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Life Cycle Assessment of Solar-Driven Post-Combustion Carbon Capture Systems: The Way Forward to Slash the Energy Penalty

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Abstract. Post-combustion carbon capture (PCC) technique has been extensively investigated over the past two decades to mitigate the effects of greenhouse gas (GHG) emissions. Nowadays, integrating solar energy with a PCC retrofit has become an active area of research due to its potential to slash the energy penalty on power plants. The economic aspects of both solar-assisted PCC (SA-PCC) and solar-powered PCC (SP-PCC) counterparts have already been studied in literature. Therefore, this paper aims at analysing and comparing the environmental footprints of SA-PCC and SP-PCC systems throughout their life cycle using the ReCiPe 2016 method. A cradle-to-grave framework is employed to specify the life cycle inventories in OpenLCA software for capturing one carbon capture unit (tonne of CO_2) over the project's lifespan. Results showed that SP-PCC significantly reduces environmental burdens (>10%) in various midpoint categories compared to SA-PCC counterpart. Furthermore, the endpoint assessment of SA-PCC revealed that particulate matter formation, global warming, land use, and mineral scarcity have substantial damaging impacts on the endpoint areas of protection, accounting for 37.29%, 49.48%, 76.18%, and 13.49% of the total impact, respectively. As a result, they are classified as critical impact categories that should receive priority attention for improvements. Further categorization of critical categories showed that the key difference between the examined systems lies in the contributions of nitrate salts and mono-ethanolamine (MEA) production. Furthermore, MEA contributions in SP-PCC are considerably lower than those of nitrate salts in SA-PCC across the critical categories. This demonstrates the superiority of SP-PCC over the SA-PCC in mitigating the environmental burdens when incorporating solar energy in carbon capture process.

Keywords: Post-Combustion Carbon Capture, Solar-Powered Carbon Capture, Cradle-to-Grave, Midpoint Impact, Endpoint Impact, Life Cycle Assessment

1. Introduction

Coal plays a vital role in global electricity generation and is the leading contributor (44%) to global greenhouse gas (GHG) emissions [1]. Replacing coal-based power plants with renewable solar and wind farms can reduce this contribution. However, it is impractical to rely on such intermittent sources for power generation in the short- to mid-terms. Furthermore,

scientists have also admitted that achieving net-zero emissions cannot be accomplished solely by limiting future GHG emissions. It is also necessary to work on the reduction of current emissions from the atmosphere. As a result, carbon capture and sequestration (CCS) technologies have gained significant attention over the last two decades [2]. Due to its minimal retrofitting requirements and low cost, post-combustion carbon capture (PCC) is now the most preferred option for capturing carbon dioxide (CO_2) from existing power plants [3].

In the PCC, the CO_2 is absorbed from the flue gas of a combustion process using a suitable solvent, as illustrated in *Figure 1*. A number of solvent classes such as amines, ammonia, amino acid salts, ionic liquids, carbonates, phase change absorbents, nanofluids, and phenoxide salts can be used as absorption liquids [4]. Each class has advantages and also limitations in terms of the regeneration energy, loading capacity, thermal/oxidative degradation rate, volatility, and cost which highly affect the selection criteria for an absorption liquid. Mono-ethanolamine (MEA), a subclass of amines, is widely recognized as a reference solvent due to its high-reactivity and cost-effectiveness, has been adopted in this study. The resulting CO_2-rich mixture is then directed to the desorber for solvent regeneration, and separation of the CO_2 molecules. Subsequently, this CO_2 gas is routed to a knock-out drum before being compressed and transported to an appropriate storage site through pipelines or other transportation methods. During this intricate process, the desorption unit requires a substantial amount of thermal energy, which significantly affects the overall power production and imposes a notable energy penalty (~ 19.5 to 40%) on the power plant [5]. This thermal energy is mostly required for the reboiler duty in addition to the electric power for auxiliary loads (*Figure 1*).

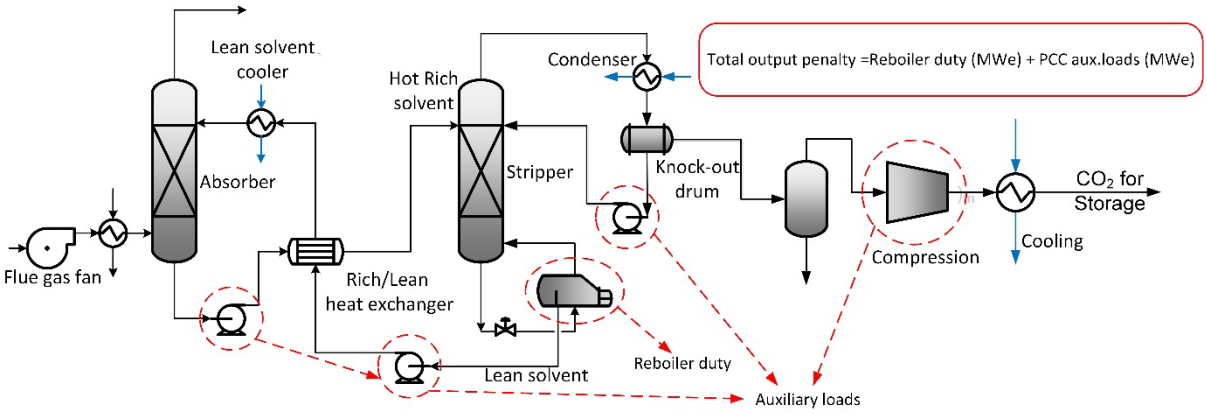

Figure 1. *Schematic illustration of a typical PCC unit*

To slash the energy penalty on the power plant, one potential solution is the integration of solar energy with PCC units, known as solar-assisted PCC (SA-PCC) systems [6]. In SA-PCC, the solar collector field (SCF) made of parabolic trough collectors provides the necessary amount of steam to the desorber unit, eliminating the need for steam bleeding from the actual power cycle of the power plant. However, the intermittency of solar power and the high cost of solar components, including thermal energy storage (TES), create barriers to its commercialization. As a result, a new approach called solar-powered PCC (SP-PCC) was proposed [7], in which the CO_2-rich mixture is sent to a network of innovatively designed solar-strippers (So-St) to directly regenerate the solvent in the SCF. A So-St unit works as a micro-desorber and the whole SCF work together to replace the traditional desorption unit in the PCC [8].

While the economic aspects of aforementioned systems have been comprehensively studied [9], the environmental impacts of such technologies have not yet been explored, to the best of the authors' knowledge. To address this gap, no other tool surpasses life cycle assessment (LCA) in identifying environmental hotspots throughout the entire life cycle of a system. LCA stands incomparable in its ability to comprehensively assess the environmental

impacts at every stage, from raw material extraction to manufacturing, product use, and eventual disposal at the end of life.

Recent LCA findings on bioenergy with CCS [10], direct air capture [11], and SA-PCC [12] indicate that the climate benefits of any CCS technology are highly sensitive to critical parameters such as the type of energy source, solvent regenerative process, etc. Since the main difference between SA-PCC and SP-PCC lies in their strategies for regenerating the rich solvent, it would be interesting to conduct a comprehensive LCA of both systems. Furthermore, in some cases, the PCC effectively lowers one impact; however, it also augments other impact categories [13]. In this context, a trade-off must be carefully considered between the different impact categories when comparing different CCS technologies, including those integrated with solar thermal energy, as a measure to mitigate the impact of fossil fuel-based energy consumption.

Therefore, this paper compares the environmental footprints of SP-PCC with the SA-PCC system throughout its life cycle using a comprehensive cradle-to-grave framework. Firstly, the life cycle inventories for both configurations are specified, starting from coal production to the sequestration of compressed CO_2. Then, the midpoint and endpoint impact categories are analyzed using the prominent ReCiPe 2016 method and EcoInvent database in the OpenLCA software. Based on the obtained results, critical impact categories are classified, and discussed for contributing processes. This work is very critical to understand the LCA implications for process hybridization with renewables to uncover and evaluate potential environmental hotspots.

2. System Description

Figure 2 shows the block diagrams of the examined PCC systems. *Figure 2(a)* depicts the power plant (PP) integrated with SA-PCC, where the SCF is equipped with a large thermal energy storage (TES) system to independently respond to the thermal energy demands of the PCC. On the other hand, *Figure 2(b)* illustrates the PP integrated with SP-PCC, where the solvent is directly regenerated in the innovative SCF. In both scenarios, solar energy serves as the only source of the necessary thermal energy for regenerating the solvent, thus preventing the need for steam extraction from the actual power cycle. Comprehensive explanations of both scenarios can be found in the previous technoeconomic study [9].

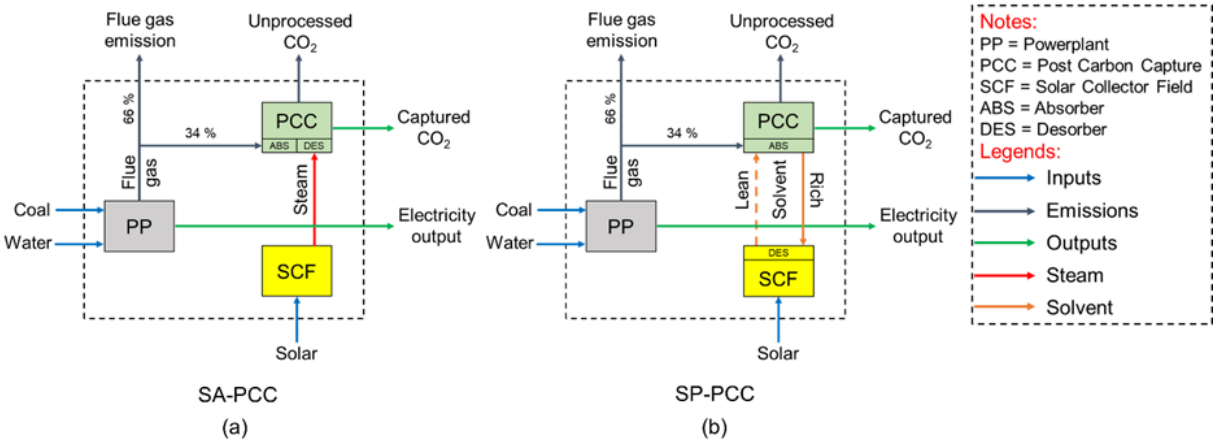

Figure 2. *Block diagrams of examined PCC systems: (a) SA-PCC and (b) SP-PCC*

2.1 LCA Boundaries

In any LCA, a crucial step is defining system boundaries based on material flow, starting from raw materials extraction to the end of the system's life. Different approaches are available for

this purpose, including (1) gate-to-gate, (2) cradle-to-gate, (3) cradle-to-grave, and (4) cradle-to-cradle [14]. Among these approaches, the cradle-to-grave approach is more appropriate for LCA studies aiming to assess environmental burdens throughout a product's life cycle as it overcomes the limitations of gate-to-gate and cradle-to-gate approaches. Besides, the cradle-to-cradle approach additionally includes the decomposition and recycling of the disposable materials, which are then reintroduced as inputs at the initial cradle stage. Hence, it requires a substantial amount of data, and sometimes the lack of inventory data can complicate LCA studies. As a result, the cradle-to-grave approach is used for this study, as shown in *Figure 3*.

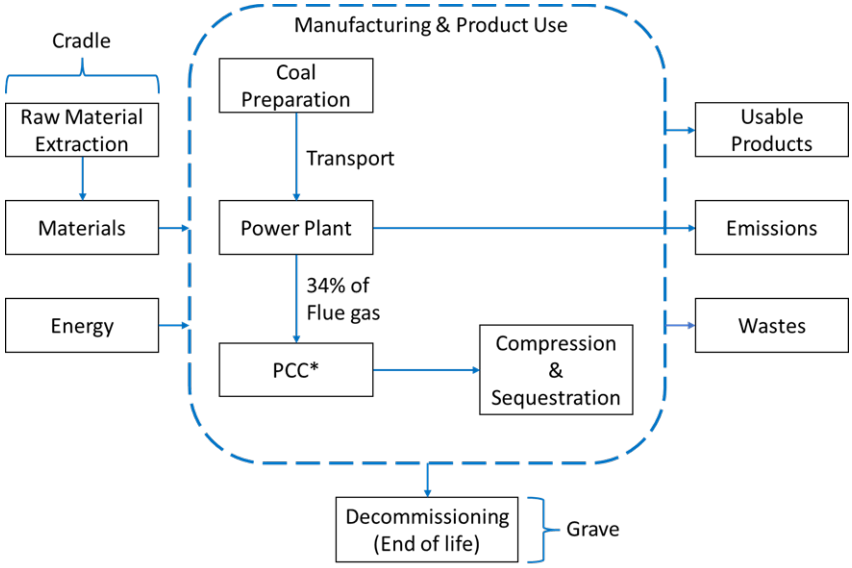

Figure 3. *LCA system boundaries for a cradle-to-grave approach*

2.2 LCA Inventories

Life cycle inventory involves specifying the material inputs, product outputs, wastes, and emissions for particular processes across the system boundary. In this paper, it is assumed that the PP produces 660 MWe of energy and has a lifespan of 30 years. The PCC unit has a capacity to capture 1.5 Megatonnes of CO_2 per year. These assumptions align closely with the literature [15]. However, analyzing such a large system requires big datasets to handle, which makes LCA complicated. As a result, the given system must be scaled down by assuming a CO_2 functional unit. To achieve this, a capital multiplier is defined to levelize all energy and material interactions, accounting for the capture of one unit (1 tonne) of CO_2 throughout the project's lifespan, as shown below:

$$\text{Capital Multiplier} = \frac{CO_2 \text{ functional unit}}{CO_2 \text{ over lifespan}} = \frac{1\ t_{CO_2}}{1.5 \times 10^6 \frac{t_{CO_2}}{y} \cdot 30y} = 2.22 \times 10^{-8} \quad (1)$$

2.2.1 Coal Preparation and Transportation

This inventory accounts for emissions linked to the entire coal production process, encompassing mining, washing, and transportation to the power plant site. In this study, black coal is assumed as the primary fuel for power generation, and it is transported over 20 km by rail and an additional 10 km by conveyor to reach the power plant location. The total coal input calculation assumes the high heating value efficiency of 34% and a calorific value of 23.8 MJ/kg [15].

2.2.2 Power Plant

This inventory includes all inputs required for operating the power plant and all emissions and outputs produced by the plant. The main inputs to the power plant are coal, construction materials, and water. Some of this data is determined using the well-validated Aspen® model, while the remainder is assumed based on literature. The outputs consist of the generated energy (both thermal and electrical), and major emissions such as CO_2, fly ash, and waste construction materials at the end of its life. As defined earlier, all these parameters are levelized to represent the capture of 1 tonne of CO_2. This study considers concrete, steel, aluminium, and iron as the main construction materials and assumes a 75% material recovery at the decommissioning phase [16]. Emissions related to the construction process are omitted due to incomplete data sets. For additional details, please refer to *Table 1*.

Table 1. *Assumptions and technical data for the PP inventory*

Parameter	Value	Units	Reference
Inputs			
Total coal input	1.571	tonne	-
Boiling and cooling water	146.3	L/MWh_e	[17]
Outputs			
Thermal energy generated	10.386	MWh_t	Aspen®
Electrical energy generated	3.74	MWh_e	Aspen®
Emissions and waste			
Specific CO_2 emissions	0.874	$tonne/MWh_e$	[15]
CO_2 total PP emissions	3.27	tonne	-
CO_2 unprocessed (66%)	2.16	tonne	-
Fly ash specific emissions	26580	kg/GWh_e	[16]
Fly ash emissions	99.4	$kg/tonne_{CO2}$	-
Construction materials			
Concrete	158758	kg/MWe	[16]
Steel	50721	kg/MWe	[16]
Aluminium	419	kg/MWe	[16]
Iron	619	kg/MWe	[16]

The composition of the flue gas contains only the main elements, such as H_2O, CO_2, O_2 and N_2, to ensure the computational simplicity of the Aspen® model. Consequently, emissions data related to the omitted elements are obtained from the literature [15].

2.2.3 PCC Unit

The PCC inventory involves emissions associated with CO_2 absorption and solvent regeneration, including SCF construction, TES construction, solvent storages, heat exchangers, etc. It is assumed that the PCC unit has the capacity to process 34% of the total flue gas emissions with a 90% CO_2 capture efficiency [18]. Consequently, the uncaptured CO_2 is considered as an output from the PCC, which will be equal for both systems. Furthermore, the main difference between SA-PCC and SP-PCC lies in their proposed strategies for regenerating the rich solvent. Hence, emissions associated with the common components, such as the absorber, lean cooling heat exchanger, and the condenser, remain constant.

2.2.4 Compression and Sequestration

This inventory includes emissions associated with CO_2 compression, pipeline construction, pipeline recompression, pipeline emissions, and sequestration. The necessary technical parameters for determining compressor work and pipeline transportation can be found in [19].

The sequestration site is located in the Darling Basin, with a total transport distance of 850 km, as shown in *Figure 4*.

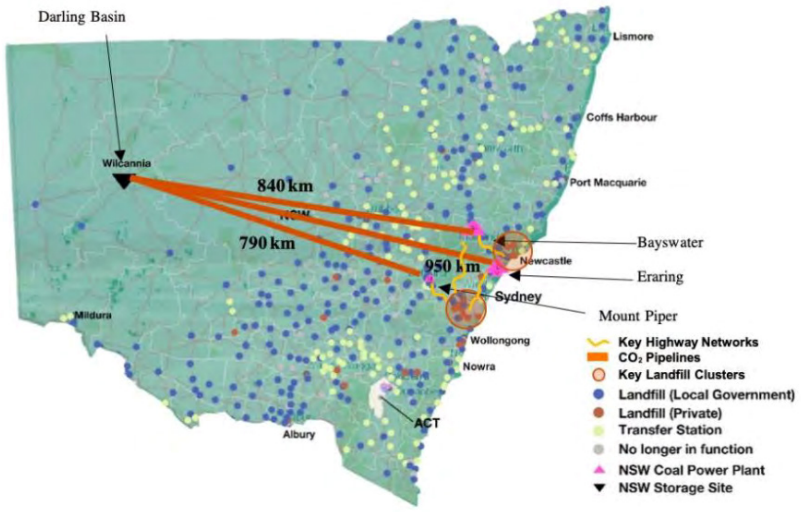

Figure 4. *Location of the sequestration site (Darling Basin). The figure is adopted from literature [15]*

2.3 Impact Assessment Method

Despite the availability of various methods for LCA, this study employs ReCiPe 2016 method to quantify the environmental burden into well-defined impact categories [20]. The ReCiPe method determines the various environmental impacts at the midpoint level using characterization factors and subsequently combines them into three endpoint categories through damaging pathways, as shown in *Figure 5*. This analysis was carried out in the OpenLCA (v.2.0.1) software using the EcoInvent 3.6 database. The obtained results are discussed in the following section.

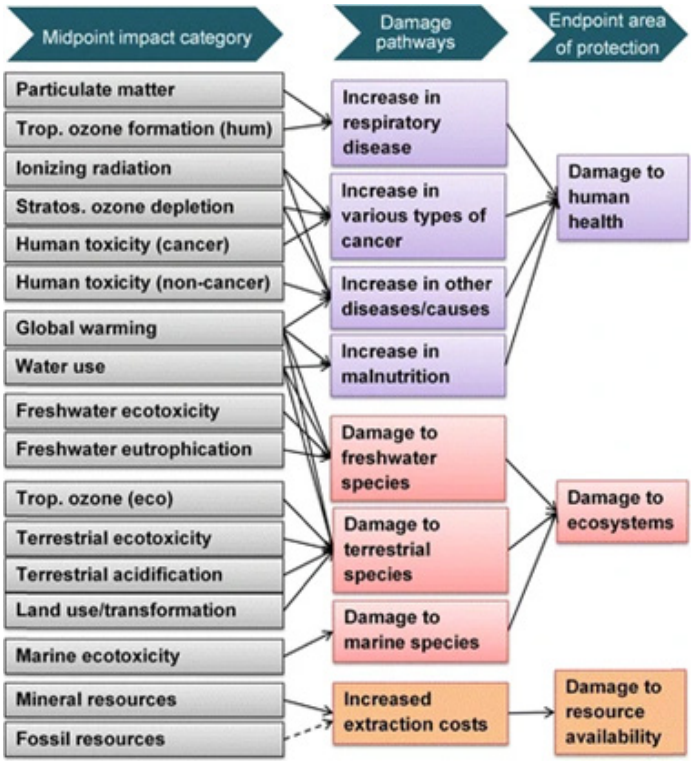

Figure 5. *Schematic of cause-effect pathway in the ReCiPe 2016 method [20]*

3. Results and Discussions

This section discusses the results obtained from the LCA for both SA-PCC and SP-PCC systems. First, the sixteen midpoint environmental impacts are analyzed, and then, the discussion converges in three endpoint impact categories. Some of the midpoint impacts, such as human carcinogenic toxicity and human non-carcinogenic toxicity, are added together to create a single measure of human toxicity, as shown in *Figure 6*. This simplifies the analysis of the results. OpenLCA provides all impacts in 'emissions per tonne of CO_2 captured' as the capture rate is levelized in capturing 1 tonne of CO_2 over the project's lifespan. To facilitate a fair comparison, the results obtained are levelized to a unitless scale from zero to one by dividing the direct emissions by the absolute maximum of the respective impact category across both scenarios.

Figure 6 illustrates the comparison of different midpoint categories for SA-PCC and SP-PCC systems at equal power production capacity. The relative advantages of the SP-PCC system are clearly visible as it occupies lesser midpoint impact area than that of the SA-PCC. Furthermore, both systems make a very similar impact on several midpoint categories, such as freshwater ecotoxicity, freshwater eutrophication, human toxicity, and marine ecotoxicity. Consequently, they are not discussed in this study. It is noteworthy that a couple of categories, i.e., marine eutrophication and water consumption, increase by 71.40% and 32.07%, respectively, when using the SP-PCC system, indicating a negative impression of using SP-PCC compared to SA-PCC.

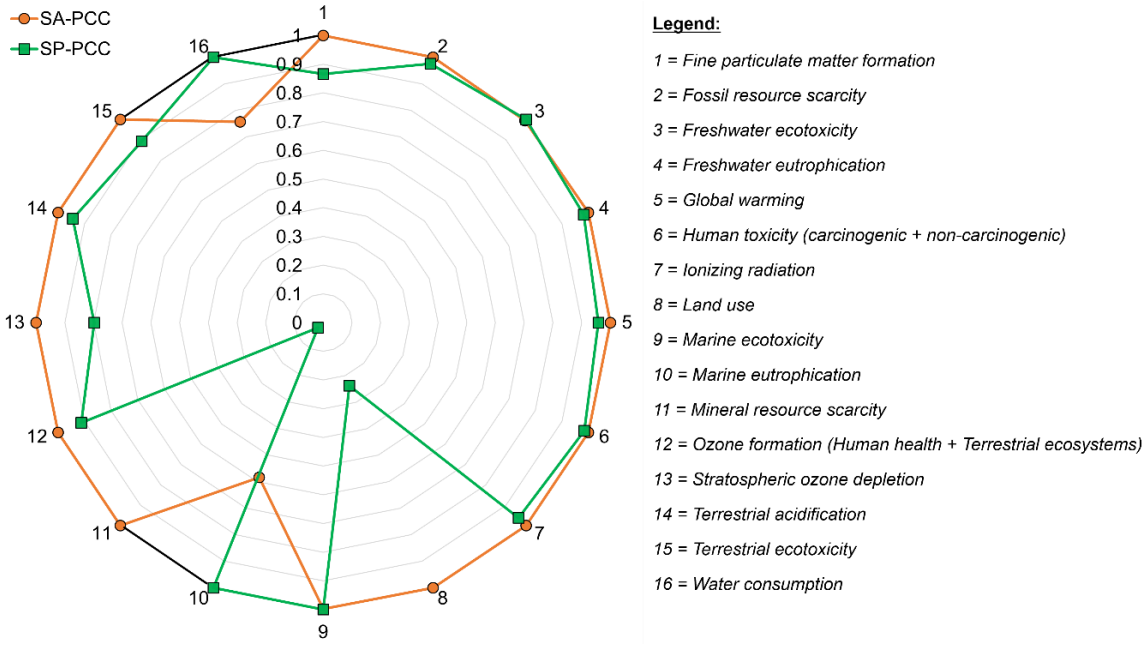

Figure 6. *Comparison of sixteen midpoint categories across the examined systems*

Among the remaining impact categories, some, such as fossil resource scarcity, global warming, ionizing radiation exposure, ozone formation, terrestrial acidification, are marginally reduced (< 10%) by SP-PCC, whereas the rest, including fine particulate matter formation, land use, mineral resource scarcity, stratospheric ozone depletion, terrestrial ecotoxicity, are significantly reduced (> 10%) by SP-PCC. This indicates that SP-PCC in the overall assessment significantly lowers the environment burdens.

Before understanding the reasons behind these reductions, one must filter out the critical midpoint categories based on their nature of impact on the environment. This will help in setting up priorities for improvement in PCC systems. Therefore, the midpoint impacts are grouped according to the damaging pathways shown in *Figure 5*, and the final endpoint categories are

calculated using midpoint-to-endpoint conversion factors. More details on these factors can be found in the literature [20]. There are three main endpoint-protected areas: (1) human health, (2) ecosystems, and (3) resource availability.

The effect on human health is measured in Disability-Adjusted Life Years (DALY), which include the years of life lost due to premature death and the years lived with disability due to illness [21]. The influence on ecosystems quality is measured in the loss of species, including terrestrial, freshwater, and marine, over time (species/yr.). The effect on resource availability is represented in United States dollars (USD), characterizing the additional costs involved in future mining and fossil resource extraction.

It can be seen in *Figure 7(a)* that ionizing radiation, ozone formation, stratospheric ozone depletion, and water consumption do not significantly affect human health through their respective damaging pathways. As a results, they are not discussed in this study. However, it is noteworthy that fine particulate matter formation and global warming contribute to DALY by 37.29% and 49.48%, respectively, for the SA-PCC system. Furthermore, when using the SP-PCC configuration instead of SA-PCC, these contributions are reduced by 13.43% and 4.13%, respectively. This further demonstrates the significance of using the SP-PCC system compared to the SA-PCC. The human carcinogenic toxicity and human non-carcinogenic toxicity share just 6.85%, and 6.19%, respectively, in DALY, both of which are below 10%. As a result, they are not focused on for further analysis.

Regarding the impact on ecosystems, among the various impact categories, only global warming (terrestrial), land use, and terrestrial acidification have a significant contribution to species loss each year, as depicted in *Figure 7(b)*, with contributions of 60.57%, 10.56%, and 14.95%, respectively. Furthermore, when using the SP-PCC configuration instead of SA-PCC, these contributions are lowered by 4.13%, 76.18%, and 5.61%, respectively. Freshwater eutrophication and ozone formation (terrestrial) depict minimal impacts on the ecosystem.

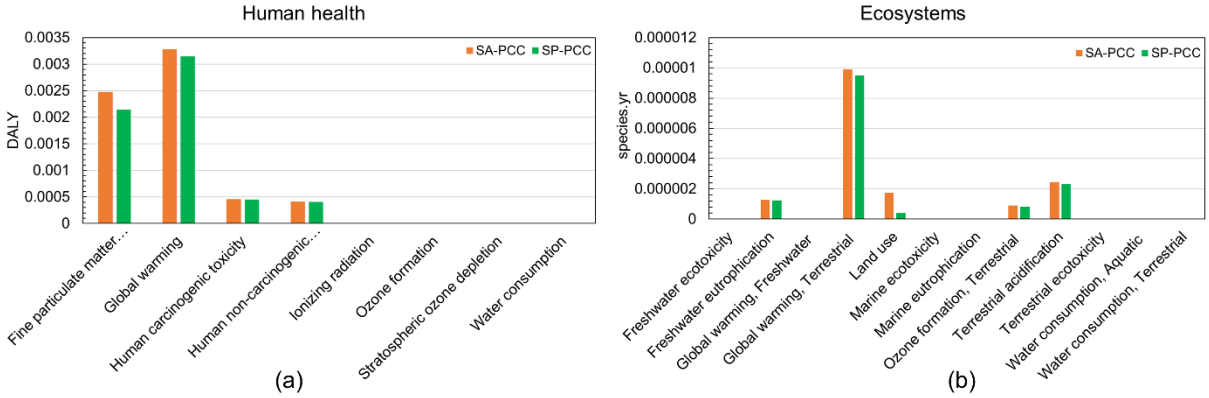

Figure 7. *Impact of various midpoint categories on (a) human health and (b) ecosystems*

Similarly, the SA-PCC system significantly affects the resource availability by generating fossil scarcity (86.51%) and mineral scarcity (13.49%), as illustrated in *Figure 8*. The applicability of SP-PCC reduces these contributions by 4.14% and 97.48%, respectively. The preceding analysis highlights several critical impact categories that deserve attention for improving PCC systems. This includes fine particulate matter formation, global warming, land use, and mineral resource scarcity. To further analyse the results, these midpoint impacts are categorized by the contributing processes, as shown in *Figure 9*.

It is evident that both PCC systems share the same power plants, coal preparation, and fly ash treatment as the primary contributors to the generation of particulate matter and the exacerbation of global warming, as shown in *Figure 9(a)* and *Figure 9(b)*. Furthermore, their contributions are similar due to equivalent coal intake in both PCC systems. The emissions

related to the PCC operation also show consistent impact on global warming. The environmental interventions due to the electricity demand are slightly lowered in SP-PCC compared to SA-PCC system. This is mainly due to the difference of pump rating across both PCC systems.

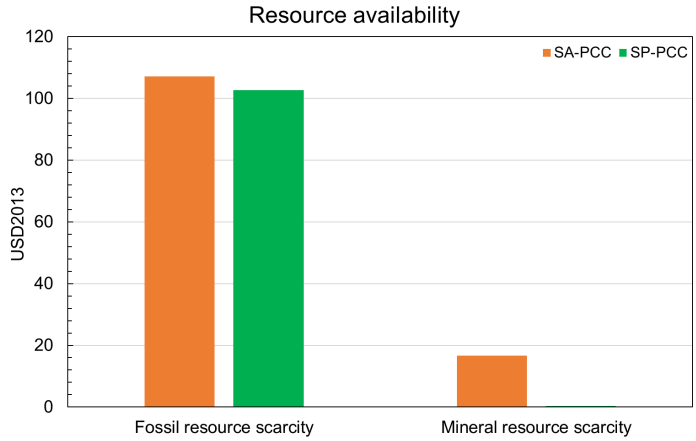

Figure 8. *Impact of various midpoint categories on resource availability*

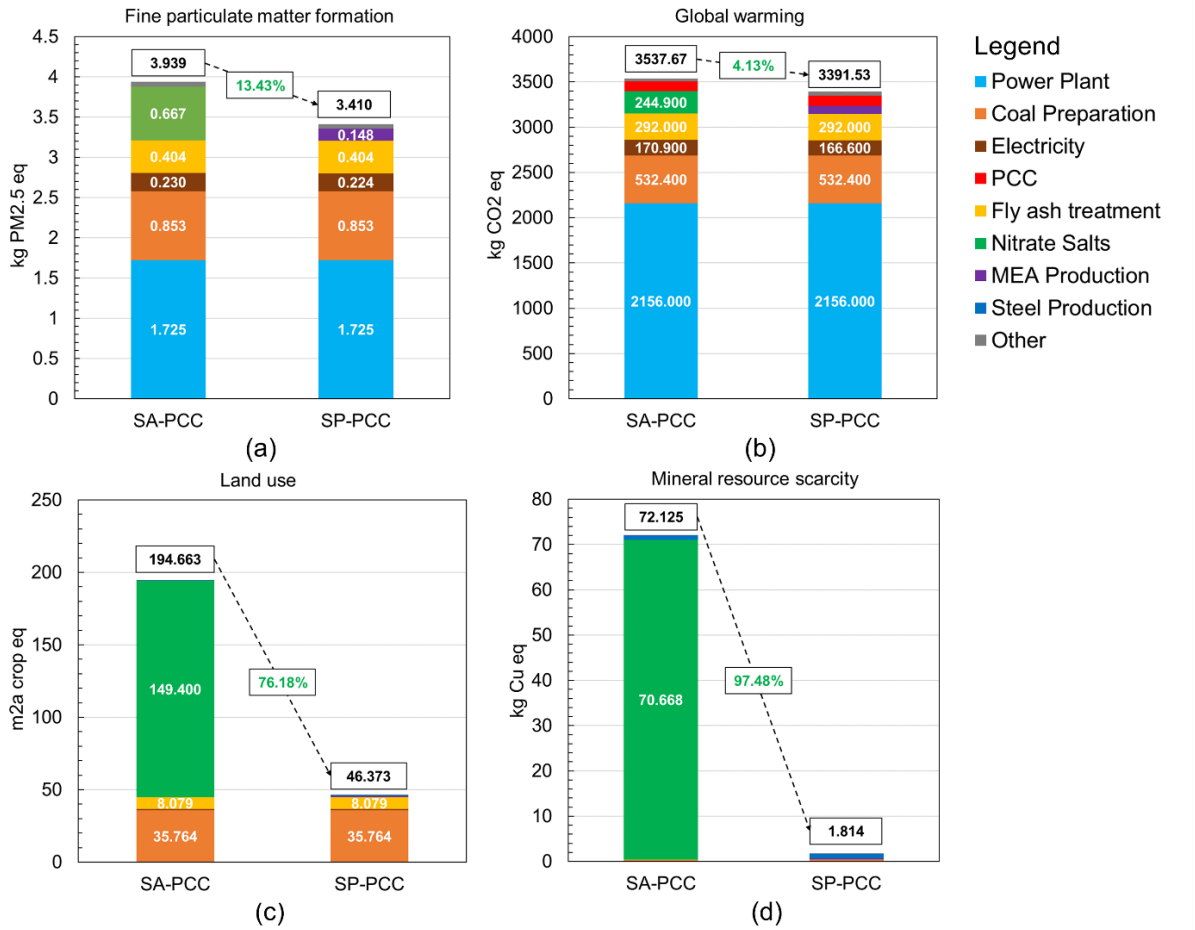

Figure 9. *Critical impact categories stacked by the source of emissions: (a) fine particulate matter formation, (b) global warming, (c) land use, and (d) mineral resource scarcity*

The key distinction between the SA-PCC and SP-PCC systems lies in the contributions of nitrate salts and mono-ethanolamine (MEA) production. The SA-PCC requires large thermal energy storage systems that utilize nitrate salts as a heat transfer fluid. The usage of nitrate

salts contributes 16.93%, 6.92%, 76.75%, and 97.98% to particulate matter formation, global warming, land use, and mineral resource scarcity, respectively. This is due to the production process of nitrate salts, which involves land acquisition for mineral extraction, mineral consumption (specifically magnesium), and emissions of sulphur dioxide, particulate (< 2.5 μm) into the air.

On the other hand, SP-PCC requires a large quantity of circulating aqueous MEA within the solar field to release the captured CO_2. The usage of MEA contributes just 4.34%, 2.66%, 2.45%, and 16.21% to particulate matter formation, global warming, land use, and mineral resource scarcity, respectively. This is mainly due to the manufacturing of MEA, which involves land acquisition for MEA production plant, mineral consumption (iron, nickel, copper, etc.), and emissions of sulphur dioxide, particulate (< 2.5 μm) into the air. It is noteworthy that the contributions of MEA are much lower than that of the nitrate salts across the discussed impact categories. This justifies the superiority of SP-PCC over the SA-PCC counterpart.

4. Conclusions and Future Work

The paper analysed and compared the environmental impacts of solar-assisted post-combustion carbon capture (SA-PCC) and solar-powered PCC (SP-PCC) systems throughout their life cycles using the ReCiPe 2016 method. A power plant of a 660 MW_e capacity was considered, and all the life cycle inventories were levelized to capture one tonne of CO_2 over the project's lifespan. A cradle-to-grave approach was employed to specify the life cycle inventories in OpenLCA software, and comparisons were made based on both midpoint and endpoint impact categories. The findings revealed that SP-PCC occupies a lesser area on the spider chart compared to SA-PCC, indicating a significant reduction in environmental burdens across various midpoint categories. The endpoint impact assessment classified particulate matter formation, global warming, land use, and mineral scarcity as critical impact categories since they exhibited a substantial damaging impact on the endpoint areas of protection. Further categorization of critical impact categories showed that the contributions of the MEA solvent in the SP-PCC configuration are considerably lower than those of nitrate salts in the SA-PCC configuration across these critical categories, demonstrating the superiority of SP-PCC over the SA-PCC system in mitigating environmental burdens using solar energy, since the SP-PCC configuration does not require thermal energy storage media (i.e. nitrate salts).

Since the presented work has focussed on the reference solvent (i.e., MEA) for SP-PCC, it would be interesting to investigate the effects of more-promising solvents on various impact categories. This research direction would be recommended in the potential future works.

Data availability statement

Data available on request from the authors.

Author contributions

N. Modi: Conceptualization, Visualization, Investigation, Methodology, Validation, Writing – original draft. D. Milani: Conceptualization, Methodology, Visualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. N. Abdul Manaf: review & editing. M. T. Luu: Investigation, Formal Analysis, Validation. X. Wang: Supervision, review & editing. A. Abbas: Supervision, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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