processes. The main focus of significant research efforts is thus to reduce investment costs and improve efficiency of CCS technologies. Despite significant costs related to CCS, future emission scenarios aiming to keep global warming below 2 degrees Celsius above pre-industrial temperature, project CCS to provide 20% of the lowest-cost reductions in manmade GHG emissions in 2050 [3]. Power generation is pointed out as the single most important sector for future CCS applications in these scenarios.

In most electricity markets the demand of electricity exhibit daily, weekly and seasonal cyclical patterns. Meeting these fluctuating demands requires a portfolio of electricity supply technologies with different operating modes, determined by their cost structures and ability to alter electricity supply. The demand for flexible electricity supply capacity is based on the special properties of electricity markets, with short term fluctuations in electricity demand and fuel prices, combined with the non-storable property of electricity. This creates an electricity price profile which to a large extent mirrors the cyclical demand pattern. Fossil fuel power generation technologies dominate the world's electricity systems today, both with regards to generation capacity and as provider of electricity supply flexibility. The value of flexibility for power generation technologies has been studied, both from single power plant and electricity system perspective. In markets where traditional power generation technologies, providing electricity supply capacity do not provide sufficient supply flexibility, specific facilities are constructed solely to provide electricity supply flexibility and no net electricity production. Pumped-storage hydropower is one such commonly used technology. The future need for flexible electricity supply is expected to increase in a future power generation scenario with more intermittent renewable sources of power generation and potentially also more inflexible nuclear [4]. While the demand for flexible fossil fuel power generation is expected to increase, the ability to meet this demand could be reduced by adding complex CCS installations.

Chalmers and Gibbins [5] present a concept where a major part of the energy penalty related to post combustion CO_2 capture could be delayed by establishing flexible solvent regeneration and storage. For a base load power plant, as studied in this paper, this creates an opportunity to adjust the electricity output profile over time, despite constant fuel feed and thereby still fully utilize the power plant combustion capacity. Base load coal fired power plants are considered to be of the most attractive candidates for CCS, with constantly high consumption of carbon-rich fuel.

In this paper we evaluate the concept of flexibility and associated plant operation parameters on an economic basis by performing analysis on the effect of flexible solvent regeneration and storage for base load coal fired power plant with post combustion CO_2 capture in a market with cyclical electricity price patterns. A dynamic mixed integer linear programming model is developed to determine the optimal weekly operating strategy, based on assumed plant component sizes, specified operability and electricity prices from the German electricity market, EEX. While similar concepts of flexibility have been studied earlier [5], this work ensures optimal operating profiles while including significant technical and practical realism. It must however be emphasized that the model and parameters used in this work are simplifications, and a number of areas of plant operation will not be fully understood before they are systematically investigated using full plant models or pilot and demonstrations plants.

2. Flexible Solvent Regeneration and Storage in Post Combustion CO_2 Capture

Post combustion CO_2 capture via chemical absorption, where CO_2 is separated from the flue gas after combustion of carbon-containing fuels, is considered to be the most mature CO_2 capture technology at present[6], see Figure 1. For a description of post-combustion capture technology using chemical absorption based on solvent please refer to [7]. The production profiles in Figure 1 show how a base load power plant with post combustion CO_2 capture is expected to consume a constant amount of fuel, while producing a constant amount of electricity and CO_2 ready for transport and storage.

As discussed briefly in the introduction, the CO_2 capture plant will not only require investment in the required capture components, but also consume energy during operation. In the power generation sector, the energy use of the capture plant is normally expressed in % point's penalty to the power generation efficiency.

Typically the efficiency reduction is 8-12% points, resulting in roughly 20% less electricity produced for a power plant with prior generation efficiency of 50% [8].

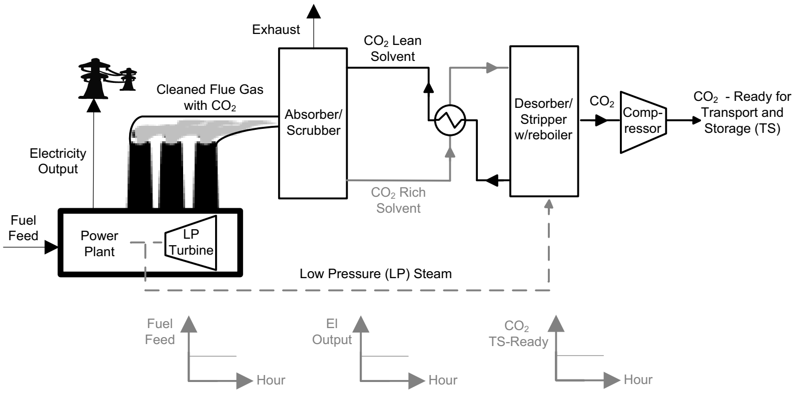

Figure 1: Simplified Schematic of Power Generation with Post Combustion CO_2 Capture, Static Base Load Production Profiles

The efficiency loss is dominated by the thermal energy required to regenerate the solvent (separate CO_2 from the solvent), typically provided through extraction of steam from the power plant low pressure (LP) steam cycle prior to the LP turbine and thereby leading to lower power generation in the LP turbine. The other contribution to efficiency loss is the electricity consumed to operate flue gas blowers/fans, solvent pumps and CO_2 compressors. A typical breakdown of the energy penalty at full load operation of post combustion capture at a super critical pulverized combustion (SCPC) coal-fired power plant is given in Table 1.

Table 1: Efficiency Penalty for SCPC with Post Combustion Capture at Full Load [5]

Process	**% Points Penalty at Full Load**
Steam for CO_2 separation	5 %
Power for CO_2 separation	3 %
CO_2 compression	1 %

The breakdown of the energy penalty (see Table 1) implies that if solvent regeneration and subsequent CO_2 compression is deferred, the efficiency penalty and thereby the electricity output could be altered over time. This is the motivation behind the idea of flexible solvent regeneration and storage presented by [5], where solvent storage tanks are placed between the absorber column and the desorber column.

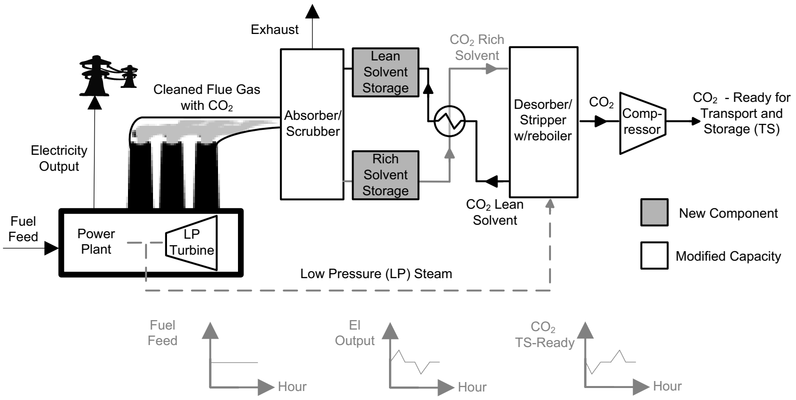

Figure 2: Modified Post Combustion CO_2 Capture with Flexible Solvent Regeneration and Storage

With the possibility of accumulating solvent through solvent storage, the amount of solvent flowing through the absorber does not need to be equivalent to the amount flowing through the desorber. For a base load power plant with constant CO_2 capture rate (constant solvent flows through the absorber), the storage tanks gives the opportunity to alter level of solvent regeneration (and CO_2 ready for transport and storage)[2]. Two individual storage tanks systems are required, one for rich solvent prior to regeneration and an equally sized storage system for lean solvent after regeneration. It would then be possible to achieve an operation profile where periods of lower production of CO_2 ready for transport and storage gives higher electricity output and vice versa, see time profiles Figure 2.

Adjustments in solvent regeneration will require flexibility in affected components. For this work, only the LP turbine, desorber and CO_2 compressor are assumed to be affected by varying the solvent flow. The impact of other affected components such as solvent recirculation pumps, heat exchanger etc., are considered neglectable in this work. In periods with high solvent regeneration, excess capacity is needed at e.g. the desorber with reboiler and the CO_2 compressor, while the LP turbine will run at lower load due to less steam available. During low regeneration activity the opposite situation occurs, with low load at the regeneration components, while excess capacity is needed at the LP turbine receiving excess LP steam. The components affected by the level of solvent regeneration in this study are the shaded areas in Figure 2.

3. The Model

The incremental value of being able to adjust electricity output for a base load power plant with flexible solvent regeneration and storage is defined as the value of the differential in electricity sales from a base case with static post combustion CO_2 capture (Figure 1) and the alternative case with flexible solvent regeneration and storage (Figure 2). It is envisaged that from an operational standpoint the flexibility in solvent regeneration will be limited to three discrete pre-programmed levels; high (maximum) solvent regeneration, low (minimum) solvent regeneration and normal (static design) solvent regeneration modes. Static design mode is equivalent to the solvent regeneration level of the static base case, hence no solvent accumulation. To be able to operate the flexible system for a base load plant with constant fuel feed, the static design mode needs to be an intermediate load level, between minimum and maximum regeneration.

$$Minimum\ mode < Static\ Design\ mode < Maximum\ mode \quad (1)$$

The capacity and specifications of the static base case defines the solvent flows and regeneration level required when the flexible case is operating at static design mode (hence when the flexible case is running at static design mode the regeneration level is equal to the static base case). The extent of the operating range, defined as the difference between maximum and minimum solvent flows, is a measure of the degree of flexibility in regeneration levels. The flexibility will be limited by the least flexible process being influenced by the regeneration level. As indicated in Figure 2, the components affected by the change in solvent regeneration are typically the LP turbine, compressor(s), solvent pumps, and desorber with reboiler.

The *lower boundary* as percentage of maximum capacity could either be a physical constraint or a point at which the component efficiency drops below a certain level. Figure 3 shows the expected variation in efficiency penalty of post combustion CO_2 capture with load, indicating a trend of increasing efficiency penalty with decrease in load [9]. It is assumed that the pumps, CO_2 compressor train and blower aren't constrained, as the flexibility of these components can be enhanced by adding another suitably sized component in parallel. A typical CO_2 compressor is likely to be capable of efficient turndown to approximately 75 % of full flow at constant discharge pressure [5]. In case of large CO_2 volumes, it is possible with multiple compressors in trains, and possibly also in parallel to provide sufficient capacity. With multiple compressors the degree of flexibility increases compared to a single compressor. For example in a compressor train where 2 compressors each could vary between 75-100 %, you would have a continuous interval of efficient operation between 50 – 100 %. Further, it is assumed that there is no appreciable change in energy penalty related to these components when the capture plant is operated at different loads, supported by Figure 4. The increase in efficiency penalty is dominated by increased power loss from the steam turbine(s), due to increase in steam demand per kg_{CO2} captured. A breakdown of the post combustion capture efficiency penalty as a function of load is presented in Figure 4, distributed on main components.

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[2] Please note that the total CO_2 emissions of the plant over the operating period will remain constant.

Limitations on the maximum load, *upper boundary*, of components could typically be given by available space or technical challenges related to large constructions, when multiple components are not possible. In this study the operating range is limited to loads in the range of 50-100% of maximum capacity to avoid large efficiency drop.

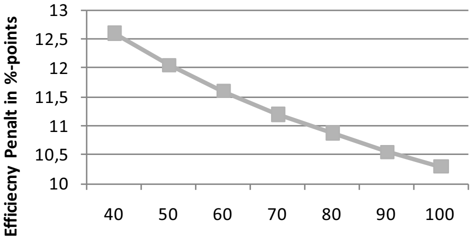

Figure 3: Post Combustion Capture Efficiency Penalty [9]

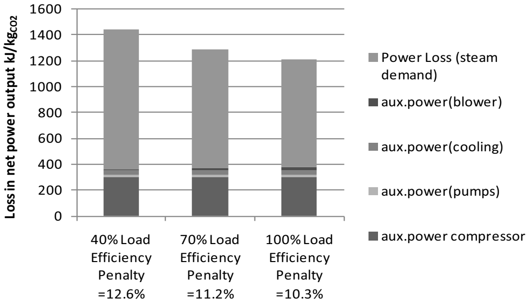

Figure 4: Component Breakdown of Efficiency Penalty [9]

The solvent flow rate in the static design mode is defined based on the static base case as discussed earlier. The maximum capacity of the flexible case can be determined when the % load of the static design mode relative to the maximum mode is defined. E.g. if the static base case has a flow rate of 100, and the static design mode is 80% of maximum capacity, the desorber of the flexible case need to be oversized with 20/80= 25% compared to the static base case. Given a defined static base case capacity, determining the location of the static design mode in the operating range of the flexible case is thus equivalent to determining the size of the desorber.

If it is expected that the plant will operate in the static design mode for majority of the time, the static design load should be as close to maximum capacity as possible to ensure minimal energy penalty. However, this would mean relatively long periods with maximum regeneration compared to period with minimum regeneration, since deviation from static design mode is little. The static design mode is set to be 90% of maximum capacity in the flexible operating case, implying that maximum capacity of the flexible case is 11% higher than the static base case.

3.1. Electricity Differential as Function of Load

When operating range (50% -100%) and placement of static design mode (90%) is determined, we can find the energy penalty and electricity output, as function of operating modes. For the static base case we can determine the following electricity output

$$EL_{\mathrm{static}} = E_{\mathrm{input}} * (\eta_{\mathrm{el,generation}} - \eta_{\mathrm{capture,100\%\,load}}) \tag{2}$$

The total energy input E_{input}, the thermal energy input to the plant in megawatt hours of thermal energy (MWh_{th}), is given by the capacity of the specified power plant and independent of flexible or static operation. $\eta_{\mathrm{el,generation}}$ is the generation efficiency of the selected power generation technology and $\eta_{\mathrm{capture,100\%\,load}}$ the capture efficiency penalty at 100% load. For the flexible case we assume the capture efficiency penalty from steam demand to be a function of regeneration level, *m*, while efficiency penalty of the remaining components are assumed to be constant

$$EL_{\mathrm{flexible},m} = E_{\mathrm{input}} * \left(\eta_{\mathrm{el,generation}} - \frac{R_{\mathrm{flex},m}}{R_{\mathrm{static}}}(\eta_{\mathrm{steam\,demand},m} + \eta_{\mathrm{el\,demand}})\right) \tag{3}$$

The constant level of solvent regeneration in the static case, R_{static}, is based on flue gas volume & CO_2 content, specified capture rate and effective loading of the solvent. An implicit assumption here is that the effective loading of the solvent remains constant, despite the fluctuations in flow of solvent through the regeneration system and storage tank levels. The capture efficiency of the flexible case is scaled to the level of solvent regeneration, $R_{\mathrm{flex},m}$. The differential in electricity production, ΔEL_m, in a given time period is then found by taking the difference between the flexible and static case

$$\Delta EL_m = EL_{\mathrm{flexible},m} - EL_{\mathrm{static}} \tag{4}$$

The electricity differential is hence independent of the technology specific power generation efficiency. From an operational viewpoint frequent switching between the operational modes is not ideal and it is expected that each switch will be associated with a penalty or cost. This switching cost is modeled based on loss in regeneration efficiency during period of transient conditions. The switching cost is assumed to be proportional to the change in regeneration level, occurring at the hour of switching operation mode

$$SWC_t = P_t \cdot |\Delta EL_{m,t} - \Delta EL_{m,t-1}| \cdot \eta_{switch} \tag{5}$$

where η_{switch} is the switching efficiency, set to be 3% as a base assumption. The cost of switching from design mode to non-design mode is taken to be equal to the cost of switching from the same non-design mode back to design mode. The flexible solvent regeneration and storage concept is formulated and structured as a dynamic mixed integer dynamic linear programming (MILP), using General Algebraic Modeling Systems (GAMS) to optimize weekly profit by establishing optimal operating strategy. The model is not presented in this paper due to space limitations.

3.2. Electricity Price Vector

Base load power plants typically have the lowest costs per unit of electricity produced, being designed for maximum efficiency and high capacity factor. Even though base load power plants often cover a large share of the electricity demand, additional load following and peak load capacity is required during periods with high electricity demand. More expensive low load capacities result in higher electricity prices during periods with high demand. The cyclical pattern of electricity demand, give rise to some partly deterministic cyclical characteristics in electricity price patterns (e.g. hourly, daily, and monthly). The average hourly prices per week for the German EEX market, in the period 2002-2008 are given in Figure 5.

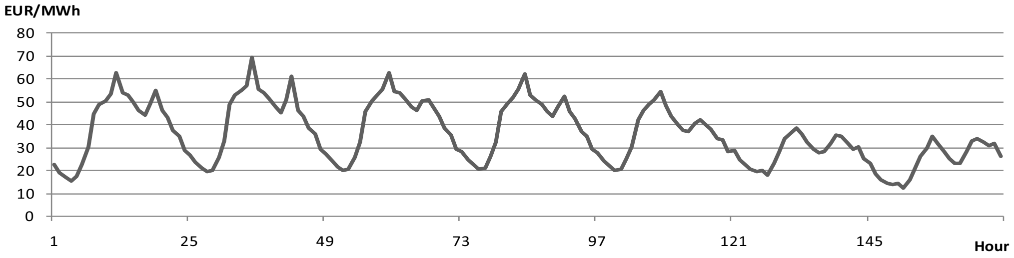

Figure 5: Average Hourly Prices for Weeks in the Period 2002-2008, EEX

The average price profile shows clear trends in intraday price pattern and also difference between weekends and weekdays. Electricity price peaks, typically during day hours, are on average significantly higher than electricity prices during low price period. By developing weekly operating strategies, compared to daily, we can include the trend of lower prices in weekends compared to weekdays. Hence we consider a horizon of one day to be too short to consider optimal operating strategy, while a horizon of one month could be too long with regards to future price uncertainty. The algorithm developed in this paper therefore optimizes the optimal strategy on a weekly basis based on weekly hourly prices.

4. Results & Analysis

The properties of the base case with flexible solvent regeneration and storage is summarized in the Appendix. The weekly electricity price vector has a significant effect on the optimum operating strategy and resulting weekly profits. An ideal weekly operating strategy would assume perfect electricity price information. This, even though not realistic, gives an upper bound on the weekly profits. A more realistic approach would be to use historic data to develop a forecasting model for the price vector used in the optimization. One of the simplest such models is to use average hourly prices of the historic data available as the basis for evaluating the optimum operating strategy. This gives a lower bound on weekly profits. It is assumed that obtainable weekly profits will lie somewhere between these two boundaries, depending on the precision of the forecasting model used.

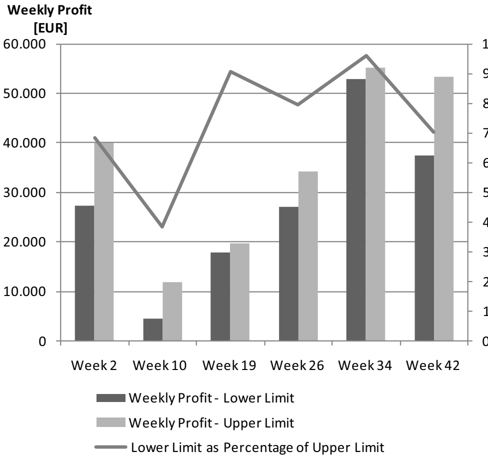

Figure 6: Upper and Lower Limits on Weekly Profit

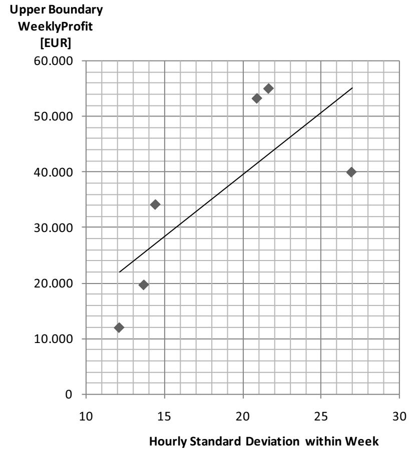

Figure 7: Correlation Weekly Profit and Standard Deviation

Figure 6 shows the upper and lower limits on the weekly profits for six selected weeks[3] in 2009, starting on Mondays at 00:00 and ending and Sundays at 24:00. The lower limit value uses average weekly hourly electricity price for the out-of-sample period 2002-2008 of the German EEX market as the input price vector while the upper limit value is based on the realized prices in 2009 of the German EEX market.

We observe large fluctuations in weekly profit and differential between the upper and lower boundaries for selected weeks, see Figure 6. The lower boundary in weeks with high profit exceeds by far the upper boundary in low profit weeks, despite perfect price information. This indicates that the flexibility concept, based on our model, is more sensitive to the market specific price profile than the accuracy of the price forecast. Figure 7 indicate a correlation between the amounts of hourly price volatility (represented by the hourly standard deviation) within a week, and the calculated upper weekly profit. The results are reasonable and emphasize that the motivation of this concept is essentially based on volatile electricity prices. The price profile and storage tank levels for week 26 (See Figure 8), clearly indicates that the model takes into account both the daily and weekly trends within the electricity price profile.

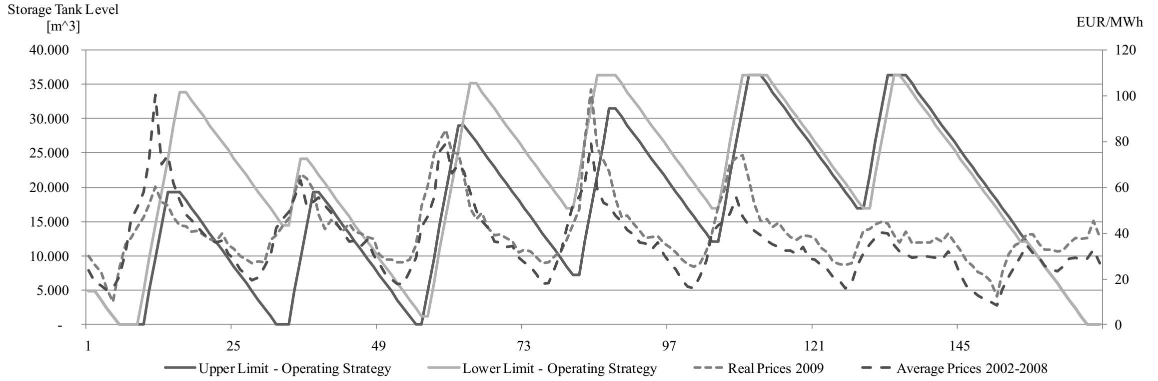

Figure 8: Electricity Price and Storage Tank Level Profiles for Week 26

5. Conclusions and Discussion

The concept of flexible solvent regeneration and storage for a coal fired power plant with amine based post-combustion capture presented in [5] was further explored. An MILP model for generating the optimum operating strategy by maximizing weekly profit was developed and results presented. The model and subsequent analysis

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[3] Week 1 is defined as the first week where all days are within the same year

highlights the potential value of flexible solvent regeneration and storage. A positive correlation is indicated between weekly profits and the level of electricity price volatility. The shape and stability of market specific weekly electricity price profiles dominate the level and volatility of weekly profits.

Flexible solvent regeneration will require both new and modified components, as illustrated in Figure 2. This paper, however, has not focused on the associated investment costs, which will be looked at in a future work. The regeneration flexibility can be limited by case specific parameters such as available land area for storage tanks, and/or more general technical limitations, e.g. maximal size of a single desorber column. The techno-economic model developed in this paper is not only relevant for new projects, but can also be used to assess retrofit options. Besides providing flexible solvent regeneration and storage during "normal" operation, the proposed plant modifications could be beneficial for power plant start up and shut down operations. It should be noted that this work does not consider how flexible operation of the studied system affects the subsequent CCS chain components, namely transport and storage.

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Appendix

CO_2 Emissions	654 ton CO_2/hour
Capture Rate	90 %
Solvent Composition	30% MEA, 70% H_2O
Effective Solvent Loading	0.25 mol CO_2/mol MEA
Efficiency Penalty,	10,3% - 10,6% - 12,1%
Switch Penalty,	3%
Solvent Storage Capacity	36800 m^3 (each for lean and rich solvent)