LIFE CYCLE ANALYSIS OF A DIRECT AIR CAPTURE AND UTILIZATION SYSTEM – TOWARD NEGATIVE EMISSIONS

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Overview

Reduction of CO_2 concentration in the atmosphere is now a global challenge, necessary to solve the problem of climate change. A Direct Air Capture and Utilization (DAC-U) system is one of an emerging set of technologies that removes CO_2 directly from the air and can, therefore, address emissions from any source. In this paper, we focused on evaluating the environmental load, especially the carbon emissions of DAC technology throughout its life cycle to further measure the feasibility of the technology from the perspective of environmental sustainability. Based on the results of the life cycle assessment, this paper presents the CO_2 reduction potential of a DAC-U system as a negative emission technology under three usage senarios including methane production. There is still room for improvement in the accuracy of both our assessment and the performance of the system. One key finding at this stage is that if a hydrogen supply is available in Japan in the future, it will have a significant impact on both fuel production and the overall carbon budget. The findings of this study may provide incentive and future guidance for the development of negative emission technologies and the Japanese hydrogen economy.

Methods

In this study, we use life cycle assessment (LCA) to measure and evaluate the environmental impact of the DAC-U system. The LCA methodology is used to address the environmental aspects and potential environmental impacts throughout a product's life cycle. Four phases are considered in this LCA: goal and scope definition; inventory analysis; impact assessment and interpretation(International Organization for Standardization, 2006). The goal of this study is to evaluate the environmental impact of a direct air capture (DAC) and conversion unit based on the prototype envisage under the NEDO Moonshot project. The DAC-U system is a functional system that captures carbon dioxide directly from the air, enriches it 1000 times to approximately 40% by volume and converts it to useful carbon-based fuels. The system under consideration is divided into two subsystems: the capturing unit (SS1) and conversion unit (SS2). SS1 utilizes a membrane separation module that selectively separates CO_2 from the atmosphere. SS2 contains a module that converts the enriched CO_2 into methane. Figure 1 shows the main energy and material flows of the system. A cradle-to-gate approach is used in the present study (with a cradle to grave approach envisaged in the future), including raw materials extraction, equipment production, operation and maintenance. In this study, the disposal stage was not taken into consideration in the analysis, as well as capital goods.

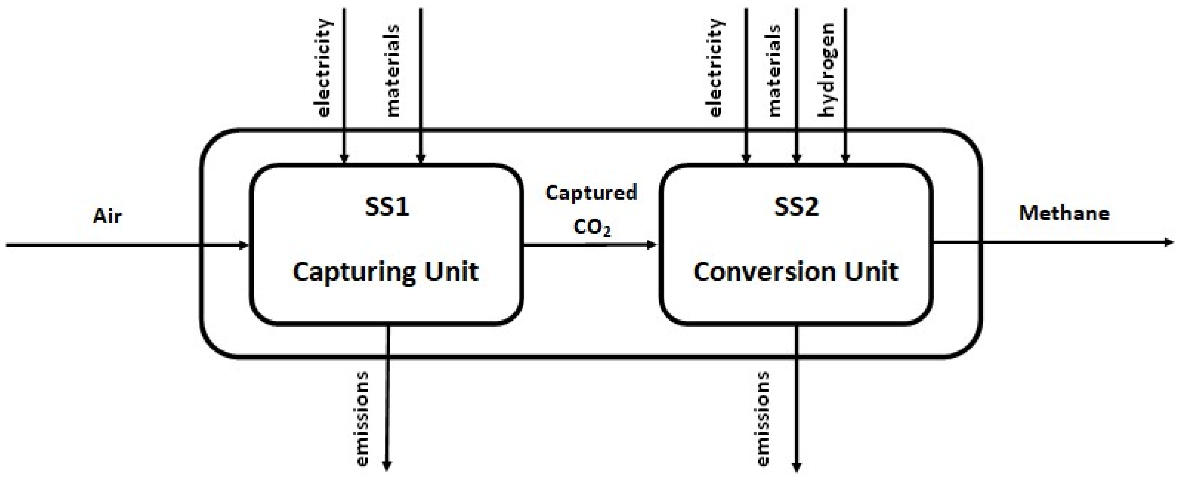

Figure 1-simplified life-cycle flowchart of the DAC-U system

The material and energy flows for the construction of the DAC unit are inventoried based on specific project data, as well as the conversion unit. Three scenarios are defined: base, office and class according to different situations for the location of the device, where CO_2 concentration are different. We assume that the Base Scenario has a CO_2

concentration of 400 ppm, the Office Scenario with 800 ppm and Classroom (class) Scenario with 1000 ppm, affecting the electricity required to capture and enrich CO_2. The data of the operation stage for both subsystems was inventoried based on simulations using Aspen. The inventory data for each process was adapted from the IDEA v2 database. Several simplifying assumptions are made to render the analysis more traceable. First, the capacity of the unit is set such that it captures and converts 1kg of CO_2 per day, and the lifetime of the device is assumed to be 15 years with the separation membrane replaced once a year. Second, the materials in the device and their mass are used to determine the emissions of material manufacturing. Also, all of the electricity consumed for operation of the system comes from solar power and hydrogen is supplied externally and not included in thecurrent analysis. It is an essential point of this research that we assume that by the time the DAC-U system is launched to market, that there is already a mature hydrogen infrastructure in Japan.

Results

As we mentioned in the former section, the inventory data except for hydrogen is entered into LCA software SimaPro 9.1 to carry out environmental characterization of the DAC-U system. We mainly focused on the impact on CO_2 emissions, so the impact category of global warming potential is evaluated (GWP, 20-year time horizon) using the IPCC GWP20a method. Table 1 presents the results of the environmental characterization of the DAC-U system as well as the contribution of each subsystem to the GWP. The contributions of the capturing unit (SS1) are 97.9%, 97.8% and 97.7% respectively in base, office and class scenarios, accounting for the majority of CO_2 emissions for the whole system. Among the processes in SS1, it can also be noticed that assembling the capturing unit emits the most carbon dioxide (around 50% of SS1 emissions) and maintenance comes in second (around 35%).

Table 1-Characterization results of the DAC-U system

Scenario	Unit	SS1			SS2		CO_2 emissions of the DAC-U system	Methane offset	Total emission considering methane offset
		Assemble capturing unit	operation	maintainance (replacing membrane)	Assemble conversion unit	operation			
Base	kg CO_2 e	2421.00	426.30	1480.88	7.34	85.07	4420.59	-355.88	4064.71
Office		2421.00	220.40	1480.88	7.34	85.07	4214.69	-355.88	3858.81
Class		2421.00	177.87	1480.88	7.34	85.07	4172.15	-355.88	3816.28

Taking a closer look at what contributes the most toward SS1 emissions, two processes stand out: 1) the use of 4 vacuum pumps in the capturing stages (1630 kg CO_2) and, 2) the use of Kapton tape to assemble membrane modules which are replaced 14 times over the DAC-U lifetime (945kg CO_2). The production of both of these materials consumes heavy fuel oil which applies a great burden on the environment. A key facet of the Moonshot project is the amelioration of these LCA hotspots. Fit-for-purpose vacuum pumps maybe able to be employed in the future, and physical LCA can be conducted to acquire higher accuracy. Further, more sustainable materials will be sought to work as substitutes for Kapton tape. Table 1 also shows the total carbon emission assessment results considering a methane offset for methane which would otherwise have to be imported into Japan. It is estimated that a total of 421.5 kg of methane will be produced during the lifetime of the functional unit. As methane will be combusted, imported or not, we offset the amount of CO_2 resultant from importing LNG to Japan, equivalent to that generated by the DAC-U. The DAC-U system absorbs 5475kg of carbon dioxide in its lifetime and emits 4064kg, 3858kg and 3816kg CO_2 in the 3 scenarios respectively. It was identified that the DAC-U system could provide a negative emission outcome in the category of global warming potential. It should also be noted that our results did not take into account disposal or recycling processes after the defined lifetime of 15 years, and the emergence and LCA cost of the future hydrogen supply into consideration. A future aim will be to account for these processes within the carbon budget.

Conclusions

Based on the results of the life cycle assessment, this paper presents the CO_2 reduction potential of DAC-U system deploying new technologies that capture CO_2 directly from the air and convert it into carbon fuel in three scenarios with different CO_2 concentration. Our results shows that DAC-U system could contribute to carbon reduction depending on the existance of a mature hydrogen network.

References

International Organization for Standardization (2006) *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*. 2nd edn. Available at: https://www.iso.org/standard/37456.html.