SciEn

Proceedings of 8th International Conference on Mechanical, Industrial and Energy Engineering 2024
02-04 January, 2025, Khulna, BANGLADESH

SciEn Conference Series: Engineering Vol. 3, 2025, pp 459-462 https://doi.org/10.38032/scse.2025.3.126

Life Cycle Energy and GHG Emission Analysis of a Direct Air Carbon Capture System

Md. Shazib Uddin, Tanvir Ahmed Rifat, Md. Shaon Asif Ahmed*

Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh

ABSTRACT

This paper investigated the life cycle energy and Greenhouse gas (GHG) emission analysis of a direct air carbon capture (DACC) system. The cradle-to-grave life cycle approach has been adopted in the inventory stages. The life cycle stages namely extraction of the raw materials (Fe, Si, etc.), manufacturing of the component materials (stainless steel, mild steel, etc.), construction of the system, operation, disassembly, and disposal are considered for the analysis. The data were collected from the local industry through field surveys and available literature. Local and international transportation were considered. The result showed that the total life cycle energy consumption and CO_2 emission found are 4,368 MJ and 428 kg respectively. The extraction causes the major energy consumption and GHG emissions throughout the life cycle. The SOx and NOx emissions are the dominant other GHG gases in the life cycle stages. Energy consumption and GHG emissions can be reduced by adopting recycling and reusing materials rather than importing from international sources.

Keywords: Energy consumption, GHG emission, Direct air carbon capture, Life cycle analysis.

1. Introduction

The increasing trend of global fossil fuel consumption and industrialization intensifies the carbon dioxide (CO_2) emissions in the atmosphere and it continues to rise and enhance the greenhouse effect resulting in global warming [1]. The Paris Agreement in 2015 and COP26 in Glasgow 2021 recommended keeping the global temperature rise within 1.5^0C above the pre-industrial level. The development of carbon capture technology is one of the most impactful actions addressing the above challenges [2]. Direct Air Carbon Capture (DACC) is one of the carbon capture technologies that is simple and cost-effective and can extract CO_2 from the ambient air at any location [3]. A modified DACC system has been constructed at RUET, Bangladesh to capture CO_2 from the atmosphere. Though the system captures the emission from the atmosphere it consumes fossil energy during the extraction of the raw materials, component materials manufacture, system construction, transport, and other states and produces harmful emissions in the atmosphere. The life Cycle Assessment (LCA) approach quantifies the energy consumption and emissions of a product or technology throughout the life cycle stages namely, extraction of the raw material, manufacture of the component materials, transportation, etc. Hence, the LCA study of the DACC system constructed at RUET is the focus of this paper.

There are a limited number of related studies available in the literature. Nagapurkar et al., 2024 [4] conducted a life cycle assessment of a direct air carbon capture (DACC) system using OpenLCA software in USA. The boundary stages considered are upstream manufacturing of solid sorbent. The result showed that the global warming potential of $166*10^{-3}$ kg CO_2eq was found per kg CO_2 captured in the DACC plant. Deutz and Bardow, 2021 [5] showed a life cycle assessment study of a commercial direct air-captured plant in Switzerland. Construction of the DACC plant, operation, recycling, and disposal were considered as the life cycle stages. The result showed that the plant emits up to 45b gCO_2-eq per kg CO_2 captured. Madhu et al., 2021 [6] presented a comparative life cycle assessment of two direct air capture technologies (adsorption and aqueous solution type) in Germany. The results showed that with low carbon energy supply the net carbon removal of up to 73% to 86% per ton of CO_2 captured. Terlouw et al., 2021 [7] presented a comprehensive life cycle assessment of DACC system in Switzerland. The component production, transportation, and storage were considered as the boundary stages. The results showed that 6 kg CO_2-eq was generated per ton of CO_2 captured in DACC construction. Liu et al., 2020 [8] conducted the life cycle GHG emission of a DACC system in Canada. Process energy use, construction, and decommissioning (raw material supply to end use) were the boundary stages. The results showed that the system emits 0.51 gCO_2e per gCO_2 captured from the air.

The aforementioned related literature review highlighted the studies conducted other than Asian countries namely in the USA, Canada, and Europe. Their system configuration and capacity are different. LCA boundary stage considerations are different and other assumptions are different.

The life cycle assessment results vary from location to location due to the variation of local industrial performance, national energy mix, environmental regulations, life cycle boundary stages consideration, etc. The present study focused on the life cycle assessment of the direct air carbon capture system based in the Asian developing country Bangladesh which seems unusual in the available literature.

This paper aims to analyze the energy and CO_2 emission in different life cycle stages of a direct air carbon capture (DACC) system constructed at RUET, Bangladesh. A life

*Corresponding Author Email Address: msu@me.ruet.ac.bd

cycle cradle-to-grave approach has been adopted for the assessment.

2. Methodology

The life cycle approach includes goal and scope definition, inventory analysis, assessment, and interpretation.

2.1 Goal and scope definition

The goal of this study is to quantify the energy consumption and CO_2 emission for each life cycle stage namely raw material extraction, manufacturing of the component materials, assembly, operations, transportation, and disassembly of the system at the end of the life. The DACC system capacity considered in this study is 1.5 kg solid sorbent captured 100 gm CO_2 from the air. The DACC system considered in this study is shown in Figure 1.

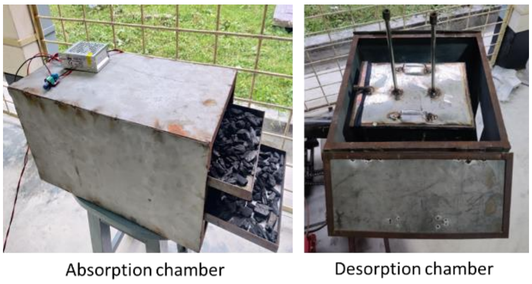


Fig. 1 Direct air carbon capture (DACC) system

2.2 Inventory boundary stages

Figure 2 shows the life cycle boundary stages of the DACC system. The life cycle stages are extraction of the raw materials, component materials production, DACC construction, DACC operation, disassembly at the end of life, disposal of the system, and associated transportation.

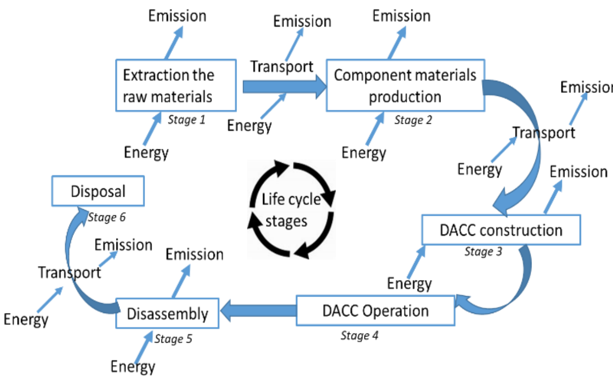


Fig. 2 Life cycle boundary stages of the DACC system

The energy consumption and corresponding emissions in the atmosphere are shown in the Figure. Raw materials such as Si, Mn, Fe, etc extraction is considered abroad and imported. The manufacturing industry uses raw materials and manufactures component materials like stainless steel sheets, bars, mild steel sheets, etc. in Bangladesh. The materials are then transported to the DACC system construction stage. During the operation, it is assumed that the power required to run the electrical component by solar energy. After its lifetime, the system is disassembled and then disposed of in to landfill. Since the system is simple and small in size, the energy required for disassembly is insignificant. The emissions in the disposal stage are neglected as their value is insignificant compared to the total life cycle value. Hence, the raw materials extraction, component material production, construction of the system, and transportation are the major contributors to the life cycle assessment.

2.3 Data and estimation procedure

The DACC system has mainly two components namely absorption chamber and desorption chamber. The mild steel and stainless steel materials are used to construct the system. The mass of component materials (mild steel, stainless steel) is measured and the mass of corresponding compositions called raw materials (Fe, Si, Mn, etc.) is collected through industry visits. The amount of composition is considered for the extraction. The raw materials are imported mainly from China and India. The energy, materials, and transportation data are shown in Table 1.

Table 1 Energy, material, and transportation data for one unit DACC system

Component materials	Raw materials	Total Weight (gm)	Energy for material production (kWh)	Energy for construction (MJ)	Total travel (tkm)
mild steel bar 6.6 kg, mild steel sheet 26.1 kg, Stainless steel bar 2.6 kg, stainless steel sheet 11.5 kg	Fe	41,928	153.21	882	267.3 (ship) and 24.35 (truck)
	C	73.36			
	Si	307.5			
	Mn	480.45			
	S	18.06			
	Cr	2541			
	P	17.65			
	Cu	11.88			
	Ni	1133.26			
	Mo	253.8			

Extraction energy corresponds to each raw material and transportation adopted from the literature [9-13]. Energy for the material production and construction is collected from the local industry visit (KSML, AKS, SSRM, etc.) and the corresponding report.

Carbon dioxide (CO_2) is the major contributor to greenhouse gases (GHGs). The GHG emission is estimated using the emission factor adopted from the literature [14-17]. The emission factor adopted in this study is shown in Table 2. The relation for the calculation is shown by the following equation.

$$CO_2\ emission\ (kg) = Energy\ consumption\ (MJ\ or\ kWh) \times Emissionfactor\ \left(\frac{gm}{MJ}\ or\ \frac{gm}{kWh}\right) \quad (1)$$

Table 2 GHG emission factor [14-17]

GHG emissions	Emission factor (gm/MJ)	Emission factor (gm/kWh)
CO_2	55.52	637
CO	0.033	2.26
CH_4	0.35	0.012
NOx	0.17	4.0
SOx	2.4×10^{-4}	1.47

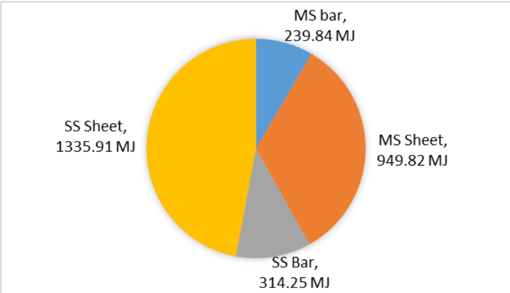
3. Results and Discussion

This section describes the results of the life cycle energy and CO_2 emission analysis of the DACC system.

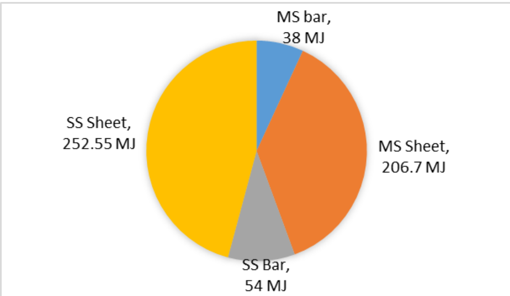
3.1 Energy consumption

Figure 3 shows the energy consumption during raw materials extraction, material production, and transportation.

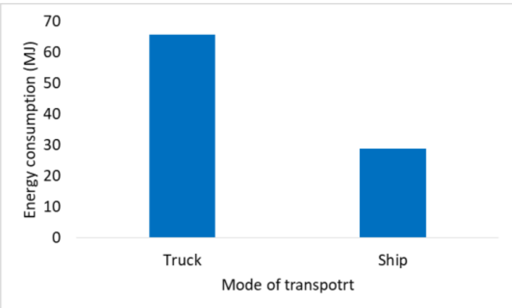
The SS sheet is the most energy-consuming material, consuming around 47% of the total energy estimated for the corresponding stages. The MS bar shows the lower energy consumption. This is because of the high energy consumption during Si extraction compared to other materials. In Fig. 3 (c), the energy consumption for the truck is higher than that of the ship. This is due to the per tkm energy consumption for the truck being higher than the ship.



(a)



(b)

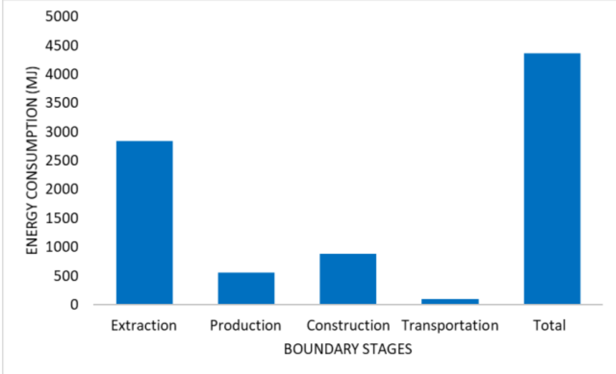


(c)

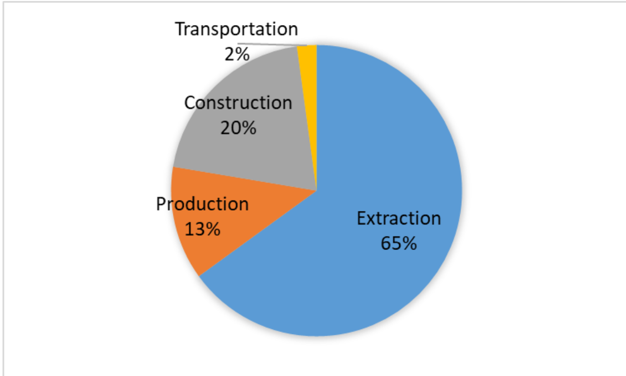
Fig. 3 Energy consumption (a) extraction (b) Material production (c) Transportation

Figure 4 shows the energy consumption throughout the life cycle stages of the DACC system. It is seen that the energy consumption in extraction is higher than in the other boundary stages. This implies that material travel is more dominant over the other stages. The extraction stage is the second highest.

The total life cycle energy consumption found is 4,368 MJ (Fig. 4a). In Fig. 4 (b), it is seen that 65% of the life cycle energy is shared by the extraction stage. The energy share of the transportation found is 2 %. The system construction required more energy than the material production.



(a)



(b)

Fig. 4 Energy consumption throughout the life cycle stages (a) In terms of numerical value (b) Percentage contribution

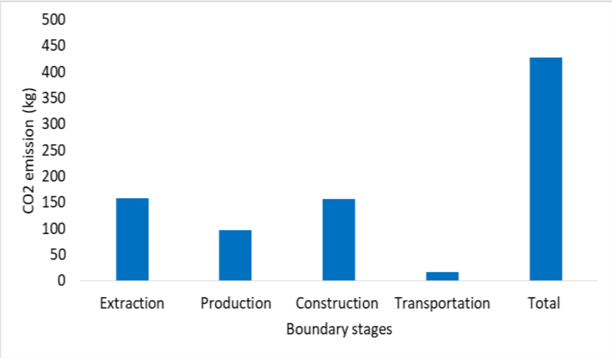
3.2 Carbon dioxide emission

Figure 5 shows the GHG emission of the DACC system throughout the life cycle stages. In Fig. 5 (a), it is seen that the CO_2 emission is higher in the extraction. This is reasonable as extraction shows greater energy consumption. The total life cycle CO_2 emission found is 428 kg. In Fig 5 (b), extraction and construction share 37% and 36% of total life cycle CO_2 emission respectively which is significant. The extraction and construction give an equal share.

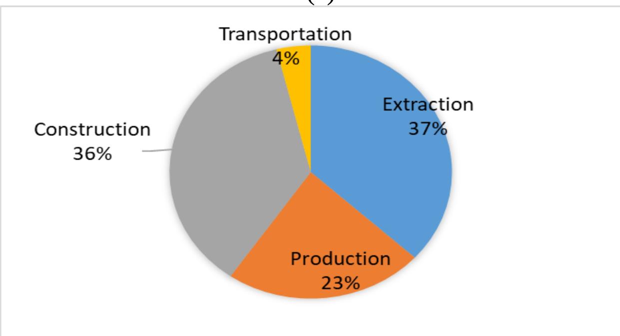
In Fig. 5 (c), the other GHG gases namely CO, CH_4, NOx, and SOx found insignificant in the transportation. The NOx and SOx emissions are higher in the production, and construction stages but lower in the extraction stage. The NOx and CH_4 are higher in the extraction stage. Hence, SOx and NOx have a dominant role in the upstream life cycle stages.

4. Conclusion

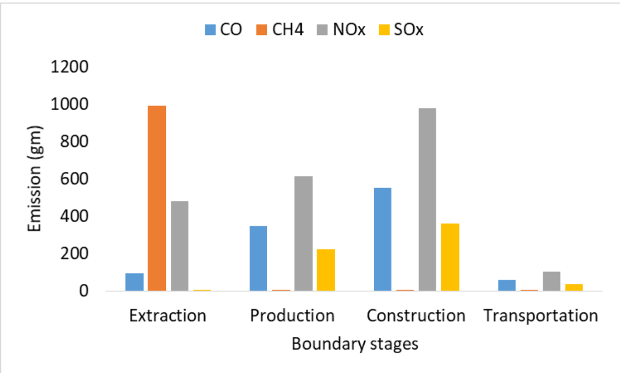
The life cycle energy and greenhouse gas (GHG) emission analysis of a direct air carbon capture system (DACC) has been studied in this paper. Raw material extraction and disposal at the end of its life have been considered the boundary stage. The field survey data from the local industrial production has been adopted for the estimation. The result showed that the total life cycle energy and CO_2 emission found are 4,368 MJ and 428 kg respectively. The extraction stage is responsible for the higher energy consumption and emissions. The other GHG gases like SOx and NOx emissions play a dominant role in the life cycle stages. The results presented in this paper will be useful for the material manufacturer and technology developer to select the energy and environment-friendly pathway to develop the technology.



(a)



(b)



(c)

Fig. 5 GHG emission throughout the life cycle stages (a) CO_2 emission in terms of numerical value (b) CO_2 emission percentage contribution (c) Other GHG gases

5. Acknowledgement

The author would like to acknowledge the Rajshahi University of Engineering & Technology (RUET) for providing the appropriate platform to conduct the study. Also thanks to the industry personnel in Bangladesh for providing the necessary industrial data.

References

[1] Gao, X., Yang, S., Hu, L., Cai, S., Wu, L., Kawi, S., Carbonaceous materials as adsorbents for CO_2 capture: synthesis and modification, *Carbon Capture Science & Technology*, 3, No. 100039, 2022.

[2] Barzagli, F., Peruzzini, M., Zhang, R., Direct CO_2 capture from air with aqueous and nonaqueous diamine solutions: a comparative investigation based on 13C NMR analysis, *Carbon Capture Science & Technology*, 3, No. 100049, 2022.

[3] Beuttler, C., Charles, L., and Wurzbacher, J., The Role of DirectAirCaptureinMitigation of Anthropogenic GreenhouseGasEmissions, perspective published,21November2019doi:10.3389/fclim.2019.00010

[4] Nagapurkar, P., Thirumaran, K., Kidder, M. K., Techno-economic and environmental life cycle assessment of next-generation fiber-encapsulated nanoscale hybrid materials for direct air carbon capture, *Sustainable Materials and Technologies*, Volume 39, e00803, 2024.

[5] Deutz, S., & Bardow, A., Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption, *Nature Energy*, Volume 6, pp. 203–213, 2021.

[6] Madhu, K., Pauliuk, S., Dhathri, S., & Creutzig, F., Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment, *Nature Energy*, Volume 6, pp.1035–1044, 2021.

[7] Terlouw, T., Treyer, K., Bauer, C., and Mazzotti, M., Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources, *Environ. Sci. Technol.*, 55, pp. 11397−11411, 2021.

[8] Liu, C. M., Sandhu, N. K., McCoy, S. T. and Bergerson, J. A., A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production, *Sustainable Energy Fuels*, 4, pp. 3129-3142, 2020.

[9] Nuss, P., Eckelman, M.J., Life cycle assessment of metals: a scientific synthesis. PLoS ONE, 9, 2014. https://doi.org/10.1371/journal.pone.0101298.

[10] Khayyam, H., Naebe, M., Milani, A. S., Fakhrhoseini, S. M., Date, A., Shabani, B., & Jazar, R. N., Improving energy efficiency of carbon fiber manufacturing through waste heat recovery: A circular economy approach with machine learning, *Energy*, *225*, 120113, 2021.

[11] Fan, M., Yu, Z., Ma, W., & Li, L., Life cycle assessment of crystalline silicon wafers for photovoltaic power generation, *Silicon*, *13*, 3177-3189, 2021.

[12] Brehmer, B., & Sanders, J., Energetic and energetic life cycle analysis to explain the hidden costs and effects of current sulfur utilization, *International Journal of Exergy*, *4*(2), 117-133, 2007.

[13] Sylwan, I., Zambrano, J., & Thorin, E., Energy demand for phosphorus recovery from municipal wastewater, *Energy Procedia*, *158*, 4338-4343, 2019.

[14] Ghosh, H., Estimation of greenhouse gas emission factors for natural gas in Bangladesh, *ISES solar world congress*, pp.1-4, 2016. doi:10.18086/swc.2015.07.18

[15] Basu, G., Effect of bio-friendly conditioning agents on jute fiber spinning, *Industrial Crops and Products*, 29 (2-3), pp.281-288, 2009. https://doi.org/10.1016/j.indcrop.2008.05.008

[16] Statista Research Department, Distribution of electricity generation in Bangladesh in 2022, by source (Retrieved June 6, 2023). https://www.statista.com/statistics/1234884/bangladesh-distribution-of-electricity-production-by-source/

[17] US Environmental Protection Agency, Natural gas consumption, 2020. (Retrieved March 28, 2024) https://www.epa.gov/sites/default/files/2020-09/documents/1.4_natural_gas_combustion.pdf

NOMENCLATURE

CO_2 : Carbon dioxide, kg
CO : Carbon monoxide, gm
DACC: Direct air carbon capture
GHG : Greenhouse gas, kg
SOx : Sulfur oxides, gm
NOx : Nitrogen oxides, kg