A Linear Optimization Model for Reducing CO_2 Emission from Power Plants

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Abstract

The adverse impact of climate change is possibly decreased by reducing the anthropogenic carbon dioxide in the atmosphere. As the coal-fired power plant is the primary source of anthropogenic carbon dioxide generation, our research work focuses on the maximization of capturing of released carbon dioxide from the power plant. This paper proposes capturing carbon dioxide by considering decisions regarding clean technology such as carbon capture technology by linear optimization model. This paper's other contribution is to solve the optimization problem considering the loss of energy due to the implementation of the clean technology, which is compensated by incorporating the coal-fired compensatory plant. With the introduction of compensatory plants, the model becomes nonlinear, which is managed by auxiliary equations. It is observed from analysis results that the proposed model is 35.62% more effective to capture carbon dioxide from the coal-fired power plants of Orissa state in India due to the optimal selection of clean technology. These research works provide one of the paths in reducing the risk of exceeding a global temperature increase of 2 ^{0}C compare to the preindustrial period in the context of sustainable operations.

Keywords
Climate change, Coal-fired power plants, Clean technology, Carbon Capture, Sustainability.

1. Introduction

The warming of the earth's atmosphere due to the release of greenhouse gases (GHGs) accelerates climatic change. According to the synthesis report (Albritton & Dokken 2001), the witness of climate change is by a remarkable variation in change in weather events and a rise in earth's global mean surface temperature over a long period. The other elements that demonstrate that climate is changing are thinning sea ice, a decrease in snow cover leading to increased global mean sea level, frequent and intense El-Nino events, and unpredictable extension of seasons. The natural and human fingerprint of greenhouse gases (GHGs) ascribes the temperature rise. However, the natural greenhouse effect makes life easier on the earth, but the anthropogenic greenhouse gases (CO_2, CH_4, NO_X) act as catalysts and accelerate climate change. The uncontrollable increase in GHGs concentration level will enhance the greenhouse effect and lead to global warming (Houghton et al. 1990; Mitchell et al. 1990).

Among different GHGs, carbon dioxide is the most prominent GHGs enhancing the greenhouse effect much faster due to its long-lived characteristics. The inefficiency in the absorption of CO_2 further enhances an imbalance in the carbon cycle. A Swedish scientist Svante Arrhenius in 1895 has established a relationship between the increase in CO_2 concentration and the rise in the earth's temperature (Arrhenius 1896). According to the paper of Rodhe, Arrhenius explains that if the concentration of CO_2 doubles, then this conduces to increase in temperature around 5 ^{0}C to 6 ^{0}C (Rodhe et al. 1997). The first assessment report of IPCC (Houghton et al. 1990) elaborates the relationship further, where researchers create the four scenarios. The four scenarios help to study the impact of the rise in the CO_2 concentration on the earth's temperature. The first scenario refers to the business-as-usual scenario, where the researcher made no effort to reduce emissions. The doubling of the CO_2 concentration in the first scenario will occur by 2025. The extra CO_2 in the atmosphere led to an increase in temperature rate by around 0.3 ^{0}C per decade compared to the preindustrial period. Subsequently, the other scenarios deal with the control of the emission of CO_2 in the atmosphere. The simulated results of these scenarios indicated that the maximum doubling of the CO_2 concentration would happen in the year 2050, and the maximum rise in temperature at the rate of 0.1 ^{0}C per decade compared to the pre-industrial period.

If carbon emissions do not get controlled, billions of people will be exposed to the heatwave every year. If the effect continues further, millions of people would be affected by river flooding and increased water stress. Even a million square kilometer cropland does not remain viable for agriculture every year (Wise et al. 2014). The anthropogenic emission of CO_2 is originated from around 7500 sources (Metz et al. 2005), which when cluster shows that 60% of total CO_2 emissions occur by the industrial sector. The dominating activities in these sectors are the generation of power by the burning of fossil fuels. Thus, the power generated by a coal-fired power plant contributes to an increase in the CO_2 concentration in the atmosphere. In the natural carbon cycle, the CO_2 emitted is absorbed by the ocean or forest. Continuous deforestation leads to the creation of void, which has also played a significant part in increasing CO_2 levels in the atmosphere. From the pre-industrial period to the current era, the uncontrollable emission of CO_2 creates one of the biggest challenges to the environment. The management of energy is the art and science of the optimum utilization of energy, which reduces the cost, reduces the emission of carbon, and reduces the risk (Johnson 2010). To solve climate change issues, increasing earth temperature, clean technology such as Carbon capture and storage (CCS) is a viable approach for reducing carbon emission from the atmosphere (Ashworth et al. 2014). Therefore, the paper aims to decide the effective clean technology in the power sector to minimize the CO_2 emission rate elaborated in the following subsection.

1.1 Objective

The research objective is to select a CCS clean technology in the coal-fired power plant to reduce the emission release rate using an optimization model. The formulation of the mathematical model is linear, which provides a unique and global optimal solution. The model framework also includes emission release from the compensatory power plant, which is used to compensate for the loss of power generation by implementing carbon capture (CC) technology. Coal-fired compensatory power plants operate at the supercritical condition and emit less emission compared to other coal-fired plants. The model framework also incorporates the option of selection of CC technology in the compensatory power plants.

Section 2 elaborates the literature supporting clean technology CCS and its application. Section 3 talks about the methodology with the mathematical formulation. Subsection 3.1 validates the methods with case studies of Odisha, which is situated in the eastern region of India. Section 4 discusses the result of mathematical optimization. Finally, the conclusion of the research article is mentioned in section 5.

2. Literature Review

CCS is defined as the "process of capturing the carbon dioxide from stationary sources such as power plants, cement industry, steel industry, or any other energy-related sources and then transport it to the storage location to remove the carbon from the atmosphere." (Mathieu 2006). CCS helps to contribute to mitigating climate change. It involves three stages, namely, capture, transport, and storage. The capture of carbon is feasible from the abundant point sources rather than mobile or small point sources. The capture of CO_2 can be done by post-combustion, pre-combustion, and oxyfuel combustion (Gibbins and Chalmers 2008). However, the post-combustion carbon capture technology for the retrofitting of the power plant is more popular. In the post-combustion process, the coal and air react in the power plant, which generates CO_2 and other gases. The gases then pass through the equipment (amine, ammonia, membrane), which separate most of CO_2 and other pollutants from the flue gases before entering the atmosphere (Wang et al. 2011) and is shown in **Figure 1**. The literature scrutinized various carbon capture post-combustion technology used to retrofit power plants, such as amine system, ammonia system, and membrane system. However, in an amine system, MEA (Monoethanolamine) is bargainous and has more absorptive power than compare to other amine-based solvents DEA (Diethanolamine), MDEA (N-methyl diethanolamine) (Ullah et al. 2019).

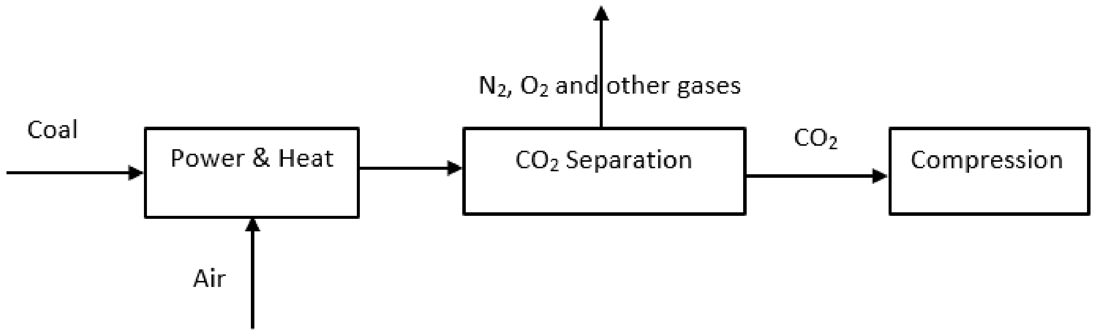

Figure 1 Post combustion process

The implementation of capture technology in power plants, the supporting literature describes the mixed integer nonlinear optimization approach used in Kumari and Bera paper (2020). However, pinch analysis, AHP method is used to support the usability of CCS in the power industry (Tan et al. 2013; Ooi et al. 2013). The integrated CCS with a biomass power plant reduces carbon emission, and this integrated plant is called BioCCS (Pang et al. 2017). The study tries to analyze the benefit of carbon reduction and the cost of installing CCS environmental performance to the power plant. Arnette (2017) developed a model and compared the CCS with renewable energy to achieve maximum GHG reduction. Santibanez-Gonzalez (2017) used a stochastic model to compare carbon pricing versus CCS. Agrali et al. (2018) studied the coal-fired power plants in Turkey and use a mixed integer programming method to decide the capacity of capture units. According to the literature, the defined unique and optimal conclusive decision by nonlinear approach is challenging to achieve. Therefore, in the next section, we discuss the linear mathematical formulation.

3. Methodology

3.1 Mathematical Formulation

In the present section, the formulation of the optimization model is elaborated. The ultimate objective is to maximize the amount of CO_2 emission captured from the power plant and compensatory power plant and as discussed in Eq (1). The indices defined in the model are $i = 1, 2, \ldots, n$; $j = 1. 2, \ldots, t$; $k = 1, 2, \ldots, m$ corresponding to power plants, CC technologies and compensatory power plants. Initially, when no CC technology is selected in any of the i[th] power plant ($\alpha_{ij} = 0$) then there is no capture of CO_2 take place, and thus no electricity is required from any of the k[th] compensatory plants. The first term of Eq (1) delineates the decision for selection of j[th] CC technology in the i[th] power plants, which will capture the amount of CO_2 by $E_iF_iR_j$. The E_iF_i is the amount of emission generated by producing E_i amount of electricity in the power plant. The capture ratio as R_j reduces the emission generated by capturing the amount of CO_2. The second term in Eq (1) describes the amount of capture of CO_2 when CC technology is selected in the k[th] compensatory plant. The nomenclature of the parameter is mentioned in **Table 1**.

Table 1. List of Symbols, description of Parameter, Variables and Abbreviation

Indices	**Description**
i	The coal-fired power plant (i=1,2,3…, n)
j	The carbon capture technology (j=1,2,3…, t)
k	The compensatory power plant (k=1,2,3…, m)
Decision Variables	
α_{ij}	A binary variable for selecting j[th] technology in i[th] power plant α_{ij} = 1 indicates CC technology = 0 indicates no CC technology
α_{kj}	A binary variable for selecting j[th] technology in k[th] compensatory power plant α_{kj} = 1 indicates CC technology = 0 indicates no CC technology
β_k	Electricity generated by the k[th] compensatory plant

β_{kj}	Electricity is generated by the kth compensatory plant when jth CC technology is selected.
Parameters	
E_i	Electricity generated in the power plant *i* (MW)
F_i	The emission factor of the ith coal-fired of power plant (t CO_2/h)
F_k	The emission factor of the kth compensatory power plant (t CO_2/h)
R_j	Capture ratio of jth CC technology (dimensionless)
L_j	The relative loss factor of electricity by jth CC technology (dimensionless)
FLC	The full load capacity of the compensatory plant (MW)
c_k	The relative cost factor of electricity generated from the kth compensatory plant with respect to the base cost. (dimensionless)
c_j	The relative cost factor of selecting jth CC technology in the power plant with respect to the base cost. (dimensionless)
c	The relative cost factor of the overall cost of electricity with respect to the base cost. (dimensionless)
Abbreviation	
GHGs	Greenhouse gases
CO_2	Carbon dioxide
CCS	Carbon capture and storage
CC	Carbon capture
MILP	Mixed-integer linear programming
Units	
MW	Megawatt
H	Hours
t CO_2	Tons of carbon dioxide

Eq (2) describes the cost constraint that limits CC technology selection in the power plant. The cost constraint helps maintain the trade-off between emission release and overall electricity cost (c). The cost factor c_j indicates the cost of the selection of jth CC technology in the power plants. The loss of electricity in selecting jth CC technology in the ith power plant is maintained by producing electricity by compensatory plant with the cost factor of c_k. However, the compensatory plant's loss of power due to jth CC technology usage is maintained by producing extra electricity in the compensatory plant itself. Eq (3) indicates the demand constraint, which balances the supply of net electricity generated with or without CC technology. Eq (4) and Eq (5) suggest that only one CC technology is selected in a power plant. Eq (6) to Eq (8) describes an auxiliary equation that converts the non-linear formulation to linear formulation to provide a unique and optimal solution by considering generating electricity from the compensatory plant. When $\alpha_{ij} = 1$ and $\alpha_{kj} = 1$ the electricity generated from the compensatory plant (β_k) and electricity generated from the compensatory plant using CC technology (β_{kj}) is equal, otherwise in all other scenarios $\beta_{kj} = 0.$ Eq (9) and Eq (10) indicates the binary nature of α_{ij} and α_{kj} respectively. Eq (11) and Eq (12) bound the electricity generation in the FLC's compensatory plant.

Objective Function:

$$\text{Max}\, z = \sum_{i=1}^{n} E_i F_i \left(\sum_{j=1}^{t} \alpha_{ij} R_j \right) + \sum_{k=1}^{m} \left[\sum_{j=1}^{t} \beta_{kj} F_k R_j \right] \tag{1}$$

Constraints:

$$\sum_{i=1}^{n} E_i \left(1 - \sum_{j=1}^{t} \alpha_{ij} + \sum_{j=1}^{t} \alpha_{ij} c_j (1 - L_j) \right) + \sum_{k=1}^{m} \left(c_k \beta_k + \sum_{j=1}^{t} (c_j - 1) \beta_{kj} \right) \leq c \sum_{i=1}^{n} E_i \tag{2}$$

$$\sum_{i=1}^{n} E_i \left(1 - \sum_{j=1}^{t} L_j \alpha_{ij} \right) + \sum_{k=1}^{m} \left(\beta_k - \sum_{j=1}^{t} L_j \beta_{kj} \right) \geq \sum_{i=1}^{n} E_i \tag{3}$$

$$\sum_{j=1}^{t} \alpha_{ij} \leq 1 \qquad \forall i \in \{1,2,3,\dots,n\} \tag{4}$$

$$\sum_{j=1}^{t} \alpha_{kj} \leq 1 \qquad \forall k \in \{1,2,3,\dots,m\} \tag{5}$$

$$\beta_{kj} \leq \beta_k \qquad \forall j \in \{1,2,3,\dots,t\} \text{ and } \forall k \in \{1,2,3,\dots,m\} \tag{6}$$

$$\beta_{kj} \geq \beta_k - FLC(1-\alpha_{kj}) \qquad \forall j \in \{1,2,3,\dots,t\} \text{ and } \forall k \in \{1,2,3,\dots,m\} \tag{7}$$

$$\beta_{kj} \leq FLC\ \alpha_{kj} \qquad \forall j \in \{1,2,3,\dots,t\} \text{ and } \forall k \in \{1,2,3,\dots,m\} \tag{8}$$

$$\alpha_{ij} \in \{0,1\} \qquad \forall j \in \{1,2,3,\dots,t\} \text{ and } \forall i \in \{1,2,3,\dots,n\} \tag{9}$$

$$\alpha_{kj} \in \{0,1\} \qquad \forall j \in \{1,2,3,\dots,t\} \text{ and } k \in \{1,2,3,\dots,m\} \tag{10}$$

$$0 \leq \beta_k \leq FLC \qquad \forall k \in \{1,2,3,\dots,m\} \tag{11}$$

$$0 \leq \beta_{kj} \leq FLC \qquad \forall j \in \{1,2,3,\dots,t\} \text{ and } \forall k \in \{1,2,3,\dots,m\} \tag{12}$$

3.2 Case studies

In India, Odisha is one of the coastal states located in the eastern region. The location of Odisha state is at the head of the Bay of Bengal. Due to this geographical configuration of the state, the water body's slight changes create a massive impact in the region due to climatic disasters. With the high humidity and the temperature with short and mild winters Odisha is more vulnerable to the cyclone, coastal erosion, flood and drought which causes more than 30,000 (Mishra 2017) lives of the people in the state. The recent Amphan cyclone caused due to the high sea temperature of the Bay of Bengal occurs in May 2020, which creates massive destruction in the Odisha state. The actual reason behind the climatic chaos due to the CO_2 emission release. In Odisha, there are seven coal-fired power plants, namely Derang thermal power plant (TPP), IB Valley TPP, Utkal TPP, Kamalanga TPP, Sterlite TPP, Talcher Old, and new TPP. The electricity generation capacity and the net emission release in the atmosphere from the respective power plant are mentioned in Table 2. Due to the high capacity of Talcher's new TPP, the emission release is also the highest of 2880 tCO_2/h. The data of electricity generation and emission factors has been taken from the central electricity authority of India. The coal-fired power plant's total electricity generation capacity to meet the electricity demand of Odisha state consumers is 10550 MW. For generating 10550 MW of electricity, the net emission release is 11233.6 tCO_2/h and is mentioned in Table 2.

Table 2. List of Power Plants in Odisha State in India

S.No	Power plants (i)	E_i (MW)	F_i (tCO_2/MWh)	E_iF_i (tCO_2/h)
1	DERANG TPP	1200	0.94	1128
2	IB VALLEY TPP	1740	1.05	1827
3	UTKAL TPP	700	0.9	630
4	KAMALANGA TPP	1050	1.04	1092
5	STERLITE TPP	2400	1.3	3120
6	TALCHER (OLD) TPP	460	1.21	556.6
7	TALCHER (New) TPP	3000	0.96	2880
Total		**10550**		**11233.6**

The three-post combustion CC technology has been selected to control the emission release and utilize the released CO2 emission, namely CC_1, CC_2, and CC_3. The capture ratio of CO_2 emission of these three CC technologies has 95%, 85%, and 80%, with having loss of electricity by 30%, 16% and 10%, respectively. The relative cost factor of CC_1, CC_2, and CC_3 technology are 2.01, 1.93, and 1.90. One of the factors for selecting these technology depends on the relative overall cost of electricity. Thus, the overall cost of electricity is 30% which means 1.30 is the relative overall cost of electricity, and this technology is selected on the power plant within the range of 30% increase. The two coal-fired compensatory plants are selected with a full load capacity of 660 MW. The emission factor of the coal-fired compensatory power plant is 0.7 tCO_2/MWh. The factor of cost of producing loss of electricity from the coal-fired compensatory plant is 1.7.

4. Result

The above mathematical formulation results are presented in this section with consideration of data from the case study. In Odisha, considering three post-combustion CC technology, Kamalanga TPP, and Sterlite TPP are retrofitted and captured 1037.4 tCO_2/h and 2964 tCO_2/h amount of CO_2. Initially, Kamalanga TPP releases 1092 tCO_2/h (mentioned in **Table 2**), but after retrofitting, the CO_2 emission decreases to 54.6 tCO_2/h. Similarly, Sterlite TPP initially releases 3120 tCO_2/h (shown in Table 2), retrofitted by CC_1 technology releases 156 tCO_2/h. Both the power plant is retrofitted by CC_1 technology. Two compensatory plants balance the loss of 1035 MW of electricity. One of the compensatory produces electricity at its full load capacity, which is 660 MW. The other compensatory plant generates 375 MW of electricity. Thus, the net capture of CO_2 emission is 4001.4 tCO_2/h which has a 35.62% capture rate compare to the initial emission release by the coal-fired power plant in Odisha state. The total incurred overall cost of electricity increases to 30%, where each retrofitted plant contributes a 101% increase in cost and each compensatory plant incur a 70% increase in cost. None of the compensatory plants gets equipped with CC technology, as mentioned in Table 3. However, this may occur when the limitation of increase in the overall cost of electricity will be more than 30%.

Table 3. MILP result of Odisha State.

S. no	*Power plants (i)*	*E_i (MW)*	*CC technology*	*Emission captured (tCO_2/h)*	*Loss of electricity (MW)*	*Increase in cost (%)*
1	DERANG TPP	1200	-	0	0	
2	IB VALLEY TPP	1740	-	0	0	
3	UTKAL TPP	700	-	0	0	
4	KAMALANGA TPP	1050	CC_1	1037.4	315	101%
5	STERLITE TPP	2400	CC_1	2964	720	101%
6	TALCHER (OLD) TPP	460	-	0	0	
7	TALCHER (New) TPP	3000	-	0	0	
S.no	***Compensatory Power plants (k)***	***β_k (MW)***	***CC Technology***	***Emission captured***	***Loss of electricity***	***Increase in cost***
1	CP_1	660	-	-	-	70%
2	CP_2	375	-	-	-	70%
Total				**4001.4**	**1035**	**30%**

5. Conclusion

The information provided in the above study concludes that CC technology must be developed to become effective in terms of cost. However, CC technology is a viable and clean technology to mitigate the problem of climate change. Long-term and more stable storage facilities must be developed. An interdisciplinary approach must be taken to tackle CCS issues like technological aspects, economic factors, timing issues, carbon cycle dynamics, and unstable and uncertain sustainability. It had to be widely accepted that government incentives are needed, and other stakeholders must support the power plant firm. Government incentives can provide incentives in many ways like giving tax incentives, provide funds at a cheaper rate for installation, provide funds for research and development of advancement in CCS to reduce its cost, and increase operational efficiency and lower energy requirement. Further, CCS technology's validity in different manufacturing sectors helps in sustainable energy management and reduces overall CO_2 emission in the atmosphere.

References

Albritton, D. L., & Dokken, D. J. (2001). Climate change 2001: synthesis report (p. 398). R. T. Watson (Ed.). Cambridge, UK: Cambridge University Press.

Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (1990). Climate change: the IPCC scientific assessment. American Scientist;(United States), 80(6).

Mitchell, J. F. B., Manabe, S., Meleshko, V., & Tokioka, T. (1990). Equilibrium climate change and its implications for the future. Climate change: The IPCC scientific assessment, 131, 172.

Arrhenius, S. (1896). XXXI. On the influence of carbonic acid in the air upon the temperature of the ground. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 41(251), 237-276.*

Rodhe, H., Charlson, R., & Crawford, E. (1997). Svante Arrhenius and the greenhouse effect. *Ambio, 2-5.*

Wise, M., Dooley, J., Luckow, P., Calvin, K., & Kyle, P. (2014). Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century. *Applied Energy, 114, 763-773.*

Metz, B., Davidson, O., & De Coninck, H. (Eds.). (2005). Carbon dioxide capture and storage: special report of the intergovernmental panel on climate change. *Cambridge University Press.*

Johnson, Timothy Lawrence. (2010). "Energy Models." *Encyclopedia of Geography. SAGE Publications*

Ashworth, P., Boughe, N., Mayhe, M., & Milla, F. (2010). From research to action: Now, we have to move on CCS communication*. International Journal of Greenhouse Gas Control, 4, 426–433*

Mathieu, P. (2006). The IPCC special report on carbon dioxide capture and storage. *In ECOS 2006 - Proceedings of the 19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (pp. 1611–1618). National Technical University of Athens.*

Kumari, S., & Bera, S. (2020, December). An Analysis of Decision to Retrofit Coal Based Power Plant with Carbon Capture Technology Having Uncertain Parameters. In *2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 215-219). IEEE.

Ullah, A., Soomro, M. I., & Kim, W. S. (2019). Ammonia-based CO2 capture parameters optimization and analysis of lean and rich vapor compression processes*. Separation and Purification Technology, 217, 8-16.*

Ooi, R. E., Foo, D. C., Ng, D. K., & Tan, R. R. (2013). Planning of carbon capture and storage with pinch analysis techniques. *Chemical Engineering Research and Design*, *91*(12), 2721-2731.

Tan, R. R., & Promentilla, M. A. B. (2013). A methodology for augmenting sparse pairwise comparison matrices in AHP: applications to energy systems. *Clean Technologies and Environmental Policy*, *15*(4), 713-719.

Pang, M., Zhang, L., Liang, S., Liu, G., Wang, C., Hao, Y., … Xu, M. (2017). Trade-off between carbon reduction benefits and ecological costs of biomass-based power plants with carbon capture and storage (CCS) in China. *Journal of Cleaner Production, 144, 279–286.*

Arnette, A.N. (2017). Renewable energy and carbon capture and sequestration for a reduced carbon energy plan: an optimization model*. Renewable and Sustainable Energy Reviews, 70, 254–265.*

Santibanez-Gonzalez, E. D. (2017). A modeling approach that combines pricing policies with a carbon capture and storage supply chain network. *J. Clean. Prod.167, 1354–1369*

Ağralı, S., Üçtuğ, F. G., & Türkmen, B. A. (2018). An optimization model for carbon capture & storage/utilization vs. carbon trading: A case study of fossil-fired power plants in Turkey. *Journal of Environmental Management, 215, 305–315*

Wang, M., Lawal, A., Stephenson, P., Sidders, J., & Ramshaw, C. (2011). Post-combustion CO2 capture with chemical absorption: A state-of-the-art review. *Chemical engineering research and design*, *89*(9), 1609-1624.

Gibbins, J., & Chalmers, H. (2008). Carbon capture and storage. *Energy policy*, *36*(12), 4317-4322.

Biography

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