



HAL
open science

Higher efficiency and lower environmental impact of membrane separation for carbon dioxide capture in coal power plants

Yan Wang, Zhen Pan, Wenxiang Zhang, Shaochang Huang, Guojie Yu, Mohamad Reza Soltanian, Eric Lichtfouse, Zhien Zhang

► **To cite this version:**

Yan Wang, Zhen Pan, Wenxiang Zhang, Shaochang Huang, Guojie Yu, et al.. Higher efficiency and lower environmental impact of membrane separation for carbon dioxide capture in coal power plants. *Environmental Chemistry Letters*, 2023, 21, pp.1951 - 1958. 10.1007/s10311-023-01596-0 . hal-04528735

HAL Id: hal-04528735

<https://hal.science/hal-04528735>

Submitted on 2 Apr 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Public Domain

Higher efficiency and lower environmental impact of membrane separation for carbon dioxide capture in coal power plants

Yan Wang¹ · Zhen Pan¹ · Wenxiang Zhang² · Shaochang Huang¹ · Guojie Yu³ · Mohamad Reza Soltanian⁴ · Eric Lichtfouse⁵  · Zhien Zhang^{4,6} 

Abstract

Global warming may be slowed down by carbon capture and storage systems that allow to sequester carbon dioxide from large fixed point sources such as power plants or industrial facilities that use fossil fuels or biomass as fuel. Nonetheless, these processes often consume a lot of energy and materials, and they emit pollutants. In particular, monoethanolamine regeneration after carbon dioxide absorption is energy-intensive. Alternatively, membrane separation presumably consumes less energy than absorption, yet there is no reported quantitative comparison. Here we compared monoethanolamine absorption and two-stage membrane separation for carbon dioxide separation in a supercritical pulverized coal power plant, using life cycle assessment. We considered 13 midpoint impact categories including global warming, ozone depletion, freshwater eutrophication, marine eutrophication, terrestrial acidification, fossil resource depletion, water resource depletion, metal depletion, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity and particulate matter formation. Results show that membrane separation is 5% more efficient and requires 11.6% less energy than monoethanolamine absorption. Membrane separation has also lower environmental impact scores versus monoethanolamine absorption, such as 0.495 versus 0.546 for global warming, 0.219 versus 0.243 for human toxicity and 0.284 versus 0.318 for fossil depletion. Overall, the two-stage membrane separation should induce less damage to ecosystems, human health and resources.

Keywords Carbon capture and storage · Post-combustion capture · Chemical absorption · Membrane separation · Life cycle assessment · Environmental impacts

Introduction

With the continuous progress of industrialization, global warming and climate disruption are increasing due to greenhouse gas emissions of CO₂, in particular (Wei et al. 2020). Combustion power generation is the biggest emission driver. The Paris Agreement sets out a long-term temperature target

for efforts to limit temperature rise to no more than 1.5 °C above pre-industrial levels (Fawzy et al. 2020). This ambitious goal calls for achieving net zero emissions by 2050 (Tiruta-Barna 2021). In particular, CO₂ emissions related to electricity generation need to be reduced by 55% by 2030 to achieve a net zero emission by 2050 (Wang et al. 2022). Therefore, the decarbonization of the traditional

✉ Zhen Pan
zhenpan_fs@hotmail.com

✉ Zhien Zhang
zhienzhang@hotmail.com

Eric Lichtfouse
eric.lichtfouse@gmail.com

¹ College of Petroleum Engineering, Liaoning Petrochemical University, Fushun 113001, China

² Water Desalination and Reuse Research Center, King Abdullah University of Science and Technology, Thuwal 23955, Saudi Arabia

³ Chinese National Petroleum Corp Jilin Petroleum, Songyuan 138000, China

⁴ Department of Geosciences and Environmental Engineering, University of Cincinnati, Cincinnati, OH, USA

⁵ State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, Shaanxi, China

⁶ William G. Lowrie Department of Chemical and Biomolecular Engineering, The Ohio State University, Columbus, OH 43210, USA

power sector is critical to achieve this goal, and the smooth transition of the traditional power sector to net zero emissions relies heavily on the large-scale deployment of carbon capture and storage. Carbon capture and storage is energy-intensive and is often accompanied by the consumption of resources (Sharma and Dhir 2021). Additional fuel demand will also increase direct and indirect emissions. To reach 90% CO₂ capture rate and 95% CO₂ product flow purity, the ideal post-combustion capture process should show lower environmental impact and economic cost, which can be assessed by life cycle assessment (Goglio et al. 2020; Terlouw et al. 2021; Cruz et al. 2021).

Post-combustion capture is considered to be the most feasible way to capture CO₂ from existing pulverized power plants because of its end-of-pipe characteristics (Wang et al. 2017). In the past years, various post-combustion capture technologies for separating CO₂ from power plant flue gas have been developed and implemented, which can be divided into chemical absorption, membrane separation and solid adsorption processes according to different CO₂ separation principles (Raganati et al. 2021). According to the type of absorbent, the chemical absorption process is divided into alkanolamine absorption, ammonia absorption, dual alkali absorption, carbonate solution absorption and ionic liquid absorption (Chao et al. 2021). Among primary amines, monoethanolamine has the highest reaction rate. The concentration of available monoethanolamine solution is usually limited by viscosity and corrosiveness. The concentration of monoethanolamine solution used for CO₂ capture ranges from 20 to 60 wt%, and a typical value is 30 wt% (Matin and Flanagan 2022).

However, two challenges in the chemical absorption process are the high regeneration energy of solvents and solvent degradation. Compared with the traditional chemical absorption method based on monoethanolamine solution, the membrane separation process equipment is compact and modular, and the capture process does not consume chemicals and water, does not corrode the equipment and does not require additional energy for solvent regeneration (Khalilpour et al. 2015). Common polymer membrane materials for post-combustion capture include polyvinylidene fluoride, polyimide, polyvinylamine, polyphenylene ether, polysulfone, cellulose acetate and polyethylene oxide. Although there is no consumption of chemical solvents in the process of membrane separation, the production process of fossil-based polymers and toxic solvents related to the manufacture of membranes will also have additional environmental impacts. In addition, the process of improving the driving force of CO₂ will also consume a lot of energy, mainly for the power consumption of compressors and vacuum pumps. It is necessary to understand the environmental benefits of typical chemical absorption process and membrane separation process. Therefore, we studied the efficiency and

environmental impact of monoethanolamine absorption and polymer membrane separation in a supercritical pulverized coal power plant, by life cycle assessment.

Experimental

Processes

Figure 1 shows the process of monoethanolamine absorption and two-stage membrane separation. In the monoethanolamine scrubbing process, the flue gas after the pre-treatment process is usually cooled to between 40 and 80 °C (Clarens et al. 2016). The cooled flue gas enters the absorber from the bottom of the absorber and then moves upward along the absorber. Meanwhile, the monoethanolamine solution flowing down from the top of the absorber contacts with the flue gas countercurrent, and a reversible chemical reaction occurs to form carbamate and bicarbonate solution (Chao et al. 2021). The scrubbed flue gas was discharged from the top of the tower and emitted into the atmosphere after washing. The rich solvent from the bottom of the absorber is pumped to the heat exchanger where it is heated by the lean solvent from the stripper. The heated rich solvent is sent to the stripper and flows downwards from the top of the stripper to contact with the steam upward from the bottom of the stripper so that the CO₂ is desorbed from the solution. The desorbed gas enters the condenser through the top of the stripper and is condensed. The condensed gas is further settled to obtain a pure CO₂ product flow. The water obtained from condensation and settling is refluxed to the absorber.

The membrane separation process is a serial enricher circuits system, in which the permeate from the first-stage membrane is used as the feed of the second-stage membrane. The flue gas needs to be cooled before membrane separation. The compressor and vacuum pump arranged on the feed and permeation sides of the first- and second-stage membranes provide the necessary driving force for separation. In addition, an expander is used to recover the surplus energy of the retentate of the first-stage membrane.

Life cycle assessment

Life cycle assessment is a recognized decision support tool that considers all intermediate steps from raw material production to final disposal at the end of the product (Bicalho et al. 2017). It can quantify multiple environmental impacts simultaneously, providing the possibility for decision makers to trade-offs different life cycle environmental impacts. In this work, we use the software OpenLCA1.10.3 to model all stages of the life cycle of a supercritical pulverized coal power plant with integrated post-combustion capture technologies.

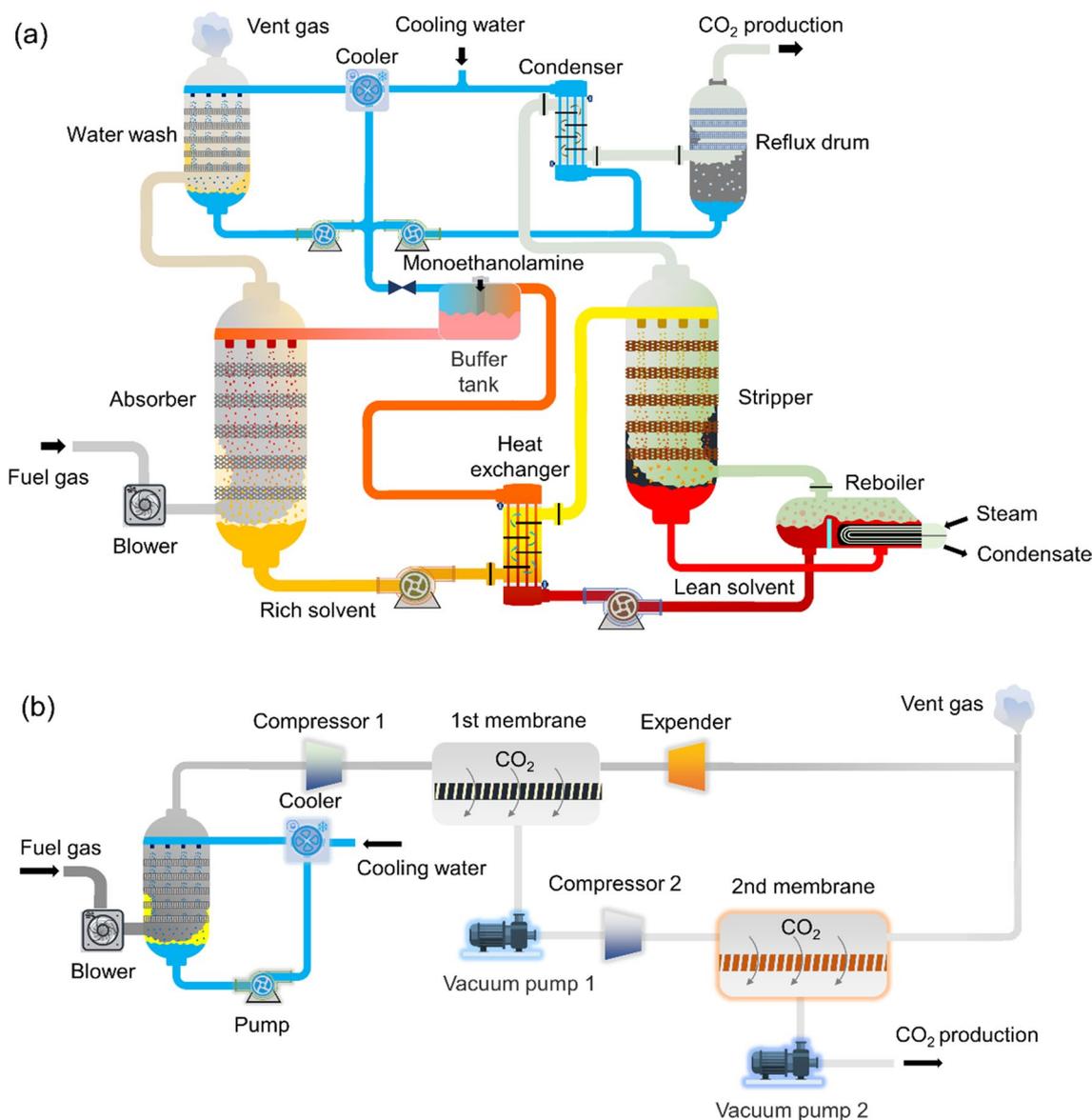


Fig. 1 Processes for post-combustion CO₂ capture: **a** the traditional monoethanolamine absorption process, and **b** two-stage membrane separation process. **a** The traditional chemical absorption process includes CO₂ absorption, desorption and solvent regeneration. **b** The

cooled flue gas is separated by a two-stage membrane to obtain high-purity CO₂. The compressor and vacuum pump provide the driving force for separation

Goal and definition

This work considers two post-combustion capture technologies based on a 500-MW supercritical pulverized coal power plant with a net efficiency of 43%: 1) chemical absorption process with 30wt% monoethanolamine and 2) polymeric separation process with hollow fiber membrane. According to reports available in the literature (Fadeyi et al. 2013), the capture system has been set to achieve a CO₂ capture rate of 90% and a CO₂ purity of 95%. Table S1 lists typical parameters of the supercritical

pulverized coal power plant. The purpose of the study is to quantify and assess the environmental impact at the power plant level and compare the midpoint and endpoint impact results under the two post-combustion capture technologies. Through sensitivity analysis, find out the process that has a great impact on the environment, and seek improvement measures. Provide better trade-offs for decision makers. It should be noted that this work does not consider the initial cost of the capture technologies. This work is based on the following assumptions:

1. The regeneration energy consumption of monoethanolamine is 3.1GJ/t CO₂.
2. NO_x in the flue gas consists of 95% NO and 5% NO₂.
3. Auxiliary power for plant equipment comes from the power market in China.
4. Only the steel consumption of the capture equipment is considered.
5. The transportation process in the life cycle of the power plant is ignored.

Functional unit

We focus on the environmental impact at the power plant level, rather than the entire carbon capture and storage chain, and the mix power grid will be responsible for the auxiliary power consumption of power plant equipment. Therefore, the functional unit is defined as the 1 kWh electricity generated by the power plant. This is different from the functional unit (the net power of 1 kWh or 1 MWh transmitted to the grid) defined by many related studies. There are also a few studies that use 1 t CO₂ captured as the functional unit, because the object of these studies is usually the entire carbon capture and storage chain that includes CO₂ compression, transportation and storage. And there is no need to consider system expansion or distribution since electricity is the only product of the system.

System boundary

Ideally, the system boundary of life cycle assessment study should include the whole life cycle from cradle to grave. But this tends to cover a large number of processes, making the whole system complex. Usually, researchers will consciously simplify the system according to the goal of the study, and in principle can directly ignore the process of environmental impact less than 1% (Wang et al. 2022). The carbon capture and storage system includes terminal system processes and intermediate unit processes, which are linked through different intermediate products (Nie et al. 2011). The focus of this work is the comparison of environmental performance between two different CO₂ capture processes, so only the life cycle environmental impact at the power plant level is considered, and the system boundary does not include the CO₂ transport and storage process, that is, life cycle assessment from cradle to gate. Moreover, subsequent power transmission and distribution are not considered. The system boundary of the supercritical pulverized coal power plant with integrated post-combustion capture is shown in Figure S1.

Inventory analysis

The data used in this work are divided into two parts: background and foreground data. The background data come

from the business life cycle inventory database Ecoinvent (version3.7.1). We use the allocation, cut-off by classification (i.e., cut-off) system model. In this system model, producer is fully responsible for wastes (polluter pays) that is a motivation to use recyclable products (Saunier et al. 2019). The foreground data mainly come from open data sets, related literature and professional research reports. The values of the collected foreground data have been adjusted according to the reference flow of each process.

The energy consumption of the monoethanolamine absorption process includes the heat needed for solvent regeneration and the power consumption of system auxiliary equipment. In the absorber, monoethanolamine will also react with substances other than CO₂ in the flue gas, resulting in the loss of part of monoethanolamine due to degradation. The degradation of monoethanolamine can occur through a variety of pathways, including oxidation, reaction with acidic gases, e.g., SO₂, NO_x, HCl and HF, and polymerization (Vega et al. 2014). Table S2 summarizes the impurity gas removal rate in the monoethanolamine scrubbing process. In addition, a small part of monoethanolamine will be lost due to slip.

Because monoethanolamine can react with SO₂ and NO_x in flue gas to form thermostable salts, the capture process includes not only the consumption of monoethanolamine solution and cooling water, but also caustic soda and activated carbon used to recover monoethanolamine from thermostable salt solution (Schakel et al. 2014). Table S3 shows the details of monoethanolamine loss and regeneration. In addition, in the case of considering only the amount of steel used in the equipment of the capture system, the steel consumption of the whole capture system is about 2900 t (Troy et al. 2016). Table S4 lists the input and output information of the CO₂ capture unit based on monoethanolamine absorption.

The membrane separation process is a typical two-stage membrane separation system. The type of module is hollow fiber membrane, and the membrane material is polysulfone. The industrial process of membrane production mainly includes two processes: the production of polymer and the preparation of hollow fiber membrane. Information on membrane manufacturing has been described in detail in a study by (Yadav et al. 2021) and will not be repeated here. Data related to membrane materials and hollow fiber membrane production are presented in Tables S5, S6 and S7. In this work, the 1.9×10^{-5} m² membranes are needed for the power plant to generate 1 kWh electricity (Troy and Wagner 2011). In addition, the manufacture of membrane modules and separation facilities requires 10 kg steel per m² membranes (Troy et al. 2016). The power consumption of capture 1 t CO₂ in the membrane separation system is 200 kWh (Troy and Wagner 2011). More detailed input and output data are shown in Table S8.

Table S9 lists the main input and output data of power plant operation under two capture processes. According to the detailed input and output data of the above process, we established the system model of the supercritical pulverized coal power plant with integrated post-combustion capture in OpenLCA (Figure S2 and Figure S3).

Impact assessment

As a widely used life cycle assessment method, the midpoint indicator of ReCiPe includes 18 impact categories, and the endpoint indicator includes 3 types of impact. This work focuses on 13 midpoint impact categories related to climate change, resource consumption and toxicity, including climate change (global warming), ozone depletion, freshwater eutrophication, marine eutrophication, terrestrial acidification, fossil resource depletion, water resource depletion, metal depletion, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity and particulate matter formation. Three endpoint indicators including damage to human health, damage to ecosystem quality and damage to resources are also considered.

Results and discussion

We compared monoethanolamine absorption and polymer membrane separation in a supercritical pulverized coal power plant, by life cycle assessment. The following sections present the evaluation of performance, environmental impact and process contribution.

Technical performance assessment of supercritical pulverized coal power plants

Since the membrane separation process does not involve solvents regeneration as shown in Fig. 1, and power consumption of pumps and compressors comes from the power grid, the efficiency of the power plant has not decreased. However, we find that the net efficiency of the power plant with the monoethanolamine absorption process decreased by 5% because 3.1 GJ energy is required for 1 t CO₂ desorbed during solvent regeneration. And part of the steam in the low-pressure steam turbine of the power plant is consumed as the heat source of the reboiler; the coal consumption of 1 kWh electricity generation in the power plant increases by 0.05 kg (0.48 kg versus 0.43 kg). Additional fuel consumption resulted in 11.6% energy penalty for the power plant.

Comparison of environmental impacts

Table 1 compares the environmental impacts between monoethanolamine absorption and membrane separation.

Table 1 Relative impact of monoethanolamine adsorption and membrane separation for CO₂ capture, on life cycle assessment results at midpoint level. Life cycle assessment results with high scores are considered 100%

Impact category	Monoethanolamine absorption	Membrane separation
Global warming potential	100.00%	90.58%
Ozone depletion potential	100.00%	87.06%
Terrestrial acidification potential	100.00%	86.51%
Particulate matter formation potential	100.00%	92.33%
Freshwater eutrophication potential	100.00%	89.92%
Marine eutrophication potential	100.00%	92.09%
Water depletion potential	100.00%	90.17%
Fossil depletion potential	100.00%	89.58%
Metal depletion potential	88.51%	100.00%
Human toxicity potential	100.00%	90.12%
Terrestrial ecotoxicity potential	100.00%	89.98%
Freshwater ecotoxicity potential	100.00%	91.70%
Marine ecotoxicity potential	100.00%	91.69%

Our results show that global warming potential, ozone depletion potential, terrestrial acidification potential and particulate matter formation potential of monoethanolamine absorption are 9.42% (5.46×10^{-1} vs 4.95×10^{-1} kg CO₂-Eq), 12.94% (3.65×10^{-9} vs 3.17×10^{-9} kg chlorofluorocarbon-11-Eq), 13.49% (2.02×10^{-3} versus 1.75×10^{-3} kg SO₂-Eq) and 7.67% (1.15×10^{-3} vs 1.07×10^{-3} kg particulate matter 10-Eq) higher than those of membrane separation, respectively. The main factors affecting global warming are the emissions of CO₂ and CH₄, including direct emissions from power plant operation and indirect emissions from upstream supply chain (Wang et al. 2018). Although direct emissions of SO₂ and particulate matter are further reduced during solvent scrubbing, the huge energy demand for solvent regeneration increases the consumption of fuel and electricity, which increases indirect emissions associated with the fuel supply and electricity supply processes. However, the increase in indirect emissions is often greater than the decrease in direct emissions. For terrestrial acidification potential and particulate matter formation potential, the final result of monoethanolamine absorption is still higher than membrane separation.

Eutrophication is highly related to the emissions of phosphate and NO_x. Freshwater eutrophication is mainly affected by phosphates emission to water during coal supply and electricity supply. The main factors affecting marine eutrophication are NO_x, ammonia and nitrate emission to the atmosphere during electricity supply and coal supply. As shown in Table S10, freshwater eutrophication potential and marine eutrophication potential of membrane separation are lower than those of monoethanolamine absorption.

Freshwater eutrophication potential and marine eutrophication potential of monoethanolamine absorption are 10.08% (2.39×10^{-4} vs 2.15×10^{-4} kg P-Eq) and 7.91% (5.27×10^{-4} vs 4.85×10^{-4} kg N-Eq) higher than those of membrane separation, respectively (Table 1). The extra coal consumption and the degradation of monoethanolamine are the main reasons for this difference.

In terms of resource consumption, the membrane separation process also shows lower impact in water depletion and fossil depletion (Table 1). Since the membrane separation process does not involve the chemical reaction of the solvent, the water depletion potential of membrane separation is lower than that of monoethanolamine absorption. And the energy penalty caused by the high energy consumption of solvent regeneration also makes the fossil depletion potential of monoethanolamine absorption higher than that of membrane separation. In Table S10, an interesting finding is that the metal depletion potential of monoethanolamine absorption is 7.7×10^{-4} kg Fe-Eq lower than that of membrane separation. This phenomenon also exists in the research of Troy et al. (2016). This is largely due to the extensive use of membrane module components. In addition, membrane modules need to be replaced periodically due to their service life. This all adds to the consumption of metals.

As shown in Table 1, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity potentials of monoethanolamine absorption are 9.88% (2.43×10^{-1} vs 2.19×10^{-1} kg 1,4-dichlorobenzene-Eq), 10.02% (5.21×10^{-5} vs 4.69×10^{-5} kg 1,4-dichlorobenzene-Eq), 8.30% (1.08×10^{-2} vs 9.88×10^{-3} kg 1,4-dichlorobenzene-Eq) and 8.31% (9.98×10^{-3} vs 9.15×10^{-3} kg 1,4-dichlorobenzene-Eq) higher than those of membrane separation, respectively. As found in the study by Zhang et al. (2014), the high toxicity impact of monoethanolamine absorption is mainly due to the additional coal consumption (emissions from combustion and waste disposal) and the emissions and degradation of monoethanolamine.

Overall, the two-stage membrane separation process appears to be more attractive in terms of environmental sustainability than the 30 wt% monoethanolamine absorption process. The endpoint indicator results in Table S10 further support this finding. Compared with membrane separation, the damage scores of 1 kWh electricity generated by power plants with monoethanolamine absorption to ecosystem quality, human health and resources are higher than those of 1.1×10^{-3} , 2.2×10^{-3} and 4×10^{-3} points, respectively.

Process contribution analysis

Figure 2 presents the process contributions for both capture technologies, monoethanolamine adsorption and membrane

separation, from this work. Due to the large fuel and energy consumption of the capture system, the total contribution of coal supply and electricity supply processes is more than 70% in most environmental impact categories. As shown in this figure, the coal supply contributions for membrane and absorption techniques in all impact categories vary from 2.4 to 74.6%, and from 2.4 to 75.0%, respectively. The coal supply process contributes more than 50% to freshwater eutrophication, terrestrial ecotoxicity and human toxicity, of which the contribution rate to freshwater eutrophication is more than 70%. Landfill in the process of coal mining and washing is the main influence of terrestrial ecotoxicity and human toxicity, and the emission of wastewater is the main influence source of freshwater eutrophication.

It should be noted that there is a large gap in the contribution rate of power plant operation to terrestrial acidification and metal depletion. Compared with monoethanolamine absorption, the contribution rate of power plant operation of membrane separation to terrestrial acidification and metal depletion is 6.4 and 17.5% higher, respectively. Compared with membrane separation, some acid gases in the monoethanolamine absorption process will be further eliminated due to the reaction with the solvent. Therefore, the contribution of the power plant operation of monoethanolamine absorption to terrestrial acidification is much lower than that of membrane separation. Due to the extensive use of membrane modules in the membrane separation process, the contribution of power plant operation of membrane separation to metal depletion is much higher than that of monoethanolamine absorption.

Conclusion

In this work, we use life cycle assessment to assess the environmental impacts of a 500-MW supercritical pulverized coal power plant with two post-combustion capture processes. The results of midpoint and endpoint indicators of life cycle impact assessment show that the post-combustion capture system with the two-stage membrane separation process shows better overall environmental benefits than the traditional monoethanolamine absorption process. The net efficiency of the power plant with the monoethanolamine absorption process decreased by 5% due to additional fuel consumption. The large energy consumption of solvent regeneration leads to 11.6% energy penalty. Further process contribution analysis shows that coal supply and electricity supply are the main sources of most environmental impacts. Their total impact contribution of the 12 midpoint indicators is more than 50%. Therefore, in addition to reducing the direct emissions from the operation of the power plant, the

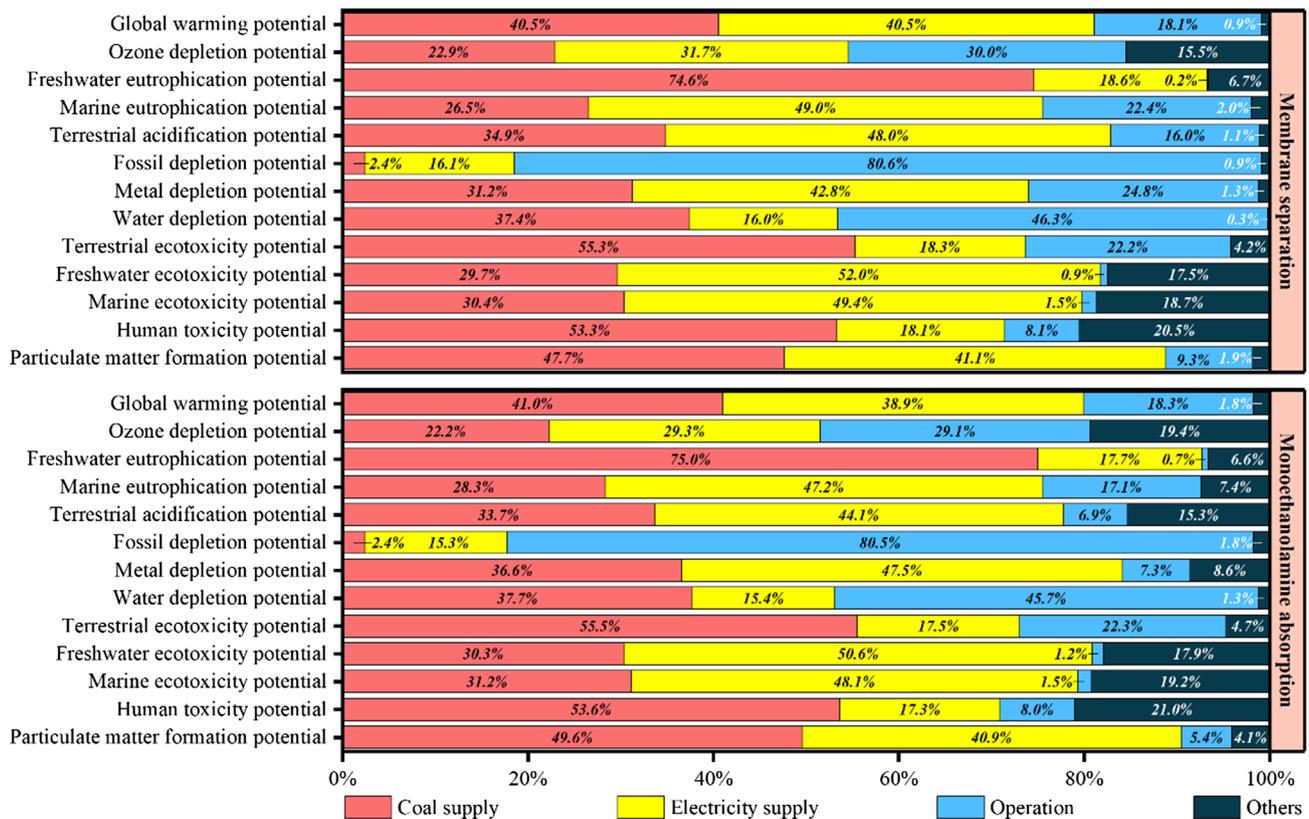


Fig. 2 Contributions of monoethanolamine adsorption and membrane separation on midpoint indicators. These two capture technologies have similar process contributions, and coal supply and power supply account for a large contribution of most impact categories

reduction in indirect emissions from the upstream supply chains also becomes very important.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10311-023-01596-0>.

Acknowledgements This work is partially supported by Liaoning Provincial Doctoral Research Startup Fund Project (2019-BS-159), Liaoning Provincial Department of Education Key Research Project (L2020002) and Scientific Research Fund Project of Education Department of Liaoning Province (LJKZ0381).

Declarations

Conflict of interest The authors declare no conflict of interest.

References

Bicalho T, Sauer I, Rambaud A, Altukhova Y (2017) LCA data quality: a management science perspective. *J Clean Prod* 156:888–898. <https://doi.org/10.1016/j.jclepro.2017.03.229>

Chao C, Deng Y, Dewil R et al (2021) Post-combustion carbon capture. *Renew Sustain Energy Rev* 138:110490. <https://doi.org/10.1016/j.rser.2020.110490>

Clarens F, Espí JJ, Giraldi MR et al (2016) Life cycle assessment of CaO looping versus amine-based absorption for capturing CO₂ in

a subcritical coal power plant. *Int J Greenh Gas Control* 46:18–27. <https://doi.org/10.1016/j.ijggc.2015.12.031>

da Cruz TT, Perrella Balestieri JA, de Toledo Silva JM et al (2021) Life cycle assessment of carbon capture and storage/utilization: from current state to future research directions and opportunities. *Int J Greenh Gas Control* 108:103309. <https://doi.org/10.1016/j.ijggc.2021.103309>

Fadeyi S, Arafat HA, Abu-Zahra MRM (2013) Life cycle assessment of natural gas combined cycle integrated with CO₂ post combustion capture using chemical solvent. *Int J Greenh Gas Control* 19:441–452. <https://doi.org/10.1016/j.ijggc.2013.10.008>

Fawzy S, Osman AI, Doran J, Rooney DW (2020) Strategies for mitigation of climate change: a review. *Environ Chem Lett* 18:2069–2094. <https://doi.org/10.1007/s10311-020-01059-w>

Goglio P, Williams AG, Balta-Ozkan N et al (2020) Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. *J Clean Prod* 244:118896. <https://doi.org/10.1016/j.jclepro.2019.118896>

Khalilpour R, Mumford K, Zhai H et al (2015) Membrane-based carbon capture from flue gas: a review. *J Clean Prod* 103:286–300. <https://doi.org/10.1016/j.jclepro.2014.10.050>

Matin NS, Flanagan WP (2022) Life cycle assessment of amine-based versus ammonia-based post combustion CO₂ capture in coal-fired power plants. *Int J Greenh Gas Control* 113:103535. <https://doi.org/10.1016/j.ijggc.2021.103535>

Nie Z, Korre A, Durucan S (2011) Life cycle modelling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO₂ capture, transport and injection processes.

- Energy Procedia 4:2510–2517. <https://doi.org/10.1016/j.egypro.2011.02.147>
- Raganati F, Miccio F, Ammendola P (2021) Adsorption of carbon dioxide for post-combustion capture: a review. *Energy Fuels* 35:12845–12868. <https://doi.org/10.1021/acs.energyfuels.1c01618>
- Saunier F, Fradette S, Clerveaux F et al (2019) Comparison of life-cycle assessment between bio-catalyzed and promoted potassium carbonate processes and amine-based carbon capture technologies. *Int J Greenh Gas Control* 88:134–155. <https://doi.org/10.1016/j.ijggc.2019.05.009>
- Schakel W, Meerman H, Talaei A et al (2014) Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. *Appl Energy* 131:441–467. <https://doi.org/10.1016/j.apenergy.2014.06.045>
- Sharma H, Dhir A (2021) Capture of carbon dioxide using solid carbonaceous and non-carbonaceous adsorbents: a review. *Environ Chem Lett* 19:851–873. <https://doi.org/10.1007/s10311-020-01118-2>
- Terlouw T, Bauer C, Rosa L, Mazzotti M (2021) Life cycle assessment of carbon dioxide removal technologies: a critical review. *Energy Environ Sci* 14:1701–1721. <https://doi.org/10.1039/D0EE03757E>
- Tirutu-Barna L (2021) A climate goal-based, multicriteria method for system evaluation in life cycle assessment. *Int J Life Cycle Assess* 26:1913–1931. <https://doi.org/10.1007/s11367-021-01991-1>
- Troy SV, Wagner H-J (2011) Screening life cycle analysis of post combustion CO₂-capture technologies—a comparison of construction phase results. *Energy Procedia* 4:480–487. <https://doi.org/10.1016/j.egypro.2011.01.078>
- Troy S, Schreiber A, Zapp P (2016) Life cycle assessment of membrane-based carbon capture and storage. *Clean Techn Environ Policy* 18:1641–1654. <https://doi.org/10.1007/s10098-016-1208-x>
- Vega F, Sanna A, Navarrete B et al (2014) Degradation of amine-based solvents in CO₂ capture process by chemical absorption. *Greenh Gases: Sci Technol* 4:707–733. <https://doi.org/10.1002/ghg.1446>
- Wang Y, Zhao L, Otto A et al (2017) A review of post-combustion CO₂ capture technologies from coal-fired power plants. *Energy Procedia* 114:650–665. <https://doi.org/10.1016/j.egypro.2017.03.1209>
- Wang J, Wang R, Zhu Y, Li J (2018) Life cycle assessment and environmental cost accounting of coal-fired power generation in China. *Energy Policy* 115:374–384. <https://doi.org/10.1016/j.enpol.2018.01.040>
- Wang Y, Pan Z, Zhang W et al (2022) Life cycle assessment of combustion-based electricity generation technologies integrated with carbon capture and storage: a review. *Environ Res* 207:112219. <https://doi.org/10.1016/j.envres.2021.112219>
- Wei X, Manovic V, Hanak DP (2020) Techno-economic assessment of coal- or biomass-fired oxy-combustion power plants with supercritical carbon dioxide cycle. *Energy Convers Manag* 221:113143. <https://doi.org/10.1016/j.enconman.2020.113143>
- Yadav P, Ismail N, Essalhi M et al (2021) Assessment of the environmental impact of polymeric membrane production. *J Membr Sci* 622:118987. <https://doi.org/10.1016/j.memsci.2020.118987>
- Zhang X, Singh B, He X et al (2014) Post-combustion carbon capture technologies: energetic analysis and life cycle assessment. *Int J Greenh Gas Control* 27:289–298. <https://doi.org/10.1016/j.ijggc.2014.06.016>

Higher efficiency and lower environmental impact of membrane separation for carbon dioxide capture in coal power plants

Yan Wang ^a, Zhen Pan ^{a,*}, Wenxiang Zhang ^b, Shaochang Huang ^a, Guojie Yu ^c, Mohamad Reza Soltanian ^d, Eric Lichtfouse ^e, Zhien Zhang ^{d,f*}

^a College of Petroleum Engineering, Liaoning Petrochemical University, Fushun 113001, China.

^b Water Desalination and Reuse Research Center, King Abdullah University of Science and Technology, Thuwal 23955, Saudi Arabia.

^c Chinese National Petroleum Corp Jilin Petroleum, Songyuan 138000, China.

^d Department of Geosciences and Environmental Engineering, University of Cincinnati, Cincinnati, OH, USA.

^e State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China. Email: eric.lichtfouse@gmail.com. Orcid: 0000-0002-8535-8073

^f William G. Lowrie Department of Chemical and Biomolecular Engineering, The Ohio State University, Columbus, OH 43210, USA

* Corresponding authors. zhenpan_fs@hotmail.com (Z. Pan); zhienzhang@hotmail.com, zhang.4528@osu.edu (Z. Zhang)

Table S1 Typical parameters of the supercritical pulverized coal power plant (SCR - selective catalytic reduction, ESP - electrostatic precipitator for particulate matter, FGD - flue gas wet desulfurization)

Parameter	Value
Capacity	500 MW
Net efficiency	43%
Capacity factor	80%
Lifetime	30yr
Auxiliary power rate	4%
SCR efficiency	90%
ESP efficiency	98%
FGD efficiency	95%

Table S2. The impurities gas removal rate for monoethanolamine scrubbing process

SO ₂ removal efficiency	90%
NO _x removal efficiency	25%
HCl removal efficiency	95%
HF removal efficiency	90%
PM removal efficiency	50%
Hg removal efficiency	25%

Table S3. Monoethanolamine loss and regeneration of CO₂ capture unit

Consumption (kg/t CO ₂)	Value	References
Oxidation	0.46	Schakel et al. 2014
Acid gases ^a	0.94	Calculated
Polymerization	0.69	Schakel et al. 2014
Slip	0.014	Koornneef et al. 2008, p. 2
Reclaimed ^b	0.2	Calculated

^a The molar amount of monoethanolamine consumed per removal of 1mol acid gas (SO₂ = 2; NO₂ = 2; HCl = 1; HF = 1).

^b 1mol NaOH consumed for reclaiming 1mol monoethanolamine.

Table S4. Input and output of the CO₂ capture unit based on 30wt% monoethanolamine absorption

		Unit	Amount	References
Input	Monoethanolamine	kg	1.91	Calculated
	Caustic soda	kg	0.13	Rao et al. 2004
	Activated carbon	kg	0.075	Rao et al. 2004
	Cooling water	m ³	0.8	Rao and Rubin 2002
	Steam (heat)	GJ	3.1	Calculated
	Electricity	kWh	193	Clarens et al. 2016
	Steel	kg	0.0322	Troy et al. 2016
Output	CO ₂	t	1	Calculated
	NH ₃	kg	0.13	Calculated
	Monoethanolamine	kg	0.014	Calculated

Table S5. Inputs and outputs in production of 1 kg of polysulfone (Yadav et al. 2021)

		Unit	Value
Input	Oxygen	kg	0.41
	Water, deionised	kg	0.04
	2,4-dichlorophenol	kg	0.94
	Benzene	kg	0.99
	Bisphenol	kg	0.36
	Electricity	kg	0.49
	Heat	kg	0.33
Output	polysulfone	kg	1
	Phenol	kg	0.0007
	Phenol, 2,4-dichloro	kg	0.002
	Water	m ³	0.012
	Wastewater, average	m ³	0.025

Table S6. Inputs and outputs in production of 1 kg of ethylene carbonate (Yadav et al. 2021)

		Unit	Value
Input	Carbon dioxide, liquid	kg	0.50497
	Ethylene oxide	kg	0.50053
	Electricity	kWh	0.002
	Heat	MJ	0.14333
Output	Ethylene carbonate	kg	1
	Ethylene oxide	kg	0.00025027
	Carbon dioxide, fossil	kg	0.0053021
	Spent catalyst base from ethyleneoxide production	kg	0.005

Table S7. Inputs and outputs for producing 1000 m² hollow fiber membrane (Yadav et al. 2021)

		Unit	Value
Input	Polysulfone	kg	80
	Ethylene carbonate	kg	320
	Water, unspecified natural origin	L	3000
	Nitrogen	L	0.561
	Electricity	kWh	2832
Output	Hollow fiber membrane	m ²	1000
	Wastewater, average	L	3000

Table S8. Input and output of CO₂ capture unit based on membrane separation

		Unit	Amount	Reference
Input	Hollow fiber membrane	m ²	0.0248	Troy and Wagner 2011
	Electricity	kWh	200	Troy and Wagner 2011
	Steel	kg	0.248	Troy et al. 2016
Output	CO ₂	t	1	Calculated

Table S9. Input and output of supercritical pulverized coal power plant operation with post-combustion capture process

		Unit	Monoethanolamine absorption	Membrane separation
Input	Coal	kg	4.800×10^{-1}	4.300×10^{-1}
	Electricity	kWh	4.000×10^{-2}	4.000×10^{-2}
	Fuel oil	kg	1.846×10^{-4}	1.654×10^{-4}
	Water, softened	kg	6.517×10^{-2}	5.838×10^{-2}
	water, decarbonised	kg	2.172	1.964
	Water, cooling	m ³	4.967×10^{-2}	4.450×10^{-2}
	NO _x retained	kg	7.300×10^{-4}	7.300×10^{-4}
	SO _x retained	kg	2.010×10^{-3}	2.010×10^{-3}
	CO ₂ captured	kg	7.660×10^{-1}	7.660×10^{-1}
Output	Electricity	kWh	1.000	1.000
	CO ₂	kg	9.502×10^{-2}	8.512×10^{-2}
	CO	kg	9.579×10^{-5}	8.582×10^{-5}
	CH ₄	kg	1.012×10^{-5}	9.064×10^{-6}
	N ₂ O	kg	1.507×10^{-5}	1.350×10^{-5}
	SO ₂	kg	1.437×10^{-5}	1.287×10^{-4}
	NO _x	kg	2.327×10^{-4}	2.780×10^{-4}
	HCl	kg	1.439×10^{-5}	2.578×10^{-4}
	HF	kg	3.074×10^{-6}	2.754×10^{-5}
	NM VOC	kg	1.010×10^{-5}	9.049×10^{-6}
	PM	kg	3.07×10^{-5}	5.497×10^{-5}
	Hard coal ash	kg	8.124×10^{-2}	7.278×10^{-2}
	Residue from cooling tower	kg	5.974×10^{-5}	5.351×10^{-5}

Table S10 Midpoint and endpoint indicator results for 1 kWh electricity generated in two capture processes

Impact category	Unit	Monoethanolamine absorption	Membrane separation
Midpoint indicators			
Global warming potential	kg CO ₂ -Eq	5.46×10^{-1}	4.95×10^{-1}
Fossil depletion potential	kg oil-Eq	3.18×10^{-1}	2.84×10^{-1}
Freshwater ecotoxicity potential	kg 1,4-DCB-Eq	1.08×10^{-2}	9.88×10^{-3}
Freshwater eutrophication potential	kg P-Eq	2.39×10^{-4}	2.15×10^{-4}
Human toxicity potential	kg 1,4-DCB-Eq	2.43×10^{-1}	2.19×10^{-1}
Marine ecotoxicity potential	kg 1,4-DCB-Eq	9.98×10^{-3}	9.15×10^{-3}
Marine eutrophication potential	kg N-Eq	5.27×10^{-4}	4.85×10^{-4}
Metal depletion potential	kg Fe-Eq	5.92×10^{-3}	6.69×10^{-3}
Ozone depletion potential	kg CFC-11-Eq	3.65×10^{-9}	3.17×10^{-9}
Particulate matter formation potential	kg PM10-Eq	1.15×10^{-3}	1.07×10^{-3}
Terrestrial acidification potential	kg SO ₂ -Eq	2.02×10^{-3}	1.75×10^{-3}
Terrestrial ecotoxicity potential	kg 1,4-DCB-Eq	5.21×10^{-5}	4.69×10^{-5}
Water depletion potential	m ³	5.07×10^{-3}	4.57×10^{-3}
Endpoint indicators			
Damage to ecosystem quality	points	1.14×10^{-2}	1.03×10^{-2}
Damage to human health	points	2.49×10^{-2}	2.27×10^{-2}
Damage to resources	points	3.91×10^{-2}	3.51×10^{-2}

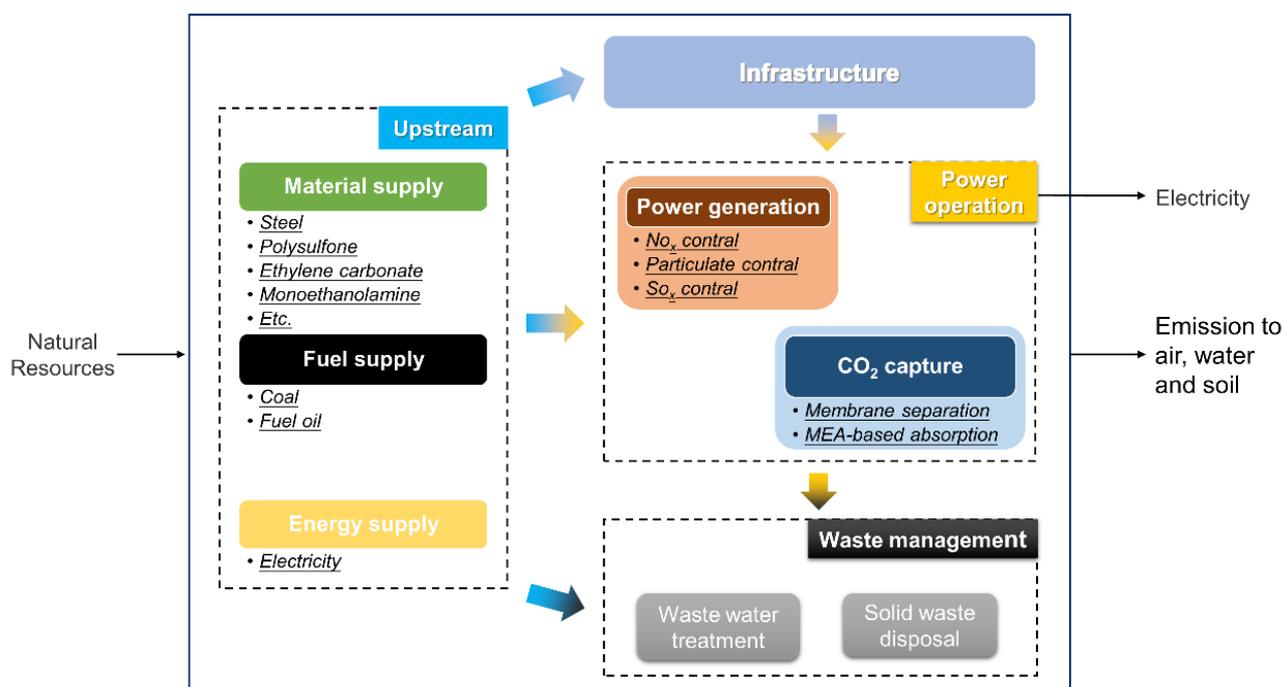


Figure S1. System boundary of the post-combustion capture system based on power plant level. The system boundary includes three stages: upstream raw material acquisition, power plant operation and waste disposal

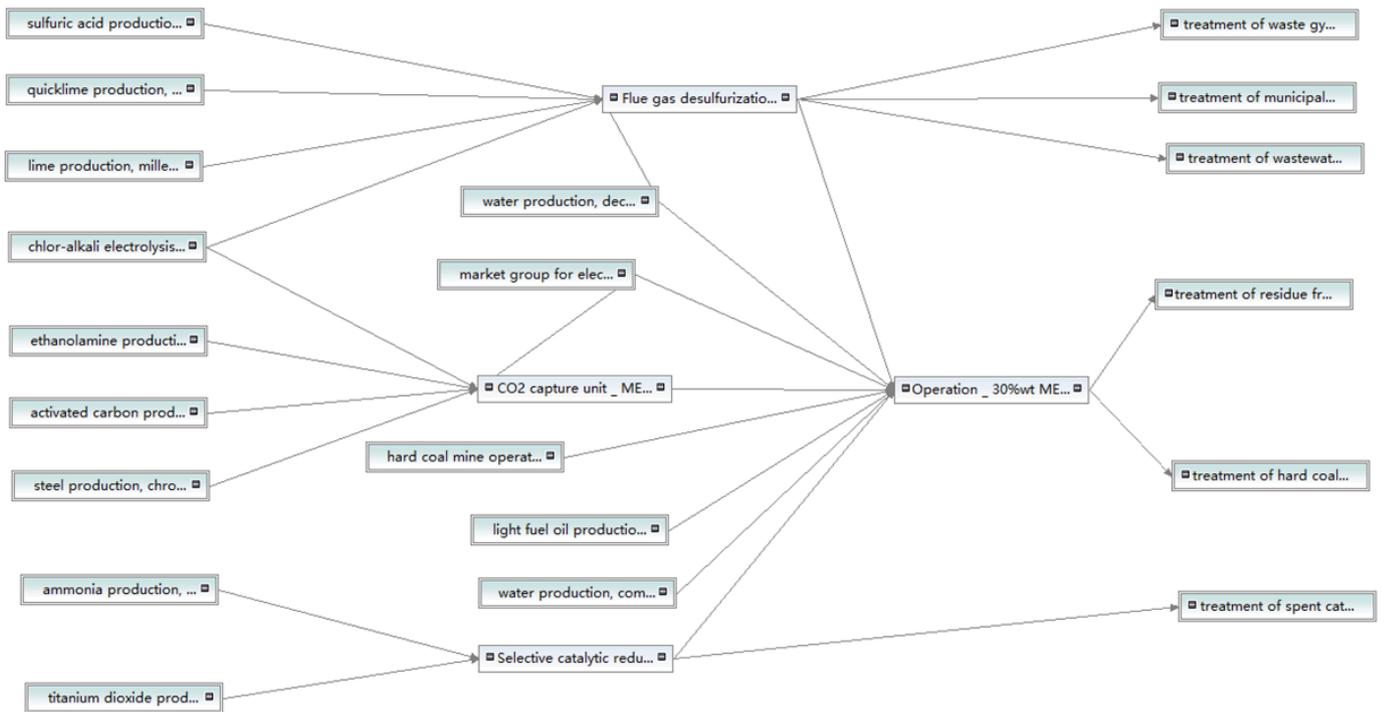


Figure S2. Life cycle assessment model of supercritical pulverized coal power plant with post-combustion capture based on 30wt% monoethanolamine absorption

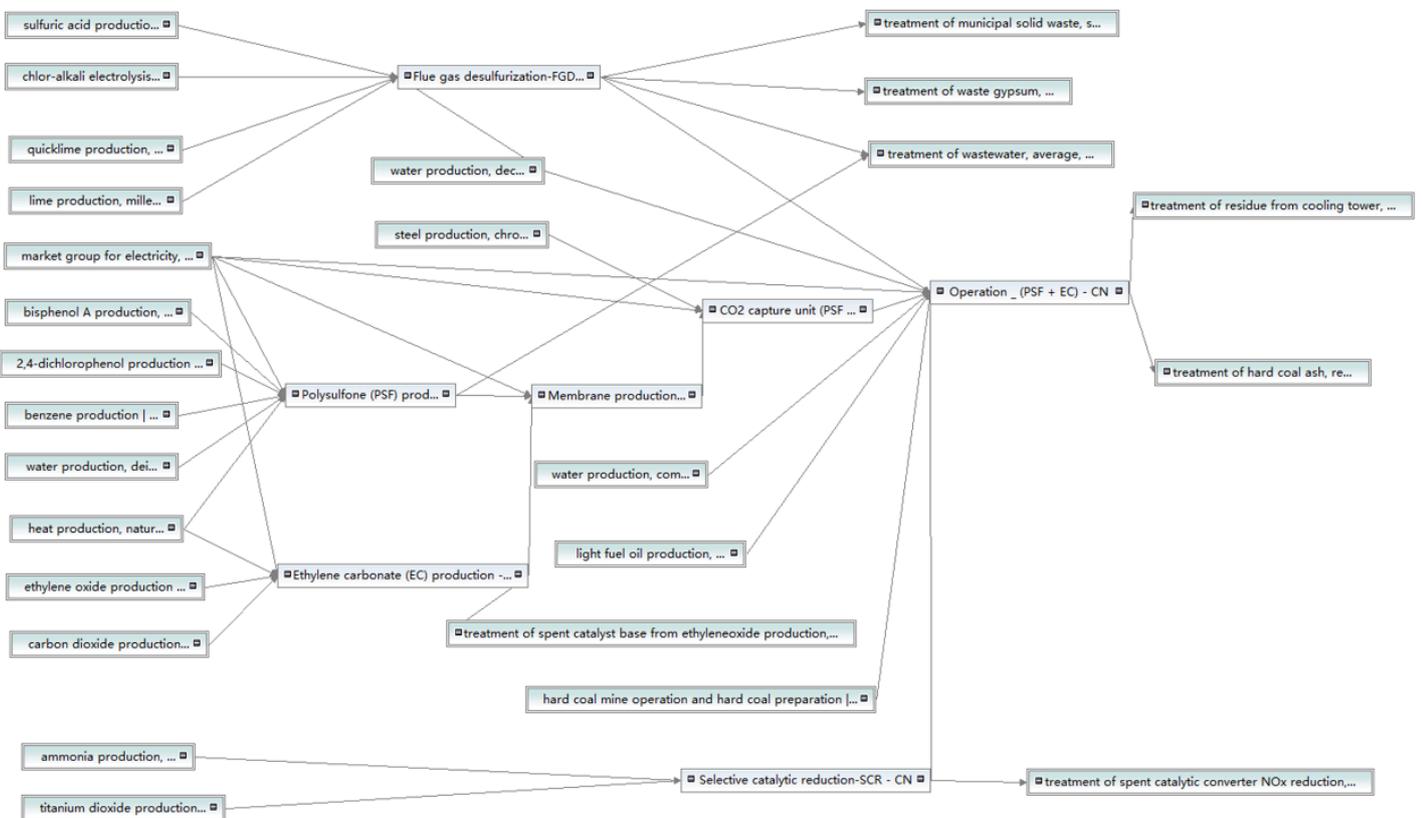


Figure S3. Life cycle assessment model of supercritical pulverized coal power plant with post-combustion capture based on membrane separation