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Life cycle assessment of formic acid synthesis utilizing CO₂ from direct air capture†

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This study presents a comprehensive cradle-to-gate life cycle assessment (LCA) of formic acid (FA) synthesis from direct air captured (DAC) carbon dioxide (CO₂) utilizing chemical plant waste heat. The research focuses on a project to implement a low-temperature solid sorbent DAC system co-located with a FA production facility at a fertilizer plant, utilizing industrial waste heat from nitric acid production. This study employs projected operational data from two companies which own the DAC and FA conversion technologies to examine the environmental impacts and benefits of this DAC-to-FA conversion process. By leveraging waste heat and renewable energy, the proposed project demonstrates the environmental advantages of advanced carbon utilization technologies, providing valuable insights for future policy and industrial applications in sustainable chemical manufacturing. Key results indicate that the capture and conversion process, when powered by renewable energy, achieves a net negative global warming potential of -0.806 kg CO₂ eq. per kg FA produced, contrasted against traditional FA production methods which are calculated to emit at best $+2.03$ kg CO₂ eq. The use of waste heat significantly reduces the energy consumption of the process. Compared to traditional FA production methods, the processes also show substantial reductions in ozone depletion, fossil fuel depletion, and other environmental impacts. The novelty of this study lies in its analysis of DAC technology using projected and actual operational data from a DAC development company, which is unique in academic studies. This enhances the accuracy of the LCA and provides a robust foundation for understanding the environmental impacts and benefits of the proposed system. This study also aims to be the first LCA to analyze the life cycle impacts of DAC-to-FA conversion technology.

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Sustainability spotlight

The transition to a circular carbon economy requires innovative, real-world solutions for low-carbon chemical production. In collaboration with direct air capture (DAC) developer Aircapture and OCOchem, this study demonstrates the environmental benefits of a DAC-integrated electrochemical process for producing formic acid (FA) from atmospheric CO₂. Unlike conventional FA synthesis, which relies on fossil-derived feedstocks, this method leverages renewable energy and industrial waste heat to create a scalable, sustainable alternative with real deployment potential. This research represents a new advancement in sustainable chemical engineering, providing a viable pathway for CO₂ utilization in industrial applications. It aligns with SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

1. Introduction

Climate change remains one of the most pressing global challenges of our time, demanding innovative and effective solutions to mitigate its impacts and achieve a sustainable future. The urgency to address climate change is driven by the increasing concentration of greenhouse gases (GHG) in the Earth's atmosphere, primarily due to the burning of fossil

fuels.¹ These activities have led to a rise in global temperatures by over 1.1 °C since 1850, which has already led to extreme weather events and climate extremes across the globe.¹ The need for immediate action is accentuated by scientific consensus, as highlighted in reports by the Intergovernmental Panel on Climate Change (IPCC), which call for drastic reductions in GHG emissions to limit global warming to 1.5 °C above pre-industrial levels.¹

Natural carbon sinks, such as forests, soils, and oceans, can play a key role in absorbing CO₂. However, these systems are limited by land availability, degradation, and saturation effects. To meet climate targets, engineered solutions like DAC provide a scalable and reliable means of removing atmospheric CO₂, complementing natural sequestration. In this context, DAC technologies emerge as a crucial component of

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a comprehensive climate strategy by offering a unique approach to reducing atmospheric CO₂ levels. While many climate change mitigation strategies such as renewable energy integration or point source carbon capture can at best hope to lessen the growth rate of atmospheric carbon, DAC systems, which capture CO₂ directly from the ambient air and subsequently store or utilize it in various applications, provide a potential means to achieve negative emissions and complement emission reduction efforts across other sectors.² The IPCC identifies carbon dioxide removal (CDR) as a critical pathway and projects a need for CDR in the range of 5–15 Gt of CO₂ per year by 2050, depending on the trajectory of emissions reductions.¹ DAC is a scalable and promising technology for achieving this goal while simultaneously providing alternative sources of CO₂ for industry use and carbon conversion technologies in addition to permanent removal. This technology is particularly relevant in hard-to-abate regions where direct emission reductions are challenging, as DAC can be located anywhere, including near a geological storage or chemical conversion sites.^{3,4}

One popular result of captured CO₂ is to sequester it in geological storage or in other permanent applications such as concrete or building materials. This is preferable because the CO₂ is permanently or near permanently removed from the carbon cycle on a time scale relevant to climate change goals,⁵ which can remove previous emissions or offset industries which are unable to reduce emissions substantially. However, geological storage has economic challenges, as it does not allow for the synthesis of a product which can offset the capital or operational cost. Furthermore, CO₂ is a critical feedstock commodity for many industrial applications with a growing supply demand imbalance. In many cases, incumbent supplies of CO₂ used in industry have a high carbon intensity, therefore, replacing high carbon-intensity CO₂ supplies with low carbon-intensity CO₂ can have a superior net negative impact on the global carbon cycle. Direct air capture and carbon utilization (DACCU) can be on the critical path by creating financial incentives by offsetting costs, reducing Scope 1 and Scope 3 emissions industrially, and even achieving profitability through using CO₂ as feedstock for fuels, chemicals, or other products.^{6,7} One proposed development is the synthesis of FA from captured CO₂. FA is a versatile chemical with a wide range of industrial applications; it is extensively used as a preservative and anti-bacterial agent in livestock feed, owing to its ability to inhibit the growth of harmful bacteria and mold.⁸ In the textile industry, FA plays a crucial role in dyeing and finishing processes, improving the quality and durability of fabrics and in the tanning of leathers.⁹ FA is also utilized in various chemical syntheses as a reducing agent and as an intermediate in the manufacture of various pharmaceuticals and pesticides.¹⁰

To achieve the goal of climate change mitigation through sustainable negative emissions technology (NET), a new project proposed by Aircapture and OCOchem aims to implement low temperature solid sorbent DAC technology with FA synthesis, co-located at a Nutrien site to utilize industrial waste heat in the process. This study is performed based on direct inputs from DAC developer Aircapture for projected operational data and inventories and will utilize LCA methodology to determine the

holistic environmental impacts of this proposed project. The novelty of this study lies not only in its description of state-of-the-art DAC technology from Aircapture but also in its methodological approach, utilizing actual and projected operational data from Aircapture and OCOchem, which is unique in academic studies. This enhances the accuracy of the LCA and provides a robust foundation for understanding the environmental impacts and benefits of the proposed system. This evaluation represents a significant step forward in the development and application of DAC technologies. By integrating DAC with FA production and utilizing industrial waste heat, this project demonstrates a practical, scalable solution to mitigating climate change impacts.

In the body of literature of carbon dioxide utilization for FA production, several studies have identified environmentally and economically beneficial processes. Pérez-Forbes *et al.*¹¹ underline the potential market integration and environmental benefits of FA production using CO₂, emphasizing its viability as a hydrogen carrier and for storing renewable electricity. Building on this, Wang, Feng, and Bao¹² explore various catalytic methods for converting CO₂ into FA and highlight the substantial reduction in environmental impact, showcasing FA's potential in energy storage systems.

Further studies by Rumayor *et al.*¹³ and Thonemann and Schulte¹⁴ focus on the environmental competitiveness of electrochemical reduction to illustrate how this method can significantly reduce natural resource consumption and overall environmental impacts, especially when scaled from laboratory to industrial levels. Aldaco *et al.*⁵ demonstrate the environmental and economic advantages of integrating renewable energy with CO₂ utilization processes, suggesting the need for further technological advancements to enhance their competitiveness with conventional carbon capture and storage methods. Thonemann and Pizzol¹⁵ conduct a consequential LCA of multiple CO₂ conversion technologies, identifying FA production as one of the most environmentally beneficial processes. This is complemented by Rumayor, Dominguez-Ramos, and Irabien¹⁶ who explore the sustainability of producing FA from CO₂, noting the importance of cathode lifetime in minimizing environmental impacts and the cost-competitiveness of the process. Sternberg, Jens, and Bardow¹⁷ add to this by highlighting the environmental advantages of using renewable energy for hydrogen production in FA synthesis.

Furthermore, studies by Ahn *et al.*,¹⁸ Weillhard, Argent, and Sans,¹⁹ Kang, Byun, and Han,^{20,21} Dutta *et al.*,²² Kim *et al.*,²³ Ai, Ng, and Ong,²⁴ Biçer *et al.*,²⁵ and Banu *et al.*²⁶ contribute to the literature by advocating for the integration of advanced catalytic methods and renewable energy sources, which enhance the efficiency and sustainability of the FA production process. Each of these studies emphasizes the transformative potential of FA as an enticing possibility in carbon capture and utilization, offering significant reductions in greenhouse gas emissions and fossil resource depletion.

In the literature for LCA of DAC, von der Assen *et al.*^{27,28} provide valuable guides for conducting LCA studies on DACCU systems, while the US DOE provides a more robust framework



for both DACCS and DACCU.^{29,30} Groundbreaking studies such as those by Deutz and Bardow,³¹ Madhu *et al.*,^{32,33} and Terlouw *et al.*³⁴ examine the scalability and environmental impacts of various DAC technologies. They emphasize the importance of energy source and operational efficiencies in achieving negative emissions and highlight potential trade-offs and challenges in implementing DAC at a climate-relevant scale. Similarly, Liu *et al.*³⁵ assess the life cycle GHG emissions from synthetic fuel production using captured CO₂, advocating for the use of low-carbon electricity sources to maximize environmental benefits. Recently, Badger *et al.*³⁶ proposed a low temperature solid sorbent DAC-to-methanol system and found that using renewable energy sources, especially hydroelectric and wind power, significantly reduces greenhouse gas emissions compared to traditional methods of methanol production. These assessments provide a comprehensive view of how DAC technologies, when integrated with sustainable practices, can contribute significantly to climate change mitigation.

Together, these studies form a solid foundation for understanding the environmental and economic implications of advanced carbon utilization and capture technologies, stressing the importance of integrating renewable energy sources to optimize their benefits and feasibility in contributing to a low-carbon future. However, a significant gap in the literature is the lack of access for researchers to partner directly with DAC development engineers to be able to perform assessments that utilize real company data for proposed or completed projects, with Deutz and Bardow³¹ being a notable exception for their work on two Climeworks plants. Most studies must rely on reasonable assumptions due to the lack of empirical data, which could affect the accuracy and applicability of their conclusions. Additionally, while the conversion of point source captured carbon to FA is well-documented, the specific pathway from DAC to FA is not extensively explored in the literature,

suggesting a critical area for further research as one route of CO₂ utilization from one of the most promising carbon removal technologies. This study intends to close these gaps by providing more definitive assessments through a close partnership with Aircapture and OCOchem, and by broadening the scope of viable applications for these technologies in carbon management strategies. Further, the methodology and data derived from the FEED study work for this project can be applicable to other DACCU processes such as methanol, methane, ethylene, synthetic fuel processes, and more.³⁷

2. LCA goal and scope

2.1 Goal

The goal of this LCA is to evaluate the environmental implications and benefits of the “Low Carbon Intensity FA Chemical Synthesis from Direct Air Captured CO₂ Utilizing Chemical Plant Waste Heat” (DACUS) project. This carbon utilization project, as shown in Fig. 1, represents a proposed initiative to synthesize FA from carbon dioxide captured directly from the atmosphere, utilizing waste heat from industrial processes, located at a Nutrien fertilizer operation facility in Kennewick, WA, USA. This work is derived from a FEED study funded by the US DOE.³⁸

There are several pathways for utilizing captured CO₂, including the production of synthetic fuels, methanol, and other value-added chemicals, each with distinct energy and sustainability trade-offs. FA was selected for this study due to its low-carbon electrochemical synthesis potential, its role as a hydrogen carrier, and its established demand in industries such as agriculture, textiles, and chemical processing.

This article will assess the GHG impacts and broader environmental benefits of integrating DAC technology with carbon conversion systems to produce low carbon intensity FA,

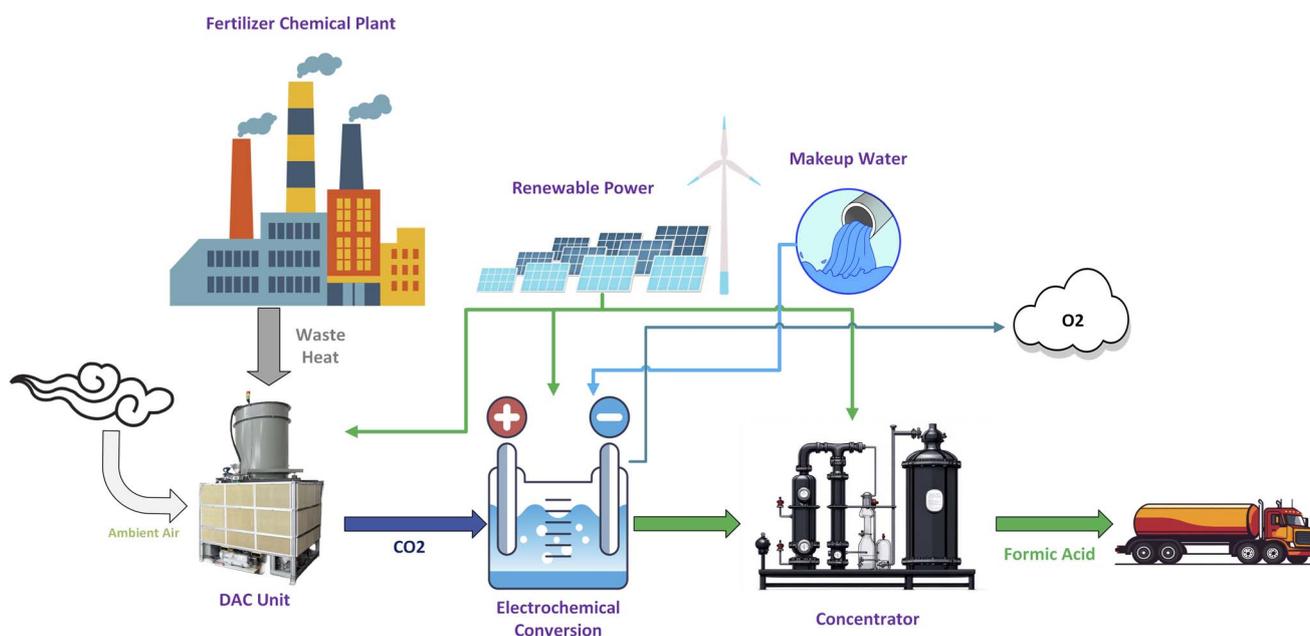


Fig. 1 Overview of the proposed process to convert ambient CO₂ to FA.



compared to traditional FA production methods. The study focuses on quantifying the carbon footprint, energy efficiency, and potential environmental impacts of this DACCU process, from CO₂ capture through to the production of FA, using LCA methodology. FA was selected as the product analyzed in this phase of the project to align with OCOchem's advancements in electrochemical CO₂ conversion technology. This decision followed extensive review of available CO₂ utilization pathways. While FA served as the focus for this initial assessment, alternative products such as methanol are considered as well for the future.

This LCA aims to demonstrate the commercial viability and environmental impacts of the project by providing comprehensive data on the environmental performance of the DACUS process, emphasizing its potential to reduce carbon intensity in chemical manufacturing. This includes detailed GHG emissions analysis throughout the life cycle of FA production, from CO₂ capture to final product synthesis, leveraging DAC of CO₂. As the primary goal of this project is to reduce atmospheric GHG, this study will calculate the net GHG emissions associated with the cradle-to-gate life cycle of FA production *via* the DACUS process, including the capture of atmospheric CO₂, its conversion into FA, and all associated energy and material inputs. Additionally, this study identifies and evaluates the potential environmental benefits of the DACUS project, including reductions in GHG emissions compared to conventional FA production methods and the utilization of waste heat for energy efficiency improvements.

This study is intended for public disclosure and aims to contribute valuable data to the body of knowledge surrounding DACCU technologies. It seeks to inform both policy and industrial practices, aiming to foster the development and

adoption of sustainable chemical synthesis processes that leverage direct air capture of CO₂. By demonstrating the environmental benefits of the DACUS process, this LCA supports the broader goals of reducing carbon intensity in the chemical manufacturing sector and advancing technologies that can contribute to climate change mitigation, as well as provide important information for industries required to reduce Scope 1 and Scope 3 emissions.

The intended application of this LCA is to compare the life cycle GHG impact of the proposed project – FA synthesis from direct air captured CO₂, as modeled of a Proposed Product System, to a Comparison Product System. The reason for the study is to understand how the environmental impact (measured as life cycle GHG impact) of the FA synthesis life cycle compares to the life cycle of a system that produces the same product.

2.2 Scope

The functional unit of this study is “1 kg of FA produced”. This study has three comparison processes which represent three traditional methods of FA production: (1) oxidation of butane, (2) hydrolysis of methyl formate through the carbonylation of methanol, and (3) decarboxylative cyclization of adipic acid. For comparison with the functional unit of the study, the functional unit of each comparison process is “1 kg of FA produced” *via* the referenced method.

Included in the system boundary as shown in Fig. 2 is the capture of carbon dioxide from ambient air in the DAC system, the conversion of carbon dioxide to FA, electrical energy for the processes and infrastructure, all process material inputs including chemicals and make-up water for electrolysis, and the

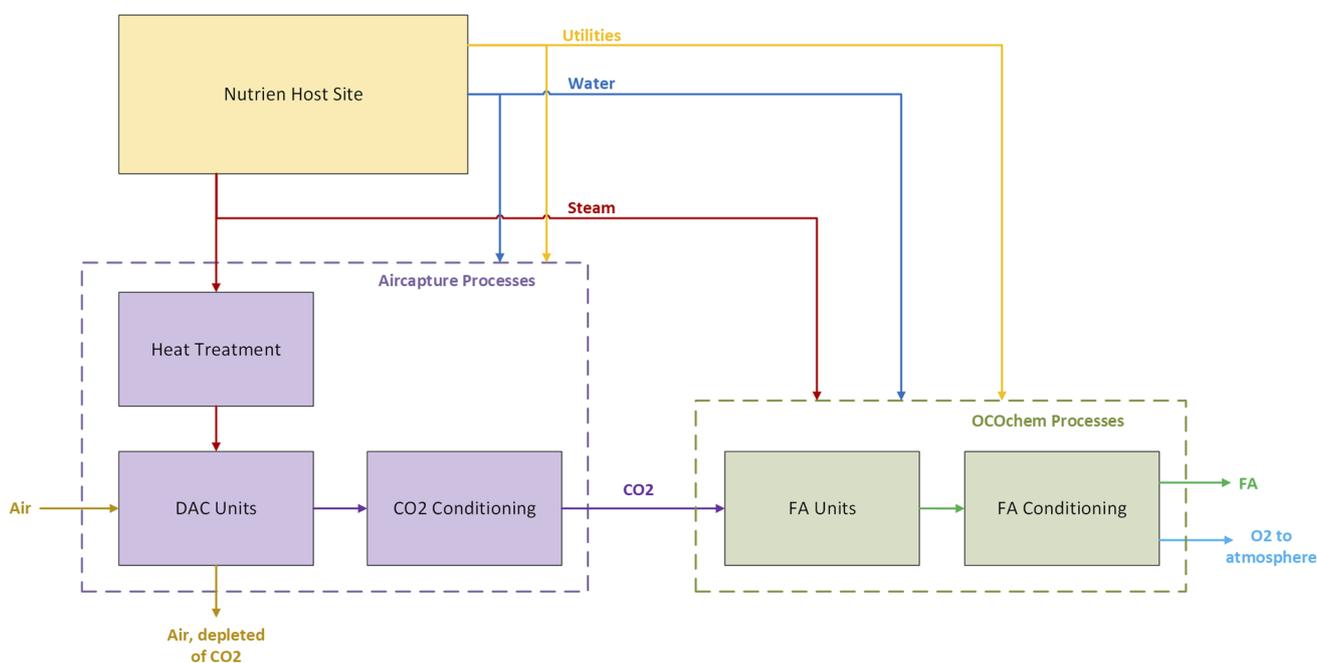


Fig. 2 System boundary for the direct air capture of CO₂ and production of FA from CO₂ feedstock. All processes are included in the boundary except the production of process steam and end use of FA.



construction and end of life processes of the facilities and equipment. Not included in the scope of the study are the end-use of FA and the production of process heat as it is provided from the local fertilizer plant as waste heat from nitric acid production. The methodology of the allocation of waste heat in this study is described in greater detail in Section 3.3.

This study follows a cradle-to-gate LCA approach, in alignment with DOE's Carbon Utilization LCA Guidance³⁰ and the requirements outlined in the FOA.³⁹ Since the goal is to compare the environmental impact of DAC-based FA production to conventional industrial routes, focusing on production-stage emissions, energy use, and resource consumption, the utilization phase of FA, where CO₂ may be re-emitted, is not included in this study. DOE guidance recognizes that cradle-to-gate LCAs are appropriate when evaluating intermediate chemicals whose downstream applications vary significantly. FA can be used in industrial synthesis, hydrogen carriers, or fuel cells, each with different CO₂ release characteristics. Including the utilization phase would introduce high variability and reduce comparability between production pathways, making it difficult to isolate the benefits of DAC-based FA production.

3. Life cycle inventory analysis

3.1 Modeling platform

This LCA is performed using PRé Sustainability's SimaPro version 9.6, a leading LCA software widely recognized for its comprehensive suite of tools and databases. SimaPro facilitates the detailed modeling of complex processes and their environmental impacts, offering robust functionalities for conducting thorough life cycle inventory analyses (LCI) and life cycle impact assessments (LCIA). This software supports multiple LCA methodologies and integrates various environmental impact assessment libraries, such as the ecoinvent database v3.10,⁴⁰ which provides extensive data on energy, materials, and emissions associated with global industrial processes.

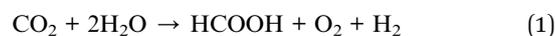
The choice of SimaPro for this project is based on its ability to handle large, complex datasets and for its compatibility with international standards for LCA, including ISO 14040/14044. SimaPro also has the most widely accepted normalization methodologies built-in, including the EPA's TRACI 2.1,^{41,42}

which was modified for the purpose of this assessment to align with the most recent IPCC guidance for GWP weighting factors. The software's user-friendly interface and flexible data handling capabilities allow for precise modeling of the DACUS process, from construction of the facility to CO₂ capture using DAC to the production of FA.

3.2 Formic acid production

The main process in this study is based on the synthesis of FA from CO₂ through three key processes proprietary to OCOchem: the electrocatalytic reduction of CO₂ into formate intermediate, the electrosynthesis of FA from formate, and formic separations.⁴³ The main parameters used in this analysis are recorded in Table 1. An overview of the conversion process is shown in Fig. 3.

The first major process in chemical conversion is the reduction of CO₂ into formate intermediates. This electrochemical transformation occurs at the cathode interface of an electrochemical cell, where CO₂ molecules undergo successive reduction reactions under the influence of an applied electrical potential. Initially, CO₂ molecules are adsorbed onto the surface of the cathode, facilitated by catalytic sites that promote interaction between CO₂ and the electrode. Then, a series of electron transfer events occur, leading to the formation of various intermediate species including carbon monoxide (CO), formate ions (HCOO⁻), and protonated species (H⁺). These intermediates serve as key building blocks in the overall reduction pathway, ultimately yielding formate ions, the precursor to FA. Proprietary electrode materials are used to enhance the desired reduction pathways while minimizing unwanted side reactions. While the specific reactions of the project are proprietary to OCOchem, the overall reaction for a similar process¹⁶ is shown below in eqn (1):



Next, the chemical process proceeds to the electrosynthesis of FA from formate ions through OCOchem's proprietary methods. During this stage, proprietary electrode materials and electrolyte compositions are used to optimize the efficiency and selectivity of FA production.

Finally, FA separation is employed to isolate the synthesized FA from the reaction mixture. A combination of separation techniques is used, tailored to the specific properties of FA and other components present in the reaction mixture. One of the primary methods employed is distillation where FA is concentrated to its target level (85%) and separated from water by introducing an extractive agent, a proprietary sulfolane-based compound, that enhances the relative volatility of water compared to FA. This process overcomes the azeotrope that FA and water form and minimizes energy consumption.

The first distillation column achieves the separation of water from FA with the addition of sulfolane. Sulfolane, together with FA, potassium formate, and traces of water, leaves the bottoms of this column while a highly concentrated water stream leaves in the distillate. This water stream is then cooled and recycled back into the electrolysis and electro dialysis systems. The

Table 1 Key parameters used in this analysis for FA production, per kg FA produced. Anode and cathode surface area consider required material amounts for production rate and the lifetime of materials. Annual FA capacity is based on the conversion of 7143 tons CO₂ per year from DAC

Parameter	Value
CO ₂ inlet mass	0.956 kg per kg FA (ref. 43)
H ₂ O inlet mass	0.391 kg per kg FA (ref. 43)
O ₂ outlet mass to atmosphere	0.348 kg per kg FA (ref. 43)
Electrolysis electricity load	0.841 kW h per kg FA (ref. 43)
Auxiliary electricity load	0.240 kW h per kg FA (ref. 43)
Anode surface area	1.13 cm ² per kg FA (ref. 16)
Cathode surface area	19.84 cm ² per kg FA (ref. 16)
Calculated annual FA capacity	7470 tons per year (ref. 43)



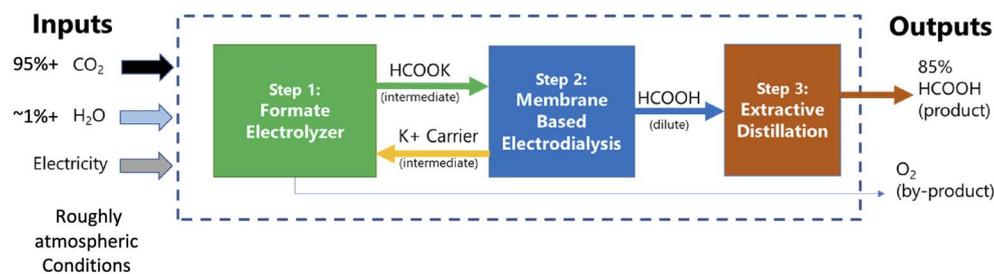


Fig. 3 Overview of OCOchem's FA conversion process.

packed bed column operates at a pressure of 101 kPa gauge with a temperature range of 99–130 °C.

The second distillation column is utilized to recover the entrainer sulfolane. A pressure reducing valve reduces the pressure of the feed stream to the column to the operating pressure of 13 kPa gauge. Sulfolane and remaining potassium formate leave in the bottoms and are recycled back into the first column where a makeup stream of sulfolane is provided. The distillate of the second column is the product stream containing 85 wt% FA and 15 wt% H₂O. This column operates at a temperature range of 53–154 °C, also using a packed bed. This separation technique ensures high purity of the final product and significantly reduces energy consumption compared to traditional distillation methods.

To model these processes in this LCA, CO₂ from DAC and deionized water are considered the two feedstocks in this method of production. Oxygen is produced as a co-product to FA, but this study considers it to be released to the atmosphere as an emission as described in the project proposal.⁴³ All mass input and output values are based on the relative molar masses of the proprietary chemical reactions, and the amount of electrical energy required for the reaction is the 0.841 kW h per kg, and additional 0.2398 kW h per kg for auxiliary building and production equipment. Additionally, process water is deionized from tap water on site at an electricity consumption of 27.15 kW h per ton.

Catalysts are crucial in the chemical synthesis of FA, particularly the catalytic materials used on the electrodes in the

electrochemical reduction process. The anode and cathode serve as the sites for the reactions, and the catalytic materials they incorporate are essential for facilitating the reactions. An LCA study inventory by Rumayor, Dominguez-Ramos, and Irabien¹⁶ was utilized as a proxy to estimate the lifetimes and materials of catalysts. Their study analyzed the environmental impacts of FA manufacturing from carbon dioxide with an emphasis on the influence of electrode lifetime. The cathode used in their study a of gas diffusion electrode with carbon supported by tin nanoparticles (Sn/C-GDE), and the anode is a commercially available dimensionally stable anode (DSA-2 on Pt). While the proprietary electrode materials in this project may differ from those described by Rumayor, Dominguez-Ramos, and Irabien, the results of this study will not differ significantly because this study will demonstrate that electrode materials have a low impact over the life cycle compared to operational and infrastructure impacts; therefore, the referenced study will serve as a suitable proxy.

3.3 Direct air capture

The CO₂ used for FA production is captured directly from the air using a groundbreaking new DAC system designed by Air-capture, which utilizes a polymeric amine sorbent (polyethyleneimine, PEI) coated on a commercially available alumina support to capture CO₂ from ambient air.^{43,44} The main components of the DAC system considered in this LCA are described in Table 2, and the key DAC operational parameters used in this analysis are available as Table 3.

Table 2 DAC equipment considered in this LCA

Component	Description	Primary material	Source
DAC unit structure	Main structure	Steel, aluminum	Manufacturer data
Air contactors	Structured packed bed with PEI-based sorbent and lifetime of several years	PEI sorbent on alumina support	Manufacturer data
Fan system	Induced draft fan to pull air through contactor	Steel	Manufacturer data
Condensate system	Pump, filter, and tank to recirculate condensate	Steel, plastic	Manufacturer data
CO ₂ collection skid	Compression, liquefaction, and short term storage of CO ₂	Steel	Manufacturer data
Steam accumulation tank	Stores and accumulates excess DAC process steam	Carbon steel	Manufacturer data
Vacuum skid	Draws vacuum during desorption phase	Steel	Manufacturer data



Table 3 Key parameters used in this analysis for DAC operation

Parameter	Value
DAC design capacity	7143 tons CO ₂ per year ⁴³
DAC equipment lifetime	20 years ⁴³
DAC location	Kennewick, WA, USA ⁴³
Base electricity load	0.444 kW h per kg CO ₂ (ref. 43 and 44)
Regeneration heat load	4 GJ per ton CO ₂ captured ⁴³
Regeneration temperature	80–100 °C (ref. 43)
Electrical source	Current US grid, 2050 US grid, fossil fuels with CCS, renewables ³⁹
Heat source	Waste heat from co-located Nutrien facility ⁴³
Sorbent type	PEI ^{43,44}
Sorbent consumption (replacement) rate	3.346 g per ton CO ₂ captured ⁴³

The system employs a two-step temperature vacuum swing adsorption process, beginning with ambient air passing over a low-pressure drop monolithic contactor that adsorbs CO₂. This is followed by desorption and sorbent regeneration using steam sourced from industrial waste heat. The DAC cycle is shown in Fig. 4. The DAC system is designed to be highly energy-efficient, using ultra-low pressure drop contactors (150–200 Pa) that operate in laminar flow, minimizing the required energy for air movement. CO₂ capture is facilitated by the transport of CO₂ perpendicular to the air movement through the contactors into mesoporous walls of the contactor, where it binds to the amine sites on the sorbent, effectively lowering the partial pressure of CO₂ and enhancing its absorption.

For regeneration, the system employs low-grade saturated steam (80–100 °C)^{43,44} to release the CO₂, and a vacuum is applied beforehand to remove any air, improving the purity of CO₂ and reducing potential oxidative damage to the sorbent at high temperatures. The DAC machinery is configured to optimize the adsorption and desorption cycles, with multiple contactor assemblies sharing a common infrastructure for fans and the desorption chamber. The physical architecture of the DAC system is designed to enhance the mass transfer rate of CO₂, with air flowing at an optimized speed and the contactor's

mesoporous walls allowing CO₂ to diffuse and bind to the amine sites. This ensures a continuous draw of CO₂ into the contactor, maximizing capture efficiency. Each modular unit has a rotational baseplate that cycles through various adsorption positions and a static desorption position to facilitate efficient CO₂ collection and sorbent regeneration.

The system, shown in Fig. 5, features a unique clam-shell design that opens and closes pneumatically, ensuring even distribution of low-temperature steam across the contactor surfaces for efficient desorption. In addition to the regenerative heat exchanger integrated to recycle water after desorption, the DAC system includes multiple water recovery steps. Condensate generated from the DAC exhaust stream is collected in a dedicated receiver vessel following cooling in a condenser, and additional condensate is recovered from the liquid ring vacuum seal system. Further downstream, water is also separated in the CO₂ conditioning unit through cooling and knockout processes. Where feasible, this recovered water may be reused, while the remainder is directed to the host site's wastewater treatment system. However, for this LCA, the recovered condensate is not credited as recycled due to insufficient data on site-specific water recovery rates, treatment requirements, and reuse practices. If recovered and reused, this water could offer slight reductions in overall environmental impacts by lowering the demand for external water in the FA production process, which is included in this study, or in the host site's fertilizer production processes, which are outside the scope of this study.

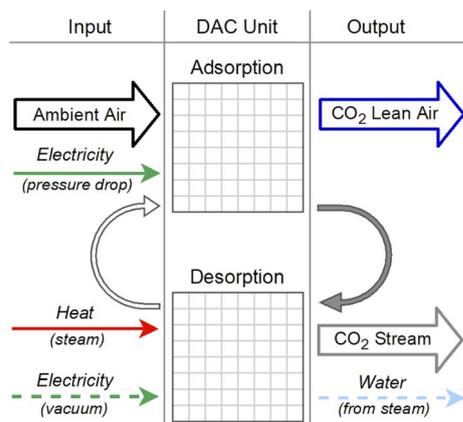


Fig. 4 Aircapture's DAC cycle. CO₂ is collected by moving air across a proprietary contactor which adsorbs CO₂. The contactor is moved into a regeneration box where low-temperature steam flows across the contactor, removing CO₂ from the contactor, and the CO₂ is collected.



Fig. 5 One of Aircapture's DAC units (left) and collection skid (right). Located in Wilsonville, Alabama, USA at the US National Carbon Capture Center, this unit has been operating since March 2023.



Once the CO₂ is collected from the bricks, it passes through this exchanger before entering the desorption chamber. The chamber is then repressurized, the seal is broken, and the monolith turntable rotates, returning the desorbed monoliths to adsorption mode while moving CO₂-loaded monoliths into the desorption chamber, allowing for continuous cyclic operation. Additionally, the system includes a dedicated fan subsystem that helps maintain consistent airflow through the contactors, contributing to the overall power draw.

Since one of the biggest detractors to the sustainable implementation of DAC technology is the large energy requirement for regeneration,⁴⁵ many DAC developers have proposed or implemented industrial waste heat integration as both a cost and life cycle impact mitigation strategy.^{31,32,34,44} Waste heat recovery can reduce CO₂ emissions significantly by utilizing otherwise lost energy streams. The potential savings are economically substantial, estimated at \$20–77 billion annually under a conservative carbon tax, depending on the extent of recovery and carbon pricing policies.⁴⁶

In the Aircapture process, the sorbent undergoes desorption using waste heat steam from highly exothermic chemical processes at the co-located Nutrien fertilizer facility to regenerate and release the captured CO₂ in a concentrated form. This system is characterized by its low energy requirements, attributed to the ultra-low pressure drop contactors that operate in laminar flow, optimizing the capture process. The electrical load required for the DAC systems is 0.444 kW h per kg CO₂,⁴³ and the heat required *via* steam for regeneration is projected to be 3–4 MJ per kg CO₂, supplied as waste heat from the Nutrien facility. The design basis for the Nutrien waste energy stream supports up to 25 000 net tons CO₂ captured per year against the DAC design capacity of 7143 tons CO₂ per year. Because this specific project does not have use or planned projects for the available waste heat stream which is currently released to the environment, the heat input is considered to be burden free as in the study of Climeworks systems by Deutz and Bardow;³¹ however, the impacts of this allocation choice are explored further in Section 4.4.

Regarding the DAC sorbent material, the PEI is planned to be exchanged several times over the lifetime of this project,⁴³ corresponding to a consumption rate of 3.346 g sorbent per ton CO₂ captured. The production and waste treatment of the sorbent is considered in this study, based on the inventory by Deutz and Bardow.³¹

3.4 Energy scenarios

The energy scenarios studied and methodology for the application in this LCA are selected based on requirements from the funding agency for conducting this project.³⁹ Each production process is analyzed under four distinct electricity cases: current U.S. grid mix, projected 2050 U.S. grid mix, fossil fuel power with carbon capture and storage (CCS), and renewables.³⁹ Current and 2050 grid mix are based on the ecoinvent process for U.S. medium voltage electricity mix, which is based on 2022 data.⁴⁰ Because only the amount of CO₂ released for the U.S. grid was changed to create the current and 2050 cases, the non-GWP

Table 4 Energy scenarios used in this analysis, with required carbon intensities as prescribed in the DOE FOA, per MW h of electricity

DOE energy scenario	Carbon intensity
Current U.S. Grid mix	546 kg CO ₂ eq. (ref. 39)
Projected 2050 U.S. Grid mix	434 kg CO ₂ eq. (ref. 39)
Fossil fuels with CCS	220 kg CO ₂ eq. (ref. 39)
Renewables	23 kg CO ₂ eq. (ref. 39)

impacts are mostly identical. As required in the grant, all four processes derive their carbon intensities from NETL's own LCA processes based on DOE research.⁴⁷ Fossil fuel with CCS is modeled as a 50 : 50 mix of pulverized coal and natural gas combined cycle with the captured carbon stored underground as energy production is assumed not to be sufficiently close to the Nutrien site. Renewables is a 50 : 50 mix of the ecoinvent processes for wind and solar photovoltaic. All energy scenarios have been modified as prescribed by the funding agency³⁹ to result in GWP carbon intensities as shown in Table 4.

3.5 Construction

The construction of the facility is considered based on provided inventories from the project proposal and the expected project lifetime of 20 years.⁴³ End of life (EOL) waste treatment is also considered, including the recycling of some of the metals, through methodology described by Deutz and Bardow.³¹

3.6 Comparison to other production methods

The LCA results from the four FA energy scenarios will be compared against three traditional methods of FA production: from oxidation of butane, hydrolysis of methyl formate through the carbonylation of methanol, and decarboxylative cyclization of adipic acid. The three comparison processes are derived from the associated ecoinvent 3.10 production processes, which are based on historical plant data and literature.⁴⁰

This comparative analysis was conducted in accordance with the requirements of the funding announcement,³⁹ which stipulated that LCAs for CO₂ utilization projects must benchmark against traditional production routes. The goal is to determine whether novel CO₂-based pathways provide measurable environmental benefits over conventional fossil-based production methods. Although these methods differ in feedstock, direct comparison remains meaningful as it enables a comprehensive evaluation of carbon intensity and energy use. Comparing DAC-based FA synthesis against industrially established processes ensures that any claimed sustainability benefits are grounded in real-world benchmarks.

For all three conventional FA production pathways, the LCA models incorporate all input materials, energy demands, and emissions across their full life cycle from cradle to the gate of delivery of FA to the customer. The inventory data is derived from real-world industrial plant data and represents global production averages, incorporating upstream impacts such as raw material extraction, refining, and process energy consumption to ensure that comparisons between DAC-based



FA and traditional methods are both comprehensive and representative of real-world production conditions.

4 Life cycle impact assessment

4.1 Impact categories

The methodology used to calculate results as required by the DOE FOA is TRACI 2.1 version 1.08 with the characterization for GWP modified to reflect 2021 IPCC AR6 100-year factors⁴⁸ to match the current scientific consensus. This study employs midpoint indicators rather than endpoint indicators to align with standard LCA methodologies such as those outlined in ISO 14040/44. Midpoint indicators such as global warming potential, acidification potential, and fossil fuel depletion, focus on specific environmental impact mechanisms without aggregating them into broader damage categories. Compared to endpoint indicators, which model long-term damage to human health and ecosystems, midpoint indicators introduce less uncertainty because they are directly tied to measurable environmental mechanisms rather than complex extrapolations. This provides a more transparent, scientifically robust evaluation of process-level impacts which is more comparable with other studies in the field. As required by the grant, the following describes the midpoint impact assessment categories included in this analysis:

- **Global warming potential (GWP):** the potential global warming or climate change impact based on a chemical's radiative forcing and lifetime relative to the impact of carbon dioxide.⁴² Reporting units are kg carbon dioxide equivalent (CO₂ eq.).

- **Ozone depletion potential (ODP):** the deterioration of ozone within the stratosphere by chemicals such as CFCs. Stratospheric ozone provides protection for people, crops, and other plant life from radiation.⁴¹ Reporting units are kg ozone equivalent (O₃ eq.).

- **Photochemical smog formation potential (PSFP):** ground-level ozone, formed by the reaction of NO_x and volatile organic compounds in the presence of sunlight.⁴¹ Reporting units are kg trichlorofluoromethane equivalent (CFC-11 eq.).

- **Acidification potential (AP):** the increased concentration of hydrogen ions in a local environment. This can be from the direct addition of acids, or by indirect chemical reactions from the addition of substances such as ammonia.⁴¹ Reporting units are kg sulfur dioxide equivalent (SO₂ eq.).

- **Eutrophication potential (EP):** the potential for nutrients such as nitrogen and phosphorus to cause excessive growth of algae and other aquatic plants in water bodies, which can lead to decreased oxygen levels in the water, adversely affecting fish and other aquatic life.⁴⁹ Reporting units are kg nitrogen equivalent (N eq.).

- **Carcinogenic potential (CP):** the potential for emissions to contribute to cancer risk in humans. It evaluates the impact of emitting substances known to have cancer effects.⁴² Results are expressed in comparative toxic units for humans (CTUh), reflecting the potential impact per unit of chemical released into the environment.

- **Non-carcinogenic potential (NCP):** the potential for emissions to cause non-cancer health effects in humans, such as neurological, reproductive, or developmental harm.⁴² It involves quantifying the likelihood of adverse health effects based on exposure to non-carcinogenic toxins, also expressed in comparative toxic units for humans (CTUh).

- **Particulate matter formation potential (PMFP):** particulate matter (PM) is the collection of particles in air 10 microns or smaller, which can cause negative human health effects including respiratory illness and death.⁴¹ Smaller diameter particulate matter (2.5 microns or smaller) can be formed by chemical reactions in the atmosphere (*e.g.*, SO₂ and NO_x). Almost all PM impacts are caused by PM 2.5 microns or smaller (PM_{2.5}).⁵⁰ Reporting units are kg PM_{2.5} eq.

- **Ecotoxicity potential (ETP):** the potential of chemicals released into an evaluative environment to cause ecological harm to plants, animals, or the ecosystem in general.⁴² The measurement is based on the predicted environmental concentration of chemicals relative to their no-effect concentration, which is derived from ecotoxicological studies. Reporting units are comparative toxic units for ecosystems (CTUe).

- **Fossil fuel depletion (FFD):** the demand on fossil fuel resources caused by the project's energy consumption. It measures the additional energy burden that future generations would need to bear due to the depletion of these non-renewable resources.⁴² The result is in megajoules of fossil fuel energy consumed (MJ surplus).

4.2 GWP

The LCIA for this project quantitatively evaluates the environmental impacts associated with the production of FA through DAC and utilization of carbon dioxide. Utilizing the TRACI 2.1 methodology, this analysis covers a broad spectrum of impact categories to provide a holistic view of environmental performance. Normalized results for all impact categories are displayed in Fig. 6 and 8, while numerical values are shown in Table 5.

All energy scenarios demonstrate the potential for negative GHG emissions, with renewables emerging as the most carbon negative at -0.806 kg CO₂ eq. per kg FA produced. The three comparison production processes for FA were calculated to have a greater GWP burden, with the lowest being 2.03 kg CO₂ eq. per kg FA for production of FA *via* oxidation of butane. The biggest positive contributor to GWP across all processes for current grid mix is the electricity supply at 0.828 kg CO₂ eq. per kg FA. This improves significantly to 0.0348 kg CO₂ eq. per kg FA for the case of renewable power. In all cases, construction impacts play only a small role in the overall GWP impacts while EOL waste processes are negligible, as shown in Fig. 7. FA production demonstrates to be the largest positive contributor to GWP mainly due to electrical requirements for electrolysis and deionized water, but this impact is lessened substantially when more sustainable energy sources such as renewables are used. The positive GWP contributions of DAC are also improved by renewable energies, but to a lesser extent considering the electrical demand for DAC is much lower than for FA production.



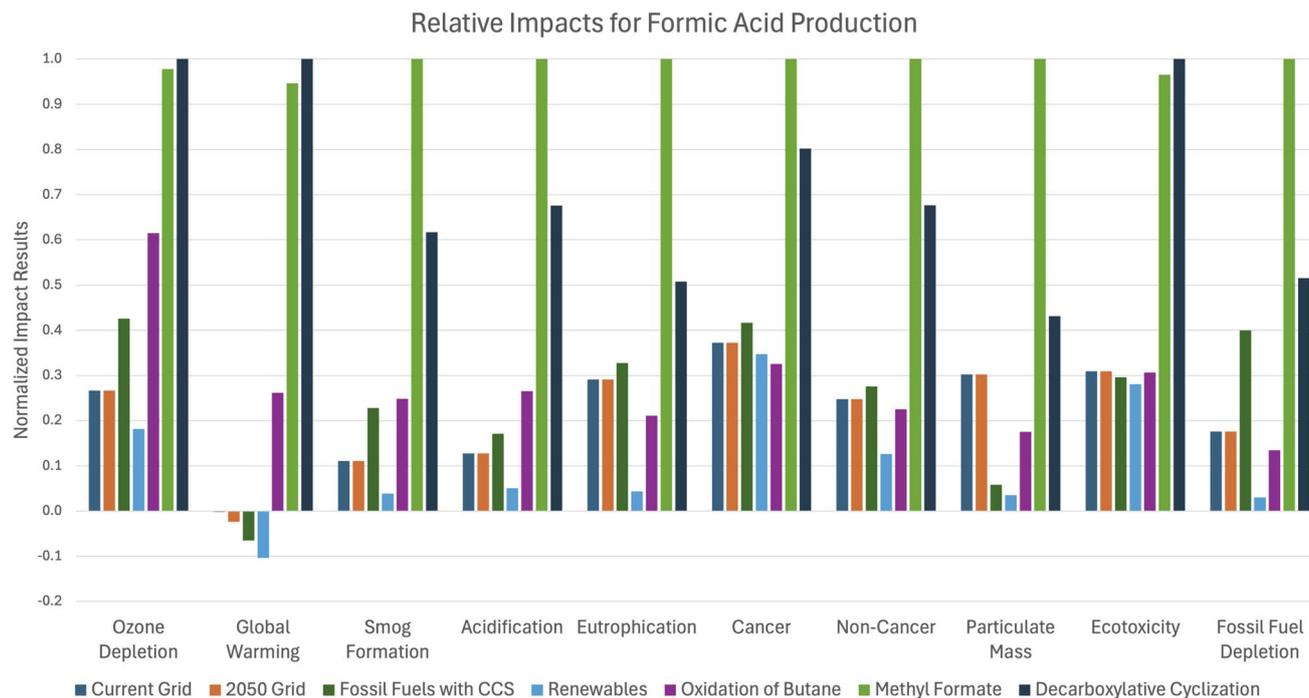


Fig. 6 Impacts of each DACCU energy configuration compared to three comparison processes, normalized to the highest of each impact category.

In this study, the co-produced O_2 was assumed to be released to the atmosphere based on the project proposal. However, if the O_2 were instead compressed and used at an environmental credit (and possible secondary revenue source), this has potential for substantial GWP impact improvements by up to 0.709 kg CO_2 eq. per kg FA. If the project were able to determine market potential and financial benefits for O_2 , this could significantly improve the impacts of the already beneficial DACCU system.

The GWP impact for the construction of plant capital is 0.0814 kg CO_2 eq. per kg FA based on the 20-year lifetime of the equipment, and the impact from end of life demolition and recycling is 8.41×10^{-4} kg CO_2 eq. per kg FA produced. Based on the actual lifetime of the facility, these construction and EOL impacts will vary inversely proportional to the percent increase or decrease in lifetime. For example, if the lifetime is 25 years

instead of the expected 20 years, the construction and EOL impacts will be lessened by 25%. The GWP impact of sorbent production and end of life sorbent processing is negligible at 1.43×10^{-4} kg CO_2 eq. per kg FA.

4.3 Other impact categories

4.3.1 PSFP and ODP. The renewable production of FA through DAC integration significantly lowers the potential for smog formation and has a minimal impact on ozone depletion, illustrating the process's alignment with environmental safety and public health standards.

4.3.2 AP. This study shows that the DACUS process, due to its minimal reliance on fossil fuels and efficient technology, produces lower sulfur dioxide equivalents compared to traditional methods in all energy cases, which demonstrates better results for acidification.

Table 5 Calculated impacts of producing FA from each energy configuration and comparison production process, per kg FA produced

Impact category	Unit	Current	2050	Fossil with CCS	Renewables	Oxidation of butane	Methyl formate	Decarboxylative cyclization
GWP	kg CO_2 eq.	1.70×10^{-8}	1.70×10^{-8}	2.72×10^{-8}	1.16×10^{-8}	3.92×10^{-8}	6.24×10^{-8}	6.38×10^{-8}
ODP	kg CFC-11 eq.	-1.32×10^{-2}	-1.83×10^{-1}	-5.08×10^{-1}	-8.06×10^{-1}	2.03×10^0	7.36×10^0	7.77×10^0
PSFP	kg O_3 eq.	2.39×10^{-2}	2.39×10^{-2}	4.90×10^{-2}	8.30×10^{-3}	5.34×10^{-2}	2.15×10^{-1}	1.33×10^{-1}
AP	kg SO_2 eq.	2.30×10^{-3}	2.30×10^{-3}	3.08×10^{-3}	9.09×10^{-4}	4.78×10^{-3}	1.80×10^{-2}	1.22×10^{-2}
EP	kg N eq.	3.81×10^{-3}	3.81×10^{-3}	4.29×10^{-3}	5.77×10^{-4}	2.77×10^{-3}	1.31×10^{-2}	6.66×10^{-3}
CP	CTUh	2.78×10^{-7}	2.78×10^{-7}	3.11×10^{-7}	2.60×10^{-7}	2.43×10^{-7}	7.47×10^{-7}	5.99×10^{-7}
NCP	CTUh	2.40×10^{-7}	2.40×10^{-7}	2.67×10^{-7}	1.22×10^{-7}	2.18×10^{-7}	9.69×10^{-7}	6.56×10^{-7}
PMFP	kg $PM_{2.5}$ eq.	1.21×10^{-3}	1.21×10^{-3}	2.35×10^{-4}	1.40×10^{-4}	7.01×10^{-4}	4.01×10^{-3}	1.73×10^{-3}
ETP	CTUe	1.47×10^1	1.47×10^1	1.40×10^1	1.33×10^1	1.46×10^1	4.58×10^1	4.74×10^1
FFD	MJ surplus	3.57×10^{-2}	3.57×10^{-2}	8.10×10^{-2}	6.16×10^{-3}	2.74×10^{-2}	2.03×10^{-1}	1.05×10^{-1}



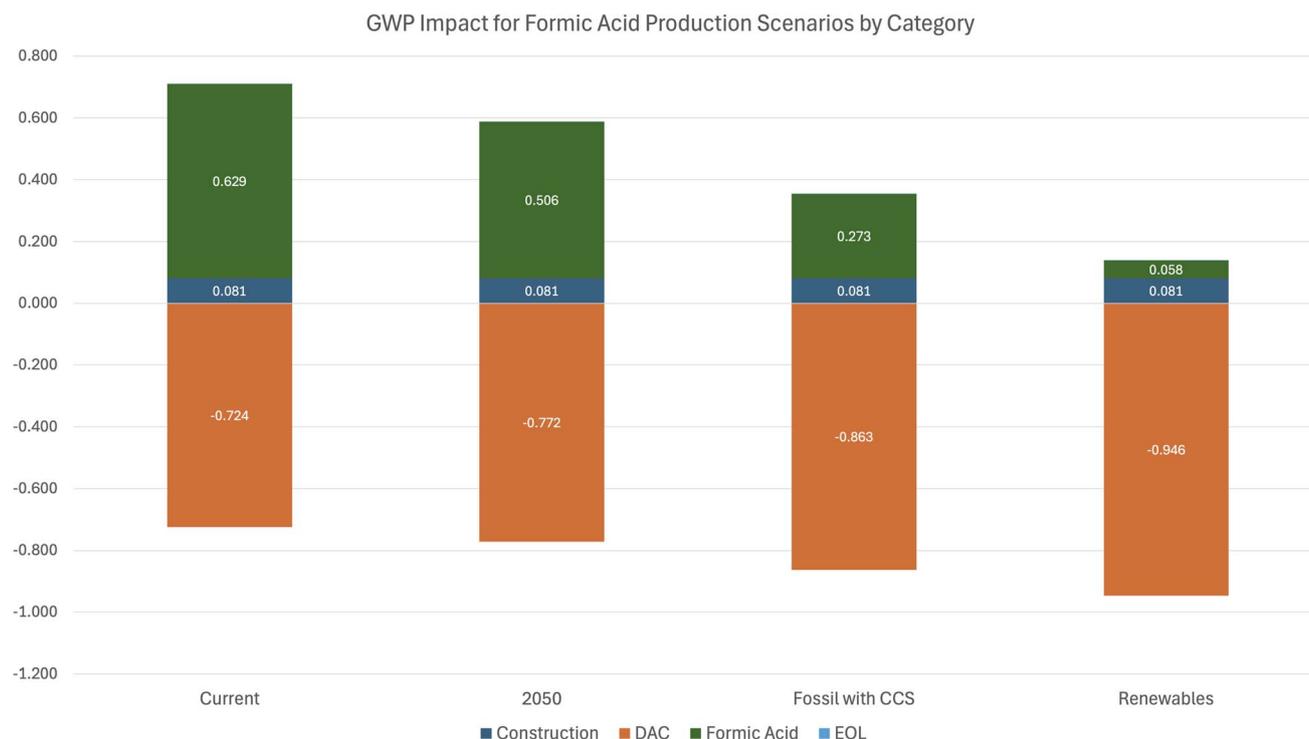


Fig. 7 GWP impact for FA production for each energy scenario, broken down by category. All results are per kg of FA produced.

4.3.3 EP. This impact category is notably lower in the renewably powered DACUS process than through traditional FA production due to reduced nitrogen emissions into water bodies, highlighting an environmental advantage in preventing nutrient run-off and water quality degradation. All energy cases show improvement over FA production through the methyl formate and decarboxylative cyclization routes.

4.3.4 CP and NCP. The DACUS process, when utilizing renewable energy, shows notably lower carcinogenic and non-carcinogenic potentials compared to conventional FA production methods such as hydrolysis of methyl formate, and decarboxylative cyclization of adipic acid, with comparable results to oxidation of butane. This reduction in both CP and NCP emphasizes the health and environmental benefits of minimizing emissions of toxic substances, which is achieved through the adoption of renewable energy sources and cleaner technology in the DACUS process. The lower values in these categories highlight the dual health benefits of reducing exposure to both carcinogenic and non-carcinogenic toxic substances, reinforcing the sustainability and public health advantages of the DACUS initiative.

4.3.5 PMFP. The formation of particulate matter is substantially lower in the renewable and fossil fuel with CCS DACUS processes compared to traditional methods, which demonstrates the process's lower emissions of particulate matter precursors such as sulfur dioxide and nitrogen oxides, especially in scenarios that leverage renewable energy. This reduction contributes to better air quality and lower health risks associated with air pollution, aligning with public health and environmental protection objectives.

4.3.6 ETP. The DACUS process demonstrates a notably lower ecotoxicity potential across all energy scenarios when compared to decarboxylative cyclization and methyl formate FA production. The reduced ETP is primarily due to the minimized use of harmful chemicals and emissions in the DACUS process. The use of renewable energy sources further decreases the potential for ecosystem toxicity, which emphasizes the project's environmental sustainability and its reduced impact on terrestrial and aquatic life.

4.3.7 FFD. The DACUS energy cases which still rely on fossil fuels, can have a significant impact on the depletion of fossil fuel resources, but the renewable DACUS scenario process exhibits a significantly lower demand on fossil fuel resources than all other cases. This reflects the project's alignment with sustainable practices by reducing reliance on non-renewable resources.

4.4 Sensitivity analysis

Sensitivity analysis is conducted to address the variability of several parameters to determine the effects of on the results of variations in the life cycle inventory. Specifically, variations of the construction material usage, energy demand, and catalyst material amount or lifetime were reviewed in this analysis.

First, analysis was conducted on the construction inventory to determine the impact of the study due to possible uncertainties in the quantities of materials used in the capital infrastructure. To examine the sensitivity of this parameter, the expected construction inventory was varied by high and low values of $\pm 25\%$. This adjustment accounts for possible



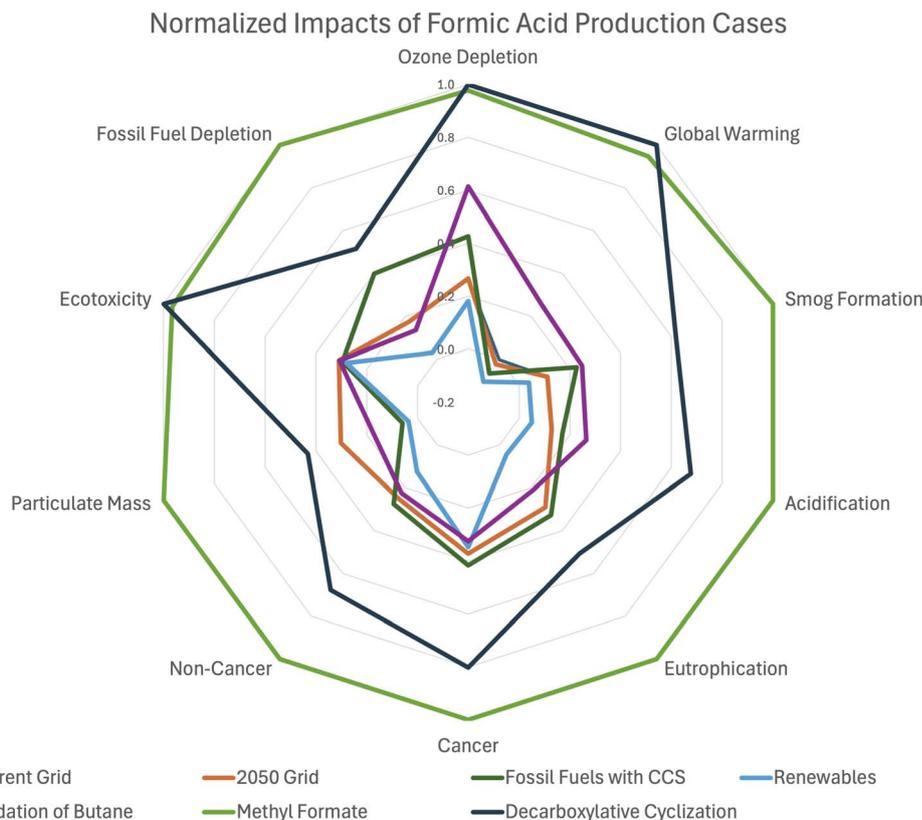


Fig. 8 Relative impacts of DACUS FA production cases of each energy source compared to three traditional reference cases. All values are normalized to the highest in each impact category. Note that Current Grid is identical to 2050 Grid for all impact categories except GWP.

deviations arising from differences in construction methodologies or material substitutions. By exploring these variations, the analysis aims to capture a broader range of potential environmental impacts, highlighting the significance of construction-related decisions in the sustainability of the project. Analysis shows that varying construction inventory by $\pm 25\%$ will change the GWP impact category by ± 0.0206 kg CO₂ eq. per kg FA produced, demonstrating that construction has a low overall impact on the lifetime emissions of the project, which is consistent with DAC literature.^{31–34,44}

Similarly, energy usage for all processes of the project, including the DAC operation, FA production, and water distillation, underwent a sensitivity analysis similarly with a $\pm 25\%$ variation. This adjustment reflects the uncertainty associated with operational energy demand, considering factors such as process efficiency improvements, shifts in energy sourcing, and operational optimizations that may occur over the life cycle of the project. Energy consumption is a pivotal factor in determining the carbon footprint and overall environmental performance of chemical synthesis and carbon capture systems. Therefore, understanding the bounds of energy demand variability is essential for assessing the project's resilience to changes in energy efficiency and for identifying opportunities to reduce environmental impacts through energy management strategies. The impact that energy usage displays with a 25% change varies depending on the energy source, since each of the

four scenarios has a distinctly different GWP impact value per kW h, as shown in Fig. 9. For the best case of renewables and worst case of current U.S. grid mix, a 25% modification to total electrical energy consumption corresponds to a change in GWP of 0.00872 and 0.207 kg CO₂ eq. per kg FA, respectively. Depending on the choice of energy supply, this parameter could be one of the most sensitive, so choosing a low carbon energy source is paramount to maximizing the net negative GWP impact.

Catalysts play a key role in the chemical production of FA, but the specific metals and lifetimes for the anode and cathode are not available for this study. A similar LCA study inventory by Rumayor, Dominguez-Ramos, and Irabien¹⁶ was therefore used as a proxy for the lifetime and materials for catalysts, and sensitivity analysis was conducted to determine the impact that uncertainty in catalysts could have on the study by varying the amount of catalysts used over project lifetime by $\pm 50\%$. Results demonstrate that the overall change in GWP for varying catalyst material requirements is ± 0.0157 kg CO₂ eq. per kg FA, making this a low impact activity.

Process heat remains one of the most impactful parameters in DAC operation, which is the reason for waste heat to be so enticing in DAC systems. In this study, process heat is considered to be burden free due to large available energy content released as waste to the environment from Nutrien's exothermal chemical processes, with no plans for future use. To understand



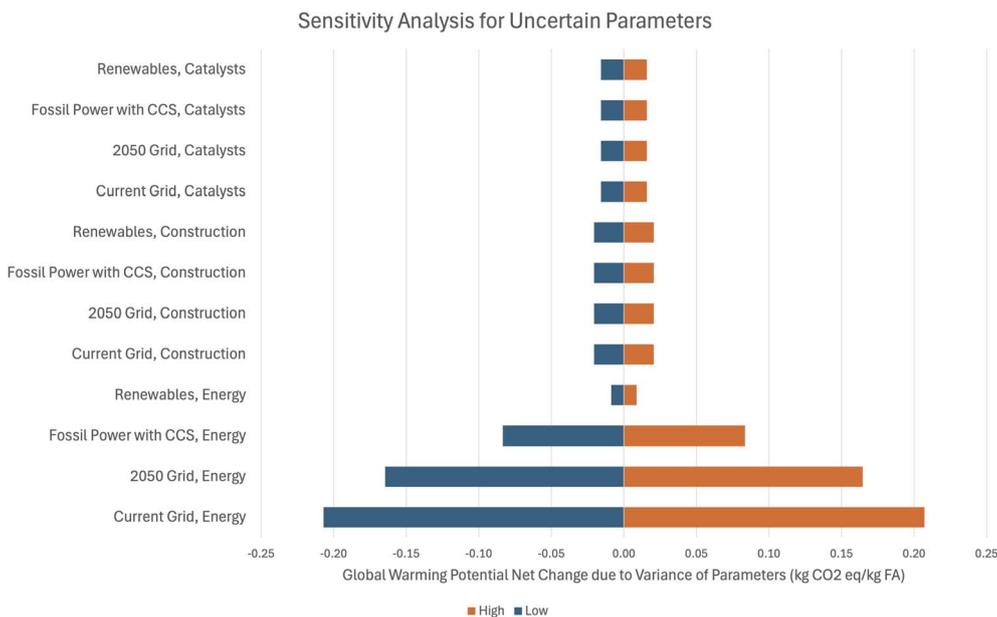


Fig. 9 Variance in GWP impact for sensitivity analysis of catalyst lifetime, construction inputs, and electrical energy usage, in kg CO₂ eq. per kg FA produced.

the impact of this decision, further analysis was conducted to determine the impact if a thermal exergy-based allocation method were selected *via* eqn (2),⁵¹ as done in previous work by the authors.³⁶ Q is the heat requirement, T_0 is the ambient temperature of 25 °C, and T is the system temperature of 100 °C, with both temperatures are units of absolute temperature.⁵¹ The inventory used in this allocation is theecoinvent process for heat from steam used in the chemical industry, which is based on the average fuel mix used in the chemical and petrochemical industry.⁴⁰ Results for the change in impacts are shown in Table 6. Notably, considering the exergy burden of waste heat as a process input would reduce the GWP impact by 0.148 kg CO₂ eq. per kg FA.

$$Ex = Q \left(1 - \frac{T_0}{T} \right) \quad (2)$$

Table 6 Change in results when changing waste heat allocation from no burden to an exergy based method. Note that the results are identical for each of the four energy cases

Impact category	Unit	Difference due to waste heat allocation
GWP	kg CO ₂ eq.	1.31×10^{-9}
ODP	kg CFC-11 eq.	1.48×10^{-1}
PSFP	kg O ₃ eq.	3.03×10^{-3}
AP	kg SO ₂ eq.	2.84×10^{-4}
EP	kg N eq.	1.18×10^{-4}
CP	CTUh	7.34×10^{-9}
NCP	CTUh	1.08×10^{-8}
PMFP	kg PM _{2.5} eq.	3.40×10^{-5}
ETP	CTUe	2.87×10^{-1}
FFD	MJ surplus	2.25×10^{-3}

5. LCA interpretation

The LCIA results clearly demonstrate the potential environmental benefits of the DACUS process, particularly when integrated with renewable energy sources. The LCIA results as shown in Fig. 10 highlight a significant reduction in GWP when comparing the DACUS process powered by renewables to traditional FA production methods. Specifically, the DACUS process with renewable energy exhibits negative GWP values, indicating a net removal of CO₂ from the atmosphere, whereas traditional methods, such as the oxidation of butane and the carbonylation of methanol, show considerably higher positive GWP values. This contrast signifies the effectiveness of integrating DACCU technology with renewable energy in mitigating climate change impacts because not only is existing atmospheric carbon removed, but the impacts of more burdensome methods of chemical production are avoided.

A critical analysis of the other impact categories, such as acidification, eutrophication, and smog formation, also reveals that the DACUS process has lower environmental impacts across these categories compared to all three analyzed traditional methods of production: oxidation of butane, hydrolysis of methyl formate through the carbonylation of methanol, and decarboxylative cyclization of adipic acid. The use of renewable energy significantly contributes to these reductions, showcasing the potential of sustainable energy integration to enhance environmental performance in industrial applications. However, the impact of the DACUS process on categories like carcinogenic and non-carcinogenic effects appears negligible across all scenarios, indicating that these impacts are not significantly influenced by the process changes and remain a minor concern for this LCA study.



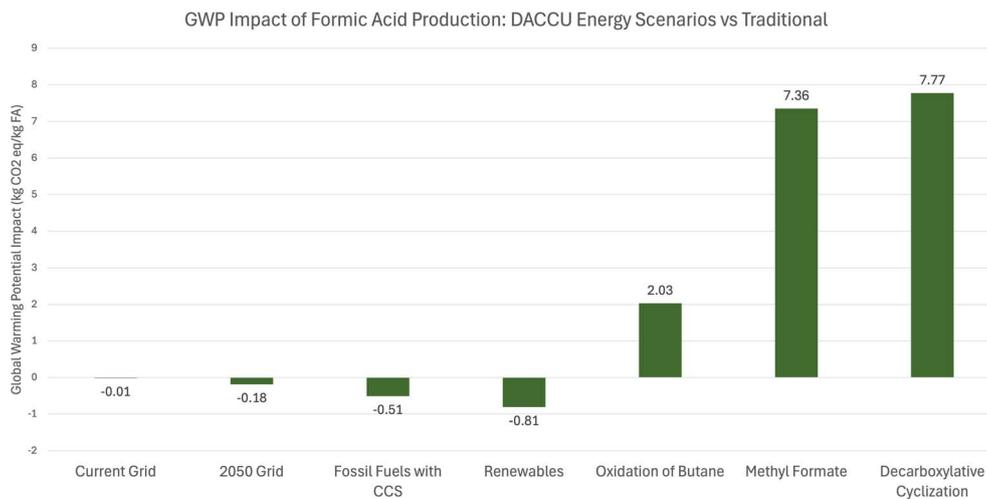


Fig. 10 GWP impact of FA production for different energy cases and comparison methods, in units of kg CO₂ eq. per kg FA produced.

The sensitivity analysis conducted as part of the LCIA indicates that the results are particularly sensitive to changes in energy sources and process efficiencies. For example, shifts from current to future grid mixes, assuming an increase in renewable energy penetration, result in substantial improvements in GWP outcomes. This sensitivity highlights the importance of continued advancements in renewable energy technologies and energy efficiency measures to maximize the environmental benefits of new processes like DACUS.

The net carbon removal was calculated as part of this study, and the results are shown in Fig. 11. To calculate the net capacity of the DACUS system, the functional unit of the study

was modified to give results in “kg of CO₂ captured from ambient air and converted to FA”. For a DAC system design rate of 7143 tons CO₂ per year, the best case energy scenario of renewables has a carbon removal efficiency of 84.3% for a net removal of 6024 tons per year.

6. Comparison to other studies

There remains a gap in the literature in LCAs reviewing FA production from DAC-sourced CO₂, making a direct comparison challenging. To bridge this and compare with existing literature, the focus from the current work is on the FA

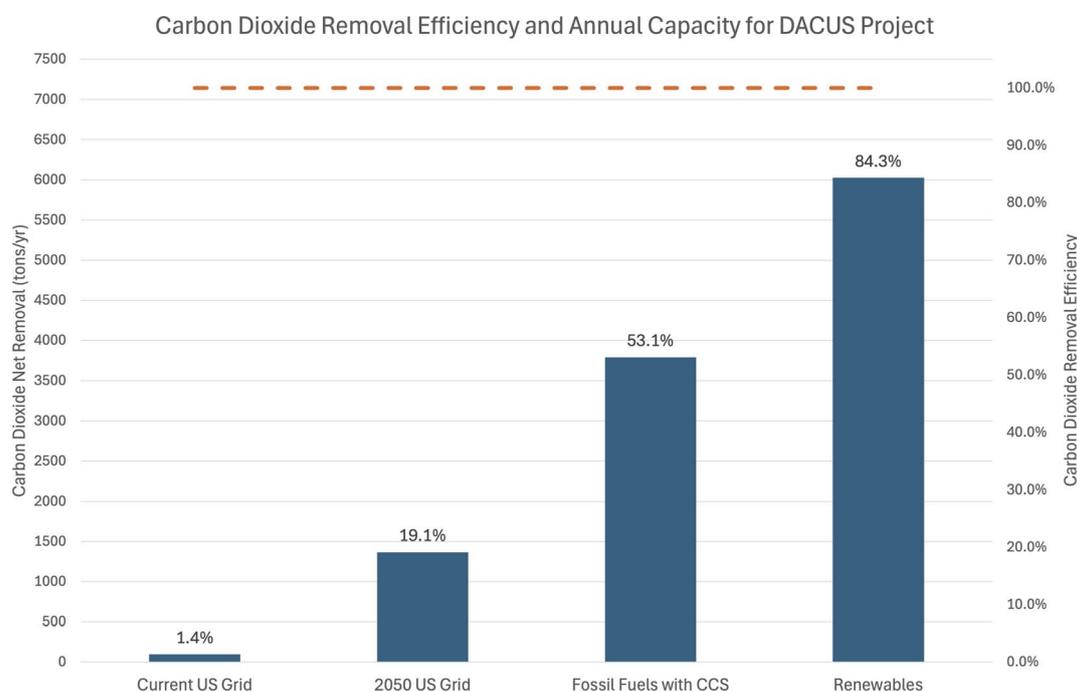


Fig. 11 Carbon removal efficiency and net annual capacity (tons per year) of proposed DACUS system as compared to the gross annual design capacity of 7143 tons (orange).



production without DAC, as powered by the fossil fuels with CCS energy scenario, since this most closely matches several studies conducted on CCU. First, this scenario is compared against the conventional and CO₂-based processes evaluated in Ahn *et al.*¹⁸ In their study, the conventional fossil-based FA production route reports a GWP of 2.007 kg CO₂ eq. per kg FA, while their CO₂-based process with H₂ from electrolysis powered by fossil energy achieves a GWP of 0.098 kg CO₂ eq. per kg FA. Our fossil CCS scenario yields a significantly lower GWP of 0.273 kg CO₂ eq. per kg FA, highlighting the impact of integrating CCS even within a predominantly fossil energy framework.

Results were similarly compared to those from Biçer *et al.*,²⁵ who evaluated FA production *via* electrochemical CO₂ reduction. Their process, relying on a lab-scale H-type cell, resulted in a much higher GWP primarily driven by the significant energy demands of the electrochemical setup. Despite utilizing captured CO₂, the reliance on energy-intensive inputs in their system leads to a GWP of 5.94 kg CO₂ eq., still less favorable environmental performance compared to our fossil CCS configuration.

Our findings were also compared to Blazer *et al.*,⁵² who assessed the electrochemical reduction of captured CO₂ to FA, reporting a GWP of 4.8 kg CO₂ eq. per kg FA. Their study highlights that the environmental impact is heavily influenced by the electricity required for cell operation, which remains substantial even with optimized cell performance.

Despite the varying methods and energy sources across these studies, this study's GWP results remain within the range of reported GWP values, demonstrating consistency with other findings in the field. Our approach of analyzing an industrial-scale DACCU system offers a credible and competitive environmental profile compared to other energy-intensive processes like electrochemical reduction. The alignment with these studies reinforces the reliability and relevance of our findings within the broader context of sustainable FA production.

7. Conclusion

The DACUS project proposal represents an enticing advancement in the integration of DAC technology with FA synthesis, offering substantial environmental benefits over traditional FA production methods. This LCA demonstrated that the DACUS process, especially when powered by renewable energy, achieves notable reductions in greenhouse gas emissions, global warming potential, and other environmental impacts. By leveraging waste heat from industrial processes, these integrated processes further enhance sustainability and energy efficiency.

Future research should build on this work by exploring other potential CO₂ utilization routes. Beyond formic acid, the CO₂ captured through this DAC system could serve as a feedstock for a diverse range of carbon utilization pathways, including the production of synthetic fuels, methanol, methane, and ethylene *via* thermochemical or electrochemical conversion. Additionally, CO₂ is widely used in non-conversion applications across various industries, such as in carbonated beverages, food processing, refrigeration, welding, and enhanced oil recovery.

Emerging applications also include mineralization for building materials like concrete and aggregates, as well as algae cultivation for biofuels or bioplastics. Each pathway presents unique life cycle considerations in terms of energy demand, permanence of carbon storage, and market maturity. Expanding DAC integration into these sectors could enhance CO₂ removal impact and broaden the economic case for DAC deployment.

This study contributes to the growing body of literature on carbon utilization and DAC technologies by providing empirical data and a detailed environmental assessment based on operational data. The findings highlight the feasibility of combining DAC with chemical production to create scalable, negative emission technologies that can significantly mitigate climate change impacts. The results emphasize the potential of DACUS to align with global sustainability goals and transition to greener industrial practices.

Nomenclature

AP	Acidification potential
AR6	IPCC sixth assessment report
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CDR	Carbon dioxide removal
CFC-11	Trichlorofluoromethane
CP	Carcinogenic potential
CTU _e	Comparative toxic units for ecosystems
CTU _h	Comparative toxic units for humans
DAC	Direct air capture
DACCU	Direct air capture and carbon utilization
DACUS	Reference name of the proposed project
DOE	US Department of Energy
DSA	Dimensionally stable anode
e ⁻	Electron
EOL	End of life
EP	Eutrophication potential
EPA	Environmental protection agency
ETP	Ecotoxicity potential
eq.	Equivalent
FA	Formic acid
FEED	Front-end engineering and design
FFD	Fossil fuel depletion
FOA	Funding opportunity announcement
GDE	Gas diffusion electrode
GHG	Greenhouse gas
Gt	Metric gigaton
GWP	Global warming potential
HCOOH	Formic acid
IPCC	Intergovernmental panel on climate change
ISO	International organization for standardization
kt	Metric kiloton
kW h	Kilowatt hour
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
MW h	Megawatt hour
Mt	Metric megaton



N	Nitrogen
N ₂ O	Nitrous oxide
NCP	Non-carcinogenic potential
NET	Negative emissions technology
NETL	US National Energy Technology Laboratory
NO _x	Oxides of nitrogen
NZE	Net zero emissions
ODP	Ozone depletion potential
PEI	Polyethylenimine
PM	Particulate matter
PMFP	Particulate matter formation potential
PSFP	Photochemical smog formation potential
Pt	Platinum
Sn	Tin
SO ₂	Sulfur dioxide
SO _x	Oxides of sulfur
ton	Metric ton (1000 kg)
TRACI	Tool for reduction and assessment of chemicals and other environmental impacts
TRL	Technology readiness level
U.S.	United States
USA	United States of America
USD	United States dollar
WA	Washington
wt%	Percent by weight

Data availability

The life cycle inventory and project economics data used in this study contain proprietary process parameters and economic details provided by Aircapture and OCOchem. Due to the sensitive nature of this information, the complete datasets will only be made available with written permission from both Aircapture and OCOchem. All releasable LCI data relevant to this study are presented in the article as tables. No additional data is available in external repositories or ESI.† All releasable results are included in the ESI.†

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

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