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Review of Research on Direct Air Capture – Nuclear Sector Coupling

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1. Introduction

Direct Air Capture (DAC) technology is a technology that directly removes carbon dioxide (CO_2) from the atmosphere. It is getting attention as one of the key technologies to achieve carbon neutrality and is considered an important technology for responding to climate change. According to the 2022 report by the International Energy Agency (IEA) [1], DAC technology has been evaluated as a critical complementary measure for reducing CO_2 emissions. Among the various DAC technologies, the most used methods are the liquid solvent-based L-DAC technology and the solid adsorbent-based S-DAC technology. L-DAC technology involves capturing CO_2 at high temperatures using liquid absorbents (e.g., potassium hydroxide (KOH)), whereas S-DAC technology uses solid absorbents (e.g., zeolite, amine-based, alkali metal-organic based) to capture CO_2 at low relatively temperatures. Table 1 shows a simple description of L-DAC and S-DAC technologies.

Table 1. Descriptions of L-DAC and S-DAC [2][3]

	L-DAC	S-DAC
Concept	Capture CO_2 at high temperature with DAC method using liquid absorbent [2]	Capture CO_2 at low temperature with DAC method using solid absorbent [2]
Temperature Requirement	High temperature above 900°C is required (VHTR) can be used as high temperature gas [2]	Low temperature heat of about 150°C is required [2]
Energy Requirement	Nuclear power plant can provide base load power 5.25 GJ/t CO_2 [3]	Nuclear power plant provides base-load power(possible flexibility) 5.76GJ/t CO_2 [3]

Although DAC technology is an attractive option to reach carbon neutrality, it faces several challenges that limit its commercialization, such as high energy consumption, capture costs, and operational expenses. One of the most significant drawbacks of DAC technology is its high energy requirements. Unlike other carbon capture technologies, DAC requires a large amount of energy to capture the low concentration of CO_2 in the atmosphere (about 400 ppm). Additionally, high-temperature thermal power is needed during the process of separating the captured CO_2. From an operational perspective, DAC technology also presents several economic challenges. According to research by a team at Worcester University [4] in the United States, a significant portion of the operating costs are attributed to the power consumption of large fans needed for air intake and the thermal energy required to regenerate the adsorbent. Nuclear energy is one of the most promising and stable sources of power and heat needed without carbon emission. The integration of nuclear energy with DAC technology is considered a potential solution to overcome the limitations of DAC, such as high energy demand and operational costs. In particular, next-generation nuclear reactor technologies, such as Small Modular Reactors (SMR), are expected to improve the energy efficiency of DAC systems and reduce operating costs. From a qualitative perspective, nuclear energy and DAC technology are expected to create a synergistic effect. This study aims to review the existing research on the integration of nuclear energy and DAC technology and to propose promising research directions in this field for the future.

2. Case study for nuclear-DAC sector coupling

2.1 US Department of Energy's "Analysis of the Feasibility of Combining Nuclear Power Plants with Negative Emission Technologies and Technological-Economic Feasibility Evaluation"

On September 7, 2023, the U.S. Department of Energy (DOE) released a report titled "Assessment of Nuclear Energy to Support Negative Emission Technologies" [2]. The primary objective of this study was to analyze the feasibility of integrating nuclear power plants (NPP) with Negative Emission Technologies (NET) and to evaluate their technical and economic viability. The study reviewed and assessed seven NET technologies, including Liquid Direct Air Capture (L-DAC), Solid Direct Air Capture (S-DAC), Bioenergy with Carbon Capture and Storage (BECCS), Biochar Sequestration (PyCCS), Enhanced Weathering (EEW), and Indirect Seawater Capture (ISC). The study indicated that integrating DAC technology with nuclear power plants could reduce carbon capture costs compared to conventional systems. Figure 1 presents a graph comparing the LCOD (Levelized Cost of Direct Air Capture, \$/ton CO_2 capture cost) [2]. Specifically, L-DAC technology (\$171–262/t CO_2) is more cost-effective than S-DAC technology (\$648–680/t CO_2) and is more efficient when combined with nuclear power. While S-DAC technology currently has high costs and lacks economic feasibility, it presents potential for future technological advancements.

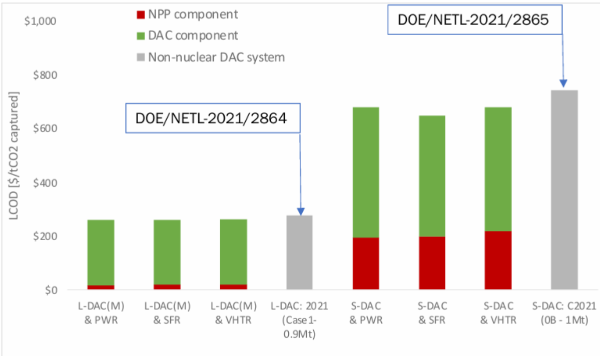

Figure 1 Comparison of LCOD (Levelized Cost of Direct Air Capture, \$/ton CO_2 capture cost) [2].

2.2 Sizewell C's "DAC and GGR innovation project"

On January 21, 2022, the UK's Sizewell C announced its Direct Air Capture (DAC) and Greenhouse Gas Removal (GGR) innovation project [5]. The primary goal of this project is to develop heat-driven DAC technology using low-carbon heat from nuclear power plants. Through research, the project aims to demonstrate the stable operation of the DAC system by utilizing the consistent thermal energy supplied by the nuclear power plant. The project also focuses on achieving an 80% carbon capture efficiency within 45 seconds of contact with the air by utilizing advanced sorbent technology. Figure 2 shows the conceptual diagram for developing demonstration DAC system configuration for Sizewell C project [5]. From an engineering perspective, the Sizewell C power plant is currently studying the feasibility of supplying 4,000 MWth of thermal energy to achieve a capture capacity of 50,000 tons of CO_2 per year by 2030. There are also plans to expand the system to a $1MtCO_2$ scale in the future.

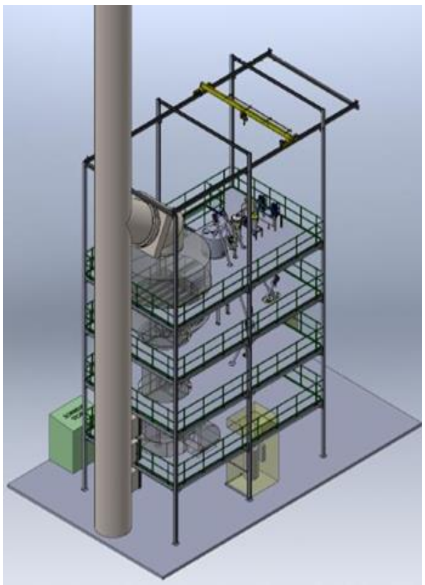

Figure 2 Conceptual Model of the Heat-Driven DAC Plant for the Sizewell C DAC/GGR Project [5]

2.3 Battelle Memorial Institute's NuDACCS (Nuclear Direct Air Capture with Carbon Storage) Project

The NuDACCS project was presented at the Carbon Management Project Review Meeting in August 2022 [6]. This project aims to utilize the available thermal energy from nuclear power plants to separate CO_2 from ambient air and store it in external geological reservoirs. The project seeks to define system costs, performance, socio-economic impacts, and business-case options, with the goal of capturing 5,000 tons of CO_2 annually using the DAC system. To reduce DAC system costs, the project employs contactors and sorbents. During the adsorption stage, a contactor moves air or CO_2-rich gas mixtures through the system, allowing a polymeric amine sorbent to capture CO_2. In the subsequent regeneration stage, the saturated contactor is moved to a regeneration box where low-temperature steam flows through, removing and collecting the CO_2 within 90 seconds. Figure 3 shows the overall flowchart of the NuDACCS project [6].

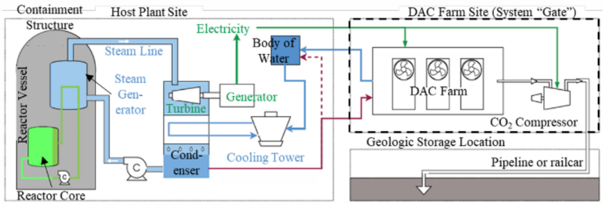

Figure 3 Overall Flowchart of the NuDACCS Project [**6**]

2.4 Other Preliminary Level Studies

There are various studies on the integration of nuclear energy and DAC, but most of them include only simple process analyses or economic feasibility assessments without detailed process design or specific DAC system design. According to McQueen, N., et al (2020) [4], from their article "Cost Analysis of Direct Air Capture and Sequestration Coupled with Low-Carbon Thermal Energy in the United States" indicates that utilizing geothermal and nuclear power plant heat could reduce CO_2 capture costs to below \$300/tCO_2 and suggests a cost reduction approach for DAC using low-temperature thermal energy. This paper explores S-DAC technology and PWRs and is currently at the preliminary feasibility study stage. From Slesinski, D., et al. (2021) [7], "How Low-Carbon Heat Requirements for Direct Air Capture of CO_2 Can Enable the Expansion of Firm Low-Carbon Electricity Generation Resources", the analysis shows that when the DAC system uses a low-temperature solid sorbent (LTSS) method and utilizes low-carbon heat sources such as nuclear and geothermal energy, economic efficiency improves. This paper is researching S-DAC technology and virtual PWR type SMR and is conducting a feasibility study. Sircar, A., et al. (2023) [8], in their article "Techno-Economic Analysis of an Integrated Direct Air Capture System with an Existing Nuclear Power Plant", evaluated the system cost and economic profitability through an economic analysis of integrating the Watts Bar Nuclear Power Plant with a low-temperature solid sorbent (S-DAC) system. This paper explores S-DAC technology and PWR (Watts Bar NPP) and is conducting a preliminary feasibility study. According to Mohan, A., et al. (2024) [9], "Process Engineering and Power System Analysis of Integrated Direct Air Capture with Low-Carbon Heat", This paper analyzed the indirect emission impacts and system costs when operating the S-DAC system using low-temperature steam generated by nuclear power plants. This paper is researching S-DAC technology and virtual PWR type SMR and is conducting a feasibility study. According to Bertoni, L., et al. (2024) [10], "Integrating Direct Air Capture with Small Modular Reactors", the study estimates that integrating a small modular reactor (SMR) with a solid sorbent-based DAC system could improve heat energy utilization and estimates CO_2 capture costs to be around $270. This paper research S-DAC technology and PWR (NuScale) and is conducting a preliminary feasibility study. According to Slavin, B., et al. (2024) [11], "Techno-Economic Analysis of Direct Air Carbon Capture and Hydrogen Production Integrated with a Small Modular Reactor", the study suggests that if the heat generated from a small modular reactor (SMR) is used to integrate DAC and high-temperature steam electrolysis (HTSE) systems, CO_2 capture costs could be reduced to about $124/t$CO_2$. This paper is researching L-DAC technology and virtual VHTR type SMR and conducting a preliminary feasibility study. According to Bekkelund, M. L., et al. (2024) [12], "Techno-Economic Assessment of Direct Air Capture Powered by Nuclear Energy", the study analyzed the economic feasibility of Climeworks' solid sorbent-based DAC system using waste heat from nuclear power plants and estimated CO_2 capture costs at $98.3~104.9/t CO_2. This paper research S-DAC and L-DAC technologies and PWR, BWR, and SCWR types and conducts a preliminary feasibility study. According to Popov, E., et al. (2023) [13], "A Concept for Integration of Direct Air Capture System in the Thermal Balance of a Nuclear Power Station", the study proposed a concept for integrating a DAC system using the thermal energy of nuclear power plants, and a study evaluating the system performance and economic impact using the Watts Bar Nuclear Power Plant as a model is in progress. This paper explores S-DAC technology and PWR and is conducting a feasibility study.

3. Summary and suggestion

Most studies have focused on integrating DAC technology with S-DAC. According to the DOE, L-DAC offers greater energy efficiency and economic viability [2], but its integration with nuclear power is challenging due to the extremely high operating temperature (~900°C) required, and it may also pose additional environmental concerns. Despite these challenges, sector coupling with L-DAC remains an attractive option from a cost-efficiency perspective. Research on DAC-nuclear integration has primarily focused on light water reactors (LWRs). However, there is significant potential for further exploration of reactors with a wider operational temperature range, such as Molten Salt Reactors (MSRs) and Very High-Temperature Reactors (VHTRs), which could enhance compatibility with DAC systems. Apart from two projects Sizewell C in the UK (currently at the pilot plant stage) and NuDACCS (at the FEED stage), most studies on DAC-nuclear integration remain at the feasibility assessment level. Most of these studies focus on basic thermodynamic or economic feasibility analyses, with limited research incorporating comprehensive system analysis. As a result of the review of previous studies, research on non-light water reactors and L-DAC has empty area until now; however, not much research has been conducted so far, indicating that further studies in this area are possible. Additionally, at the system level, detailed certain process design and analysis should be conducted to consider the changes in process flow when an actual DAC system is integrated. This should also be considered as a research topic for the next phase.

Acknowledgement

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Table 2 Summary of Research on the Combination of DAC and Nuclear Technology

Category	Title	Nation	Group/Name	Stage	Reactor Type	DAC Type	Note	Ref
Project	Sizewell C Project	UK	EDF, SizewellC, University of Nottingham …	Pilot Plant	PWR	S-DAC	50,000~5M tCO_2/yr (Goal)	[5]
Project	Assessment of Nuclear Energy to Support Negative Emission Technology	US	DOE/ANL/INL/ NETL	Feasibility Study	VHTR/SFR/PWR	S-DAC & L-DAC		[2]
Project	NuDACCS	US	BATTELLE, Air Capture, University of Alabama …	FEED	PWR	S-DAC	250,000 tCO_2/yr	[6]
Paper	Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States	US	Noah Mcqueen et al., (2020)	Preliminary Feasibility Study	PWR	S-DAC		[4]
Paper	How Low-Carbon Heat Requirements for Direct Air Capture of CO2 Can Enable the Expansion of Firm Low-Carbon Electricity Generation Resources	US	Daniel Slensinski and Scott Litzelman (2021)	Preliminary Feasibility Study	Imaginary PWR type SMR	S-DAC		[7]
Paper	Techno-Economic Analysis of an Integrated Direct Air Capture System with an Existing Nuclear Power Plant	US	A Sircar et al., (2023)	Preliminary Feasibility Study	PWR (Watts Bar NPP)	S-DAC		[8]
Paper	Direct air capture integration with low-carbon heat: Process engineering and power system analysis	US	Aniruddh Mohan et al., (2024)	Preliminary Feasibility Study	Imaginary PWR type SMR	S-DAC		[9]
Paper	Integrating direct air capture with small modular nuclear reactors: understanding performance, cost, and potential	NLD NOR	Luca Bertoni et al., (2024)	Preliminary Feasibility Study	PWR (NuSCALE)	S-DAC		[10]
Paper	Techno-economic analysis of direct air carbon capture and hydrogen production integrated with a small modular reactor	UK	Brittney Slavin et al., (2024)	Preliminary Feasibility Study	Imaginary VHTR type SMR	L-DAC	Hydrogen (HTSE) co-production	[11]
Paper	Techno-economic assessment of direct air capture powerd by nuclear energy	NOR	NTNUNorwegain Univcrsity of Science and Technology	Preliminary Feasibility Study	PWR, BWR, SCWR	S-DAC & L-DAC		[12]
Paper	A Concept for integration of Direct Air Capture System in the Thermal Balance of a Nuclear Power Station	US	Oak Ridge National Laboratory (ORNL)	Feasibility Study	PWR	S-DAC		[13]