LanzaTech

ERA Project ID (from ERIMS):	B0160656
Project Title:	Carbon Sequestration via Next-Generation Bioreactor Technology
Lead Applicant Organization:	LanzaTech, Inc.
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Requested ERA Funding:	CAD 10,000,000

0	Aug 31, 2023	ERA Final Report, Non-Confidential	LanzaTech	R. Conrado	R. Conrado
Rev	**Date**	**Reason for Issue**	**Prepared By**	**Reviewed By**	**Approved By**

Contents

1. Executive Summary

With funding from ERA BEST, and in partnership with Suncor, LanzaTech has successfully executed the project "Carbon Sequestration via Next-Generation Bioreactor Technology" to manufacture and validate the performance of LanzaTech's next-generation bioreactor technology at demonstration scale.

This project "Carbon Sequestration via Next-Generation Bioreactor Technology" was proposed to demonstrate the next advance in gas fermentation technology: a novel bioreactor design developed by LanzaTech which enables best-in-class gas-liquid mass transfer relative to the required energy input. This technology is important especially when produced gases, such as syngas, are used as feedstock. This technology has been paired with LanzaTech's proprietary gas fermentation microbe which has already been proven in commercial ethanol production. This next-generation gas fermentation platform was demonstrated at demonstration-scale.

The major advancements demonstrated by the next generation bioreactor are (i) higher gas-liquid mass transfer over the state-of-the-art technology; (ii) opportunity for much greater gas conversion; (iii) substantial systems-level capital and energy savings; (iv) de-risked technology enabling benefits to multiple types of commercial facilities.

All Success Metrics were able to be achieved in a short period of time, and without major mechanical modification. These results compare favorably to the head-to-head comparisons with pilot scale results, supporting the further scale up of the technology.

A key challenge for all projects in this period was COVID, and the disruptions to human and material supply chains. The LanzaTech and Suncor teams, along with all their contractors and suppliers worked collaboratively to complete the project on time.

Key lessons learned pertained to the technology development itself, and its detailed implementation. This project provided an invaluable opportunity to transfer those lessons to the team, and document for future commercialization.

This ERA project with Suncor has been a very successful scale-up and demonstration of LanzaTech's next generation bioreactor, following a decade of prior development. Importantly, the key metrics translated well to the larger scale implementation, related to both technical performance and cost, providing the necessary data to pursue commercial implementation. The project has achieved all its objectives.

ERA funding has filled a critical gap in the technology development pathway, as demonstration scale testing is critical to de-risking technology and yet it is expensive to do so (in both actual costs and opportunity cost). LanzaTech is grateful for its partners in ERA and Suncor to enable the execution and success of this project.

2. Project Description

Emissions Reduction Alberta (ERA) investments in technologies that reduce GHG emissions are important to meet the Province of Alberta's aim to achieve net-zero emissions by 2050, a goal consistent with federal government timelines.[1] Meeting the ambitions of Alberta's Emissions Reduction and Energy Development Plan will require large-scale production of cost-competitive low carbon transport fuels. LanzaTech, Inc.'s (LanzaTech) proven gas fermentation technology recycles carbon from abundant, low-cost wastes and residues into low carbon fuels and chemicals that will contribute to these goals. With funding from ERA BEST, and in partnership with Suncor, LanzaTech successfully executed the project "Carbon Sequestration via Next-Generation Bioreactor Technology" to manufacture and validate the performance of LanzaTech's next generation bioreactor technology at demonstration scale. Importantly, this technology will maximize the quantity of fuels produced per tonne of biomass, including wood waste and forestry thinnings, in an integrated biorefinery.

The next generation bioreactor technology, which has been validated in lab and field pilots, will expand the scope of gas fermentation by increasing efficiency and reducing production costs. The scope of work under LanzaTech's ERA project involved piloting, engineering, fabrication and assembly, and operations of the technology, to produce ethanol from the off-gas of forestry-residue gasification in Alberta. Extended benefits of the project include converting other resources such as industrial waste gases and agricultural residues using LanzaTech's gas fermentation platform.

The project will lead to accelerated technology commercialization in Alberta and across Canada. Based on the provincial residual biomass availability and its relationships, LanzaTech estimates the potential to deploy numerous commercial-scale units using gasified-woody biomass in Alberta.

This project takes a major step towards realizing a low carbon future by opening new waste resources, such as gasified agricultural residues, and serving hard-to-decarbonize sectors, such as aviation (jet fuel from ethanol) and consumer goods (materials from fermentation-derived chemicals).

2.1. Introduction and background

LanzaTech is commercializing carbon capture and transformation via gas fermentation. Gas fermentation is a new approach to recycle waste carbon and reduce CO_2 emissions while producing low-carbon liquid fuels and chemicals. The gas fermentation process harnesses the power of biology to recycle carbon from a wide variety of waste resources into valuable products, as illustrated in Figure 1.1-1. LanzaTech's initial commercial focus is on ethanol production for road transport, but gas fermentation technology has already been demonstrated in the production of over 50 different chemical products. In parallel, LanzaTech has spun out a company, LanzaJet, to commercialize its Alcohol-to-Jet (ATJ) technology which produces sustainable aviation fuel from ethanol, expanding the market for low carbon ethanol from wastes and residues.

[1] https://www.alberta.ca/emissions-reduction-and-energy-development-plan.aspx

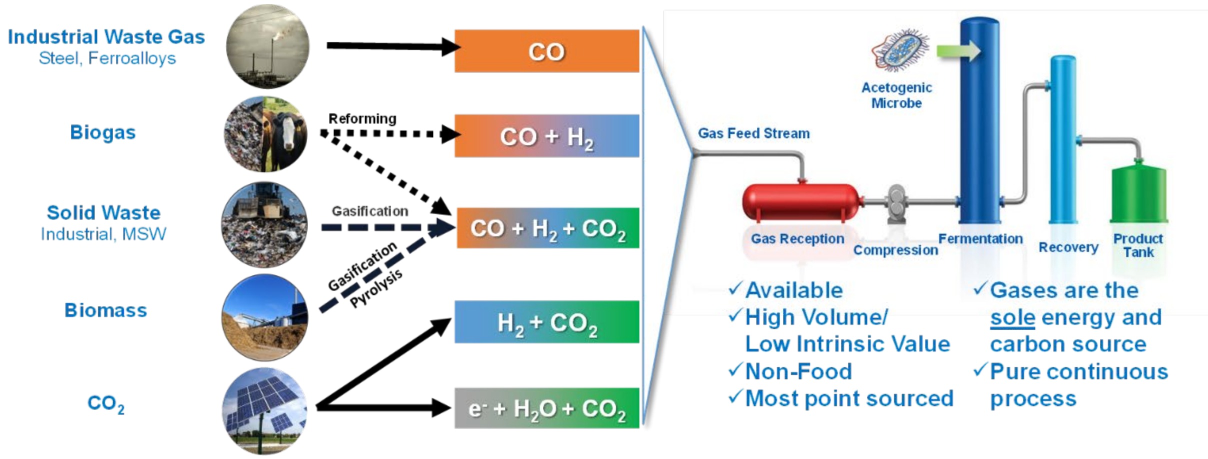


Figure 1.1-1. LanzaTech's gas fermentation process.

LanzaTech's technology to produce ethanol using off-gases from heavy industry is now being implemented at commercial scale; the first commercial units are in operation in China and India; and, others are in construction and development, including the Steelanol Plant I Ghent, Belgium. These projects use gases from steel mills, refineries, and ferroalloy plants. When combined with gasification, gas fermentation also produces ethanol from solid wastes and residues. For example, the technology is being demonstrated in Japan, to convert unsorted unrecyclable municipal waste to ethanol through an extended collaboration with Sekisui Chemical Company. The technology has also been demonstrated on gasified agricultural residues to produce ethanol from cellulosic biomass to inform the design for a commercial project being developed in the U.S.

2.2. Detailed technology description

This project "Carbon Sequestration via Next-Generation Bioreactor Technology" was proposed to demonstrate the next advance in gas fermentation technology: a novel bioreactor design developed by LanzaTech which enables best-in-class gas-liquid mass transfer relative to the required energy input. This technology is important especially when produced gases, such as syngas, are used as feedstock. The technology will be paired with LanzaTech's proprietary gas fermentation microbe which has already been proven in commercial ethanol production. This next-generation gas fermentation platform was demonstrated at scale.

The LanzaTech gas fermentation process comprises several key steps: syngas delivery, gas treatment, fermentation, and ethanol distillation.

The input to the fermentation is syngas from gasification unit which is converting waste into syngas. The syngas is first compressed and then processed in gas treatment to remove impurities. LanzaTech has experience treating similar gas streams from multiple sources, including biomass syngas, MSW syngas, steel mill off-gases (basic oxygen furnace, blast furnace, and coke oven gas), as well as refinery off-gases.

The treated input gas is then fed to the fermentation bioreactor, where a microbial biocatalyst converts CO, CO_2, and H_2 from the gas into ethanol and other organic molecules (metabolites).

Fermentation broth is sent to distillation which removes ethanol from the broth and recycles water to the bioreactor. Ethanol produced at LanzaTech's commercial and demonstration scale facilities meets the requirements for use specified in CAN/CGSB-3.516-2017 "Denatured fuel ethanol for use in automotive spark-ignition fuels".

In addition to the ethanol product, at commercial scale, the microbial biocatalyst is recovered as a co-product. The microbial biomass is 90 wt.% protein and can be sold as an animal or fish feed.

2.3. Project objectives

Milestone	Milestone Title
M1	Pilot Testing Complete
M2	Detailed Design Complete
M3	Shop Checkout of Modules
M4	ISBL equipment installed
M5	Baseline Demo Run
M6	Demo Run on Forestry Biomass
M7	Final Report

Task and Deliverables by Milestone:

Milestone 1: LanzaTech Pilot Operations Complete	**Deliverable**
Task 1: Pilot Reactor Gas Testing	Pilot testing complete
Task 2: Basic Engineering	N/A
Task 6: TEA and LCA	N/A
Task 7: Commercialization & Knowledge Transfer	N/A
Milestone 2: Detailed Design	**Deliverable**
Task 2: Basic Engineering	Equipment supply agreements signed with fabricators
Task 3: Detailed Engineering and Procurement	N/A
Task 4: Construction and Installation	N/A
Task 6: TEA and LCA	N/A
Task 7: Commercialization & Knowledge Transfer	N/A
Milestone 3: Shop Checkout of Modules	**Deliverable**
Task 3: Detailed Engineering and Procurement	Detailed design complete; all major equipment ordered
Task 4: Construction and Installation	Skid fabrication at shop complete
Task 6: TEA and LCA	N/A
Task 7: Commercialization and Knowledge Transfer	N/A
Milestone 4: ISBL Equipment Installed	**Deliverable**
Task 4: Construction and Installation	ISBL installed
Task 5: Commissioning and Operations	System commissioning complete
Task 6: TEA and LCA	N/A
Task 7: Commercialization & Knowledge Transfer	N/A
Milestone 5: Baseline Demo Run	**Deliverable**
Task 5: Commissioning and Operations	Initial fermentation campaigns complete
Task 6: TEA and LCA	Commercial TEA model and LCA complete
Task 7: Commercialization & Knowledge Transfer	Technology transfer plan draft
Milestone 6: Demo Run	**Deliverable**
Task 5: Commissioning and Operations	Fermentation campaign complete.
Task 6: TEA and LCA	N/A
Task 7: Commercialization & Knowledge Transfer	Technology transfer plan complete
Milestone 7: Final Report	**Deliverable**
Task 7: Commercialization & Knowledge Transfer	Prepare and submit final report

3. Project Outcomes and Learnings

3.1. Overall project achievements

The key project achievements are:

- Successful field pilot testing of LanzaTech second generation bioreactor.
- Successful construction, commissioning, and operations of the demonstration facility, achieving all Success Metrics
- Achieved commercial cost metrics.
- Achieved commercial GHG reduction metrics.

3.2. Modelling details

This project did not involve any modeling as all modeling (i.e., computational fluid dynamics, CFD) work was done prior.

3.3. Results of experiments, model simulation

In total, the team met the schedule, operated safely, and the technology has scaled well with no major issues uncovered.

3.4. Changes to the corporate structure of the company or project consortium

LanzaTech Global, Inc. ("LanzaTech"), formerly known as AMCI Acquisition Corp. II ("AMCI"), announced the completion of its previously announced business combination between AMCI and LanzaTech NZ, Inc., an innovative carbon capture and transformation ("CCT") company that converts waste carbon into materials such as sustainable fuels, fabrics, packaging and other products that people use in their daily lives. LanzaTech is the first CCT company to become public in the United States.

In connection with the closing of the business combination, AMCI has been renamed LanzaTech Global, Inc. and on February 10, 2023, its common stock is trading on the Nasdaq under the ticker symbol LNZA and its public warrants are expected to begin trading on Nasdaq under the ticker symbol LNZAW.[2]

3.5. Advancements made toward commercialization, commercial deployment or market adoption

Over the course of the project, LanzaTech has continued to successfully commercialize its gas fermentation technology, with multiple commercial units in operation in China and India. This has further motivated LanzaTech to scale up and commercialize this technology to continue to improve its core gas fermentation platform. In parallel to this project, LanzaTech is evaluating the engineering design for large scale commercial implementation of this technology, as well as the markets best suited for early adoption.

3.6. Description of technology advancement over the course of the project

This project validated that these metrics were achieved in a reactor design that is scalable.

The major advancements demonstrated by the next generation bioreactor are (i) higher gas-liquid mass transfer over the state-of-the-art technology; (ii) opportunity for much greater gas conversion; (iii) substantial systems-

[2] https://www.businesswire.com/news/home/20230209005418/en/LanzaTech-and-AMCI-Acquisition-Corp.-II-Announce-Closing-of-Business-Combination-Establishing-First-Public-Carbon-Capture-and-Transformation-Company

level capital and energy savings; (iv) de-risked technology enabling benefits to multiple types of commercial facilities.

In doing so, the TRL at Project Start was 7, and now the TRL at Project Completion is 8.

3.7. Analysis of results

The Success Metrics were able to be achieved in all configurations in a short period of time, and without major mechanical modification. These compare favorably to the head-to-head comparisons with pilot scale results, supporting the further scale up of the technology. That all KPIs were achieved with all configurations, one of which on the first test, is further support.

A key challenge for all projects in this period was COVID, and the disruptions to human and material supply chains. The LanzaTech and Suncor teams, along with all their contractors and suppliers worked collaboratively to complete the project.

Key lessons learned pertained to the technology development itself, and its detailed implementation. This project provided an invaluable opportunity to transfer those lessons to the team, and document for future commercialization.

4. Greenhouse Gas Benefits

LanzaTech used life cycle analysis (LCA) to assess the GHG emissions savings over a fossil-fuel baseline for ethanol produced from forest residues in Alberta at both the demonstration project and commercial scale.

The GHG emissions for the LanzaTech gas fermentation process only considers the direct emissions. The only indirect emissions are those reported as emissions savings for avoided gasoline production and use.

The Alberta Renewable Fuel Standard (RFS)[3] requires blending 5% renewable alcohol in gasoline sold by suppliers in the province. Additionally, the renewable alcohol must provide a minimum 25% reduction over fossil gasoline. The commercial rollout of the technology would result in low carbon intensity, non-food source ethanol. In addition, ethanol could also be used as a feedstock in the chemical sector, further reducing emissions.

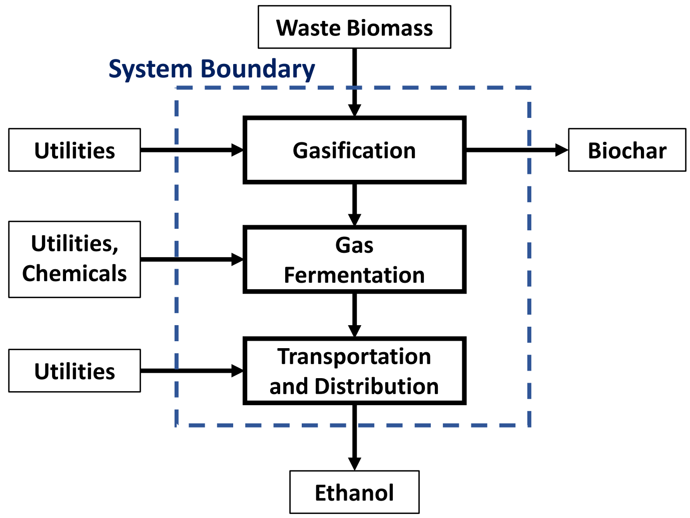
4.1. Quantification of the GHG Emissions Reduction

The project converted syngas into ethanol using LanzaTech's gas fermentation process, demonstrating the ability of this technology to reduce energy and capital costs.

System Boundary

The full system boundary of the LCA, provided in the figure below, includes all chemicals and energy needed for waste biomass collection and transport, gasification, gas fermentation, and final fuel transportation and distribution. The waste biomass feedstock used in this LCA is forest residues which are collected from the roadside and transported an assumed 100 km to gasification. The previous fate of the forest residues is burning, which releases methane and nitrous oxide emissions. Credit is taken for avoiding these emissions, but not for the CO_2 released in burning. Forest residues are gasified using electricity to produce syngas. In addition to syngas, the gasification process produces a biochar co-product which can be used as a soil amendment to sequester carbon. Syngas is converted to ethanol using LanzaTech's gas fermentation with electricity, steam, and chemicals. Wastewater produced during gas fermentation was treated off-site for the demonstration project, but it would be treated on-site for the commercial case. Energy is used during ethanol transportation and distribution for final consumer use. The life-cycle Inventory of the commercial unit is provided in the table below on a per mt of ethanol basis.

[3] Alberta Government, "Renewable Fuel Standard resources", 2023. Available at: https://www.alberta.ca/renewable-fuels-standard-resources.aspx#jumplinks-1



System boundary to produce ethanol from gasified forest residues using LanzaTech's gas fermentation technology.

Quantification Methods

The emission factors used to calculate the GHG emissions are provided in the table below. The electricity and natural gas emission factors were found in the Alberta Government's *Carbon Offset Emission Factors Handbook*[4] which provides the CO_2, CH_4, and N_2O emission factors for grid electricity usage, and natural gas extraction, processing, and combustion. These values were converted to GHG emissions (expressed as gCO_2e) using the global warming potentials of CH_4 (GWP=30) and N_2O (GWP=273) from the Intergovernmental Panel on Climate Change's 6th assessment report[5]. The lower heating value of natural gas at 36.63 MJ/m^3 was taken from the GREET model. The emission factors for chemicals, process water, and wastewater treatment were taken from the GREET model[6] and ecoinvent database[7]. The CH_4 and N_2O credit for avoided slash burning was taken from literature[8] for boreal forests. The emission factor for the fossil gasoline comparator was also taken from the Alberta Government's handbook[4].

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[4] Alberta Government, "Carbon Offset Emission Factors Handbook: Version 3.1", February 2023. Available at: https://open.alberta.ca/publications/carbon-offset-emission-factors-handbook-version-3
[5] IPCC, "Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change", 2007. Available at: https://www.ipcc.ch/report/ar4/wg1/
[6] Argonne National Laboratory, GREET 1 Model, 2022. Available at: https://greet.es.anl.gov/
[7] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8> [Accessed December 16, 2018].
[8] Akagi. S.K., et. Al., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models., Atmospheric Chemistry and Physics. 11, 4039-4072.

The carbon intensities of ethanol produced in the project and at commercial scale were found by multiplying the process inputs by the emission factors and is shown below in the table below. The project carbon intensity is 21.0 micro-mt CO_2e/MJ ethanol (21.0 g CO_2e/MJ) of ethanol. The carbon intensity of the commercial unit produced using Alberta grid and renewable power is -9.43 and -51.18 micro-mt CO_2e/MJ, respectively, providing an emission savings of 111% and 158% compared to fossil gasoline (88.88 micro-mt CO_2e/MJ). In the commercial unit, most emissions are due to electricity use during gasification and gas fermentation.

Carbon intensities of the commercial unit compared to the fossil comparator.

Carbon Intensity (micro-mt CO_2e/MJ)	Project Unit	Commercial Unit		Fossil Comparator
		Grid Power	Renewable Power	
Total Emissions	**21.0**	**-9.43**	**-51.18**	**88.88**

4.2. Baseline Scenario

The baseline scenario for GHG reduction calculations considers the previous fate of the forest residues in the absence of the LanzaTech process. According to the FiresSmart Community Zone (FSCZ) Debris Management Standard, forestry residues produced by timber operations in Alberta must either be evenly distributed through the harvest area or piled and burned[9]. The baseline uses forest residues that are already piled and burned since they would be the easiest feedstock to collect. The carbon neutrality assumption is made for the forest residues meaning credit is not taken for the avoided CO_2 released during biomass burning and a penalty is not given for fuel ethanol combustion. However, credit is taken for the avoided CH_4 and N_2O as described above. The baseline for fuel ethanol is the quantity of gasoline equivalent on a per MJ basis that is produced by the LanzaTech gas fermentation process.

[9] Alberta Government, "Debris Management Standards for Timber Harvest Operations", AF-FDP-2017-07, May 1, 2018. Available at: https://open.alberta.ca/publications/directive-af-fdp-2017-07

5. Overall Conclusions

This ERA project with Suncor has been a very successful scale-up and demonstration of LanzaTech's next generation bioreactor, following a decade a development prior to ERA funding. Importantly, the key metrics translated well to the larger scale implementation, related to both technical performance and cost, providing the necessary data to pursue commercial implementation. The project has achieved all its objectives.

ERA funding has filled a critical gap in the technology development pathway, as demonstration scale testing is critical to de-risking technology and yet it is expensive to do so (in both actual costs and opportunity cost). LanzaTech is grateful for its partners in ERA and Suncor for enabling the execution and success of this project.

6. Scientific Achievements

During this project, there have been no published patents, books, journal articles or conference presentations. The scientific development was done during the early stages of the technology development. This project has focused on the construction, implementation, and demonstration of the technology at a larger scale.

7. Next Steps

The success of this project has spurred several follow-on discussions and commercial activity. LanzaTech is working with 3rd party engineering companies to refine the cost of large-scale commercial implementation. LanzaTech is additionally discussing near-term opportunities for commercialization around specific opportunities.

8. Communications Plan

Following the success of this project, LanzaTech and Suncor have undertaken several knowledge-sharing and communication activities. These include:

Internal:

- Completion of a detailed operations and safety manual, prepared by LanzaTech and transferred to Suncor.

External:

- LanzaTech issued press release "Reducing Emissions in the Supply Chain and Diversifying the Feedstocks of the Future" on the project on Oct. 28, 2022, https://lanzatech.com/reducing-emissions-in-the-supply-chain-and-diversifying-the-feedstocks-of-the-future/
- ERA media including a video of the project, currently featured on the ERA's frontpage and in ERA's 2023-26 Business Plan, and newsletters, see https://www.eralberta.ca/ and https://www.eralberta.ca/wp-content/uploads/2023/04/ERA-2023-26-BusinessPlan-Final.pdf
- Suncor media news story on Dec. 15, 2022, https://www.suncor.com/en-ca/news-and-stories/our-stories/testing-technology-to-turn-waste-into-want

Further plans for communicating information about the LanzaTech ERA project include:

- Confidential discussions with potential customers.
- Expansion of options for including the next generation bioreactor in LanzaTech commercial offerings.
- Potential for a LanzaTech peer-reviewed publication (pending LanzaTech Legal assessment).