# CLEAN RESOURCES FINAL REPORT PACKAGE

Project proponents are required to submit a Final Report Package, consisting of a Final Public Report and a Final Financial Report. These reports are to be provided under separate cover at the conclusion of projects for review and approval by Alberta Innovates (AI) Clean Resources Division. Proponents will use the two templates that follow to report key results and outcomes achieved during the project and financial details. The information requested in the templates should be considered the minimum necessary to meet AI reporting requirements; proponents are highly encouraged to include other information that may provide additional value, including more detailed appendices. Proponents must work with the AI Project Advisor during preparation of the Final Report Package to ensure submissions are of the highest possible quality and thus reduce the time and effort necessary to address issues that may emerge through the review and approval process.

*Final Public Report*

The Final Public Report shall outline what the project achieved and provide conclusions and recommendations for further research inquiry or technology development, together with an overview of the performance of the project in terms of process, output, outcomes and impact measures. The report must delineate all project knowledge and/or technology developed and must be in sufficient detail to permit readers to use or adapt the results for research and analysis purposes and to understand how conclusions were arrived at. It is incumbent upon the proponent to ensure that the Final Public Report **is free of any confidential information or intellectual property requiring protection**. The Final Public Report will be released by Alberta Innovates after the confidentiality period has expired as described in the Investment Agreement.

*Final Financial Report*

The Final Financial Report shall provide complete and accurate accounting of all project expenditures and contributions over the life of the project pertaining to Alberta Innovates, the proponent, and any project partners. The Final Financial Report will not be publicly released.

ALBERTA **INNOVATES**

## 1. PROJECT INFORMATION:

| | |
|---|---|
| **Project Title:** | **Carbon nanofiber production from greenhouse gases** |
| **Alberta Innovates Project Number:** | **202102621** |
| **Submission Date:** | March 10, 2023 |
| **Total Project Cost:** | $2,290,286 |
| **Alberta Innovates Funding:** | $950,000 |
| **AI Project Advisor:** | Paolo Bomben |

## 2. APPLICANT INFORMATION:

| | |
|---|---|
| **Applicant (Organization):** | **Carbonova Corp.** |
| **Address:** | PO Box 13022, RPO Beltline, T2R 1C6 |
| **Applicant Representative Name:** | Dr. Mina Zarabian |
| **Title:** | CEO |
| **Phone Number:** | XXX-XXX-XXXX |
| **Email:** | investors.relation@carbonova.com |

## 3. PROJECT PARTNERS

**Please provide an acknowledgement statement for project partners, if appropriate.**

*RESPOND BELOW*

Carbonova would like to acknowledge the generous support of its partners in the advancement of its technology:

University of Calgary
NanosTech
Kiwetinohk Energy Corp.
Perpetual Energy Inc.
Lafarge Holcim
Sika

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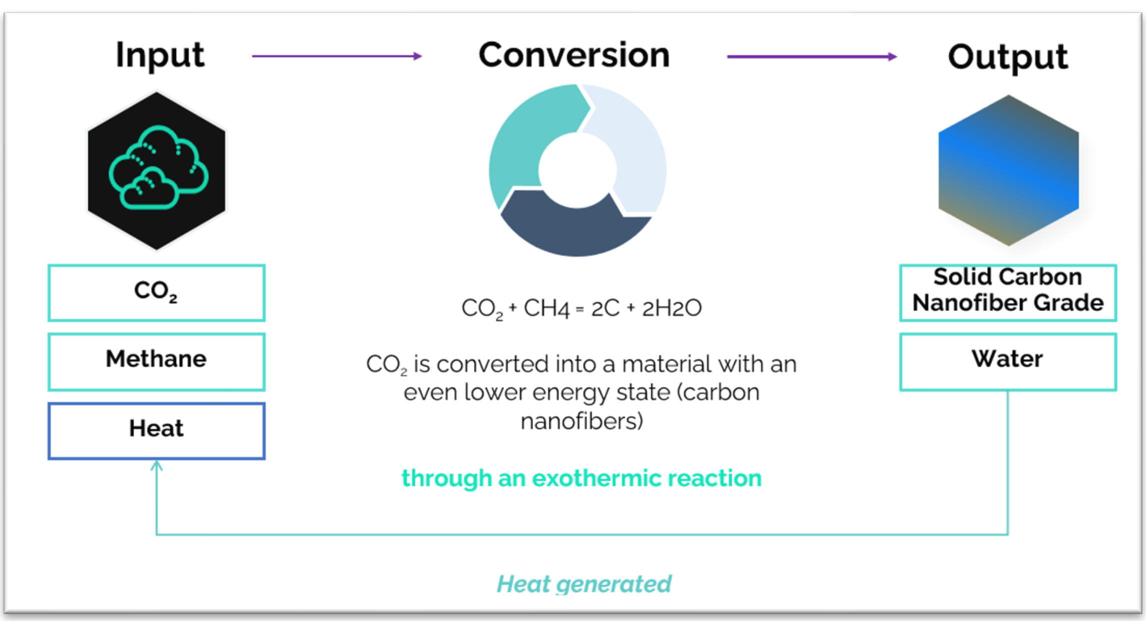
# A. EXECUTIVE SUMMARY

**Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.**

*RESPOND BELOW*

This project aims to accelerate the development of a new carbon utilization technology for $CO_2$ emitters that converts waste heat and industrial $CO_2$ streams into valuable products by producing carbon nanofibers (CNF). CNFs have received significant attention over the past decade because of their compelling multifunctionality, meaning that they incorporate several properties that are often only found in multiple different products into one product. Historically, the high manufacturing cost of CNF was the primary obstacle to its widespread adoption across various industries. This project includes constructing and optimizing a Pilot Plant scale-up of Carbonova's technology, as shown below, focusing on reducing the cost of CNF production.



During the course of this project, a design basis memorandum (DBM) for a pilot unit was prepared based on a bench scale model. An engineering company was contracted to prepare a process and instrumentation diagram (P&ID), and cost estimates. The project was kicked off with an initial site preparation, long lead equipment orders, hazard and operability (HAZOP) study and construction. The Pilot unit was commissioned and transferred to the operations team for the optimization phase. As shown below, the plant successfully validated the technology, with high value carbon product as an outcome.



In the second year of the project, the unit was operated and optimized, and critical data were collected for the customer discovery and further scale-up to a commercial scale.

This optimization work in turn facilitated the company to update its business plan and begin planning for its first commercial unit. This plan has already been successful in attracting over $2M of federal government funding and positioned Carbonova well on its path forward.

## B. INTRODUCTION

**Please provide a narrative introducing the project using the following sub-headings.**

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that is being addressed along with the context and scope of the technical problem.

*RESPOND BELOW*

**Sector Introduction**

Due to increased global attention on climate change, industries with high man-made carbon footprints are under intense pressure to reduce greenhouse gas (GHG) emissions to flatten the climate change curve. GHG emissions and the climate do not respect national borders, making the challenge to reduce the carbon footprint primarily associated with energy intensity a universal one. Steering away from a carbon economy requires an integrated and intelligent combination of solutions.

The construction industry is among the largest carbon-intensive sectors and is now being urged to manage its carbon footprint. The International Energy Agency reports that the cement sector is the third-largest industrial energy consumer and the second-largest industrial emitter of $CO_2$, generating 7% of global GHG emissions (1.5 GT in 2018). Carbon Capture, Utilization, and Storage (CCUS) technology deployment is expected to be a pivotal strategy to curtail large $CO_2$ emission sources from worldwide industrial operations significantly.

**Technology Gap**

The entirety of the cement industry must bridge a substantial technological gap to achieve this emissions reduction target, while continuing to ensure affordable residential, commercial, and industrial infrastructure globally. Carbonova initially targets the cement industry since it is a high GHG emitter globally with waste flue gas emissions that align with Carbonova's carbon utilization technology. Furthermore, Carbonova's process outcome is CNF, an additive for modifying cement. CNF enhances several properties, including weight reduction, strength, electrical conductivity, porosity, and thermal dissipation.

One of the unique features of the Carbonova technology is the circular nature of its application. With the feedstocks of both $CO_2$ and natural gas being available at cement plants, their use in the process at cement facilities to create CNFs allows the industry to utilize waste gases and create a value-adding product. In essence, this technology will enable the cement industry to create a higher-value product (CNF-enhanced cement) while improving the environmental impacts of their operating facilities.

The project involved both the scale-up of the technology and more specialized testing of the technology for cement applications. The scale-up allowed for many process assumptions to be validated, including optimum operating conditions and residence times within reactors. Each of the different operating conditions results in specific CNF characteristics, which were tested by our partners to optimize the product value for their use.

## C. PROJECT DESCRIPTION

**Please provide a narrative describing the project using the following sub-headings.**

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that will be used to measure the success of the project.

*RESPOND BELOW*

**Technology Description**

Carbonova aims to accelerate a new CCUS technology for large industrial $CO_2$ emitters by converting waste heat and $CO_2$ streams into valuable products. Its core new technology is based on a unique revolutionary chemical process utilizing novel catalysts, machinery, and equipment. This process starts with $CO_2$ and methane in a chemical reactor. They are combined with waste heat from existing processes (such as cement production or a power plant) and converted into carbon nanofibers (CNF). CNFs are strands of carbon atoms less than 100 nm in diameter and range from 100 nm up to hundreds of micrometers in length. CNFs have applications in everyday life, such as plastics, rubbers, tires, batteries, inks, and coatings, with global demands of over 16 million tons when the total solid carbon additive market is considered.

The Carbonova process is designed to recover waste heat from its own process. It directly utilizes captured and pre-conditioned $CO_2$ emissions from waste flue gas and waste heat from a co-located industrial facility to produce CNFs. The properties of composite materials, such as concrete, may be enhanced through the addition of CNFs. Such improvements to concrete include weight reduction, strength, electrical conductivity, porosity, and thermal properties, significantly improving the value of the concrete for the construction industry while displacing traditional additive minerals, such as slag or fly ash.

**Project Objectives**

This project bridges the gap between the bench-scale pilot unit and an industrially scalable and reliable commercial production unit. Carbonova has gained interest from both licensors and customers, who are collaborating with Carbonova to mature the technology.

**Performance Metrics**

The following metrics were used in the project to determine success. All metrics were achieved.

| Metric | Project Target |
|---|---|
| Multiple CF cartridge reuse | 5 times |
| Industrial gas feed impurity tolerance | +/- 5% |
| Catalyst lifetime | 3+ months |
| CNZ catalyst recirculation efficiency | minimum 10 times |
| CNF harvesting efficiency | >90% |
| CNF quality control | 90% selectivity towards crystalline CNF |
| Yield | 0.1 kg/day |
| Onboard headcount efficiently | Onboard 15 contractors and employees efficiently |
| Construct the precommercial unit | Construct the precommercial unit within 18 months of inception |
| Production of Carbon nanofiber for sample inventory with collaborators | Produce sufficient CNF samples for testing with customers |
| Revenues | Generate revenues of 70k from the precommercial unit |

## D. METHODOLOGY

**Please provide a narrative describing the methodology and facilities that were used to execute and complete the project. Use subheadings as appropriate.**

*RESPOND BELOW*

This project was executed in three phases:

1. Design and construct the pilot unit to validate the scale-up factor and secure the customer's interest.
   a) All the data from the pre-existing bench unit were organized to prepare the DBM. Examples include the conversion from the fixed bed reactors, space velocity, reduction and reaction temperatures, catalyst regeneration condition and frequency, operation pressure, and impact of the pressure. Key parameters to be studied in the pilot unit were prepared. Examples include, impact of temperature, impact of pressure, impact of space velocity, impact of impurities, impact of by product recycling.
   b) The Engineering company made the calculations on the size of the reactors and prepared the first draft of the P&ID with a cost evaluation.
   c) The P&ID was modified in multiple iterations to reduce the cost of capitals, examples include reducing the size of the pilot unit, reducing the number of parallel reactors

d) HAZOP study was completed, the project was awarded, and project management was established.
e) Site Preparation: a suitable site for the facility was identified and electrical and ventilation needs were reviewed and adjusted
f) Procurement of the equipment started by networking with vendors from all over the world.
g) Unit constructed and pre-commissioned
h) Final HAZOP was completed
i) Experimental test designed and unit commissioned in a full size
j) Standard Operation Procedures (SOPs) were prepared, and the operations team were trained.

2. Process key parameters – Validate the scale-up parameters for the processes, such as the conversion level, the tolerable level of impurities in feeds, the necessary heat for the process, the consistency of CNF specifications, and the overall efficiency of the process;
   a) Process operation condition monitoring: a number of short tests were designed to fine tune the equipment (heating control, pressure control). Automatic control systems were upgraded based on the new learnings; examples include, pressure and temperature automatic tunes, system alerts and automatic responses, and emergency shut down procedure.
   b) Long-term tests were designed with reduced needs for operator monitoring, and inventories were expanded for extended operation period (gases, catalysts, pipes and consumables)
   c) In situ data analysis was implemented: macros were designed to collect data from multiple pieces of equipment, such as control system (temperature/pressure), gas analysis (QMS and GC), water condenser, and flow meter, to prepare continuous mass balance. The outcomes were presented in a user-friendly platform (Microsoft Power BI) for quick decision making during the process
   d) Post data analysis: data were carefully collected on post condition of the process, examples include reactors metal dusting, catalyst active site poisoning or coking.
   e) Carbon Nanofiber quality was analyzed for each of the tested process conditions using RAMAN and other methods to optimize the value proposition.

3. Complete technoeconomic and lifecycle assessments of the process and develop a commercialization plan.
   a) data gathered from the pilot operation were analyzed, compiled and transferred to the engineering team to reassess the process design
      - Chemical process was then simulated with the new data
   b) Updated PFD designed prepared and using scale factor methodology, the economics of the commercial unit were estimated
      - information on market size and competitors selling price was collected to develop revenue generation model **(confidential)**
   c) The boundaries for lifecycle analysis (LCA) were established, data from the mass balance and energy balance were collected, the $CO_2$ associated with the energy consumption was estimated, and the preliminary LCA was developed.

## E. PROJECT RESULTS

**Please provide a narrative describing the key results using the project's milestones as sub-headings.**

- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

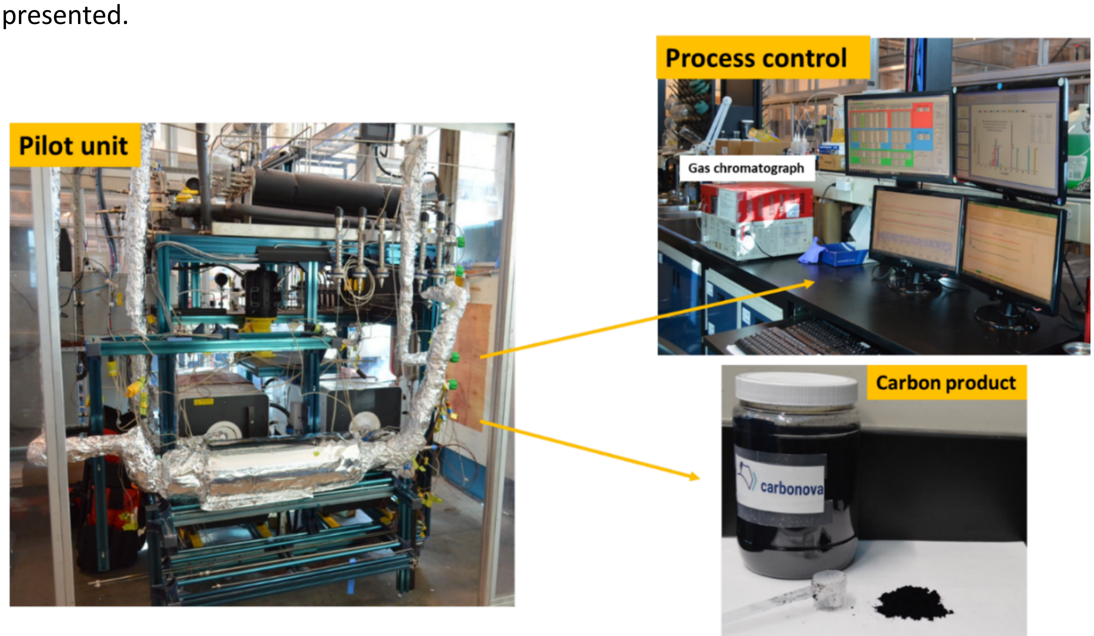
*RESPOND BELOW*

In the project's first phase, the prototype unit is designed, and major and minor equipment were procured. The construction was completed and successfully commissioned by a third-party contractor. The operations team was trained, and the operations procedures were prepared under the guidance of the engineering team. The unit was transferred to the operations team to refine the process and collect data.

With the control systems in place, including gas chromatograph, and pressure and temperature controls as shown below, the process was optimized to create the highest value carbon product.

In the second phase, the prototype was operated, and critical data were collected on reactor design, process conditions (temperature and pressure), conversion level, consistency of operation, and catalyst stability, as part of the project goals. Several batches of CNF were produced, and the product was critically analyzed to assess the consistency of CNF specifications.

In the third phase, the prototype is further upgraded and optimized. The new prototype for a continuous process was designed and successfully commissioned and tested, and critical data were collected. The sensitivity of the feedstock was analyzed. The Plug Flow Diagram (PFD) of the commercial unit is conceptualized, and based on that, the techno-economic analysis (TEA) and the preliminary lifecycle analysis (LCA) were developed. The commercialization plan for a small modular commercial unit was presented.



## F. KEY LEARNINGS

**Please provide a narrative that discusses the key learnings from the project.**

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes

*RESPOND BELOW*

1- The nature of the project as a Research and Development classification with a technology readiness level (TRL) of 5-7 comes with a lot of learning, evolution, and innovation. As part of this project, we further optimized the process and gained experimental evidence on its sensitivity. To advance the technology development and overcome the long lead times associated with complex systems, we modularized our system and de-risked every step into a separate module. This helped us reduce costs and accelerate development during the supply chain interruption caused by the COVID-19 pandemic.

2- The process design, equipment material, and initially designed operating conditions were all modified as a result of the learnings from the first scale-up design. These changes were not unexpected but did add more time to the overall project plan. Going forward, this learning will be important to the planning of the first commercial unit project.

3- The Carbonova process itself is sensitive to the quality of the inlet gases and the nature of the specific product market to be targeted, both critical learnings of the pilot plant operations. As a result, the next stage of scale-up design will rely on site-specific conditions. In addition, the chosen location is expected to have unique regulatory requirements depending upon the need to transport feed gases and products, as well as the industrial designation zoning of the property.

## G. OUTCOMES AND IMPACTS

**Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate.**

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Energy Metrics:** Describe how the project outcomes impact the Clean Energy Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** List of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

*RESPOND BELOW*

There were several positive outcomes from the project, with the material value associated with the advancement of Carbonova's technology and its environmental impacts, as shown below in Table 1:

**Table 1. Updated Technical /Economic Advancement Targets and Impacts**

| Metric | Project Target | Result/Impact |
|---|---|---|
| Industrial gas feed impurity tolerance | +/- 5% | Validates potential application of technology for multiple locations |
| Catalyst lifetime | 3+ months | Validates techno-economic analysis |
| CNZ catalyst recirculation efficiency | minimum ten times | Validates techno-economic analysis |
| CNF harvesting efficiency | >90% | Harvesting improvements are still being progressed |
| Onboard headcount efficiently | Onboard 15 contractors and employees efficiently | Carbonova is well positioned for the next phase of its development (design and construction of small modular commercial unit) |
| Construct the pre-commercial unit | Construct the pre-commercial unit within 18 months of inception | The pre-commercial (Pilot) unit was completed on time, on budget, and operational for almost 12 months within design expectations. The success of the unit provides critical data for the next stage of development |

| | | |
|---|---|---|
| Production of CNF for sample inventory with collaborators | Produce sufficient CNF samples for testing with customers | Multiple samples have been made available to potential customers globally, facilitating the advancement of Product Development Agreements |

The environmental impacts resulting from the project and potential adjustments required for the next stage of development are noted in Table below:

**Table 2. Environmental Benefits Summary**

| GHG emissions: Actual reductions from the project | Project Target | Adjustments for the Next Stage of Commercialization |
|---|---|---|
| # of End Users participating | 4 | Small Modular Unit development will involve the evaluation of a minimum of three potential sites, each with a unique set of feedstock suppliers and end users, all located in Canada |
| Unique product/process | 1 | As a result of the project, Carbonova was able to advance the design of the Carbonization step of the process, resulting in additional potential patents not previously anticipated. This advancement is expected to improve the commercial scale economics and extend the possible applications globally. |
| Cleantech companies with HQ in AB | 1 | In addition to maintaining Carbonova's head offices in Calgary (now in a new space in NE Calgary), Carbonova has engaged with several engineering, procurement, and construction companies in Alberta. |
| Future Capital Investment | $15MM to $100MM | Preliminary conceptual designs for both a small commercial unit, and industrial-scale commercial unit have been completed and are expected to result in significant capital investments and positive impacts on the environment. Both projects will be CO2 negative. |
| TRL advancement | Achieve TRL 7 | The learnings from the project are expected to allow Carbonova to advance its TRL level to 9 within the next 2-3 years. |

Two separate patents have been filed in 7 jurisdictions, and Carbonova participated in a public presentation by Greentown Labs (Carbon to Value (C2V) championed by Fluor, and the Go-Move program championed by BASF and Magna).

## H. BENEFITS

**Please provide a narrative outline the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.**

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, etc.) compared to the industry benchmark. Discuss benefits, impacts and/or trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the province. Discuss the research infrastructure used or developed to complete the project.

*RESPOND BELOW*

**Economic**

The direct economic impact of the project includes the hiring of highly skilled Albertans, in both industrial and commercial roles, including highly qualified and skilled personnel in roles ranging from technical engineering to financial and business analysts.

The total number of FTE roles was 10 during the project. Upon completion, it is expected that the employee count will increase, as there will be an increased focus on the execution of commercialization milestones.

We are targeting a 100-employee count within 5 years, up to $100M of investment, and global sales of our products.

**Environmental**

Our process advancement to a large-scale commercial level is expected to consume over 5,000 tonnes of $CO_2$ annually per unit. Following the completion of the small modular unit, it is expected that a new unit could be commissioned every 2 years well into the 2030s. In addition, our technology execution at the commercial scale will result in a non-energy, non-emitting use of Alberta's abundant natural gas resources.

**Social**

The highly skilled labour force engaged in this project will mean more jobs for Albertans and will contribute to the Alberta economy through taxes and living expenses. As the company grows, these benefits will also increase, with a high probability of transferring the entrepreneurial spirit to other technologies and industries in Alberta.

**Building Innovation Capacity**

As discussed above, the project has already resulted in 10 new highly qualified and skilled personnel. Many of these individuals are from diverse backgrounds outside of the province of Alberta. As the company grows, it is expected the attractiveness of Carbonova's technology will continue this trend.

The company has also initiated a move of its operations away from the research facility at the University of Calgary, to its own space in NE Calgary. This new facility will allow Carbonova to grow, with room for more staff and equipment to continue technology and product development.

## I. RECOMMENDATIONS AND NEXT STEPS

**Please provide a narrative outlining the next steps and recommendations for further development of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:**

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken over the next two years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

*RESPOND BELOW*

The next stage for Carbonova will be the development and optimization of the pilot plant, and then the conceptual design, pre-FEED, and FEED of the first demonstration commercial unit, which will have a capacity of up to 200 times that of the pilot plant. These key deliverables are crucial to the final investment decision (FID) to begin construction in Canada. This step has already received $2M of funding from Sustainable Development of Technology Canada and has the support of a number of third-party potential sites with various market/customer targets. This work is being undertaken with parties with which Carbonova has executed non-disclosure agreements.

## J. KNOWLEDGE DISSEMINATION

**Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry.**

*RESPOND BELOW*

The critical knowledge obtained from this project includes the completion of several patent applications in multiple jurisdictions around the world (US, Canada, Australia, Europe, China, Japan, and Korea). In addition, the company has had the opportunity to share its knowledge with potential customers, funders, and partners. This work has already resulted in a Memorandum of Understanding with new partners and further due diligence with customers.

## K. CONCLUSIONS

**Please provide a narrative outlining the project conclusions.**

- Ensure this summarizes the project objective, key components, results, learnings, outcomes, benefits and next steps.

*RESPOND BELOW*

Overall, the Carbon Nanofibers Production for Greenhouse Gases project has been very successful, with all the targeted milestones being met, allowing for the next steps of development to begin.

The pilot plant was successfully built and operated while providing products for customers. This set the stage for the critical next steps for the company. Key staff were hired, new funding was secured, and next stage development and business plans were established.

The learnings related to the importance of supply gas quality and product quality and distribution have been incorporated into the business plan.

Carbonova is excited about what lies ahead as we change how the world looks at greenhouse gases – an opportunity to improve the world!