OPTIMIZATION AND SCHEDULING OF A HYBRID ENERGY-POWERED CARBON CAPTURE PLANT

A Thesis

by

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ABSTRACT

There is an increasing need to reduce the environmental impact from fossil fuel energy-generating sources. Carbon capture is a potential pathway for reducing CO_2 emissions from stationary sources. Carbon capture is an energy-intensive process and can result in a significantly lower net energy output from a fossil-fuel based power plant to address the energy intensive carbon capture process, renewable energy sources can be integrated with a fossil fuel power plant. The integration with renewable energy not only reduces the environmental impact associated with fossil fuels, but it also allows variability in the supply of renewable energy sources.

Flexible carbon capture enables the capture plants to be run independently, and introduces ancillary facilities like tanks and venting. This flexibility in the operation can be increased by the incorporation of renewable energy which allows the power plants to treat the flue gas when the prices of electricity is low. This work aims to develop a scheduling profile for flexible carbon capture in an integrated power generation pathway that includes both fossil fuels, renewable energy resource availability and the spot price of electricity.

DEDICATION

This thesis is dedicated to my family: Professor Victor, Professor Airen, OoreOluwa and Oluwatomi Adetimirin

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

The increasing pollution and global warming awareness have piqued interest in ensuring ways to mitigate global warming. The pollution is caused by many sources but energy production from fossil fuel is the leading cause. Power plants, while meeting the demand of energy globally, have contributed to the polluted environment[1]. Coal combustion is one of the major contributors to rising CO_2 emissions, and although, other sources like oil and natural gas exist, it is impossible to replace all the coal plants fast enough. In a bid to address this, deployment of renewable technologies and carbon capture are being considered[1].

Renewable energy technologies are described as clean sources of power. The disadvantage is the intermittent supply associated with these sources[2,28]. Solar, for example, is location dependent and is not evenly distributed throughout the day. The same applies to wind. Hydropower has good potential but the competition for water resource and the investment and availability needed to create dams make hydropower limited in upscaling. Biomass also produces clean energy and is generated from burning trees and food materials. The competition of biomass with food resources makes it a limiting choice. Biomass also negates the bid to continue afforestation and reforestation to promote decarbonization. These sources, although very helpful, require time to grow to large scale and also would be unable to meet the energy demands of the world.

Carbon capture makes it possible for fossil fuel to remain in the energy mix[4,28] but at minimal negative effect on the environment. This technology focuses on

1. Converting fuel, like coal, to cleaner fuel derivatives, which can be burnt with no negative effect on the environment. The economics involved in the technology to purify fuels is very high. Also, various fuels would require different technologies to be converted, which makes it difficult to achieve.
2. Capturing the carbon post-combustion: This is a more acceptable method, as it can be applied to different fuels[28]. The exhaust from the combustion is captured and the carbon is separated and transported to other sites.

Carbon capture can provide opportunities for fossil fuels to remain in the energy portfolio and guarantee energy security. The challenge with carbon capture is the associated energy intensity[29], and consequently, how profitable the technology can become, for plants that choose to adopt this measure. To mitigate the energy intensity, renewable energy sources can be integrated with coal fired power plants with carbon capture. The problem gets further complicated for the power plants to assess and project profitability and scheduling of their operations due to the resource availability of renewable energy resources.

1.2 Research Goals

This research aims to optimize the operations of hybrid power plants with flexible carbon capture, to yield maximum profitability, while taking power generation scheduling, flue gas treatment, carbon emission credits into consideration. A model that describes the hybrid power plant's operations would be built (composed of coal, wind and solar energy generation), which includes revenue from sale of electricity in the spot market, sale of carbon credits and sale of electricity associated with long-term contracts. Costs such as operation costs of the plants, capital costs associated construction and generation from solar and wind farms would be incorporated.

The optimal schedule for a 24-hour period would be generated. This schedule would include the hourly net power generated, the power generated from each source, and storage volumes operated by flexible carbon capture plant hourly.

1.3 Outline of the Thesis

Section 2 discusses the carbon capture process, examining literature on flexible carbon capture, hybrid energy systems and renewable energy for carbon capture. This section gives a background to past work on different energy generation sources and the opportunities for improvement. Furthermore, the hybrid system being investigated is presented and described.

Section 3 describes the model being proposed. The energy sources and power generation potential are modeled. We introduce the model comprising of wind, solar, coal and a carbon capture system. The model examines the generation, ramping and system constraints associated with each of the sources and the flexible capture technology.

Section 4 presents the results, comprising of characteristic profiles of wind and solar, as well as a 600 MW coal power plant. The results discuss the operation scheduling for each plant, including the capture tank and the solvent storage strategies. The results also include the maximum bi-lateral long-term contract that should be agreed to.

Section 5 concludes the thesis, presents a summary of the work with key results and also opportunities for future related work.

CHAPTER II

LITERATURE REVIEW

2.1 Energy Sources

Energy remains one of the most important needs of individuals and countries to drive economic growth. Figure 1 shows the energy mix and each contributing energy source. Oil is the largest, providing about 39% of the energy supply[16].

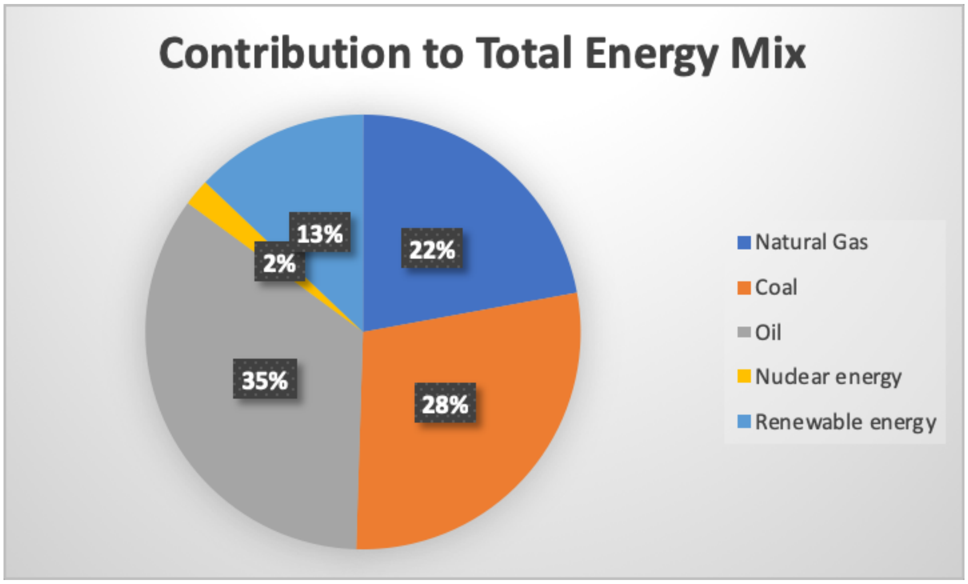


Figure 2.1 Shares of energy sources in total global primary energy supply in 2008

The total contribution of renewable energy in 2008, as indicated by the IPCC[16] in Figure 2.1 is about 13%. Hence, fossil fuel energy is still the dominant source. Although renewable energy holds some potential, the contribution from fossil sources is considerable. To ensure energy security, measures to keep fossil fuel energy like oil, gas and coal in the mix have to be taken. Pollution and environmental impacts[11] are the major concerns with fossil fuels and their combustion, and these have to be combated to allow a secure energy future.

Oil is used for transportation, power generation, industrial use and residential power. The table below shows the use of various sources and their sinks.

Table 2.1 Energy sources and sinks

	Transport	Industry	Residential	Electricity
Petroleum	✓	✓	✓	✓
Natural Gas	✓	✓	✓	✓
Coal		✓	✓	✓
Renewables	✓	✓	✓	✓
Nuclear energy				✓

Table 2.1 shows the use of each energy source as described by the US EIA[27]. Coal-fired power plants are considered to a make significant contribution. It is estimated that coal-fired plants provide about 42% of total global electricity [7].

2.2 Emission Measures

The rate of human activities has caused global warming of approximately 1.0 degrees Celsius and would reach 1.5 degrees Celsius in 30 years[8]. There has been an increase of about 40% in the level of atmospheric CO_2[11]. In a bid to combat this, the following measures have been taken[1]:

i) Promotion of conservation and energy efficiency

ii) Promotion of clean fuels[31]

iii) Adoption of clean coal technology[32]

iv) Adoption of renewable energy technologies[31]

v) Nuclear power programs[1]

vi) Afforestation and Reforestation

vii) Carbon capture and Storage[1,33]

Carbon capture and storage is applicable at carbon emission sources and can be applied on a large scale. The technology requires research and full-scale deployment to make it commercial.

The measures surrounding carbon capture have focused on removing the point-source pollution and capturing pollutants. A combination of these measures is recommended to reduce atmospheric CO_2 by over 50%[1]. It is not economically viable to reduce pollution from every point source, neither is it efficient and possible to capture all the pollutants in the environment. The promotion of measures such as renewable technology deployment, though growing, is certain to take time, and other measures to mitigate the pollution from combustion of fossil fuels have to be explored. do not afford the environment the short time to mitigate the effects of climate change. Carbon capture can be implemented to reduce the impact of fossil fuel. It has unique advantages, like being applied to cement plants and power production plants. The technology also has the ability to reduce CO_2 emissions by up to 90%[1,33].

2.3 Carbon Capture Technology Pipeline

Carbon capture and sequestration is the process of capturing polluting carbon molecules from point sources, to prevent them from constituting and leading to poor air quality and environmental destruction. After carbon is captured, it is compressed, transported and stored, mostly in geological formations[61,62], or more recently, used in applications such as enhanced oil recovery. This technology can be applied to many large-scale applications[6,12], regardless of the fuel in use. It also has various flue gas separation options that aim to increase the efficiency of the whole process. During capture, flue gas from the power plant is directed to a capture plant, where it is separated. The power plant also has the option of venting the gas to the atmosphere, but recently, there have been regulations implemented in different parts, limiting emissions of flue gas, in a bid to control global warming. The technologies required for capture and separation are presented in Sections 2.4 and 2.5. Upon separation, CO_2 is compressed. The desorption and compression processes are energy intensive processes and contribute significantly to the energy consumption by the whole carbon capture process. Due to the dependence for energy of the capture plant on the base power plant, the time for stripping and compression has to be matched with the demand for electricity to ensure profitability of the plant. After compression, the CO_2 is transported via trucks or pipelines for deposition in geological formations.

2.4 Carbon Capture Technology

Reduction of combustion emission leads to the mitigation of human-driven pollution. Upon combustion of fossil fuels in power plants, the flue gas contains about 7-14% of CO_2 which is primarily responsible for climate change[1]. Carbon capture technologies have the potential to reduce the environmental destruction associated with combustion of fossil fuels[9]. The technologies focus on preventing carbon dioxide formation or removing carbon dioxide after combustion. There are various technologies to capture and separate the CO_2 from the flue gas are:

i) Pre-Combustion Capture: this process involves pre-heating the fuel before use but the costs associated and retrofitting are major challenges[2,3].

ii) Post-Combustion Capture: this process focuses on capturing and separating the flue gas after combustion. The separation is typically carried out in a scrubber with amines such as mono-ethanolloamine[3,1]. This technology is very advanced and can be retrofitted into existing plants. The concentration of carbon-dioxide in the flue gas can adversely affect the efficiency of capture, and sorbent technologies are not robust in large scale applications[4]. This technology is also highly capital intensive as a result of the equipment and their sizes. Another significant challenge the process faces is a significant energy penalty (up to 30%)[5,6].

iii) Oxyfuel Combustion Capture**:** the process involves burning coal with pure oxygen resulting in high costs[4]. Other technologies exist to capture carbon from power plants such as algae, nanotechnology, biochar and charcoal for carbon adsorbent,[2] but the above-explained are the three main technologies and Table 2.2 compares carbon capture technologies as reviewed by Leung et al.[1]. Post-combustion, being the most mature, with the ability to retrofit to existing plants, would be the focus of this research.

2.5 Separation Techniques

Various technologies like absorption, adsorption and membrane can be used for separation[10]. Absorption employs a liquid absorbing chemical. In this process, flue gas is passed through a solvent that separates the CO_2 from the flue gas. The solvent is recycled and regenerated in a continuous process by heating. Solvents that are employed in the absorption process are monoethanolamine (MEA) and diethanolamine (DEA). MEA stripping can achieve an efficiency of about 90%, making it the most-preferred for this measure[13]. Ionic liquids can also be used as solvents[2]. Other technologies for separation are adsorption[1,15], membrane technology[17] and chemical looping. Absorption is the most commercially-used technology for carbon capture, presently, due to the ability to work with post-combustion capture. This allows for retrofitting and offers minimal disruption to the existing plant.

Table 2.2 Comparisons of capture technologies.

Process	Application	Advantages	Disadvantages
Post-combustion	Coal-fired and gas-fired plants	Technology more mature than other alternatives; can easily be retrofitted	Low CO_2 concentration affects the capture efficiency
Pre-combustion	Coal-gasification plants	High CO_2 concentration enhance sorption efficiency; fully developed technology, commercially deployed at the required scale in some industrial sectors; opportunity for retrofit to existing plant;	High parasitic power requirement for sorbent regeneration; inadequate experience due to few gasification plants currently operated in the market; high costs.
Oxyfuel combustion	Coal-gasification plants	Very high CO_2 concentration that enhances absorption efficiency; mature air separation technologies available; reduced volume of gas to be treated, hence required smaller boiler and other equipment.	High efficiency drop and energy penalty; cryogenic O_2 production is costly; corrosion problem may arise.

2.6 Flexible Carbon Capture

Many studies have focused on capture and improvement of capture technologies but due to the energy-intensive combustion of the carbon capture process, it is inefficient to run an inflexible carbon capture plant. An inflexible carbon capture plant is one in which the generation system is operated at full load, the loads of the capture system equal to that of the electricity generation system, the flow rates between the stripper and scrubber are equal[29]. Inflexible carbon capture has been studied by various authors[49,50,51]. This research considers inflexible carbon capture as continuously running, at the same capacity, without consideration to external factors such as the demand for electricity. For carbon capture to be economically viable, the capture plant has to be efficiently run[6]. Flexible carbon capture is characterized by providing alternatives, such as bypassing the carbon capture plant to release emissions into the environment and including solvent tanks in the carbon capture plant to enable decision-making on times to run the capture plant[34]. The first option, although more convenient for the plant is being faced with stringent regulations, in a bid to drive the world towards decarbonization. Hence, the economic penalty of paying for emissions would become more significant with time therefore driving power plants towards the second option. The second option involves purchasing solvent tanks for the capture plant as shown in Figure 2.2, which allows the stripper and compressor to be run at times when the electricity prices are low, generally, when the market energy demand is not as high, due to the energy intensity of the capture process. This measure does not increase the revenue associated with power plant and capture facilities, but it reduces the associated capture cost, consequently increasing the profitability of the plant. Post-combustion capture coupled with flexible operation of the power plant provides economic benefits, opposed to an inflexible capture plant.

The advantage of flexible plant operation lies in adapting operations based on the electricity demand. For fossil-fuel powered sources, this allows ramping of electricity generation due to demand or availability of renewable energy sources. In this way, the power plant determines the period in which in it most economical to operate the capture plant. The storage tanks allow for solvents to be stored till it is economical to treat it or till the tanks are full.

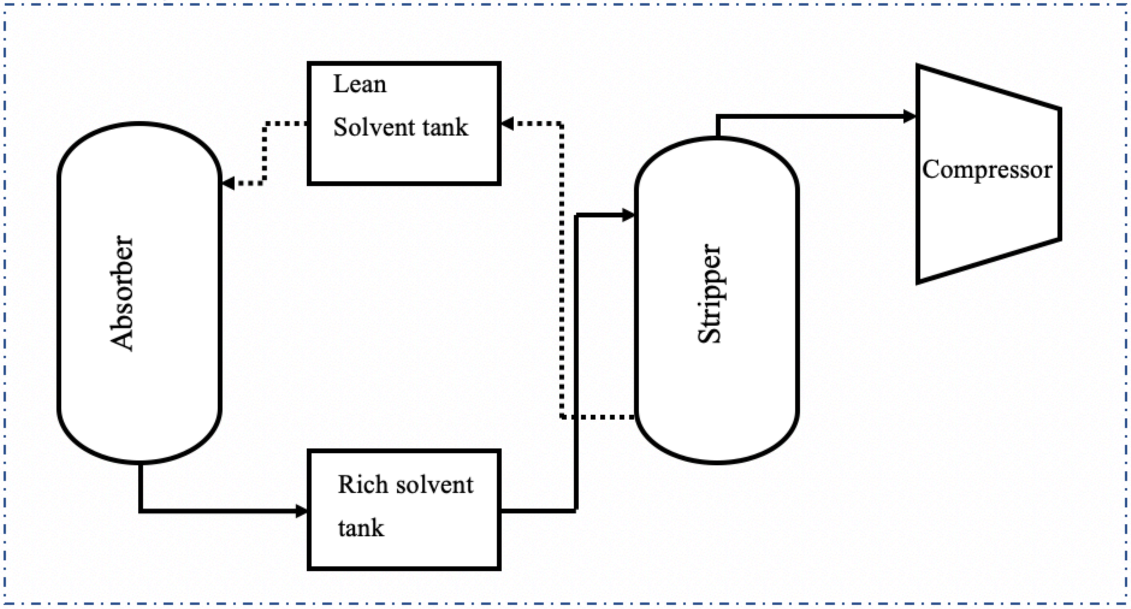


Figure 2.2 Flexible Carbon-capture Technology

For carbon capture to be economically viable, the capture plant has to be efficiently run[6]. The challenge of deciding how much power to produce, at various electricity market prices, how and when to utilize carbon credits and at what periods to run the capture plant and remain profitable are considered in this research. For flexibility, both a venting channel to maximize the carbon emission credits and storage tanks to allow for capture decision making are being considered.

2.7 Modeling Flexible Carbon Capture

Flexible carbon capture has been modeled by different authors, considering a variety of factors, based on their objectives, as shown in Table 2.3. Broadly, profit maximization and cost reduction are the most common objective of flexible carbon capture by these authors. The abbreviations for Table 2.3 are in Appendix A.

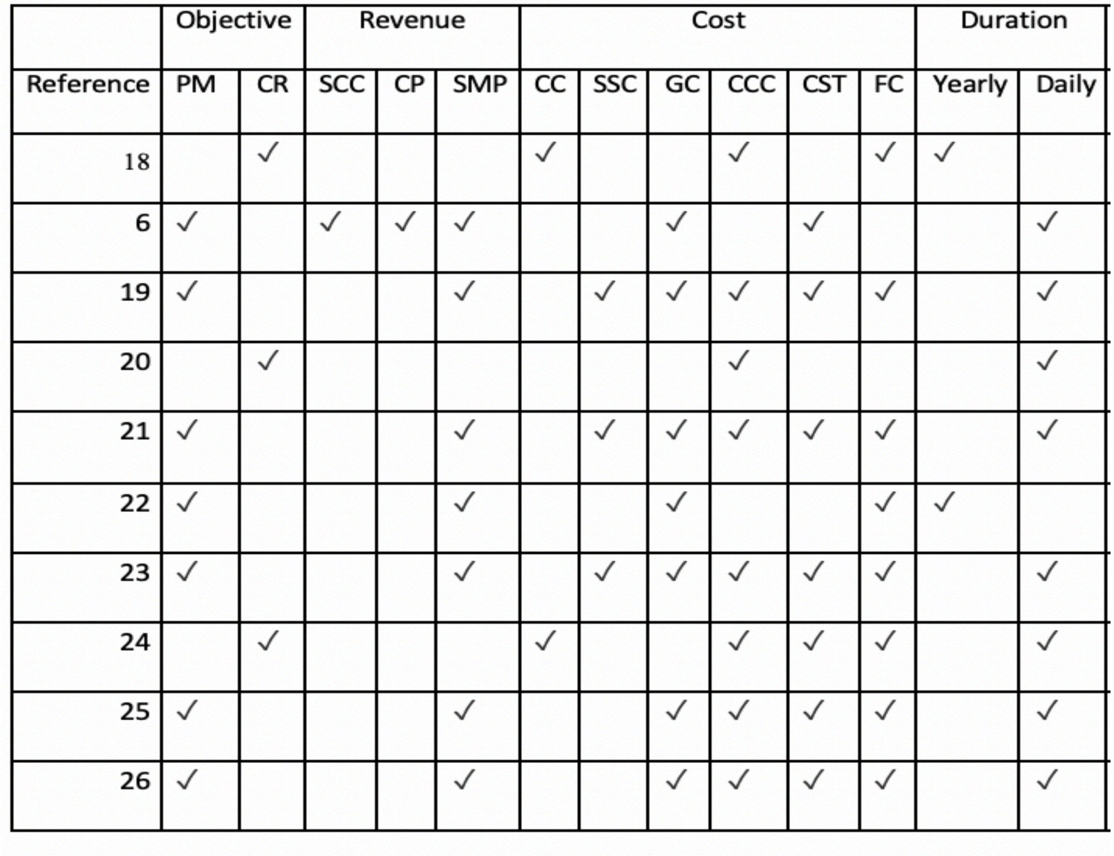
The duration of capture being modeled is also very dependent on the objective. Models intended for scheduling are usually over a one-day period (24 hours) due to the volatility involved in electricity prices. Models intended to justify investments in carbon capture are usually over longer durations, like one year.

Implementation of ancillary facilities is one of the main factors that affect carbon capture power plant[29]. Ancillary facilities such as storage systems and venting channels used in carbon capture enable flexibility of the system.

The storage tanks can be used to store lean or rich solvent while venting channels allow for the flue gas to be vented into the environment, as shown in Figure 2.2.

Cohen et al.[19] modeled a coal-fired power plant with flexible carbon capture considering various modes of operation, determined by the absorber load and the electricity prices. The research also considered both a perfect knowledge of the electricity price and a predictable scenario. It was determined that profits could be increased by up to 10% and that the knowledge of the prices are critical in determining the storage volumes and power schedules. Cohen et al.[52] evaluated the possibility of a grid-wide perspective to reduce the installation of energy infrastructure to make up for the carbon capture requirements and establishes with a case by the Electric Reliability Council of Texas (ERCOT) electric grid, that flexible carbon capture attains substantial emission cuts and also has the potential to save billions in capital costs associated with new facility infrastructure.

Table 2.3 Research on carbon capture models and factors considered



	Objective		Revenue			Cost						Duration	
Reference	PM	CR	SCC	CP	SMP	CC	SSC	GC	CCC	CST	FC	Yearly	Daily
18		✓				✓			✓		✓	✓	
6	✓		✓	✓	✓			✓		✓			✓
19	✓				✓		✓	✓	✓	✓	✓		✓
20		✓							✓				✓
21	✓				✓		✓	✓	✓	✓	✓		✓
22	✓				✓			✓			✓	✓	
23	✓				✓		✓	✓	✓	✓	✓		✓
24		✓				✓			✓	✓	✓		✓
25	✓				✓			✓	✓	✓	✓		✓
26	✓				✓			✓	✓	✓	✓		✓

Retrofitting carbon capture plants have been investigated with a throttled low pressure or floating pressure systems provides opportunities to maximize power generation during periods of high demand, providing additional flexibility and a reduction in capital costs for energy generation solely for carbon capture[53]. In addition, solvent tanks are also a means to reduce the cost associated with carbon capture. Although it increases capital cost slightly, it limits the environmental emissions and also the cost of capture.

With more strict regulations are being enforced to protect the environment, limits on emissions to the environmental are gradually picking pace, in form of carbon emission credits. Power plants face the decision to reduce their emissions drastically and this can be done by operating flexible carbon capture plants. The critical decision while operating the plants would be the periods in which to run the capture plants and how much power to generate, within the regulatory confines. This research assumes the power plant is a price-taker and cannot influence the spot price of electricity.

2.8 Renewable Power for Carbon Capture

The high energy associated with carbon capture, particularly the solvent regeneration phase in the stripper can be compensated by incorporating solar energy[35]. Jordan et al.[41] investigated the economics and technical feasibility of a solar-assisted carbon capture in Mexico. The solar energy was primarily used for solvent regeneration. The study showed that implementing a solar-assisted carbon capture alongside a cogeneration plant improved the efficiency. A major takeaway from the study is also the large investment cost associated with low-carbon technology. In cases where the renewable energy is solely for the regeneration phase of the carbon capture process, the cost is very high. In addition, capture plants also come at a cost, and energy loss. This further demonstrates the tradeoff between profitability for powerplants and the environmental impact associated with fossil fuels.

Yang et al.[42] also investigated the feasibility of a solar-assisted carbon capture process, using a dry carbonate process integrated with a 600 MW coal-fired power plant. This research proposed a different way to regenerate solvent for the carbon capture process, by directly heating in the solar collectors. This proposal reduces the investment cost associated with independent coal, solar and carbon capture system. They found that an area of 2.5 km^2 was required to provide the heat energy required for solvent regeneration while capturing about 1400 kT annually.

The effectiveness of thermal energy systems coupled with carbon capture plants have also been extensively studied[43]. A process that makes use of chemical and electrical mechanisms to capture carbon was also studied, showing that solar thermal energy reduced the energy required for capture and that the efficiency of solar power can be up to 50%[54]. The economics of a solar-assisted carbon capture was estimated to be \$100/m^2, for the regeneration stage of the carbon capture process. A feasibility method was developed to establish this amount and the solar field consisted of Fresnel collector field due to the energy requirement of the regeneration phase. The critical decision was the temperature required for regeneration and it was established that a non-concentrating collector would improve the economics associated with a solar-assisted capture process[55].

The different types of solar collectors that could be used, such as flat plate collectors, compound parabolic collectors, linear Fresnel collectors and evacuated tube collectors, were studied in Australia[56]. Two scenarios of heat integration and non-integration were considered. The evacuated tube collectors were shown to be the best for heat integration and the parabolic trough collectors were the best for non-integration of heat.

2.9 Hybrid Energy Systems

Hybrid energy systems, particularly, renewable sources like solar and wind are more likely to be incorporated with fossil fuel sources, combating the variability and uncertainty with solar and wind, while also combating the environmental challenge associated with fossil fuels[45]. Bhandri et al.[46] investigated the feasibility of tri-hybrid energy generation, for off-grid applications. The research considered Solar PV, wind and hydro and established that a combined energy generation strategy offers flexibility and reliability. The reliability of the solar and wind are very dependent on the location, and the available wind speed and the radiation available. Different locations would require varying degrees of solar and/or wind due to their availability and the demand.

The most common hybrid energy systems are PV-wind and PV-diesel[57] and electricity generation hybrid systems are more suitable. The challenge with such systems is their control and optimal operation. Other hybrid combinations involving storage such as hydrogen are not cost-efficient yet. It is also important to holistically evaluate other factors such as emissions and reliability, and not a stand-alone objective.

Deshmukh et al.[58] also affirmed that hybrid PV/Wind energy systems have gained popularity but are held back by their variability. The research also indicated that such hybrid systems are best-suited for remote locations, due to the comparable cost of electricity from the grid. The research highlighted that the energy penetration level is key and studied it by evaluating it as a network. It is critical to integrate renewable energy sources to the grid, to enable the transition from fossil-fuels[59]. The challenge of integration involves control mechanism and smart grids were studied as the preferred control mechanisms for integration.

Rehman et al.,[47] studied the feasibility of a hybrid energy system comprising of solar PV, wind and diesel for a village in Saudi Arabia. The village, as at the time, was solely powered by diesel generators and the study was conducted to evaluate the effect of a combined renewable system on the energy mix. The hybrid system met the energy demand and produced some excess energy. Renewable energy sources generated 35% of the total energy, with wind, solar PV and the diesel generating sets contributing about 4700 MWh, 1653.5 MWh and 11,542 MWh. The system also cut down emissions from fossil powered energy by avoiding about 5000 tons of carbon-dioxide.

The growing use and advantages associated with hybrid energy systems serve as justification for further investigation. In Figure 2.3, the hybrid energy system being proposed is made up of coal, solar and wind sources. The renewable sources, although intermittent, provides clean energy that complements the coal-fired plant's emissions. In Figure 2.3, the three energy sources can be used to generate electricity to be sold to the grid or used to run the carbon capture plant. The determination of the energy sink is dependent on the resource availability of the renewable energy sources, the electricity price and the flue gas being produced by the coal-fired plant. It provides flexibility for the capture system by allowing various sources for power, also reducing the power generated from coal, and consequently, the emissions produced when the renewable energy sources are available.

In general, hybrid systems offer some flexibility in energy systems, particularly renewable energy systems, due to the stochastic nature of the renewable resources necessary for generation. Many hybrid systems have been explored, but due to the emissions from fossil fuel powered plants, and recent pollution regulations, a carbon capture plant which prevents the emission of carbon dioxide into the atmosphere from a coal-fired power plant, can be retrofitted and powered by any of the energy sources.

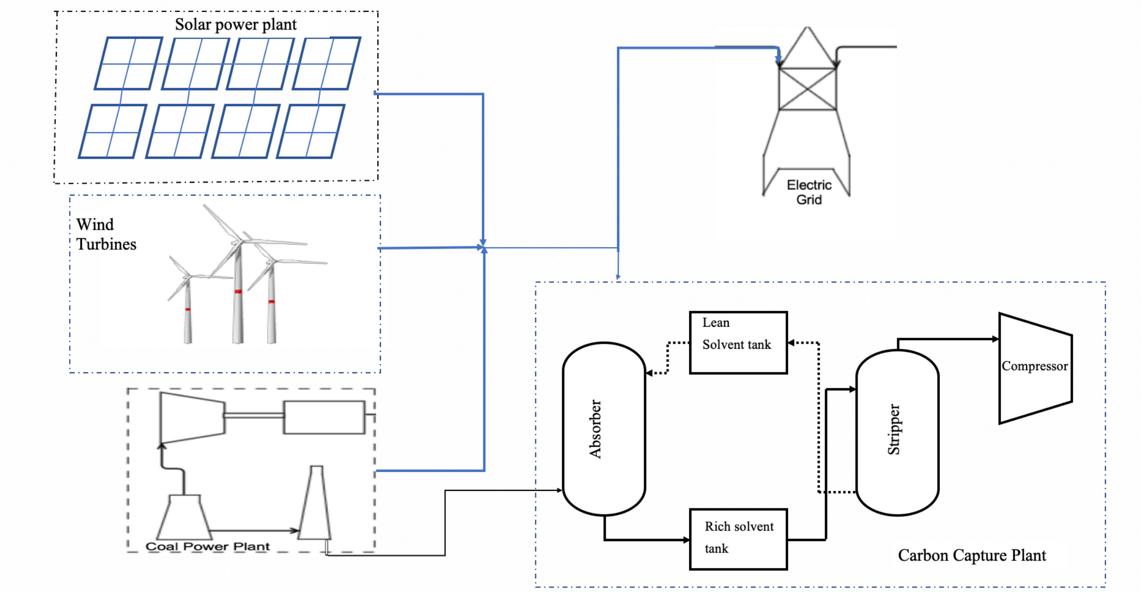


Figure 2.3 Hybrid-powered carbon capture schematic

2.10 Research Goals and Objectives

The hybrid-powered carbon capture plant would enable hybrid plants to determine the optimum power generation as well as the capture scheduling. The carbon capture plant, which has the potential to reduce carbon dioxide emissions from the power plant by up to 90%, is also very energy intensive, using up about 30% of the power generated from the coal power plant. Due to the energy intensity of the carbon capture process, a renewable energy system comprised of solar and wind power is installed to combat the energy loss of the capture plant. Unlike solar power plants that have limitations due to intermittency of the sun and the high cost of solar energy storage, coal-fired power plants are available to run without such limitations.

Research has been carried out on reducing the energy intensity of the stripping process particularly, utilizing renewable energy sources to reduce the energy penalty of the carbon capture process. Intermittent production associated with renewable energy sources has also been a challenge. Combining a coal-fired power plant with renewable energy sources provides advantages of reducing the environmental effect of burning fossil fuels and enabling energy security[38]. In a bid to explore the ability of renewable energy to compensate for the energy loss due to capture, this research aims to integrate a solar and wind farm with an already existing coal-fired power plant. By integrating the coal plant with renewable sources, greater benefits are provided[39,40]. Locations that possess high solar radiation, long summers and a strong reliance on coal power generation are the best choices[42]. In a bid for higher flexibility, this research would determine the energy sources to be used for capture activities as well as the scheduling profile, based on the resource availability. The model and results would help hybrid plants plan their power generation and capture schedule, in a bid to attain maximum profitability.

The objectives of this research are:

i) To develop a model for hybrid energy sources coupled with carbon capture plants.

ii) To develop hourly scheduling profiles for energy generation and capture operation.

CHAPTER III

METHODOLOGY

The optimization of power plants with carbon capture systems is necessary due to the energy penalty of the capture system. There exist tradeoffs between profitability and the operation of the power plant to prevent the release of emissions. Stringent policies place a limit on emissions and would require plants to operate within emission limits. Carbon capture holds strong potential to solve this. In a bid to reduce the associated cost of the capture plant, a flexible capture plant is proposed. The retrofitted flexible carbon plant consumes significant energy and takes a toll on the profit of the power plant. Running the power plant within the emission limit and ensuring profitability requires optimizing the operation of the capture plant and the hourly power generation.

Post-combustion is the most flexible carbon capture technology[28] and absorption is the most-named separation for capture[14]. A flexible carbon capture model by Chen et al.[29] developed for a coal-fired power plant is adopted. The model describes the daily profit for the power plant, with revenue sources from the long-term bi-lateral contracts and the spot market. The costs associated with the power plant result from the generation of electricity, cost of transportation and storage, and the cost penalty for emission. The flexibility modeled involves solvent storage tanks and a venting channel. This allows the capture plant to store solvent, until it is less costly to treat. The flexible operation of the plant does not reduce the energy intensity of the carbon capture process, it reduces the cost associated with the operation of the carbon capture process. During times of high prices, flexible carbon capture system uses minimal energy for the process, selling most of the energy to the grid, to increase revenue. Alternatively, inflexible carbon capture gives no credence to the electricity spot price and assumes constant capture and treatment rates. This model employs flexible carbon capture.

3.1 Hybrid Profit Maximization Model

The hybrid model contributes to existing literature by providing a means to evaluate the integration of renewable energy sources, with traditional power plants (Figure 2.3), coupled with carbon capture in a bid to reduce the environmental impact and ensure the profitability of integrated plants.

The formulation models power generated from renewable sources based on the location and the availability of the resources such as wind speed and radiation, for wind energy and solar respectively. Although these renewable energy sources provide intermittent power, they complement fossil fuel power plants by reducing the environmental effect resulting from the combustion of fossil fuels. The hybrid model developed assumes a post-combustion capture technology and absorption separation. The model would constitute revenue sources from the sale of electricity by contract and in the spot market and also the sale of carbon credit (or the loss by having to purchase). The model would also consider generation costs and capital costs associated with renewable energy. The model would be run and optimized for a known electricity price profile. The expected results are the absorber and scrubber hourly schedule and the net power production, for the known price profile and the incorporated uncertainty.

The model is a nonlinear programming model, solved with General Algebraic Modeling Systems (GAMS), version 24.1 solved on a computer with an i7-4790 CPU @ 3.6GHz and 16GB of RAM.

The objective function is a profit maximization function, given by Equation (3.1). The profit maximization objective comprises of the revenues from the sale of long-term contract power and power at the spot market as well as the revenue from the carbon emission credits. It also captures the various costs such as cost of generation for each of the technologies, and transport and storage costs. For the renewable energy technologies, the levelized cost of electricity[58] is used.

$$\max \pi = \sum_{s=1}^{S} [\sum_{t=1}^{T} [g_{t,s}^{L} . \pi_{G}^{L} + (g_{t,s}^{N} - g_{t,s}^{L}) . \pi_{G,t,s}^{S} - C_{c,t,s} - C_{w,t,s} - C_{s,t,s}] + (E_{G}^{L} - \sum_{t=1}^{T} E_{G,t,s}^{N}) . \pi_{E}^{L} - \left(\sum_{t=1}^{T} E_{G,t,s}^{S} \, C_{T/S} \right)] \qquad \forall t \in T, \ \forall s \in S \tag{3.1}$$

Equation (3.2) describes the net power generated at every time period is $g_{t,s}^{N}$ and is the sum of the power being supplied to the grid from all the energy sources. The power used by the absorber is denoted as $g_{t,s}^{a}$ and is the sum of the power generated from all sources used by the absorber. The same applies to the compressor, $g_{t,s}^{c}$and the stripper $g_{t,s}^{s}$. They are described by Equations (3.3), (3.4) and (3.5).

The energy required to run the absorber, compressor and stripper respectively in every time period are given by Equations (3.6), (3.7) and (3.8) are. They represent the power demand of the absorber, stripper and compressor respectively where μ_{A0}, μ_{c0} and μ_{D0} are the capture facility penalties. The total energy required for the equipment is dependent on the rate of absorption or desorption.

$$\sum_{p \in P} g_{p,t,s,u} = g_{t,s}^{N} \qquad \forall t \in T,\ \forall s \in S, u = grid \tag{3.2}$$

$$\sum_{p \in P} g_{p,t,s,u} = g_{t,s}^{a} \qquad \forall t \in T,\ \forall s \in S, u = absorber \tag{3.3}$$

$$\sum_{p \in P} g_{p,t,s,u} = g_{t,s}^{c} \qquad \forall t \in T,\ \forall s \in S, u = compressor \tag{3.4}$$

$$\sum_{p \in P} g_{p,t,s,u} = g_{t,s}^{s} \qquad \forall t \in T,\ \forall s \in S, u = stripper \tag{3.5}$$

The rate of desorption is also the determinant for the energy required by the compression, as there is no storage between both stages, hence, operating at steady state.

$$g_{t,s}^{a} = E_0 \mu_{A0} \mathrm{r}_{\mathrm{A},t,s} \qquad \forall t \in T,\ \forall s \in S \tag{3.6}$$

$$g_{t,s}^{c} = E_0 \mu_{c0} \mathrm{r}_{D,t,s} \qquad \forall t \in T,\ \forall s \in S \tag{3.7}$$

$$g_{t,s}^{s} = E_0 \mu_{D0} \mathrm{r}_{D,t,s} \qquad \forall t \in T,\ \forall s \in S \tag{3.8}$$

The total energy required by the capture plant is given by Equation (3.9), which is the sum of the individual components from the absorber, compressor and stripper.

$$g_{t,s}^{cap} = g_{t,s}^{a} + g_{t,s}^{c} + g_{t,s}^{s} \qquad \forall t \in T,\ \forall s \in S \tag{3.9}$$

The total power generated by the individual sources is defined by Equation (3.10), as a sum of the power used by various sinks, u.

$$\sum_{u \in U} g_{p,t,s,u} = g_{p,t,s} \qquad \forall p \in P,\ \forall t \in T,\ \forall s \in S \tag{3.10}$$

The constraint ensures the total power from all the sources meet the demand of the capture plant and the electricity sold to the grid at every time. The gross power generated by the plant, less capture power is the power available to meet the contract and to be sold in the spot market. Equation (3.11) is the breakdown of the power sold to the grid and used for carbon capture.

$$\sum_{p \in P} g_{p,t,s} = g_{t,s}^{cap} + g_{t,s}^{N} \qquad \forall t \in T,\ \forall s \in S \qquad \textbf{(3.11)}$$

The net power, $g_{t,s}^{N}$ from the power plant is described by Equation (3.12) defining that the net power at all time periods must meet the electricity demand defined by the bilateral contract.

$$g_{t,s}^{N} \geq g_{t,s}^{L} \qquad \forall t \in T,\ \forall s \in S \qquad \textbf{(3.12)}$$

The total power generated by the coal power plant in every time period is constrained by minimum and maximum power limits defined by Equation (3.13).

$$g_{min} \leq \ g_{p,t,s} \ \leq \ g_0 \qquad p = coal,\ \forall t \in T,\ \forall s \in S \qquad \textbf{(3.13)}$$

Equation (3.14) describes the ramping rate of the coal plant, which specifies how fast the coal plant can increase or reduce the power generated.

$$-\Delta g_R \leq \ g_{p,t+1,s} - g_{p,t,s} \ \leq \ \Delta g_R \qquad p = coal,\ \forall t \in T,\ \forall s \in S \qquad \textbf{(3.14)}$$

The efficiency of the coal generation system varies hourly and depends on the power generated in each time period. Equation (3.15) models the efficiency of the coal generation system.

$$\mu_{G,t,s} = -6.4\ X\ 10^{-7}.\left(g_{p,t,s} \ - 550\right)^2 + 0.44 \qquad p = coal,\ \forall t \in T,\ \forall s \in S \qquad \textbf{(3.15)}$$

The power generated by the solar plant at every time period and is a function of the solar radiation, the area of the solar plant and the efficiency of the solar panel. Equation (3.16) defines the power

$$g_{p,t,s} = \eta_{pv,t,s} A G_{t,s} \qquad p = solar,\ \forall t \in T,\ \forall s \in S \quad \textbf{(3.16)}$$

The efficiency of the solar PV is given by Equation (3.17) which relies on the cell temperature.

$$\eta_{pv,t,s} = \eta_T \eta_{pc} \left[1 - \beta\left(T_{c,t,s} - T_{c,ref}\right)\right] \qquad \forall t \in T,\ \forall s \in S \quad \textbf{(3.17)}$$

The cell temperature, which is the temperature at which the solar panels are operating, is a function of the ambient temperature and the radiation in the time period, defined by Equation (3.18).

$$T_{c,t,s} = T_{a,t,s} + \left[\frac{(NOCT-20)G_{t,s}}{80}\right] \qquad \forall t \in T,\ \forall s \in S \quad \textbf{(3.18)}$$

Representative solar radiation data for Houston, Texas is shown in Figure 3.1. Figure 3.1 shows a typical radiation profile, where radiation is zero in the first five hours of the day and the last 5 hours. In these hours, solar panels would not generate electricity.

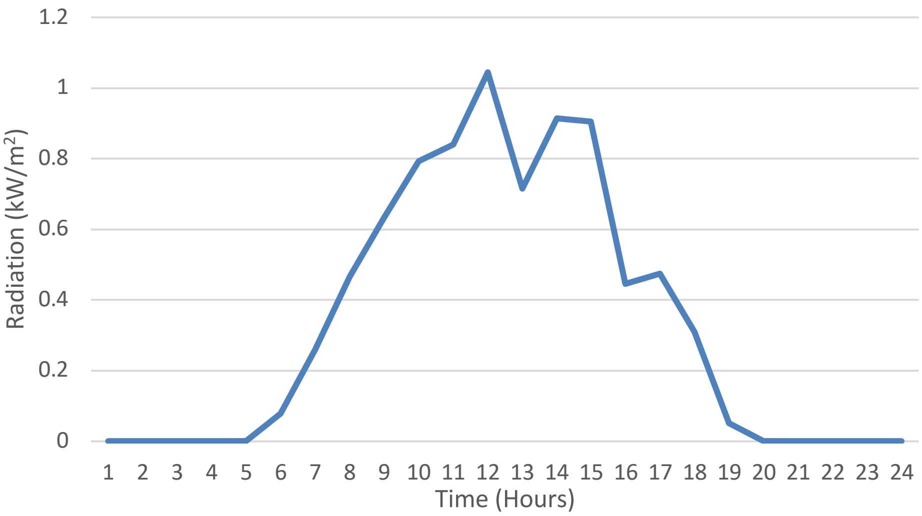


Figure 3.1 Characteristic hourly radiation profile used for solar power

The power generated by the wind turbine at every time period is defined in Equation (3.19), where n is the number of turbines needed and η_{eff} is the efficiency of conversion from wind energy.

$$g_{p,t,s} = \rho\frac{\pi r^2}{2}V_{t,s}^3\eta_{eff}n \qquad p = wind, \forall t \in T, \forall s \in S \tag{3.19}$$

The representative radiation data for Houston, Texas is shown in Figure 3.2. The data shows the hourly wind speed at 80m height, representing the height at which wind turbines are placed and describing the potential for wind energy generation across the day.

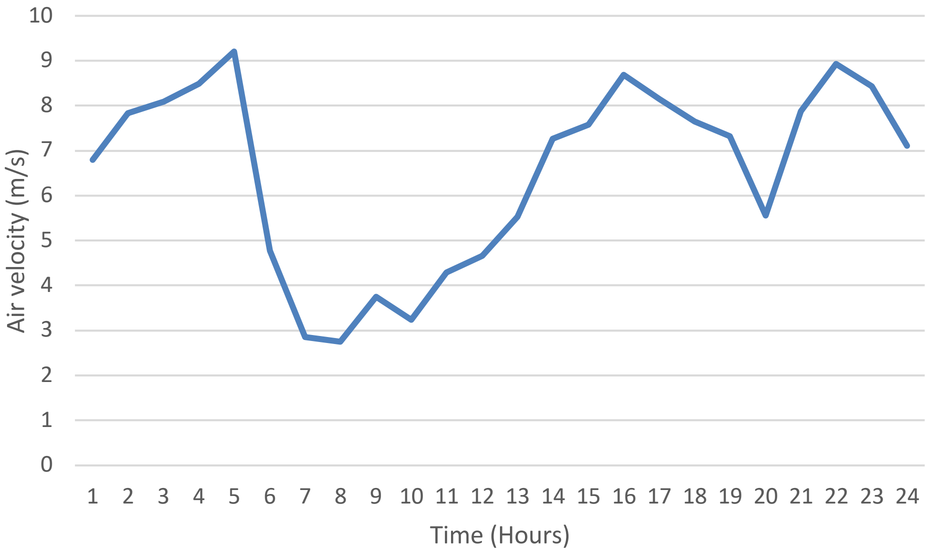


Figure 3.2 Characteristic hourly air velocity for wind power

Equation (3.20) represents cut-in and cut-out velocities, outside which the wind turbined would not run, for safety reasons. The cut-in velocity is the minimum velocity the wind turbine is designed to operate at and the cut-out velocity is the maximum velocity the turbine can operate at.

$$V_{min} \leq V_{t,s} \leq V_{max} \qquad \forall t \in T,\ \forall s \in S \qquad \textbf{(3.20)}$$

The absorption and desorption limits for the capture system are given by Equation (3.21) and (3.22) respectively. These are the limits that determine the maximum and minimum rates, and consequently, energy use, for the capture system.

$$0 \leq r_{A,t,s} \leq r_{A,max} \qquad \forall t \in T,\ \forall s \in S \qquad \textbf{(3.21)}$$

$$0 \leq r_{D,t,s} \leq r_{D,max} \qquad \forall t \in T,\ \forall s \in S \qquad \textbf{(3.22)}$$

Equation (3.23) and (3.24) describe the ramping rates which determine how quickly the capture absorption or desorption can be increased or decreased. The desorption rate and compression rate are assumed to be same as no storage is installed between those units.

$$-\Delta r_{A,max} \leq r_{A,t+1,s} - r_{A,t,s} \leq \Delta r_{A,max} \qquad \forall t \in T, \forall s \in S \quad \textbf{(3.23)}$$

$$-\Delta r_{D,max} \leq r_{D,t+1,s} - r_{D,t,s} \leq \Delta r_{D,max} \qquad \forall t \in T, \forall s \in S \quad \textbf{(3.24)}$$

The volume of fluid in the tanks at any time, cannot exceed the maximum volume of the tanks, as shown by Equation (3.25) and (3.26).

$$0 \leq S_{A,t,s} \leq S_{A,max} \qquad \forall t \in T, \forall s \in S \quad \textbf{(3.25)}$$

$$0 \leq S_{D,t,s} \leq S_{D,max} \qquad \forall t \in T, \forall s \in S \quad \textbf{(3.26)}$$

The volume of the rich solvent flowing from the absorber and lean solvent from the stripper hourly are dependent on the absorption and desorption rate respectively, represented by Equations (3.27) and (3.28).

$$S_{A,t,s} = S_{A0} r_{A,t,s} \qquad \forall t \in T, \forall s \in S \quad \textbf{(3.27)}$$

$$S_{D,t,s} = S_{D0} r_{D,t,s} \qquad \forall t \in T, \forall s \in S \quad \textbf{(3.28)}$$

The total volume in each of the tanks is the net volume treated in that hour and the volume in the tank in the previous hour, defined in Equation (3.29) and (3.30).

$$S_{A,t,s} = S_{A0} + \sum_{i=1}^{t} (S_{A,i,s} - S_{D,i,s}) \qquad \forall t \in T, \forall s \in S \quad \textbf{(3.29)}$$

$$S_{D,t,s} = S_{D0} + \sum_{i=1}^{t} (S_{D,i,s} - S_{A,i}, s) \qquad \forall t \in T,\ \forall s \in S \qquad \mathbf{(3.30)}$$

The net-emission from the capture system is a balance comprising of the total emissions less the emissions treated in the stripper and is given by Equation (3.31).

$$E_{G,t,s}^{N} = \frac{\mu_{G0} e_{G0} g_{p,t,s}}{\mu_{G,t,s}} - g_o e_{G0} \gamma_A r_{D,t,s} \qquad p = coal,\ \forall t \in T,\ \forall s \in S \qquad \mathbf{(3.31)}$$

The emission intensity, which is the maximum emission per unit of power generated is given by Equation (3.32).

$$\sum_{t=1}^{T} E_{G,t,s}^{N} - e_{G,max}^{c} \sum_{t=1}^{T} g_{p,\mathrm{t,s,u}} \leq 0 \qquad p = coal,\ \forall t \in T,\ \forall s \in S, u = grid \qquad \mathbf{(3.32)}$$

Equation (3.33) represents the quantity of emission treated by the absorber, which depends on the desorption rate and the scrubber removal rate. The scrubber removal rate is the percentage of CO$_2$ captured from the flue gas.

$$E_{G,t,s}^{S} = r_{D,t,s} g_o e_{G0} \gamma_A \qquad \forall t \in T,\ \forall s \in S \qquad \mathbf{(3.33)}$$

The unit cost of power generation from coal is a function of the power generated at every time, given by the efficiency of generation in Equation (3.34).

$$C_{G,t,s} = \frac{C_{G0} \mu_{G0}}{\mu_{G,t,s}} \qquad \forall t \in T,\ \forall s \in S \qquad \mathbf{(3.34)}$$

The cost of power generation by the coal, wind and solar plants are given by Equations (3.35), (3.36) and (3.37) and is a function of the generated power in every time period. They are a product of the unit cost and the total power generated.

$$C_{w,t,s} = g_{p,t,s} C_{wo} \qquad p = wind,\ \forall t \in T,\ \forall s \in S \qquad \mathbf{(3.35)}$$

$$C_{s,t,s} = g_{p,t,s}C_{so} \qquad p = solar,\ \forall t \in T,\ \forall s \in S \tag{3.36}$$

$$C_{c,t,s} = g_{p,t,s}C_{G,t,s} \qquad p = coal,\ \forall t \in T,\ \forall s \in S \tag{3.37}$$

The constraints on the area of the solar field and the number of wind turbines are listed as Equations (3.38) and (3.39) respectively. The constraint on the area of the solar field assumes a maximum area of 1 km^2 is available.

$$A \leq 1 \tag{3.38}$$

$$\mathrm{n} \leq 150 \tag{3.39}$$

The model comprises of four sets explained below:

p: power generating sources, made of up coal-fired power plant, solar power and wind power.

t: hourly time periods describing operations throughout the day

s: scenarios involve the number of days being considered in the model. This model considers one day.

u: energy usage. The energy usage is made up of the grid, scrubber, stripper, compressor.

The variables in the formulation are:

$g_{p,t,s}$	power generated by source p at time t in scenario s
$g_{t,s}^{N}$	net power generated at time t in scenario s
$\pi_{G,t,s}^{S}$	electricity spot price at time t in scenario s
$r_{A,t,s}$	absorption rate at time t in scenario s
$r_{D,t,s}$	desorption rate at time t in scenario s

$S_{A,t,s}$	volume of rich solvent in tank at time t in scenario s
$S_{D,t,s}$	volume of lean solvent in tank at time t in scenario s
$C_{G,t,s}$	cost of generation of electricity at time t in scenario s
$\mu_{G,t,s}$	cost of generation of electricity at time t in scenario s
$E_{G,t,s}^{S}$	quantity of emission treated by the scrubber in scenario s
$E_{G,t,s}^{N}$	net emission at time t in scenario s
$T_{a,t,s}$	the ambient temperature at time t and scenario s.

The parameters used for the formulation are:

g_t^L	power generated to meet long-term contracts	300 MW
π_G^L	price of long-term electricity contracts	\$51.7/MWh
E_G^L	Daily carbon emission allocation	4373 tons
π_E^L	cost of carbon emission	\$12.3/ton
$C_{\frac{T}{S}}$	cost of CO_2 transport	\$7/ton
g_0	Maximum power of the coal plant	600 MW
$g_{\min}$	Minimum power of the coal plant	300 MW
Δg_R	ramp limit of the coal power plant	360 MW/hr
$r_{A,max}$	maximum absorption rate	1
$r_{D,max}$	maximum desorption rate	1.25
$\Delta r_{A,max}$	maximum ramping rate for absorption	100%
$\Delta r_{D,max}$	maximum ramping rate for stripping	100%

S_{A0}	Initial volume in the rich solvent tank	7300 m^3
S_{D0}	initial volume in the lean solvent tank	7300 m^3
$S_{A,max}$	maximum volume of the rich solvent tank	14600 m^3
$S_{D,max}$	maximum volume of the lean solvent tank	14600 m^3
γ_A	CO_2 removal rate in the absorber	90%
μ_{G0}	Efficiency of the coal plant under base condition	44%
e_{G0}	CO_2 emission intensity during base condition	0.76 ton/MWh
$e_{G,max}^{c}$	CO_2 emission intensity	0.3 ton/MWh
C_{G0}	cost of generation at base condition	$31/MWh
C_{so}	Levelized Cost of Energy for Solar	$37.6/MWh
C_{wo}	Levelized Cost of Energy for wind	$36.6/MWh
μ_{A0}	Absorber Efficiency Penalty	2%
μ_{D0}	Stripper Efficiency Penalty	4%
μ_{c0}	Compression Efficiency Penalty	2%
η_{pv}	photoelectric conversion efficiency	100%
η_{pc}	power conditioning efficiency	12.5%
$T_{c,ref}$	cell reference temperature	25 °C
$NOCT$	Nominal Operating temperature	44 °C
β	generator efficiency temperature coefficient	0.005/°C
ρ	air density	1.25 kg/m^3
r	radius of turbine blades	45 m

η_{eff}	Efficiency of conversion to wind energy	45%
V_{min}	wind turbine cut-in speed	4 m/s
V_{max}	wind turbine cut-out speed	25 m/s
$\pi_{G,t}^{S}$	price of electricity in the spot market	

CHAPTER IV

RESULTS AND DISCUSSION

Hourly power schedules and capture system schedule have been generated. The rates for absorption and desorption are also shown. The power generation schedule optimizes the energy production, selling as much power to the grid, during periods of high demand. In those periods, the capture power runs at minimum load, depending on the storage tank level. The flue gas from electricity generated is stored in the tanks till the electricity demand is lower and more favorable. The work optimizes a hybrid power plant and describes the operational schedule.

4.1 Daily Profit

The profit for the day yields \$213,695. The breakdown of the profit is shown in Table 4.1. The contract revenue \$372,240 is made by selling 7200 MWh of electrical energy at \$51.7/MWh. The spot revenue generates \$332,680 by selling 7035 MWh of energy, yielding an average price of \$47.3/MWh. In this case, the revenue from bilateral contract yielded more money for the plant. The power agreed during bilateral contract is a critical factor in establishing profitability. The power agreement from the bilateral contract has to be critically evaluated, to ensure the power plant can achieve maximum flexibility. In a 600 MW power plant with flexible carbon capture, for a fixed price profile as shown, the optimization shows that the maximum contract power to yield daily maximum profit is 375 MW.

Table 4.1 Profit components for the 24-hour period

Profit component	Value
Contract revenue	372,240.000
Spot revenue	332,680.490
Carbon market revenue	7,157.056
Coal generation costs	359,443.865
Storage costs	35,147.327
Solar generation cost	33,015.254
Wind generation cost	70,775.911
Total Daily Profit	**213,695.189**

For bilateral contracts higher than this value, the optimizer is unable to solve the model for maximum profitability, suggesting that the power generated to meet the bilateral contract during periods of high electricity prices takes away the flexibility of the system. Bilateral contracts are normally signed to hedge against the risk of low electricity spot prices but due to limited knowledge and accuracy of the electricity prices, the bilateral contract is a major determinant of the profitability of the power plant. In time periods of high prices, the demand for electricity is high, hence, the power plant can attain greater profitability by selling in the spot market. By agreeing to meet the electricity demand for a high electricity demand, such as 400MW, the plant cannot take advantage of the price spikes in the spot market due to limited generation capacity.

4.2 Power Generation

The total generation across the day is 14235 MWH, with the coal power plant generating about 80%, wind generating 13.6%, and solar generating 6.4% of the daily power generation. The hourly average of generated power for the hybrid power plant is 593 MW.

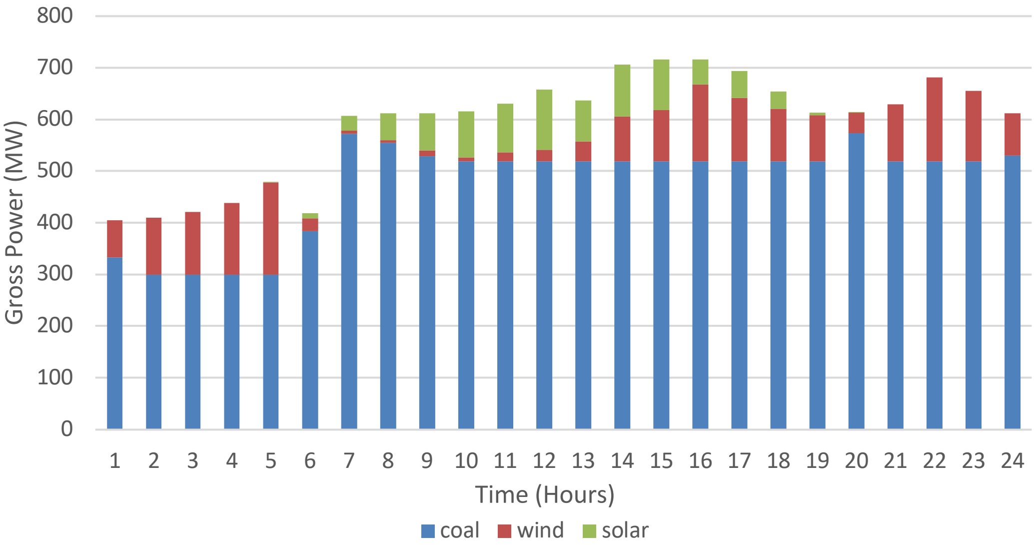


Figure 4.1 Gross Power hourly schedule

The hourly power generation is shown in Figure 4.1. As expected, in the first 5 hours and last 5 hours, the power contribution is zero, due to the unavailability of solar radiation. The solar plant generates the maximum energy between the hours 11 and 12, when the solar radiation is strongest. Wind power production also follows the air velocity profile showing the highest power produced when the wind speed is highest. To complement these renewable sources, the coal-fired plant makes up for the power when the resources are unavailable or cannot meet the demand. The results demonstrate that presently, fossil-fuels provide some guarantee for energy security. The coal-fired power plant also has the ability to ramp up as quickly as possible, as seen in hours 6 to 7, based on the price of electricity in the spot market. In this scenario, the coal-fired plant has greater operational flexibility due to the bilateral contact. Assuming a bilateral contract requiring the plant to generate 400MW, the coal-fired power plant would have generated more power to make up for the power required for carbon capture in the first four hours.

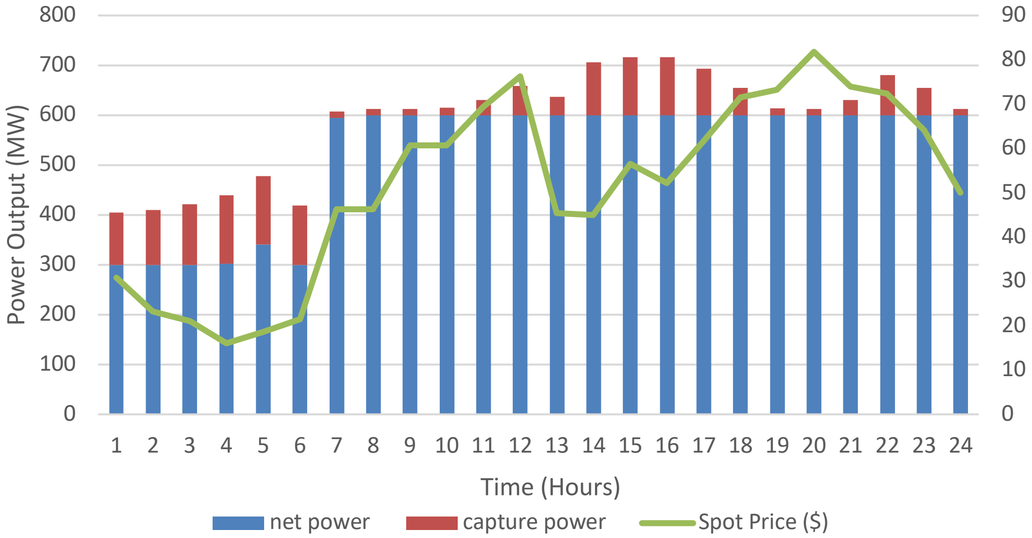


Figure 4.2 Net Power Hourly Schedule

Due to the low electricity prices, the capture plant would have operated in this period, but it would have resulted in more capture costs. The curve shows the hourly electricity price, and in periods of high prices, very little capture is done to maximize revenue and in periods of low demand, the stored flue gas can be processed in the capture plant (Figure 4.2).

In hours 13-16, the capture plant runs due to the two price spikes at hour 12 and hour 20. The result shows that at the highest prices, the capture plant is not operated. Due to the minimal operation of the capture plant between hours 7 and 12, the capture plant is forced to operate between 13 and 16, to allow the plant to take advantage of the price spike in hour 20. In a bid to maximize profit, the cost of carbon capture is minimized during hours of high electricity spot price as shown in Figure 4.2. The optimization yields a land area of 1 km^2 for the solar panels and 150 turbines.

The capture system utilizes about 11.2% of the total energy. During periods of low electricity prices such as hours 1-6, the capture system operates and utilizes a significant portion of power for desorption. During periods of high electricity demands such as hour 20, the capture plant does not run, to allow for maximum profit achieved by electricity sale during such times.

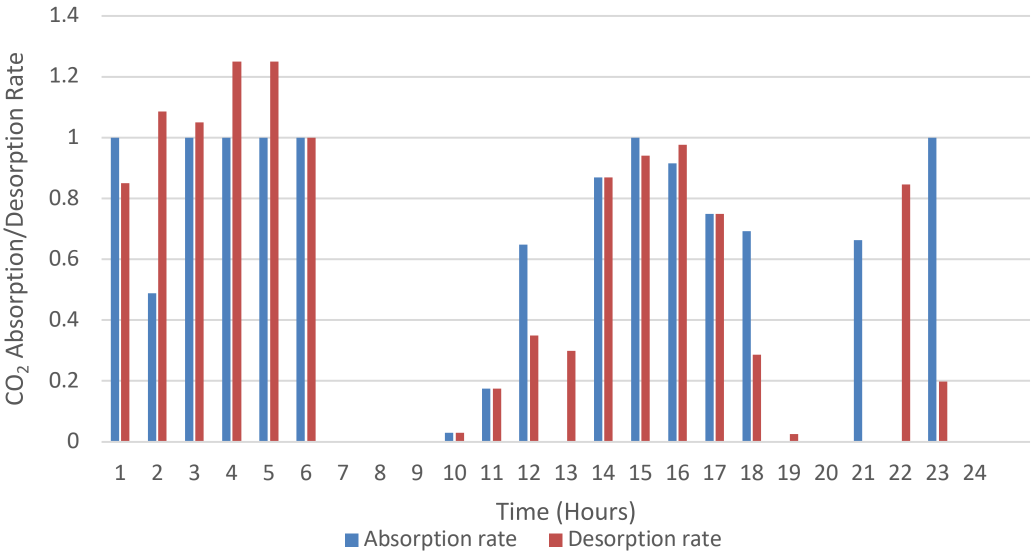


Figure 4.3 Absorption/Desorption rates of the carbon capture system

The power generated by the renewable sources is dependent on the resource availability and the installed area. In periods where high electricity demand match renewable resource availability, the coal power plant would be required to generate less, resulting in less flue gas to be captured.

Figure 4.3 shows the capture facility absorption and desorption rates. These rates also follow the pattern, indicating low rates of absorption and desorption during periods with high electricity prices and increased treatment when the prices were low. The lowest electricity prices are seen in the first five hours, where the most carbon capture was done. During the other time periods in the day, the capture plant adjusts absorption or desorption to relative to the prices of electricity and the tank volumes. Although the price of electricity is high in period 21, the absorption process is operated to meet the constraint that ensures the tank is half-filled at the end of the day. The average hourly power generated from the coal-fired power plant is 476 MW, hence, the energy required for capture is also less, compared to a coal-fired plant of similar total capacity of the hybrid plant, due to the integration of renewable energy sources, which do not produce emissions and make up for the power generation.

The total amount of solvent in the tanks are shown in Figure 4.4 which shows solvent storage across each hour. In time periods prior to periods with high prices, the rich solvent tank remains empty, to enable the rich solvent to be stored in periods where the prices are high. For example, in Figure 4.4, during period 12 with a price peak, rich solvent is stored in the tank, avoiding the desorption process from running because of the energy intensity of the process. As the electricity price dropped after this point, the rich solvent tank is kept empty, until the price starts to approach another peak in period 18.

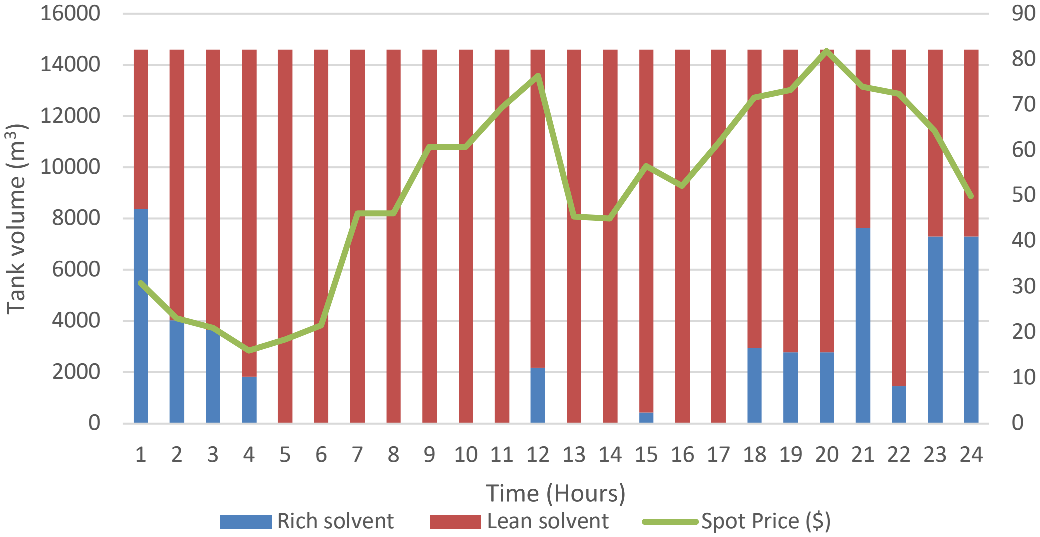


Figure 4.4 Hourly volumes contained in tanks

In periods of high prices like hour 12 and 18, the capture plant absorbs at a faster rate than it desorps, varying the level in the tanks. This ability to absorb flue gas and store it, also correlates with times when the prices are high. The desorption stage is not operated in that period to avoid the energy penalty associated with it.

This case shows that renewable energy sources provide greater flexibility for a carbon capture system, while increasing the daily profit. The major factors affecting the schedules generated are the location involved, the resource availability at the location, the electricity spot price, and the Levelized Cost of Electricity for each of the renewable sources.

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Carbon capture holds potential to reduce emissions from power plants but the energy intensity is significant. Previous work suggested having renewable sources like solar and wind to solely power the capture system. In scenarios with little or no capture requirements and abundant renewable energy power, there would result a mismatch. In other scenarios of great capture energy requirement and insufficient renewable energy, the coal-fired plant would be charged with generating the power required for the capture facility, realizing more emissions. In a bid to fill this gap, this research proposes a hybrid energy-powered carbon capture plant.

By creating a hybrid plant, made up of renewable sources and fossil fuel sources, risks associated with individual renewable power plants are mitigated and environmental emissions with fossil fuel plants are reduced. More importantly, flexible carbon capture allows the plant to store flue gas for treatment when the prices are low. In addition to solvent storage, the diversity of energy generation sources provides options about which source to use for the capture system.

In this research, a deterministic approach to optimally operating a carbon capture plant is taken. A profit maximization model is proposed to consider the revenue from the spot market and the bilateral contracts, as well as the associated costs with generation and the levelized cost of the renewable energy technologies. Characteristic air velocities and solar radiation is taken to generate the power generated by the renewable energy sources. The wind energy produced more energy due to the capacity factor. The renewable energy sources also reduced the average hourly power generation by coal, reducing the emissions from the plant. The optimal operation scheduling shows that the capture plant should be run when electricity spot prices are low. It also indicates that a key consideration should be the bilateral power contract, and that for power plants to have greater flexibility with carbon capture, the bilateral power contract must not exceed 375MW. The case suggests that the hybrid system can increase operating profits by up to 14% compared to a coal-fired plant with carbon capture. Critical factors for profit maximization include the location and the available renewable resources, the electricity spot price and the power to meet the bilateral contract.

5.2 Recommendations for Future Work

In a bid to explore other means to drive carbon capture plants to commercial levels, renewable energy sources can be very useful. In this work, characteristic profiles have been used for the wind energy, solar energy and spot prices. There is some uncertainty surrounding the knowledge of these factors and an evaluation of the uncertainty would allow for better planning in day-ahead markets. While renewable energy sources could be integrated, there are some uncertainties around resource availability.

Future work can be focused on:

i) uncertainty of renewable energy resources and the effect on a hybrid plant with carbon capture. A lot of research has been conducted around the uncertainty of electricity spot prices but not much work has been done on the uncertainty of renewable energy resources and development of operation strategies around these uncertainties.

ii) incorporation of storage for renewable energy sources. This would allow for energy storage such as batteries when the power generated from the hybrid system is greater than the transmission capacity or in scenarios where it is more profitable to store energy and sell at a later time, where the demand is higher. Design of renewable energy systems in hybrid configuration for carbon capture.

This research set upper limits on the capacities for renewable energy systems. The optimal sizes of renewable energy systems incorporated with a coal and carbon capture plant should be studied. Optimal sizing of renewable energy systems would depend on the resource availability at said location. In particular, average wind speeds and solar radiation could help in determining the right sizing at different locations.

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APPENDIX A

NOMENCLATURE

PM	Profit Maximization
CR	Cost Reduction
CP	Contract Pricing
SMP	Spot Market Pricing
SCC	Sale of Carbon Credit
CC	Capital Cost
SSC	Startup/Shutdown Cost
GC	Generation Cost
CCC	Carbon Capture Cost
FC	Flaring Cost
CST	Carbon Storage & Transport