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Article

Environmental Impact Evaluation of CO₂ Absorption and Desorption Enhancement by Membrane Gas Absorption: A Life Cycle Assessment Study

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Abstract: Membrane gas absorption technology has been considered as a promising approach to mitigate CO₂ emissions from power plants. The aim of this study is to evaluate the environmental impacts of CO₂ absorption and desorption processes by hollow fiber membrane contactors using life cycle assessment methodology. On the basis of ReCipe 2016 Midpoint and ReCipe 2016 Endpoint methods, the research results show that, membrane gas absorption system exhibits the lowest environmental impacts across the majority assessed categories in comparison with chemical absorption and membrane gas separation systems. The CO₂ capture process via membrane gas absorption has the most significant impact on METP category, with heat consumption as the primary contributing factor accounting for 55%, followed by electricity consumption accounting for 43.1%. According to the sensitivity analysis, heating by natural gas shows a better performance than other heat supply sources in improving overall environmental impacts. In addition, the increasing utilization of renewable energy in electricity supply reduces the global warming potential, fossil resource consumption and ozone formation.

Keywords: CO₂ capture; membrane gas absorption; life cycle assessment; environmental impact

1. Introduction

Carbon dioxide is one of the primary greenhouse gases contributing to global warming, which leads to a variety of environmental problems such as rising sea levels, melting glaciers and ice sheets, and species extinction. According to the special report issued by the Intergovernmental Panel on Climate Change, it is imperative to restrict the increase in global average temperature to 1.5°C above preindustrial levels in order to achieve the targets outlined in the Paris Agreement [1]. The carbon dioxide emission shall be universally reduced in order to combat climate change and resulting disasters. The European Union and Japan have set the ambitious targets of achieving net-zero greenhouse gas emissions by 2050 [2,3]. The US White House is aiming at challenging goals of reducing total economy-wide greenhouse gas emissions by 50-52% and achieving net-zero emissions by 2030 and 2050, respectively [4]. China has also announced to aim to reach a peak in its carbon dioxide emissions before 2030 and achieve carbon neutrality by 2060 [5].

CO₂ capture and storage (CCS) from large-scale emission sources has been considered as an effective approach to stabilize or reduce the CO₂ concentration in the atmosphere in the short term. CCS can be further classified into three categories: pre-combustion capture, oxygen combustion capture and post-combustion capture. For CO₂ post-combustion capture from coal-fired power plants, the chemical and physical absorption [6], solid adsorption [7], cryogenic distillation [8] and membrane separation [9] technologies have been currently proposed without significant retrofitting of existing infrastructures. Chemical absorption has been extensively used as the most well established technology at the commercial scale in the gas separation industry for decades attributed to its high removal efficiency. Nonetheless, conventional gas absorption towers and scrubbers are

generally encountered with the high regeneration costs and operation problems such as flooding, absorbent losses, entrainment, liquid channeling and foaming [10]. The membrane gas separation has been considered as another attractive technology which shows the benefits of continuous operation, flexible design, low energy consumption and simple equipment [11]. However, its applications for CO₂ capture are mainly limited by its permeability-selectivity tradeoff relation. Therefore, in recent years, many researchers have been exploiting the possibilities by integrating two or more gas separation technologies to overcome the performance gaps and enhance the removal efficiency.

Membrane gas absorption technology is such a hybrid process that combines the advantages of absorption process and membrane separation. In comparison with traditional columns, although the membrane wall introduces an additional resistance, the CO₂ absorption and stripping processes by hollow fiber membrane contactors can still enhance the CO₂ absorption flux, reduce the equipment size and the total energy costs. The gas-liquid interface area of a hollow fiber membrane contactor is 30 times higher than that of a conventional packed column, which effectively reduces the size of the CO₂ absorber by 65% [12]. Compared to a conventional absorption process, 4.63% and 6.11% energy savings can be achieved with membrane-integrated absorption in series and in parallel configuration due to reduction in the absorber size, respectively [13]. Attributed to its flexible operation, compact specification, high surface-area-to-volume ratio, linear scale-up feasibility, modular design and other benefits [14–16], membrane gas absorption technology has already been identified as one of promising alternatives to conventional technologies for CO₂ mitigation. In the past two decades, most of the researches conducted have mainly focuses on the technical and economic feasibility of the membrane gas absorption for CO₂ capture from the perspectives of membrane materials, absorbent types and operating parameters by experimental and numerical simulations [17–20]. However, the environmental impact of the membrane gas absorption for CO₂ capture, which can be used to evaluate the real sustainability of the CO₂ capture processes regarding all environmental aspects, has seldom been studied in previous literatures.

Life Cycle Assessment (LCA) is a systematic and comprehensive method used to evaluate the environmental impact categories of a product, process, or service throughout its entire life cycle. In the past two decades, numerous LCA studies have been carried out to evaluate the environmental implications of typical CO₂ post capture systems or technologies. Koornneef et al. [21], Petruscu et al. [22] and Surprenant [23] applied LCA to investigate the environmental trade-offs and co-benefits of implementing CO₂ capture and storage using different absorbents by chemical absorption technology in the supercritical pulverized coal fired power plant. Giordano et al. [24] performed a comparative LCA between MEA-based chemical absorption processes and membrane separation process for CO₂ post-combustion capture, concluding that the membrane separation could reduce lifecycle emissions compared to chemical absorption. Wang et al. [25] also applied LCA method to study the environmental impacts of MEA-based chemical absorption and two-stage membrane separation for CO₂ capture in a supercritical pulverized coal power plant. Two-stage membrane separation showed less damage on human health, resources and ecosystems compared to MEA absorption technology.

Specific to the membrane gas absorption process, Akan et al. [26] conducted a comprehensive assessment of the environmental impacts associated with CO₂ capture in hollow fiber membrane contactors, utilizing MDEA activated by piperazine under different operation conditions at the laboratory scale. Their findings indicated that the highest impacts on ecosystems, human health, and resource utilization were observed under conditions of maximal liquid flow, minimal solvent concentration, and optimal sweep gas flow rate. To date, there exists a scarcity of studies which explore the environmental impacts of CO₂ absorption and desorption processes employing hollow fiber membrane contactors at a commercial-scale power plant, specifically through Life Cycle Assessment methodology. Therefore, this study is primarily focused on assessing the environmental impacts of CO₂ capture through membrane gas absorption utilizing the LCA methodology. Furthermore, chemical absorption and membrane gas separation processes are also evaluated for comparative purposes. The structure of this paper is outlined as follows: section 2 introduces the process flow of the membrane gas absorption system, chemical absorption system and membrane separation system. Section 3 introduces the methodology for life cycle assessment. Section 4 discusses the life cycle environmental assessment results. Section 5 conducts a sensitivity analysis on the factors with the greatest impact on the system environmental performance. Finally, Section 6 summarizes the main conclusions of the study.

2. Materials and Methods

The CO₂ capture process is retrofitted to a 685 MWe supercritical pulverized coal power plant which is designed based on case B12A specified by the National Energy Technology Laboratory with the detailed parameters specified in reference [27]. The designed service life of the power plant is 30 years. The flue gas from the power plant is cooled at a temperature of 27°C, and further purified to remove NO_x, SO₂ and dust before entering the capture equipment. It is assumed that the flue gas entering the separation system is 12.46 % mol CO₂ and 87.54 N₂ mol %, at the mass flow rate of 736 kg/s. In this study, the CO₂ capture rate is set at 90%, and 100% CO₂ is regenerated for compression. To compare with the membrane gas absorption technology for reducing CO₂ emissions in thee coal-fired power plant, chemical absorption and membrane gas separation technologies are also investigated as the study scenarios.

Figure 1 is the schematic diagram of membrane gas absorption technology to capture CO₂ from flue gas of power plant. The purified flue gas, primarily N₂ and CO₂, is introduced into the bottom of the polypropylene hollow fiber membrane contactor, and flows through the shell sides of the membrane contactor. The absorbent, 30 wt.% MEA, flows through the lumen sides of the hollow fiber membrane contactor in opposite direction. The CO₂ gas diffuses and passes through the membrane micropores to the gas-liquid contact surface, and is absorbed by MEA solution under the driving force of the concentration gradient. At the same time, the hydrophobic membrane material can prevent the absorbent solution from entering the gas phase, thereby achieving the purpose of separating CO₂ from the flue gas. For the membrane gas absorption system, the liquid absorbents provide the selectivity and the microporous membrane only acts as the physical barrier between the gas and liquid phases. After absorption, CO₂-rich absorbent is pumped into heat exchanger. The heated CO₂-rich absorbent is further pumped into the bottom and flows upwards in the lumen side of the hollow fiber membrane contactors. The gas steam from the reboiler is fed through the shell side of the membrane contactors as the sweeping gas during the regeneration process. The membrane contactors for regeneration are kept at the pressure of 0.3 bar, in order to meet the requirements of membrane stability and minimize the regeneration energy penalty [28]. After condensation, pure CO₂ can be collected from the vacuum pump for storage or utilization. The regenerated absorbent is cooled in the heat exchanger and pumped back to absorption membrane contactors for next recycle capture process.

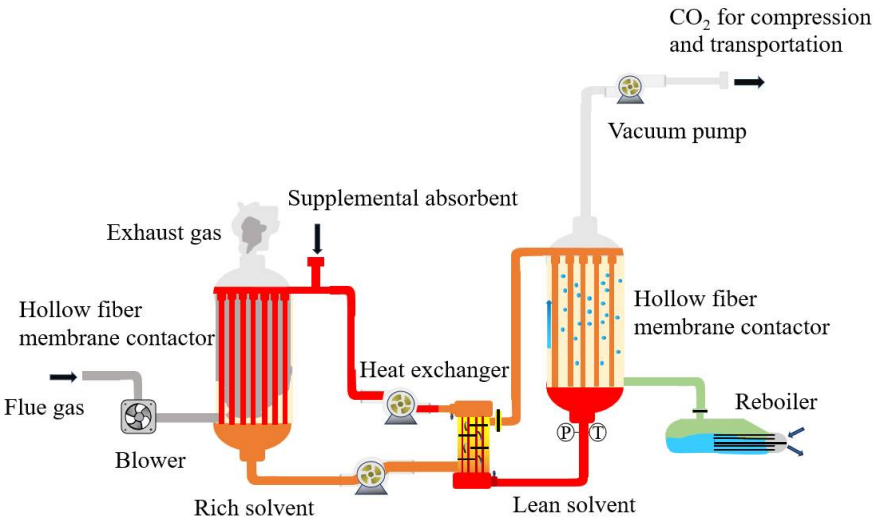


Figure 1. Schematic drawing of CO₂ capture by membrane gas absorption

Main parameters of the hollow fiber membrane contactors are obtained given in Table 1.

Table 1. Parameters of hollow fiber membrane contactors [29]

| Parameters | Value |
|------------|-------|
|------------|-------|

| | |
|-------------------------------------------------------|----------------------|
| Fiber inner diameter (m) | 3.0×10 ⁻⁴ |
| Fiber outer diameter (m) | 5.0×10 ⁻⁴ |
| Pore diameter (m) | 1.0×10 ⁻⁷ |
| Porosity | 0.5 |
| Outer specific area (m ² /m ³) | 1500 |
| Inner specific area (m ² /m ³) | 900 |
| Gas velocity (m/s) | 1.0 |
| Liquid velocity (m/s) | 0.07 |
| Number of absorber contactors | 100 |
| Number of desorber contactors | 100 |
| Effective height (m) | 4.0 |
| Membrane material | Polysulfone |

Figure 2 illustrate the process flow diagram for CO₂ capture utilizing MEA-based chemical absorption technology, which is closely similar with the configuration depicted in Figure. 1. The notable distinction is that the membrane contactors are replaced with packed or bubble towers for the absorption and desorption stages. The flue gas from the power plant is introduced into the absorber column where it contacts the MEA solution flowing counter-currently. CO₂ from the flue gas reacts with MEA to form a bicarbonate ion, and the reaction is exothermic leading to a temperature increase in the solution. The CO₂-rich absorbent is then regenerated in the stripper at the temperature of 110-120 °C by steam extracted from the reboiler. Pure CO₂ is released from the absorbent, cooled and compressed for storage or utilization, while the lean absorbent is recycled to the absorber for the next absorption process.

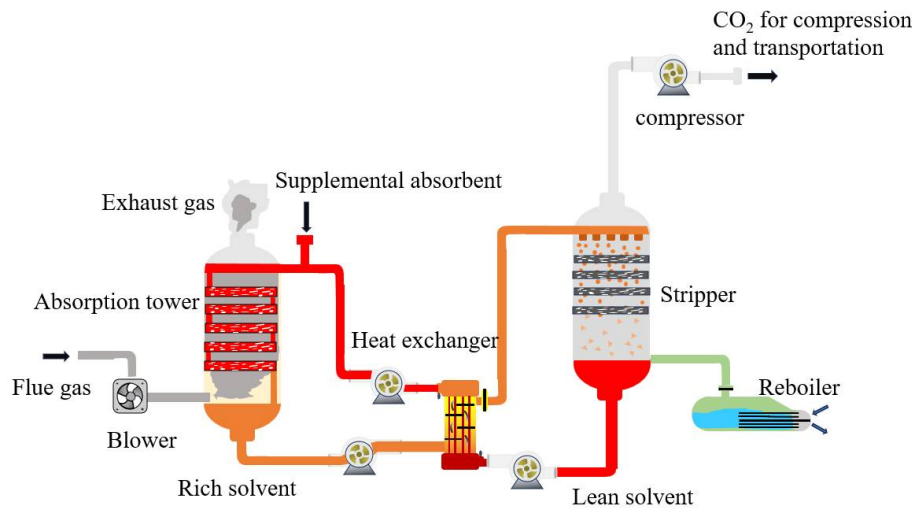


Figure 2. Schematic drawing of CO₂ capture by MEA-based chemical absorption process

Figure 3 illustrate the flow chart of CO₂ capture by a two-stage membrane gas separation system. Both stages use Polyactive™ membrane [30] characterized by higher selectivity for CO₂ to ensure fine separation and achieve high purity levels. The membrane has a dense active layer with the thickness of 1.5 μm. This two-stage approach optimizes the balance between CO₂ permeability and selectivity, resulting in improved capture rates and efficiency for industrial applications.

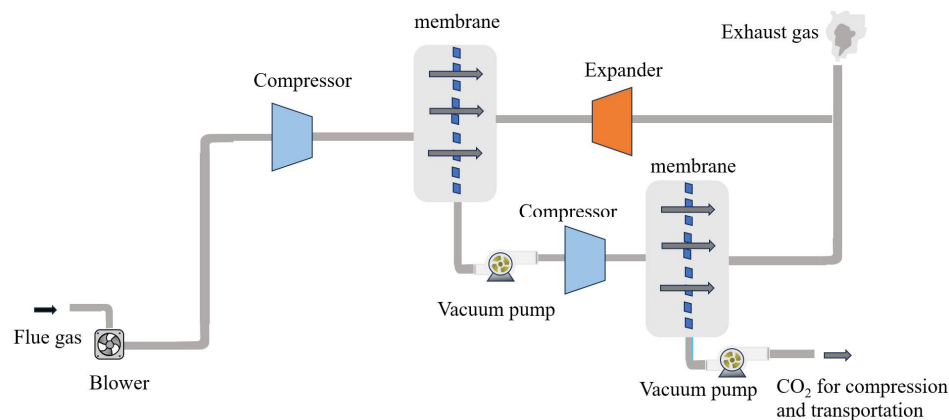


Figure 3. Schematic drawing of CO₂ capture by two-stage membrane gas separation

3. Life Cycle Assessment Methodology

Life Cycle Assessment is a comprehensive framework which can be used to evaluate the environmental aspects and potential environmental impacts associated with all the life stages of a specific product, process or service from raw material extraction up to end-of-life disposal or recycling. The application of LCA methodology in the field of CO₂ capture can identify the critical environmental hotspots within the CO₂ capture chain, and provide support for decision making from the perspectives of process design optimization and environmental sustainability. According to ISO 14040: 2006 and ISO 14044: 2006 standards issued by the International Organization for Standardization, LCA is composed of four fundamental steps: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation.

3.1 Goal and Scope Definition

Goal and scope definition establishes the LCA objective, the system boundary and the function unit of the study to lay foundation for the assessment. The goal of the present study is to evaluate the environmental impact of applying membrane gas absorption technology to capture CO₂ from the flue gas of a coal-fired power plant. Chemical absorption and membrane gas separation technologies are also considered for comparison. Based on the study focus, a "gate to gate" instead of "cradle to grave" approach is adopted to evaluate the capture process of CO₂ in absorption and desorption equipment. The overall system boundary of CO₂ capture and recovery by membrane gas absorption, chemical absorption and membrane gas separation systems is shown in Figure 4. The construction of coal-fired power plant, human activities, equipment maintenance and waste disposal stages are not considered in this study. The function unit in an LCA study serves as a key reference to quantify the system performance for comparison and assessment of environmental impacts, energy consumption and resource utilization of CO₂ capture systems. In this study, the function unit is defined as 1 ton of CO₂ captured from the power plant.

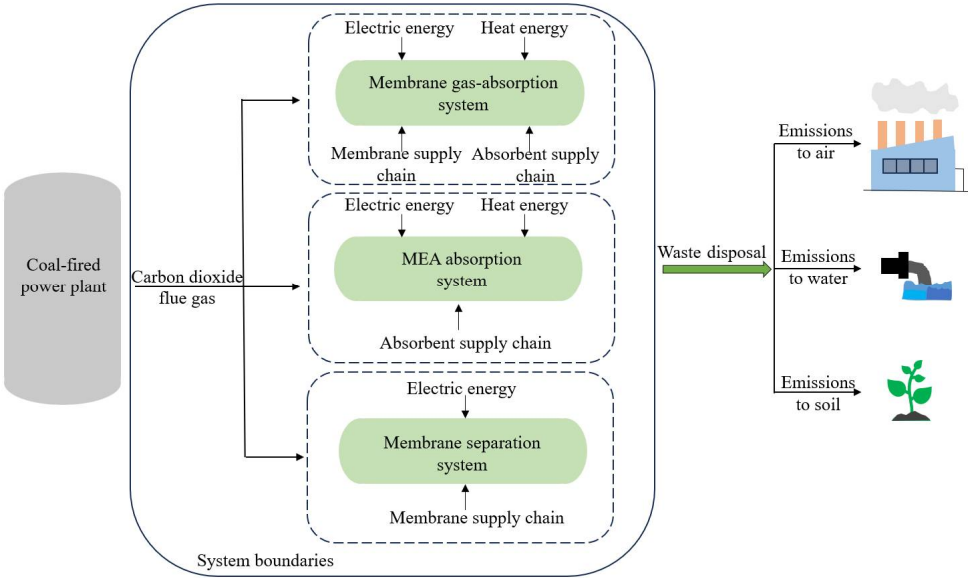


Figure 4. System boundary of CO₂ capture and recovery by three studied technologies

3.2 Life Cycle Inventory

Life cycle inventory is a crucial step of LCA methodology, which involves the collection and quantification of data inputs and outputs for all processes within the studied system boundaries. Inventory analysis is supported by two primary categories of data: background data and foreground data. Background data refers to generic data that is not specific to the capture process under study but is essential for the comprehensive analysis of the life cycle. Background data provides the necessary context for understanding the broader environmental implications. In this study, the background data are sourced from the commercially available Ecoinvent v3.0 database integrated within SimaPro software [31]. On the other hand, foreground data is specific to the particular process being assessed, which is critical for accurately representing the unique aspects of the CO₂ capture system’s life cycle and for assessing the direct environmental impacts of its production, use, and disposal. In this study, the foreground data is mainly collected through relevant literatures, professional research reports and open data sets. Adjustments have been made to the values of these foreground data to align with the flow charts for each studied capture process. Table 2 lists the foreground data for the further calculation.

Table 2. Foreground data of material and energy consumption.

| System parameters | Unit | Value |
|-------------------------------------|--------------------------------|--------|
| Membrane gas absorption [29] | | |
| MEA consumption | kg/t CO ₂ | 0.9 |
| Membrane area | 10 ³ m ² | 4400 |
| Regeneration heat | GJ/ t CO ₂ | 2 |
| Compressor | kWh/t CO ₂ | 83.3 |
| Auxiliary equipment | kWh/t CO ₂ | 67.96 |
| Chemical absorption [24] | | |
| MEA consumption | kg/ t CO ₂ | 1.44 |
| Regeneration heat | GJ/ t CO ₂ | 3.2 |
| Compressor | kWh/t CO ₂ | 64.5 |
| Auxiliary equipment | kWh/t CO ₂ | 33.8 |
| Membrane gas separation system [24] | | |
| Membrane area | 10 ³ m ² | 2828.5 |

| | | |
|---------------------|-----------------------|-------|
| Compressor | kWh/t CO ₂ | 77.1 |
| Auxiliary equipment | kWh/t CO ₂ | 230.4 |

Table 3. Inputs and outputs for producing 1000 m² hollow fiber membrane [32].

| | | Unit | Value |
|--------|----------------------------------------------------|----------------|---------|
| Input | Water, unspecified natural origin | L | 3000 |
| | Oxygen | kg | 32.8 |
| | Water, deionized | kg | 3.2 |
| | 2,4-dichlorophenol | kg | 75.2 |
| | Benzene | kg | 79.2 |
| | Bisphenol | kg | 28.8 |
| | Electricity | kg | 2871.84 |
| | Heat | kg | 72.27 |
| | Carbon dioxide, liquid | kg | 161.59 |
| | Ethylene oxide | kg | 160.17 |
| | Nitrogen | L | 0.561 |
| Output | Hollow fiber membrane | m ² | 1000 |
| | Wastewater, average | L | 5000 |
| | Ethylene oxide | kg | 0.08 |
| | Carbon dioxide, fossil | kg | 1.7 |
| | Spent catalyst base from ethylene oxide production | kg | 1.6 |
| | Phenol | kg | 0.056 |
| | Phenol, 2,4-dichloro | kg | 0.16 |
| | Water | m ³ | 0.96 |

Table 4. List of inputs and outputs for producing 1kg of MEA [33]

| | | Unit | Amount |
|--------|-------------------------------------|------|--------------------|
| Input | Ethylene oxide | g | 816 |
| | Ammonia | g | 788 |
| | Electricity | kWh | 0.333 |
| | Natural gas | MJ | 2 |
| | Transport (truck and train) | t×km | 11.23 |
| Output | Infrastructure chemical plant | p | 4×10 ¹⁰ |
| | Monoethanolamine | kg | 1 |
| | Waste heat | MJ | 1.2 |
| | Ethylene oxide to air | g | 1.63 |
| | Ethylene oxide to water | g | 1.47 |
| | Ammonia to air | g | 1.58 |
| | Ammonium to water | g | 3.04 |
| | CO ₂ | g | 26.5 |
| | Nitrate (NO ₂) to water | g | 6.97 |
| | COD.BOD | g | 21.3 |
| | TOC.DOC | g | 8.02 |

3.3. Life Cycle Impact Assessment

ReCipe 2016 Midpoint method, which integrates the midpoint assessment of CML-IA and the endpoint assessment of Eco-indicator 99, is selected as the impact assessment method. ReCipe 2016 Midpoint method contains the widest range of midpoint impact categories, allowing for the application of characterization factors within these categories at an international scale [34]. In

addition, ReCipe 2016 Endpoint method is also used, including damage to human health, damage to ecosystem quality and damage to resources. Table 5 shows the list of 18 midpoint and 3 endpoint impact categories used as the indicators of environmental impacts.

Table 5. List of life cycle impact categories

| Name of the impact category | Expression in equivalent unit | Abbreviation |
|-------------------------------------------|----------------------------------------|--------------|
| ReCipe 2016 Midpoint indicators | | |
| Global warming potential | kg CO ₂ to air eq. | GWP |
| Ozone layer depletion potential | kg CFC-11 eq. | ODP |
| Ionizing radiation potential | kBq Cobalt-60 to air eq. | IRP |
| Ozone formation, Human health | kg NO _x eq. | OFHH |
| Fine particulate matter formation | kg PM _{2.5} to air eq. | FPMF |
| Ozone formation terrestrial ecosystems | kg NO _x eq. | OFTE |
| Terrestrial acidification potential | kg SO ₂ eq. | TAP |
| Freshwater eutrophication potential | kg P eq. | FEP |
| Marine eutrophication potential | kg N eq. | MEP |
| Terrestrial ecotoxicity potential | kg 1,4-DCB to industrial soil eq. | TETP |
| Freshwater ecotoxicity potential | kg 1,4-DCB to freshwater eq. | FETP |
| Marine ecotoxicity potential | kg 1,4-DCB to marine water eq. | METP |
| Human carcinogenic toxicity potential | kg 1,4-DCB eq. | HCTP |
| Human non-carcinogenic toxicity potential | kg 1,4-DCB eq. | HNCTP |
| Land use | m ² ×yr annual cropland eq. | LU |
| Mineral resource scarcity | kg Cu eq. | MRS |
| Fossil resource scarcity | kg oil-eq. | FRS |
| Water consumption potential | m ³ water-eq. consumed | WCP |
| ReCipe 2016 Endpoint indicators | | |
| Damage to human health | points | |
| Damage to ecosystem quality | points | |
| Damage to resources | points | |

3.4. Interpretation

Interpretation is the final stage where the results are evaluated to provide conclusions and recommendations for decision making process.

4. Results and Discussion

4.1. Environmental Impact Comparison of Different CO₂ Capture Systems

The results of environmental impact assessment of three studied CO₂ capture systems at midpoint level is shown in Figure 1. The highest value in each impact category is considered as the reference of 100%, while other impact categories with lower values are presented as a ratio to the reference value. In summary, the membrane gas absorption system exhibits the lowest environmental impacts across the majority assessed categories in comparison with chemical absorption and membrane gas separation systems. At the given function unit of 1 ton CO₂ captured from the power plant, the GWP indicator values for membrane gas absorption, chemical absorption and membrane gas separation systems are 393 kgCO₂ eq., 456 kgCO₂ eq. and 461 kgCO₂ eq., respectively. It indicates that, the membrane absorption system has superior efficiency in mitigating CO₂ emissions, which can be primarily attributed to its reduced energy requirements during the capture phase. Even though membrane gas separation has the highest GWP value among the three capture systems, it exhibits the lowest environmental impact over water-related impact categories such as WCP, TAP, FEP and MEP. That is because that the dry operating condition of membrane gas separation system eliminates

the demands for water consumption or wastewater treatment. In contrast, chemical absorption system presents the most significant impact on water-related indicators, primarily because of pollution from absorbent discharges and the ensuing necessity for wastewater treatment. Water-related indicators of membrane gas absorption system are higher than membrane gas separation system but lower than chemical absorption system, which can prove the advantage of such integrated system in reducing absorbent losses.

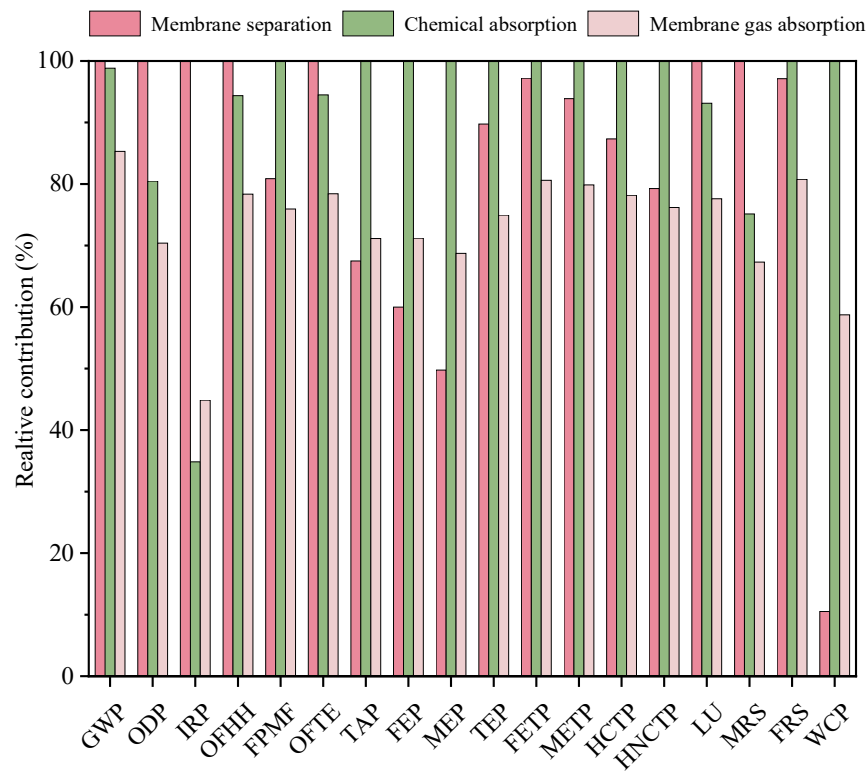


Figure 5. Environmental impact comparison based on 18 midpoint methods

To comprehensively evaluate the environmental performance of CO₂ capture systems, ReCipe Endpoint method with three categories is further employed, with the results shown in Figure 6. In the evaluation of the impacts on human health, ecosystems and resources, the indicator results derived from the characterization phase are aggregated based on their respective damage categories. The damage levels of human health, ecosystem and resources through standardization are converted into dimensionless impact potentials. The three types of impact potentials are weighted and added to form the single score. The standardized benchmark and damage weight values adopt the default values set within the SimaPro software framework. As shown in Figure 6, the impact of CO₂ capture on the damage to human health is much higher than the other two indicators regardless of capture systems, which can be attributed to the strong reliance on fossil-based heat and electricity consumption which has high emissions of harmful substances such as HF, HCl and PM. Regarding the harm to resources and ecosystems, the impact of membrane gas absorption is slightly lower than other two capture systems. In the case of total damage indicator, the impact value of membrane gas absorption system is 20% and 10% lower than that of chemical absorption system and membrane gas separation system, respectively.

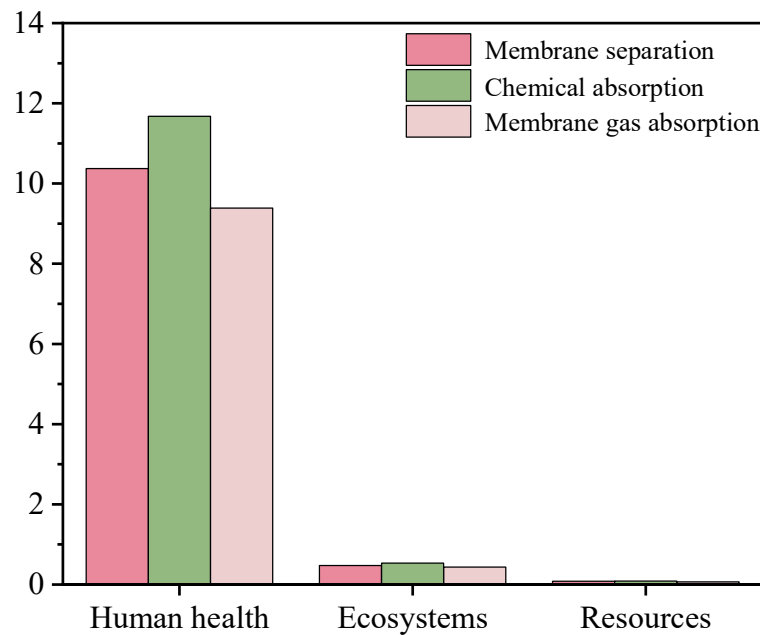


Figure 6. Comparison of three indicators of resources, ecosystems and human health

4.2. Process Contribution Analysis of Membrane Gas Absorption System

The contribution of inputs and outputs of CO₂ capture process via membrane gas absorption system to the total impact in each mid-point category is presented in Figure 7, and its corresponding normalized diagram is shown in Figure 8. Although membrane gas absorption system can reduce the electricity and heat consumption compared to membrane gas separation system and chemical absorption system, the contribution of electricity supply and heat consumption remain the primary sources of environmental impact for the life cycle of the entire system, varying from 8% to 88%, and from 7% to 91%, respectively. Except terrestrial ecotoxicity potential and water consumption potential, the electricity consumption contributes more than 32% in other impact categories. Notably, electricity consumption leads to dominant impacts in IRP, which contributes 88% of this impact category. Heat consumption for solvent regeneration accounts for 7% and 14% in IRP and TETP indicators, respectively. The heat consumption contributes more than 50% to TAP, FEP, FETP, MEP, HNCTP and WCP indicators. Especially, the heat consumption contribution in water consumption potential is more than 90%, due to large amount of water consumed during the heat production and supply process. The MEA absorbent used in the membrane contactor accounts for 20% and 66% in the case of MEP and TEP. It can be attributed to the ammonia-related emissions associated with the MEA production, which can cause eutrophication and toxicity on water bodies. It is a bit surprise that the membrane materials used during the capture process has negligible influences over all the impact categories, with the minimization and maximization contribution at 0.06% for WCP indicator and 0.45% for MRS indicator. The upcaptured CO₂ has less impact on other indicators except in case of global warming potential, which is 28%.

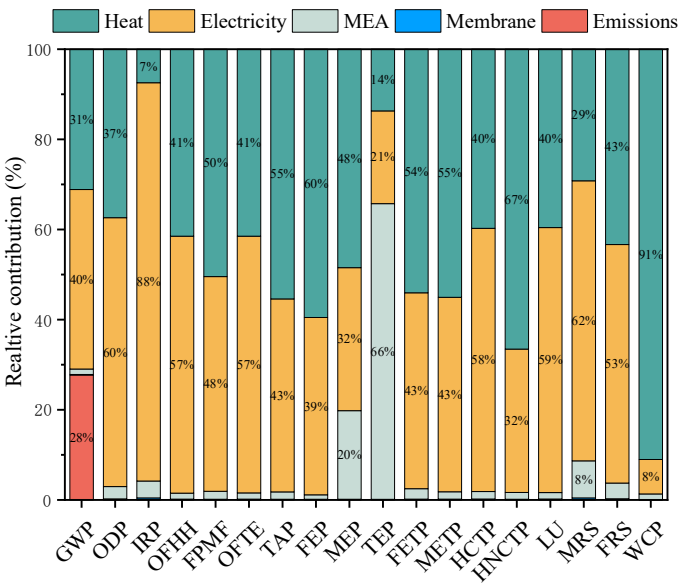


Figure 7. Contributions of membrane gas absorption on midpoint indicators

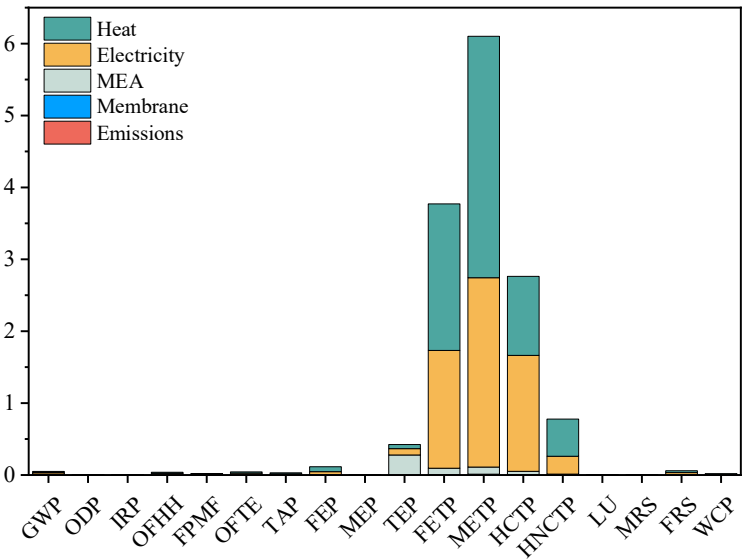


Figure 8. Normalized diagram of CO₂ capture process by membrane gas absorption system

As illustrated in Figure 8, the CO₂ capture process via membrane gas absorption has the most significant impact on METP category, with heat consumption as the primary contributing factor accounting for 55%, followed by electricity consumption accounting for 43.1%. FETP, HCTP and HNCTP are also predominantly influenced by heat and electricity consumption. The most considerable impact on TEP originates from MEA absorbent, which is mainly due to ammonia emissions within the MEA production supply chain. Based on the results shown in Figure 7 and Figure 8, it can be concluded that, electricity and heat consumptions are the primary contributors to environmental impacts, while MEA absorbent and uncaptured CO₂ have influences on limited indicators. Therefore, from the perspective of environmental impact, more efforts should be made to optimize the energy efficiency of membrane gas absorption system.

To further discuss the impacts of membrane gas absorption system on human health, ecosystems, and resources, the ReCipe Endpoint method is utilized to analyze the above processes, with results presented in Figure 9 and Figure 10. In Figure 9, according to the results obtained from SimaPro 9 software, the heat consumption and electricity consumption are identified as the most significant factors of above three indicators. Specifically, the impact of heat consumption on human

health, ecosystems, and resource consumption accounts for 42%, 39%, and 38%, respectively, while the impact of electricity consumption corresponds to 43%, 40%, and 49%, respectively. In addition, the impact of uncapture CO₂ emission on human health and ecosystems is 14% and 19%, respectively. The production supply chain of MEA absorbent accounts for 13% in the resources, which is much higher than that on human health and ecosystems.

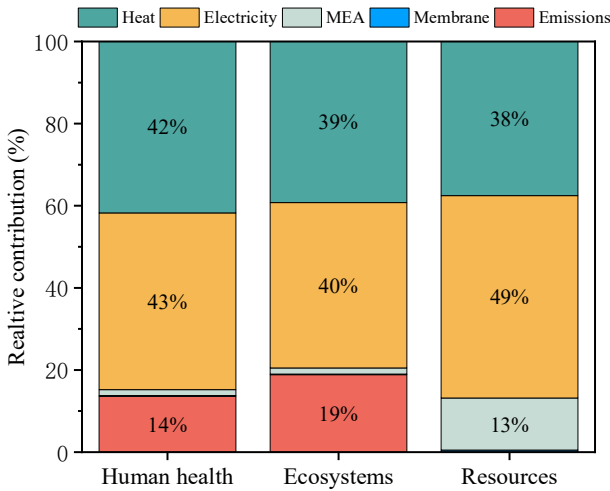


Figure 9. Process contributions of membrane gas absorption on endpoint indicators

It can be clearly observed in Figure 10 that, the impact of the CO₂ capture process by membrane gas absorption on human health is much more obvious than ecosystems and resources.

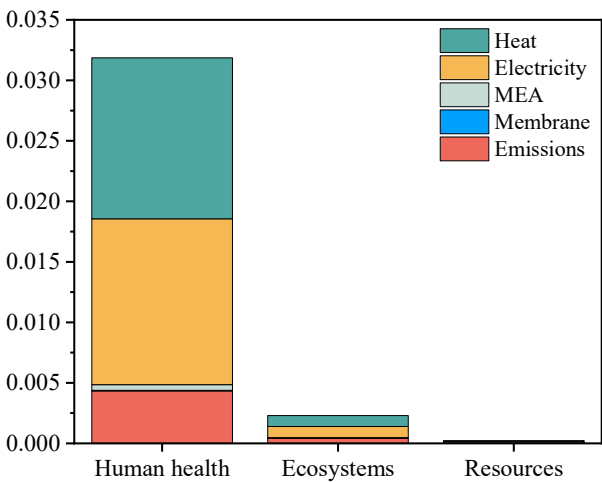


Figure 10. Normalized diagram of three endpoint indicators during CO₂ capture process

5. Sensitivity Analysis

The analysis of the environmental impacts of CO₂ capture by membrane gas absorption system reveals that heat consumption and electricity consumption are the most critical environmental impact factors within the life cycle of the system. Consequently, the sensitivity analysis on heat and electricity consumptions is crucial for decision-making process.

5.1. Sensitivity Analysis on Heat Supply Source

The heat required for absorbent regeneration in the membrane gas absorption system can be replaced by steam generated from natural gas combustion, biogas combustion and heat pump technology. Figure 11 shows the change in 18 midpoint indicators under different heat supply sources. Switching the heat supply from coal-fired steam to natural gas can reduce the majority of the impact categories, with GWP reduction by 12%. The most observable reduction is in WCP which

is reduced nearly by 90%, but the MRS and FFP indicators are increased by 15% and 5%, respectively. In case of heating by biomass combustion, the WCP indicator presents the most significant reduction by five times and GWP has a 24% reduction in comparison with the heating method in this study. However, the utilization of biomass combustion leads to a 53% increase in ODP and 25 times increase in LU. The substitution of the heat source with a heat pump brings an unclear improvement on most environmental indicators. For example, the GWP is only reduced by 5% at the cost of increase in TAP and WCP by 30% and 80%, respectively. In summary, heating by natural gas shows a better performance in improving overall environmental impacts. Although biomass combustion heating brings the largest reduction in GWP which enhances the emission reduction efficiency of carbon capture process, caution should be made as it greatly increases the risk of LU.

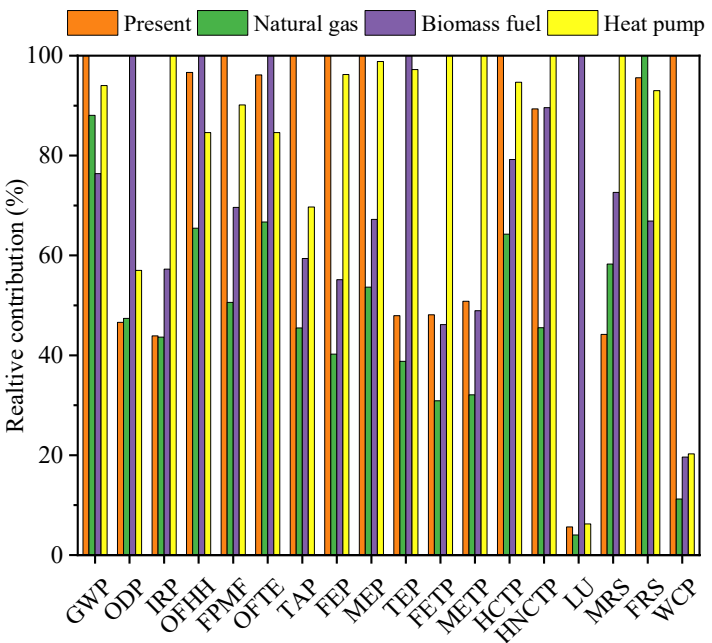


Figure 11. Sensitivity analysis on different heat supply sources

5.2 Sensitivity Analysis on Electricity Supply

With the improvement of China energy structure, share of renewable energy for electricity generation is increasing. Therefore, the impact of electricity supply from the national grid will continue to decrease with time. From 2030 to 2050, China's power structure will decarbonize progressively in order to achieve carbon neutrality goals. The electricity supply structure will transition from being coal-dominated to being primarily based on renewable energy generation, which will have significant influence on the net emissions reduction and environmental impacts of CO₂ capture by membrane gas absorption system. As the energy structure shifts towards a more sustainable direction, the increase in the proportion of renewable energy generation indicates that the environmental impact of electricity from the grid will gradually decrease. Table 6 lists the electricity generation forecast taken from China Energy Outlook 2020 [35]. The GWP of the electricity mix is calculated by modifying the Ecoinvent database through elaborating different production mixes based on different years.

Table 6. Electricity generation structure forecast

| | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|-------------|------|------|------|------|------|------|------|
| Coal | 55% | 54% | 52% | 42% | 34% | 20% | 5% |
| Natural gas | 4% | 5% | 5% | 5% | 5% | 6% | 5% |
| Hydro | 21% | 19% | 17% | 16% | 15% | 16% | 18% |
| Nuclear | 6% | 7% | 8% | 10% | 11% | 13% | 16% |
| Wind | 8% | 11% | 13% | 18% | 22% | 25% | 29% |
| Solar | 5% | 4% | 6% | 9% | 13% | 19% | 27% |

| | | | | | | | |
|------------------------------------------|-------|-------|-------|-------|-------|-------|-------|
| Electricity GWP kgCO ₂ eq/kWh | 0.724 | 0.714 | 0.691 | 0.586 | 0.482 | 0.329 | 0.143 |
|------------------------------------------|-------|-------|-------|-------|-------|-------|-------|

Note: Electricity mix production considered transmission loss and associated emission from the grid.

Figure 12 presents the sensitivity analysis on electricity supply under different scenarios. The environmental impacts of membrane gas absorption technology on greenhouse gas emissions, fossil resource consumption, ozone formation and eutrophication will be gradually decreased with the green transformation of the power structure. It is expected that by 2030, the global warming potential will be decreased by 12% with the initial decarbonization of power structure and the increasing proportion of renewable energy. However, the expected reduction in global warming potential is 5% as the decarbonization process slows down between 2030 and 2040. Subsequently, with the rapid increase in renewable energy and the significant reduction in the use of fossil fuels from 2040 to 2050, the reduction in global warming potential will exceed 15%. The trends in the impact of fossil resource consumption and ozone formation are similar to that of global warming potential, which have a significant reduction in 2030 and an expected decrease of more than 15% by 2050 mainly due to the substantial reduction in the use of fossil fuels. The analysis on impact indicators for freshwater eutrophication, marine eutrophication, human carcinogenic toxicity and human non-carcinogenic toxicity shows that, the related impacts are gradually decreased with the improvement in the energy structure. It can be mainly attributed to the reduction in coal use, which alleviates the environmental impacts of waste generated during its extraction process. With increasing reliance on renewable energy from 2030 to 2050, there is an increasing demand for mineral resource extraction, leading to an upward trend in the impacts of ionizing radiation, mineral resource consumption, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity. The results reflect the challenges from the increasing utilization of renewable energy, especially the ecological and environmental issues caused by mineral resource extraction.

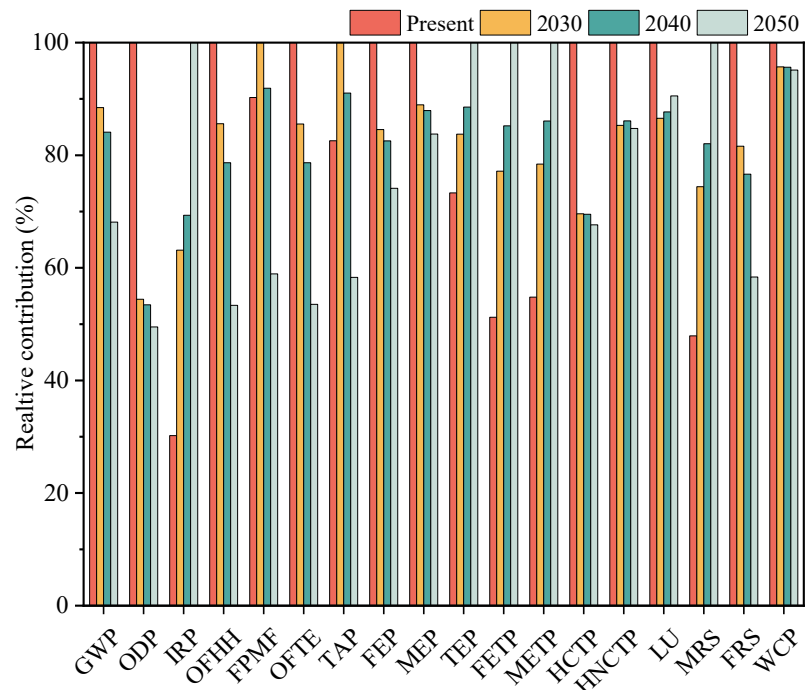


Figure 12. Sensitivity analysis on electricity supply

6. Conclusions

In this study, a membrane gas absorption system for CO₂ capture is retrofitted to a 685 MWe supercritical pulverized coal power plant, which uses the hollow fiber membrane contactors as the absorber and desorber. Life cycle assessment is carried out to evaluate the environmental impacts of the membrane gas absorption technology. Furthermore, sensitivity analysis is conducted in order to find out the critical factors affecting the system environmental performance. Based on the research results, the following conclusions can be concluded:

- (1) At the given function unit of 1 ton CO₂ captured from the power plant, the membrane gas absorption system exhibits the lowest environmental impacts across the majority evaluated categories in comparison with chemical absorption and membrane gas separation system. Specially, the GWP indicator values are 393 kgCO₂ eq., 456 kgCO₂ eq. and 461 kgCO₂ eq. for membrane gas absorption, chemical absorption and membrane gas separation systems, respectively. Furthermore, membrane gas separation exhibits the lowest environmental impact over water-related impact categories such as WCP, TAP, FEP and MEP.
- (2) For the membrane gas absorption system, the contribution of electricity supply and heat consumption are the primary sources of environmental impact within the system life cycle, varying from 8% to 88%, and from 7% to 91%, respectively. Electricity consumption leads to significant impacts in IRP, which contributes 88% of this impact category. Heat consumption contribution in water consumption potential is more than 90%, due to large amount of water consumed during the heat production and supply process. The impact of heat consumption on human health, ecosystems, and resource consumption accounts for 42%, 39%, and 38%, respectively, while the impact of electricity consumption corresponds to 43%, 40%, and 49%, respectively.
- (3) Sensitivity analysis results show that, switching the heat supply from coal-fired steam to natural gas can reduce the majority of the impact categories, with GWP reduction by 12%. The most observable reduction WCP is reduced nearly by 90%, but the SOP and FFP indicators are increased by 15% and 5%, respectively. Considering the power structure decarbonization from 2030 to 2050 in China, the global warming potential, fossil resource consumption and ozone formation can be significantly reduced by increasing utilization of renewable energy. However, the ecological and environmental issues are also caused due to mineral resource extraction.

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