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Final Outcomes Report

CO2 to Graphene Reactors
CCEMC Grand Challenge (Phase I)

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Executive Summary

Carbon Upcycling Technologies (CUT), formerly JRE Petroleum Services, is an Alberta-based corporation in Calgary that began the CO2 to Graphene project in mid-April of 2014. With the initial objective of providing a proof of concept and scale-up of a novel and proprietary process to utilize CO_2, CUT has since proven significant CO_2 uptake in its carbon-negative process which creates high quality, carbon-based nanoparticle platelets (CNP) as its end product. Additionally, CUT has pursued and executed multiple engagements with both academic and industrial partners which validate the performance of their product in a variety of end-markets, justifying the pursuit of commercial use for CNPs in these industries.

Since project commencement, CUT has utilized a lean business model and created key business relationships with various entities to leverage knowledge, facilities, equipment, and market distribution networks for various stages of the project. CUT began its operations by engaging with the University of Calgary to enable a proof of concept for a low-energy production mechanism of carbon nanoplatelets using CO_2 and a graphite feedstock. The proof of concept successfully demonstrated CO_2-uptake, as shown by various analytical methods which will be elaborated upon throughout this report. CUT then optimized this process through the alteration of its operating parameters such that it may now use industrial feedstocks with no additional pre-treatment and CO_2 gas streams of 85% purity (considerably less than industrial-grade CO_2 streams). Additionally, CUT has enabled its low-energy, mechano-chemical process to operate with a variety of feedstocks including; two grades of coal (anthracite and bitumen), delayed pet coke from Suncor oil sands operations, Class F fly-ash from TransAlta coal-power plant facilities, as well various minerals like serpentine, talc, yellow stone, and olivine. Surpassing expectations, CUT has achieved a near-theoretical maximum of 24% CO_2-uptake per gram of graphite feedstock into CNPs, which may be further processed into single-layer graphene oxide (GO), and reduced graphene oxide (rGO); both of which have commercial applications. The CO_2 uptake values have been reproduced multiple times and include value-maximums of 12% CO_2-uptake per gram of fly ash, and 14% CO_2-uptake per gram of olivine. Lastly, CUT has been able to scale up its initial production of 2 g/week to 1.2 kg/week since July 2014 when an engagement with Dr. Viola Birss at the University of Calgary commenced.

Testing for CNP market applications was conducted with various academic and research institutions in relation to numerous high-volume markets include concrete (University of British Columbia, University of Toronto), Polymers (University of Toronto), Asphalt (Carleton University), Energy Storage (Lawrence Berkeley National Labs, University of Waterloo), Coatings (Stanford Research Institute), Gas Adsorption (University of Saskatchewan, University of Toronto), Solar Cell and Drug Delivery - University of Waterloo), and Adhesives and Gas Storage, (University of Alicante, Spain). Many of these endeavours have already provided encouraging results. For example, the use of CNPs in polymers have led to an 82% increase in tensile strength of high-density polyethylene while durability and strength performance of various coatings, asphalt, and concrete mixes have also been improved dramatically. With such benefits, the indirect CO_2 emission reduction potential of CNPs have been quantified and engagements with various market partners have been initiated for beta-testing and subsequent rollout. This includes engagements with major multinational companies like OldCastle Precast in construction, Reliance Products in polymers, and others.

Project Description

Introduction & Background

As mentioned previously, CUT spun out as an independent entity from zEroCor Technologies, an oilfield service and technology development firm actively operating since 2007. zEroCor has created an active network of over 50 Universities worldwide on projects ranging from new material synthesis, water treatment technologies, and state-of-the-art lighting mechanisms.

CUT launched this project in an effort to innovate a new chemical mechanism for upcycling CO_2. After an extensive literature review of various chemical processes that convert CO_2 into solid carbonates, biofuels, organic compounds, and others, CUT's management determined that the most promising venture involved a process which facilitates the adsorption of CO_2 on exfoliated solid feedstock. Through this mechanism, the captured CO_2 is embedded into a chemical structure and is only released when exposed to temperatures between 130˚C to 400˚C, where the most release occurs around 200˚C. Although the initial intent was to use a commercial technology for exfoliation, CUT realized within the first three months of the project that an entirely new methodology had to be established for viable scale-up and technical validation. Instead, CUT proceeded to develop a low-energy exfoliation process. This required minimal intervention of catalysts, ambient temperature, low pressures, and enabled the use of various solid feedstock ranging from low-grade carbonaceous products (oil sands pet coke, coal, peat), fly-ash, and other low-grade minerals such as olivine, serpentine, and talc.

Technology Description

The base technical concept was found in a publication by Dr. Liming Dai at Case Western Reserve University, where his team found that a high energy size-reduction process could be used to shear carbon sheets from pristine graphite to not only produce few-layer graphene, but also sequester CO_2. The technology had already been tested in lab-scale conditions where a 5 gram sample of graphite was reacted with 1.28 grams of CO_2 to create a high-quality, minimal-layer version of graphene that exhibited carboxylated functional groups (-CO) on the proximities of particles. This mass proportion can be modified if more than one carboxylated functional group is added to each layer of graphene, thereby increasing the process's CO2 uptake.

However, Dr. Dai's work had severe limitations that hindered its viability as an approach to CO_2 sequestration. His approach used high-energy pulverizing to promote the exfoliation, expending large amounts of energy per gram of adsorbed CO_2. Additionally, high-energy systems like the ones used at Case Western, have no industrial precedence for scale-up in the field. Even with conservative estimates on power consumption, the electricity input required per tonne of processed CO_2 was large enough that, using the emission factors associated with Alberta's electric grid, the process required three orders of magnitude more CO_2 to operate than what was captured.

The principle behind Dr. Dai's work was that the size-reduction of graphite facilitated the shearing of carbon sheets, and the subsequent production of few-layer graphene. High energy pulverizing breaks the carbon-carbon bonds in the graphite feedstock, and facilitates a reaction between the exfoliated graphitic carbon and the C-O group derived from the CO_2. This forms carboxylated layers of graphene.

By building on the principles outlined by Dr. Dai, and understanding their constraints around energy consumption, CUT needed to innovate an effective way of creating carbon nanoparticles from sequestered CO_2 that did not require a high energy system. The concept to investigate, therefore, was defined as a low energy mechanism that promoted the exfoliation of carbon-based feedstocks to create activated sites for the chemical adsorption of CO_2 and the production of multi-layer graphene.

Project Goals

In the endeavour to produce carbon nanoparticles and graphene through a low-energy mechano-chemical exfoliation process, CUT identified the following objectives:

- Establishing a proof of concept for the proposed low-energy system that met the following criteria:

    1. *Expend very low energy per gram of product*
    2. *Achieve more exfoliation of the solid carbon feedstock and create higher surface area*
    3. *Create activated carbon sites that could promote the chemical adsorption of CO_2*
    4. *Operate in ambient temperature and low pressure conditions*

- Propose an initial design for a reactor that will demonstrate this process after the completion of a proof of concept
- Conduct an exhaustive analysis on the CO_2 uptake values and mechanisms
- Reproduce run conditions to ensure results are reliable
- Explore end market applications for CNPs:

    1. *Test the platelets, without any further modifications as fillers in polymers, coatings, concrete, asphalt, and other end applications*
    2. *Further process the carbon nanoparticles into single-layer graphene for testing in synchrotron units, Lithium-Sulfur batteries, solar cells, solid lubricants, asphalt, and water membranes, and other fields*

- Scale-up production to further validate the economic feasibility of the process
- Establish a reliable quality control protocol to expedite scale-up

The primary objectives remained consistent through the entirety of the project, though important pivots were made to target markets that offered high volume and low-resistance to adoption from a regulatory and clientele perspective. Much of the progress in the project was made by leveraging important support from university groups across the world, and establishing key relationships that eased market-related testing and analysis. In particular, early-stage collaboration with Dr. Viola Birss at the University of Calgary ensured that CUT executed a quality proof of concept and reactor design within 3 months of initiating the grant agreement with the CCEMC.

Work Scope Overview

The various tasks CUT outlined internally to meet the milestones stated in the grant agreement are listed below:

- Holistically analyze the base process published by Dr. Liming Dai to determine its carbon footprint and scalability. This task was undertaken immediately after the execution of the grant agreement and convinced CUT's management to look to alternative methods for producing CNPs from CO_2 and low-grade solid feedstock.
- Optimize the new process in its ability to exfoliate graphite, promote the maximum uptake of CO_2, and handle a variety of solid feedstock.
- List the reactor parameters that would need optimization during both lab-scale and full-scale runs to efficiently capture CO_2 and produce CNPs.
- Investigate various large-scale reactors capable of producing multiple tonnes per day and identify the large reactor constraints in order to limit the scope of lab-scale testing. The intent of this task was to immediately rule out options in the testing matrix, including centrifuges that have no feasible potential for a cost-effective scale-up of this magnitude.
- Contact various reactor manufacturers in Chicago, Philadelphia, and Mainland China, as well as visit reactor manufacturing sites in the U.S. in order to narrow the scope of lab-scale testing only to mechanisms that provided a feasible means of carbon capture. This included the elimination of systems incapable of scale-up or those that required energy intensive processes.
- Gather important data on energy consumption for various large-scale reactors. This information would provide a crucial method for estimating the energy requirements during scale-up and their implications on the processes carbon lifecycle analysis.
- Determine which form of carbon could be effectively produced by the process both short- and long-term, and identify market applications for each product type. In this instance, the decision was made to focus on the production of carbon platelets (multi-layer CNP flakes) instead of pristine graphene. This change in strategic trajectory determined the following:
    - CUT increased focus on markets where this form of CNP could be used. This included materials industries like construction and chemicals. Importantly, this eliminated short-term investigations in graphene applications like membranes for water purification or semiconductors for the electronics industry. However, these projects were not abandoned, but instead looked at as long-term development goals. Information gathered on graphene sheet production, through chemical vapour deposition and exfoliation methods, was stored for future endeavors.
    - The CNP of focus was thoroughly analyzed regarding its CO_2 capture potential per gram of solid feed processed.
    - The design of a new reactor to further optimize the baseline results in CO_2 capture, product quality, and energy consumption.

- Collaborations with various universities and research institutes were initialized in order to determine maximum CO_2 uptake values and test the carbon product in end-market applications such as concrete, coatings, asphalt, polymers, etc.
- The establishment of contact with potential clients in various target markets
- Attendance to a variety of sustainability and clean technology conferences to network with companies and individuals interested in carbon capture and utilization (CCU), or in nanoparticle applications
- Leveraging of federal and provincial grants to support technical development and scaling of production

Outcomes & Learnings

Literature Review

CUT worked with the University of Calgary to investigate various publications in academic and industrial literature to determine effective methods of exfoliating carbonaceous products into carbon nanoparticles and graphene. Various pathways, including mechanical, chemical, electrochemical, ultrasonic, and electromagnetic processes were investigated as alternative methods for creating nanoparticles and adsorbing CO_2 emissions of sub-industrial grade.

Some important techniques that have been incorporated into the nanoparticle processing method include:

- Sonication
- High temperature chemical exfoliation
- Radio Frequency Heating

It is important to note that all the market-specific testing conducted by CUT did not include any of these modifications, unless explicitly stated otherwise. Various publications outlining the exfoliation and carboxylation of carbonaceous products promote the use of hazardous acids or promote high-energy systems with low viability of scale up. The publications are also generally not extensive in covering all aspects of the process regarding its product and potential applications.

In most cases, the literature review was conducted through a university or research institute partner already associated with Carbon Upcycling. For example, over 500 publications were reviewed by Dr. Viola Birss' group and the CUT technical team with focuses on:

- Various methods of producing CNPs
- Methods of characterizing the CO_2 uptake through different analytical techniques

Similarly, CUT's engagement with Dr. Hani Naguib at the University of Toronto has surveyed over 200 papers regarding:

- The use of graphene and other carbon nanoparticles in HDPE (High-Density Polyethylene), TPU (Thermoplastics Polyurethane), rubber, and conventional epoxies
- Carbon platelets and graphene oxide (GO) dosages used in polymer resins and their impact on mechanical, thermal, electrical, and stress properties

In the field of concrete, CUT and Dr. Nemy Banthia at the University of British Columbia, and Dr. Karl Peterson at the University of Toronto reviewed over 50 papers on:

- The impact of GO and carbonaceous nanoparticles on ready-mix and self-consolidating concrete
- The impact of carbon-ceramic admixtures on durability and chloride permeability of cured ready-mix blends

Similar literature reviews were carried out to investigate CNP applications in the fields of:

- **Lithium-sulfur batteries** - (Dr. Elton Cairns at Lawrence Berkeley National Labs)
- **Gas adsorption** - (Dr. Mehdi Nemati, University of Saskatchewan, and Dr. Rosello at the University of Alicante, Spain)
- **Water treatment** - (Dr. Alan Tay at the University of Calgary)
- **Solar cells** - (Dr. Yuning Li, and Dr. Siva at the University of Waterloo)
- **Asphalt** - (Dr. Abd-El Halim at Carleton University)
- **Nanofiber sensors** - (Dr. Yu Lei at University of Connecticut)
- **Coatings** - (Dr. Frank Cheng at the University of Calgary)
- **Adhesives** - (Dr. Miguel Rodriguez at the University of Alicante)
- **Drug Delivery** – (Dr. Pu Chen, Dr. Alireza Yazdi, University of Waterloo)

Technology Development

The technological development associated with this project was managed in two distinct segments, both of which progressed simultaneously since inception. The first project segment focused on the production of various CNPs from multiple feedstock while confirming the morphology, consistency, and most importantly, the CO_2 uptake of the product. Secondly, CUT focused on validating products in end-market applications. In particular, CUT initiated efforts to establish baseline product-performance in concrete, coatings, asphalt, and polymers. In addition, other potential applications in the field of energy storage, adhesives, gas adsorption, and drug delivery were also investigated with baseline results expected within the next 3-6 months.

The experimental procedures conducted regarding process optimization, baseline production, and market-related testing were developed on a case-by-case basis. Important details for the experimental procedures used in each segment are provided in the sections below. For the characterization of CNP platelets, GO, and reduced graphene oxide various analytical techniques such as; particle size analysis, BET (Brunauer, Emmett, and Teller) surface area, Raman spectroscopy, and TGA (Thermo-gravimetric Analysis) were used. In concrete testing, industrial-standard methods approved by ASTM (American Society for Testing and Materials) were used to quantify rapid chloride permeability, workability, and compressive strength. Similarly, industry-standard tests were used to analyse the effects of CUT's products in polymers like HDPE and TPU.

It is important to note that all characterization and market related testing was completed at third-party universities and analytical services in an effort to keep CUTlean and utilize competent, industry-relevant experts. For example, CUT utilized the expertise of Dr. Viola Birss at the University of Calgary for most of the characterization work and CO_2 uptake validation. Similarly, Carleton University's expertise in the field of asphalt was utilized for testing asphalt blends.

Results & Discussion

Carbon Characterization & Uptake Results

Principal Investigator: Dr. Viola Birss, University of Calgary

Associated Investigators: Dr. Pu Chen, Dr. Alireza Yazdi, University of Waterloo

The first task of this phase was to investigate the direct CO_2 sequestration potential of the high-energy process tested by Dr. Liming Dai at the Case Western Reserve University in Ohio, which had already been tested in lab-scale conditions. However, the integrity of the publication was compromised by analytical assumptions that required verification.

The mass addition to solids achieved in the process was assumed exclusive to the chemical adsorption of CO_2, neglecting potential mass additions through the adsorption of oxygen in ambient air and moisture. This was a concern brought forth by strong positions in literature regarding high surface area carbon absorbing large masses of water through condensation. Unfortunately, no analytical techniques were utilized to exclusively quantify the amount of CO_2 uptake in the process. Even with this assumption, the energy required to achieve these solid mass deficits would produce four orders of magnitude more CO_2 than what was captured.

Due to the non-robust nature of Dr. Liming Dai's work, and lack of support from the publisher, CUT developed an internal project to pursue a low-energy mechanism for the exfoliation of graphite (and other carbonaceous solid feeds) in the presence of CO_2. The objective of the exercise was to determine if a low-energy system, aided by novel catalysts, could be utilized in place of Dr. Liming's proposed method to produce high-value nanoparticles cost-effectively and in an inherently scalable process. It was also important to ensure that more analytically rigorous methods were employed to measure the CO_2 uptake evident in multiple conditions, with various feedstock possessing differing purity levels. Steps in the development of CUT's low-energy process are outline as followed:

- Focus was placed on the procurement of commercially available feedstock for investigative use in the mechano-chemical exfoliation process. These materials included graphite, anthracite, bitumen, oil sands pet coke (provided by a Suncor), fly ash (provided by TransAlta), various grades of talc, serpentine, and olivine, as well as other non-carbonaceous materials. Although some lab-grade materials were used initially, most of the runs were conducted with industrial-grade feedstock procured directly from an extraction site with zero to minimal processing.
- In-house expertise at Dr. Birss' electrochemistry laboratory at the University of Calgary provided insight regarding the optimal conditions and feedstock which maximize the exfoliation of the solid carbon, subsequently creating more active carbon sites where CO_2 may be adsorbed.
- Lastly, analytical techniques were identified to determine the changes in physical and chemical characteristics of the final end product relative to the solid feed. An exhaustive study included the utilization of the following characterization techniques:
    - **PSA (Particle Size Analysis):** Determined the particle sizes, in microns, of the feed product and the end product.

- **NMR (Nuclear Magnetic Resonance)**: Determined the presence of functional groups, particularly an increase in polar functional groups between the feed and the product.
- **AFM (Atomic Force Microscopy):** Provided precise nanoscale imaging of end products.
- **XPS (X-ray Photoelectron Spectroscopy):** Provided a spectra associated with changes in functional groups between the feed and product.
- **TGA-MS (Thermogravimetric Analysis, coupled with Mass Spectroscopy):** The most reliable and effective method for measuring the CO_2 uptake (in terms of mass fraction) per gram of solid feedstock. The TGA unit heated the sample in an inert Helium or Nitrogen environment. The sample would first release any physically entrained moisture from the carbon. Samples then exhibited another mass loss trend between temperatures of 120˚C to 230˚C which were confirmed by the Mass Spectrometer unit as CO_2, due to its unique molecular weight. Each sample has been exposed to TGA-MS for a quantitative analysis of the CO_2 uptake in various conditions.
- **BET (Brunauer, Emmett and Teller) Surface area**: Determined the extent of exfoliation achieved through exfoliation by quantifying the difference in surface area between the feed and the product.
- **Raman Spectroscopy**: Determined if single- or few-layer graphene derivatives (Graphene Oxide) were being produced.
- **XRF (X-Ray Fluorescence):** Used to conduct elemental analysis of feedstock, particularly before any processing in the CUT reactor. This allowed the team to determine if any chemical defects could hinder or promote the exfoliation process.
- **XRD (X-ray Diffraction):** Spectra-based method which determined the presence of functional groups in feed and product.
- **TEM (Transmission Electron Microscopy):** An imaging technique used to determine the morphology and structure of various feeds and products at a 100-500 nm scale.
- **SEM (Scanning Electron Microscopy):** An imaging technique that determined the morphology of the feeds and products in 100 nm to 5 micron scales
- **EDX (Energy-dispersive X-ray spectroscopy):** Determines the elemental composition of particles up to 5 microns from the surface, allowing the identification of contaminants and bulk components in feeds and products.

- Multiple sample preparation techniques were utilized to ensure consistency in product analysis. For example, due to carbon's inherent tendency to absorb moisture from the ambient environment, precautions were made to use pre-heating in ovens prior to any of the characterization stated above. Additionally, analysis using TEM, SEM, TGA, and PSA generally required samples to be sonicated for consistent measurements. This protocol analysis was considered exhaustive by Dr. Birss's group and was further confirmed and utilized by Dr. Pu Chen and Dr. Alireza Yazdi at the University of Waterloo.

The initial scope of this project segment was to create a baseline performance for the first reactor prototype. This was completed by determining the CO_2 uptake and physical/chemical characteristics of end products and assisted in optimizing process parameters such as pressure, run time, and feed input.

Scale Up Milestones

Another important success for CUT during carbon characterization and validation has been the company's ability to scale up production since July 2014. Development information regarding scaling the mechano-chemical exfoliation process are presented below:

- The first set of runs conducted by CUT, in association with Dr. Birss's group at the University of Calgary, utilized a small factory made jar (*Alpha*) procured from a lab-equipment supplier. The jar processed between 0.5 grams to 2 grams per batch with a weekly production rate of 3-4 grams (Figure 8).

Figure 8. Alpha Jar.

- The second jar, labeled *Beta*, was produced in late summer 2014 and commissioned for operation in October 2014. It was able to produce between 5 to 20 grams per batch, with a weekly production rate of between 15 to 60 grams (Figure 9).

- In December 2014, CUT commissioned 11 additional reactors identical to the *Beta* prototype. This was purposed to accelerate the rate of data collection and optimize operating parameter. Weekly production rate increased to 500 grams starting in mid-January 2015 (Figure 9).

Figure 9. Beta Jar.

- A third prototype was designed with very similar reactor design to the second prototype. Labeled *Big Beta,* the unit offered a maximum production rate of 50 grams per batch (Figure 10).

Figure 10. Big Beta Jar.

- In March 2016, after various design modifications to the second prototype series, a 3rd prototype was launched with an average production rate of 250 grams per batch and 800 grams per week (Figure 11). Important considerations in the design and operations of unit "Gamma" include:

- Identification of materials which offer light weight for workability, and robustness from a mechanical standpoint
- Modifying the design while ensuring the versatility of unit "Beta" was maintained
- Ensuring the process created comparable results to unit "Beta" by carrying out basic runs with graphite feedstock
- Using the optimized gamma unit to create larger amounts of processed carbon platelets for small-scale market applications and testing
- Revising the reactor design, including; style of fittings, reactor opening and closing mechanisms, and a double O-ring system devised to contain pressure cylinder. Furthermore, the additional weight of the unit required that the pressurizing and depressurizing steps of the jar be more user friendly for the operator. As such, important changes were made to the auxiliary setup in the laboratory to alleviate the challenges associated with moving the reactor and its subsequent cleanup.

Figure 11. Gamma Jar.

As of March 1st, 2016, CUT had also changed their lab location to a well-equipped facility in Calgary where over 70% of the reactors can be run simultaneously, allowing a combination of small reactor to run for data collection (particularly on new feedstock) while the larger production reactors are used to increase the inventory required for market-specific testing with various end-products. This is crucial for testing in the fields of concrete, coatings, and asphalt where large samples of the product are required even for small-scale laboratory testing for product performance validation.

Market-specific Testing Results

A high priority was place on the discovery of commercial applications for our carbon-based materials. This was undertaken through the utilization of the professional consortiums mentioned previously, but also supplemented by a broad networking and market research effort to expand our connections and identify target commercial fields. This led to a collaborative testing phase with both industry partners and academic research teams. A distinct goal of revealing fields where our product offered the most monetary value was the driving force of this testing; the most highly being material sciences. Among these, polymers, concrete, coatings, and asphalt all showed promising results, while graphene oxide and reduced graphene oxide showed applications in lithium-sulfur batteries and solid lubricants:

- In **polymers**, specifically HDPE, we saw significant benefits to tensile strength and Young's Modulus with a manageable expense to colour versatility. These results are already being tested with an industry partner to evaluate commercial feasibility by reducing the amount of polymer mass used in a specific line of product.
- Our CNP platelets were also tested in **cement** at the University of Toronto where the effects were evaluated using mortar as an analogue. The parameters of focus were mortar flow rates, air entrainment, and compressive strength as they are best suited for ensuring that standards are maintained. Results showed that a specific blend, with the addition of our additive, increased compressive strength while maintaining satisfactory flow and air content. Further concrete testing was conducted at the University of British Columbia where metal oxides and phosphates were blended directly with a cement mixture and added to concrete for conclusive testing. An increase in compressive strength was found, as well as a reduction in charge transportation implying a decrease in chloride ion penetration.
- The same materials we have analyzed in mortar and cement mixtures have also been refined into various blends of **coatings**. In collaboration with Top Gun Coatings Inc. out of Calgary, as well as the University of Toronto, we have developed a functional application protocol for spraying a durable coating comprised of a ceramic binder and carbon filler with applications to corrosion prone metals. Originally a two-part blend with abrupt curing times, the Alpha Carbon coating has been reduced to a one-part blend with customizable curing times ranging from 5 minutes to 2 hours, depending on purpose-of-use.
- Carlton University has been our partner in testing CNP in **asphalt** concrete where results have shown ideal tensile strength retention and consistency through climate-analogous freeze-thaw cycles with specific blends in comparison to stock compositions. Blends showing promising results are being further refined and investigated, seeking higher performance benefits.
- Aside from CNP platelets, CUT's GO is providing optimism to **lithium-sulfur battery** research where it is acting as a significantly more cost effective replacement for what is currently being used to produce promising energy density results. Although energy density results are lower than what is evident with high-grade GO, they are still significant and provide commercial motivation for the field.
- CUT's GO) may also prove to be valuable as a filler in **solid lubricants**. Testing is being conducted with an industry partner that already utilizes carbon-based material to reduce

friction as a filler in their coating. The physical and chemical properties that their carbon-based filler utilizes to enhance lubricity are exaggerated in GO and thus provide reasons it may act as a performance enhancing substitute.

- Auxiliary testing is also being conducted in the fields of **solar photovoltaics**, **gas adsorption**, and **adhesives** to explore potential benefits.

Polymers

Principal Investigator: Dr. Hani E. Naguib, Sean Lin, Muhammad Anwer, Smart and Adaptive Polymers Lab (SAPL), University of Toronto

Associated Investigators: David Beernhart, Reliance Products Inc., Winnipeg, MB

The initial phase of testing with SAPL was focused on the strength and microstructure characterization of HDPE with a weight dosage of 5%, 15%, and 25% of carbon nanoparticles versus a neat blend. The HDPE composite was compounded using a twin-screw compounder at 210-215˚C for 15 minutes and characterization was achieved using SEM imaging and ASTM-standard tensile testing with an Instron tensile testing machine. From an average neat HDPE tensile strength of 36.2 MPa, an addition of 5%, 15%, and 25% of nanoparticle carbon by weight corresponded to averages of 64.6 MPa, 55.0 MPa, and 59.1 MPa respectively. As for the Young's Modulus, from 771.8 MPa in neat HDPE, carbon nanoparticle additions of 5%, 15%, and 25% corresponded to 1098.7 MPa, 1128.4MPa, and 1168.0 respectively. Increasing weight dosages display a degradation in material enhancing benefits, further supported by signs of agglomeration in SEM imaging.

Further testing with SAPL explored strength and microstructure characterization of HDPE with a reduced nanoparticle weight of 3% with identical testing procedures. An addition of 3% of nanoparticle carbon by weight corresponded to a mean tensile strength of 66.0 MPa and a mean Young's Modulus of 1188.8 MPa. This indicated that a 3% dosage yielded the highest observed material benefits with a mean tensile strength increase of 82.3% and a Young's Modulus increase of 54.0 %. We also conducted dielectric testing by running frequency sweep voltage on samples dosed with 15% nanoplatelets and 0.05% graphene oxide in order to define optimal conductivity. The relationship between frequency, conductivity, and AC voltage for are shown in Figure 12. Both samples showed very low conductivity as low tan δ values are representative of a typical insulator.

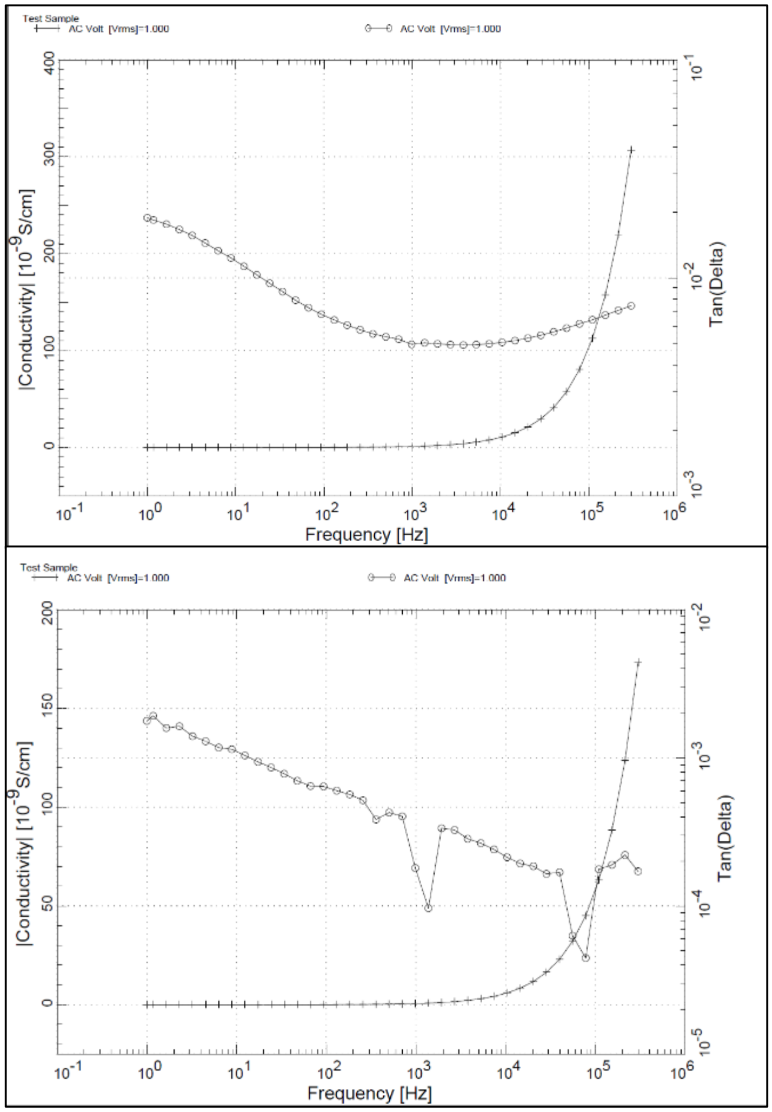

Figure 12. Conductivity results as determined by frequency sweep voltage testing. 0.05% wt. dosage of graphene oxide in HDPE (top), 15% wt. dosage of carbon nanoplatelets in HDPE (bottom)

The next stage of testing analyzed HDPE material benefits of our nanoparticle at dosages of 0.05% and 0.03% (with 0.3% green colorant) in order to establish a composition range that would be considered value-adding. Similarly, samples were created via mixing at 210˚C for 15 minutes and injection molded into ASTM-Standard Type 4 dies to be molded at 40˚C. For this, we saw a mean UTS of 43.8 and 46.6 MPa with a Young's Modulus of 946 and 780.9 MPa respectively, indicating lower but still considerable strength and flexibility increases from a neat composition. Furthermore, dosages above 0.05% resulted in black opacity for samples 2mm thick or more while translucency was achieved for the same dosage at 0.5mm thickness. This implies clear market boundaries for color sensitive products that exceed thickness of 0.5mm. A colourant addition of 0.3% into a 0.03% nanoparticle composition was purposed to evaluate the possibility of maintaining coloured products in our target markets. As seen in Figure 13, colouration is not compromised at this dosage. A summary of all HDPE UTS and modulus results can be found in Figure 14.

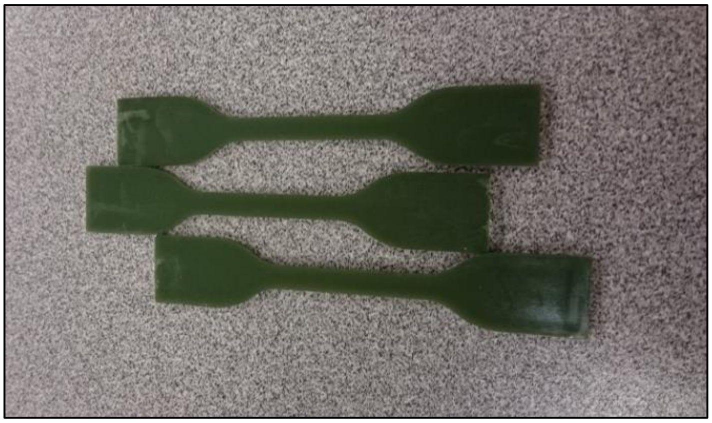

Figure 14. Photograph of HDPE samples with 0.03% wt. dosage of carbon nanoplatelets with a 0.3% dosage of colourant.

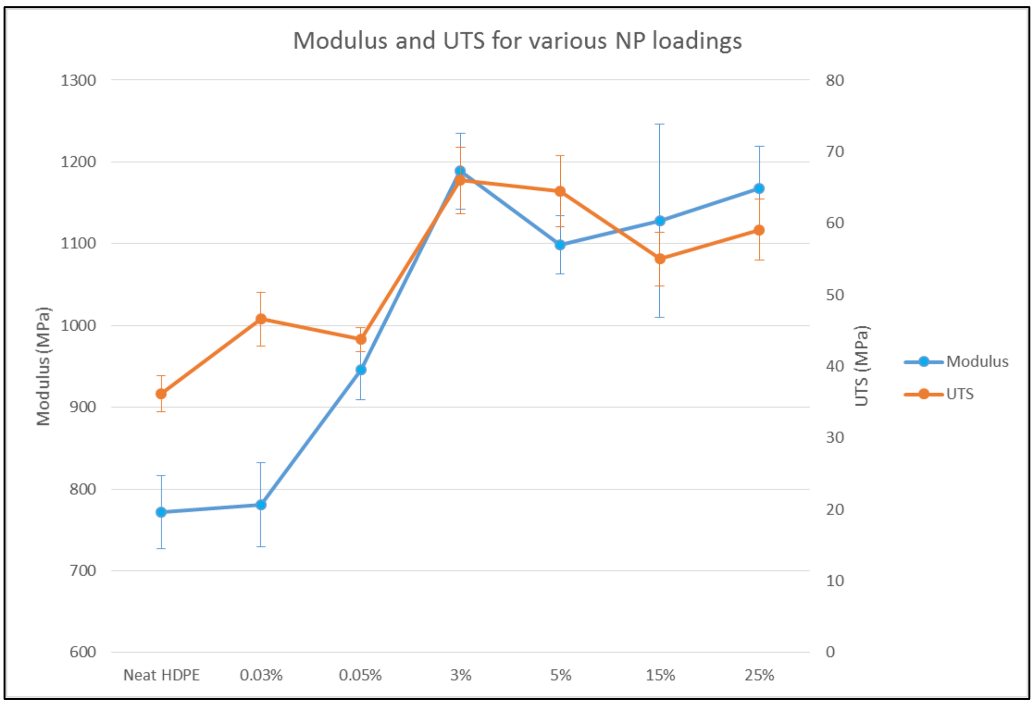

Figure 13. Comparative representation of tensile strength and Young's Modulus enhancements for various wt. % dosages of nanoplatelets.

Testing the effect of platelet dosages in TPU also involved UTS and modulus measurements like in HDPE, where compounding was done with a twin-screw compounder at 170˚C for 15 minutes, injection molded into ASTM-standard dies, and held for 1 minute. This was done with both a neat composition and a 3% weight dosage of platelets and deformed by the Instron. Results were not conclusive as the machine's extension limit was reached before samples failed. Though data implies a young's modulus increase of ~40%, tensile strength could not be determined (Figure 15).

Through the presentation of our positive results in HDPE, we gained the interest of Reliance Products, a plastic products manufacturer in Winnipeg, MB. We have negotiated a testing procedure where they will reduce the HDPE mass of their product from 350g to 280g (20%) with a 0.03% dosage of our nanoplatelets and test product quality. A 0.03% dosage was chosen to prevent losing the market benefits of colourants. The total project mass is 50 kg of HDPE and will produce ~ 178 containers. We consider this test vital to our potential for market penetration as the implications of success are very large. In 2014, the HDPE market accounted for 57.5 million tonnes in production, grossing 61.8 billion USD (http://www.ceresana.com/en/market-studies/plastics/polyethylene-hdpe/). If we prove that our nanoparticle successfully reduces HDPE mass requirements in products by 20% without effecting colour attributes, as well as achieve even larger mass reductions for "colour insensitive" products, the commercial opportunities are extreme. However, our product does not necessarily have to reduce polymer mass. Products that are expected to handle higher force will still see significant value addition by using our nanoparticles at a 3% - 5% dosage without a reduction in HDPE. A possible draw back in market potential would be disapproval for consumer/food safety which is a stage of testing we have yet to explore due to financial restrictions. Regardless, carbon is known for its inert properties and is already used as a black colourant in food products. As such, we are optimistic that our product will be approved but we can't be sure until testing is completed. Regardless, if the product is not approved for food safety, successfully penetrating a small percentage of a USD 61.8 Billion market could result in a very successful business.

Greenhouse Gas and Non-GHG Impacts

Qualitative Discussion on GHG Benefits

CUT’s novel technology has effected greenhouse gasses both direct and indirectly. However, additional impacts on GHG’s could be manifested if auxiliary technologies that utilize our products are developed.

The potential for direct capture of CO_2 in varying grades of carbon and other feedstock, was proven to be possible at high efficiencies in a low-energy mechanism. The ability of the process to accept various mineral and carbonaceous feedstock also has important GHG consequences, as each of the solid feeds showed potential for CO_2 sequestration upon exfoliation within specific operating parameters. The process was also robust with low-grade CO_2 gas feeds. Using lower purity gas feeds reduces indirect GHG emissions associated with capturing and processing high purity CO_2 through methods like amine stripping or zeolite-based adsorption.

Secondly, important data on the end-product market applications suggest significant indirect GHG reductions. The test results found in the field of polymers and concrete, where the addition of CUT's nanoplatelets led to significant performance enhancements, provide a market driver for the commercial adoption of the product by offering the end-user material reductions at a very market-competitive price. The implications that polymer and a concrete demand reduction have on GHG's are considerable. However, CUT has found that current industry partnerships have been fueled by their ability to cut costs associated with materials. The GHG benefits and sustainability benefits associated with the technology are an important bonus, but have not been the driving force behind the industrial partnerships to date.

Quantification of Potential Annual GHG Benefits with Technology Scale up

Using quantitative measurements collected over the course of this project, an analysis on the direct and indirect GHG emission reduction potential can be explored. The analysis of these benefits is shown below, exclusively in both the polymer and concrete industries under the assumption of high product integration with Alberta markets.

GHG Reduction Potential in the Polymers Industry

<u>Important Assumptions:</u>

- Conservative decrease in polyethylene (PE) use of 10% due to CUT nanoparticle composite use. (Data suggests the PE use per product can be reduced by 30-80%) at optimal dosages.
- PE market in Alberta expected to grow by 5% per year
- A dosage of 0.01% CUT nanoplatelets is assumed (i.e. 1 ton of LDPE or HDPE requires 1 kg of CUT nanoparticles)
- The CUT nanoparticle is assumed to have a 0.1 tonne CO_2 equivalence. This number is derived through a lifecycle analysis where by the total CO_2 uptake is assumed to be 25% (3% less than the maximum seen in results thus far). However, it is also assumed that 15% of this uptake is lost due to the grid electricity consumption used by the reactor. This number has been derived through the various amounts of nanoparticle processed in the alpha, beta, and gamma reactors.

Parameter	Quantity	Unit	Reference
Annual production of PE capacity in Alberta	3.9	Million Tonnes	http://www.energy.alberta.ca/Org/pdfs/factsheet_Petrochemicals.pdf
CO2e per tonne of HDPE emission	2	Kg CO2/kg HDPE	http://www.co2list.org/files/carbon.htm
Direct CO2 emission reduction per tonne of CUT nanoparticle	-0.1	tonne Co2/tonne CUT product	*This assumes that 15% of the total Co2 captured (on a mass of end-product basis) is lost due to energy input from a dirty grid, with an emissions factor of 0.7 Kg CO2/kw-hr assumed.
Cost of nanoparticle per kilogram for end-user	<< Savings from reducing PE consumption per product by 10% (*Pricing is Incumbently confidential due to competitors)		

Table 9. GHG Reduction Scenario Projections for Incumbent AB Polymer Industry and CUT nanoparticle adoption in Polymer Industry Scenario.

Year	Total PE Production Alberta (Mmtons/year)	Incumbent Emissions Profile of AB Polyethylene Market (MM tonnes CO_2/ year)	Incumbent Emissions Profile of AB Polyethylene Market (Ktonnes CO_2/ year)	CUT Platelet Production (kg)	CUT Expected Market Acceptance (MMtonnes of HDPE influenced)	CUT-influenced Emissions Profile (Ktonnes CO_2e)*	CUT-influenced Emissions Profile (MMtonnes CO_2e)	Annual CO_2e Reductions (kTonnes of CO_2 emissions)	Cumulative CO_2e Reductions (kTonnes of CO_2 emissions)
2017	3.90	7.80	7800	0	0	7800	7.80	0	0
2018	4.10	8.19	8190	5000	0.5	8085	8.09	105	105
2019	4.30	8.60	8600	10000	1	8390	8.39	210	315
2020	4.51	9.03	9029	15000	1.5	8714	8.71	315	630
2021	4.74	9.48	9481	20000	2	9061	9.06	420	1050
2022	4.98	9.95	9955	25000	2.5	9430	9.43	525	1575
2023	5.23	10.45	10453	30000	3	9823	9.82	630	2205
2024	5.49	10.98	10975	35000	3.5	10240	10.24	735	2940
2025	5.76	11.52	11524	40000	4	10684	10.68	840	3780
2026	6.05	12.10	12100	45000	4.5	11155	11.16	945	4725
2027	6.35	12.71	12705	50000	5	11655	11.66	1050	5775

**The 7th column in Table 10 refers to scenarios where the amounts of nanoparticle produced by CUT (as stated in Column 5) is accepted by the injection molders, extruders, and other end-users buying the HDPE resin. As such, these end-users are now producing the same product as before but with 10% less HDPE. In this scenario, it is assumed that emissions profile of the unaffected industry is the standard reference number while the CUT-influenced industry is the segment of end-users that have switched to a HDPE-CUT composite. Using Row 3 (Year 2018) as an example: of the total HDPE production of 8.19 million tonnes in Alberta, only 0.5 million tonnes have a modified CO_2 emissions profile. As such, the CUT-influenced emissions profile is the weighted average of the emissions from the non-modified HDPE pellets and the modified HDPE pellets. The modified HDPE pellet CO_2e value was derived by assuming the same product could be produced with 10% less HDPE than the base case and the negative emissions derived through the use of CUT's nanoparticle additive. **

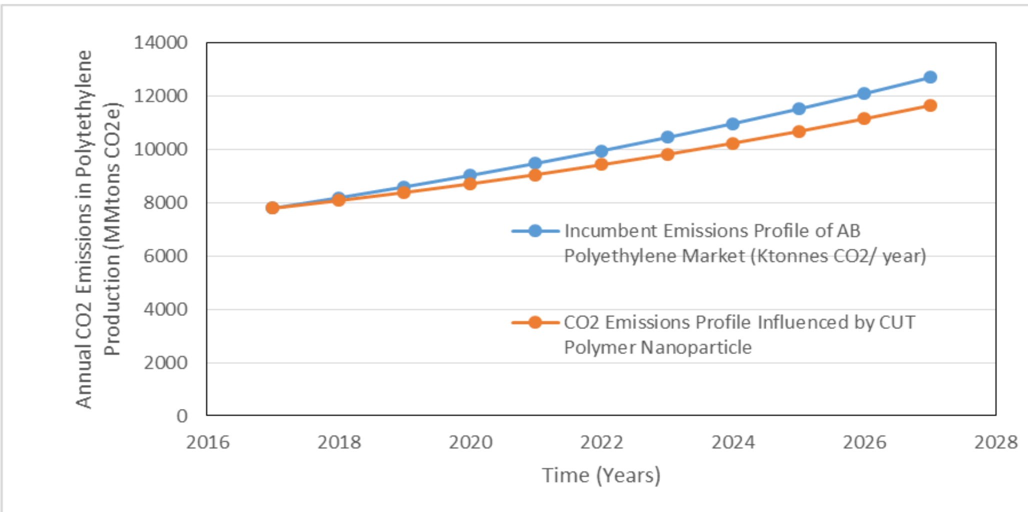

Figure 24. Illustration of GHG Reduction Scenario Projections for Incumbent AB Polymer Industry and CUT nanoparticle adoption in Polymer (i.e. end-user injection molding, compounding, and extrusion) Industry Scenario.

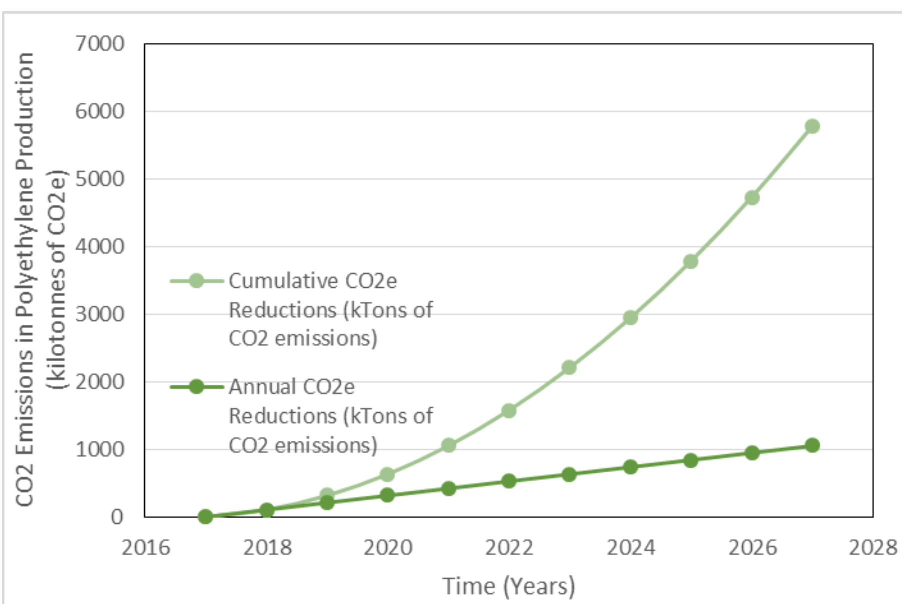

Figure 25. Illustration of Annual and Cumulative AB GHG Emission Reductions through the adoption of CUT nanoparticles in the local Polyethylene (i.e. end-user injection molding, compounding, and extrusion) industry.

GHG Reduction Potential in the Concrete industry

Parameter	Quantity	Unit	Reference
Annual production of Cement Klinker capacity in Alberta	2.5	Million Tonnes	http://www.cement.ca/en/Economic-Contribution.html
CO2e per tonne of HDPE emission	0.75	Kg CO2/kg cement	http://www.co2list.org/files/carbon.htm
Direct CO2 emission reduction per tonne of CUT nanoparticle	-0.1	tonne Co2/tonne CUT product	*This assumes that 15% of the total Co2 captured (on a mass of end-product basis) is lost due to energy input from a dirty grid, with an emissions factor of 0.7 Kg CO2/kw-hr assumed.
Cost of nanoparticle per kilogram for end-user	< Savings from reducing cement consumption per product by 10% (*Pricing is Incumbently confidential due to competitors)		

Important Assumptions:

- Conservative decrease in cement use in concrete industry of 5% due to CUT nanoparticle composite use. Data suggests the cement use in ready-mix and SCC (Self-Consolidating Concrete) precast blends can be reduced by 10-25% at optimal dosages.
- Cement market in Alberta expected to grow by 2% per year
- A dosage of 0.5% CUT nanoplatelets is assumed (i.e. 1 ton of cement would be enhanced by 5 kg of CUT nanoparticles)
- The CUT nanoparticle is assumed to have a 0.1 tonne CO_2 equivalence. This number is derived through a lifecycle analysis where by the total CO_2 uptake is assumed to be 25% (3% less than the maximum seen in results thus far). However, it is also assumed that 15% of this uptake is lost due to the grid electricity consumption used by the reactor. This number has been derived through the various amounts of nanoparticle processed in the alpha, beta, and gamma reactors.

Year	Total Cement Production Alberta (Mmtons/year)	Incumbent Emissions Profile of AB Cement Market (MM tonnes CO2/ year)	Incumbent Emissions Profile of AB Cement Market (Ktonnes CO2/ year)	CUT Platelet Production (kg)	CUT Expected Market Acceptance (MMtons of cement influenced)	CUT-influenced Emissions Profile (Ktons CO2e)	CUT-influenced Emissions Profile (Mmtons CO2e)	Annual CO2e Reductions (kTons of CO2 emissions)	Cumulative CO2e Reductions (kTons of CO2 emissions)
2017	2.50	1.88	1875	0	0	1875	1.88	0	0
2018	2.55	1.97	1969	5000	0.001	1912	1.91	56	56
2019	2.60	2.07	2067	10000	0.002	1951	1.95	117	173
2020	2.65	2.17	2171	15000	0.003	1990	1.99	181	354
2021	2.71	2.28	2279	20000	0.004	2029	2.03	250	604
2022	2.76	2.39	2393	25000	0.005	2070	2.07	323	927
2023	2.82	2.51	2513	30000	0.006	2111	2.11	402	1329
2024	2.87	2.64	2638	35000	0.007	2153	2.15	485	1814

2025	2.93	2.77	2770	40000	0.008	2196	2.20	574	2388
2026	2.99	2.91	2909	45000	0.009	2240	2.24	669	3057
2027	3.05	3.05	3054	50000	0.01	2285	2.28	769	3826

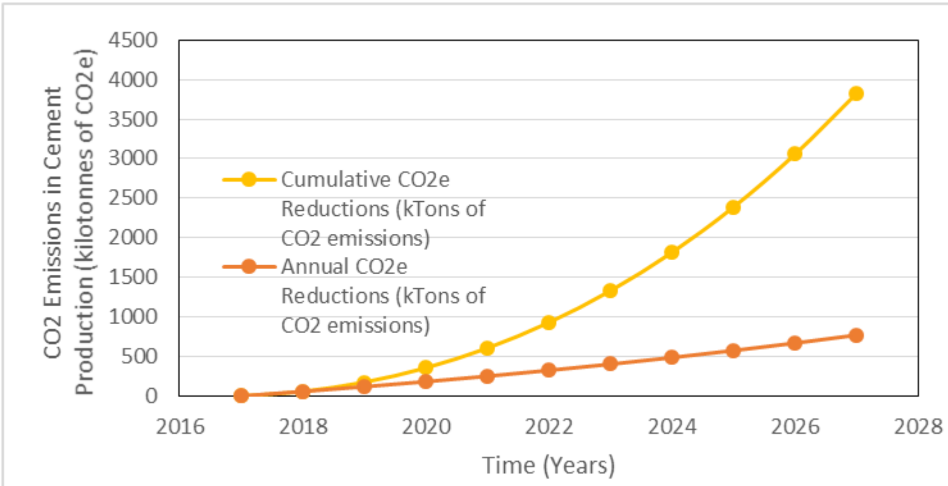

Figure 26. Illustration of Annual and Cumulative AB GHG Emission Reductions through the adoption of CUT nanoparticles in the local Cement (i.e. end-user Precast & Ready-mix Concrete) industry.

**The 7th column in Table 11 refers to scenarios where the amounts of nanoparticle produced by CUT (as stated in Column 5) is accepted by the ready-mix, precast, and other end-users buying cement and concrete prerequisites. As such, these end-users are now producing the same product as before but with 5% less cement. In this scenario, it is assumed that emissions profile of the unaffected industry is the standard reference number while the CUT-influenced industry is the segment of end-users that have switched to a cement-CUT composite. Using Row 3 (Year 2018) as an example: of the total cement production of 1.88 million tonnes in Alberta, only 0.2 million tonnes have a modified CO_2 emissions profile. As such, the CUT-influenced emissions profile is the weighted average of the emissions from the non-modified HDPE pellets and the modified HDPE pellets. The modified HDPE pellet CO_2e value was derived through a weighted average of the CO_2 emissions from base HDPE and the CUT nanoparticle. **

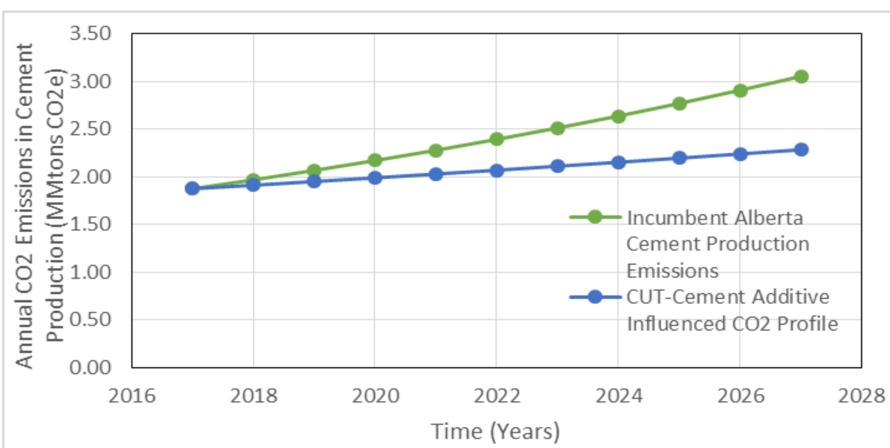

Figure 27. Illustration of GHG Reduction Scenario Projections for Incumbent AB Cement Industry and CUT nanoparticle adoption in Cement (i.e. end-user Precast & Ready-mix Concrete) Industry Scenario.

Potential and Relevance of Report Findings in Global Markets

It is important to note that both the polymer and concrete industries are of global importance and are active, high-volume markets. As such, the technical benefits of CUTs nanoparticles could be marketed internationally and supplement global emission reductions significantly. The global HDPE market consumes over 50 million tonnes annually and the global cement market produces more than 300 million tons of product annually. International adoption of CUT's nanoparticles into only 5% of these markets would have the potential of reducing global GHG emissions by over 20 million tonnes annually.

Discussion on non-GHG Benefits

The adoption of CUT's nanoparticles has a variety of non-GHG benefits that are difficult to quantify but qualitatively increase overall efficiency in the materials sector. Some important benefits include:

- Lower material consumption per end-product, particularly in the polymers industry, has significant benefits. Importantly, injection molders can increase production capacity, increase the efficiency of material logistics (most polymer pellets are transported by rail or ship), and secondary benefits in the efficiency of these transportation mechanisms would be a direct consequence of CNP adoption. End-users can also utilize their own facility space more efficiently and downgrade their facility footprint, which leads to subsequent reductions in utility and maintenance costs such as heat, electricity, and air.
- CUT's process can use a variety of solid feedstock to serve as the solid basis for the adsorption of CO_2. This is important as it allows the use of local feedstock, carbonaceous or mineral-based, for the direct sequestration of CO_2 to produce nanoparticles with market value. Primarily, CUT has been focused on conducting performance evaluations with carbon-based solid feedstocks but similar tests will be conducted with feeds such as serpentine and olivine, as the technology development progresses.
- In concrete and cement-related applications, the use of CUT's nanoparticles has shown a significant increase in the ready-mix's ability to entrain air, an important requirement for colder climate applications. Because the nanoparticle also has the ability to directly increase the durability of the ready mix blend, while replacing solvent-based air entraining agents, positive knock-on effects simplify the logistics for the end-user. In particular, solvent-based chemical reagents conventionally used in the ready mix industry can be replaced by more environmentally sustainable materials while increasing the life of concrete mixes through enhanced durability and corrosion resistance.

Overall Conclusions

Carbon Upcycling Technologies (CUT) has successfully developed a method for sequestering CO_2 from a low grade gas stream into versatile carbon nanoparticles. Various levels of CO_2 adsorption to multiple types of exfoliated feedstock has been demonstrated using TGA-MS analysis of carbon isotopes. This process has been optimized and scaled to achieve the near theoretical adsorption capacity in graphite with cost-effectiveness. Testing for market applications has been executed through multiple university consortiums and have shown positive results in the fields of polymers, concrete, coatings, lithium-sulfur batteries, drug delivery, physical adsorbents, solid lubricants, solar cells, gas adsorption, and adhesives. Investigations regarding polymers, concrete, and coatings are of the most significance due to promising results and engagements with industry partners that have taken particular interest in the development of these applications.

In polymers, considerable increases in tensile strength and Young's Modulus have gained the interested of Reliance Products where they are piloting the use of our nanoparticles through reducing their material input for a line of product. If this test is successful, CUT will have confirmation that this application is marketable in HDPE products that are not food-related. To enter food-related markets, CUT would require funds to complete a 6-month toxicity testing phase to apply for approval from the FDA and Health Canada. With a successful pilot and food safety certification, a significant portion of the HDPE market will be able to benefit directly from our product by achieving large cost reductions or performance enhancements.

Similar prospects are present in the field of concrete. Although applications are not as immediate as polymers, market application testing has shown benefits to compressive strength, curing time, and corrosion resistance in cements. These are all sought-after characteristics in concrete products, however, the blends that have been explored thus far require further refinement and cost analysis before they can be recognized as having the same commercial potential as polymer applications. Fortunately, an engagement with the Denver-based concrete company OldCastle PreCast has provided CUT with direct market experience and guidance. CUT is confident that this partnership will result in the establishment of a value add blend that utilizes its products and can be commercially implemented.

CUT has also made valuable head-way in the development of a commercial coating product, Alpha Carbon. This coating offers similar benefits to hot-dip galvanizing and preliminary cost analysis has shown that it is competitive. Advantage Tower, a Calgary-based infrastructure company, has taken particular interest in this and a commercial engagement is currently being explored. CUT is close to achieving satisfactory performance with this product and only minor adjustments in abrasion resistance and surface finish are to be made before the product is ready for standardized testing.

Considering the goal of the CCEMC Grand Challenge is reducing GHG emissions through the conversion of CO_2 emissions into carbon-based products, the development of market applications that use our product is vital in allowing our technology to effect the emissions output of these high-volume industries. Though the use of our CNPs, GO, and rGO offer direct emissions reduction, the indirect effects are much more significant through the ability of our products to reduce material demand while maintaining product quality. The most highly effected industries in this regard would be the polymer and concrete industries which each make large contributions to GHGs through the manufacturing of their products.

Scientific Achievements

Presented in chronological order, the developments that CUT's management considers scientific achievements are listed below:

- The adaptation of what was formerly an impractical method of CO_2 sequestration, to a low energy and carbon negative process that achieves near theoretical maximum for CO_2 uptake in various solid feedstock
- The successful scaling of this technology through 4 phases, increasing production from 2 grams per week to 800g per week while maintaining product quality and benefits
- The discovery of potentially significant market applications which utilize CUT's novel products to positively affect both the quality of products and reduction of GHG emissions for industries that are considered major contributors
- The development of technologies and applications that have the potential to be highly integrated between any CO_2 emissions producer and high-volume industries were applications are relevant

Communications Plan

Networking has always been of considerable importance for CUT. It is the core principle that allows them to ensure all technical investigations are completed and reviewed by qualified individuals. This has been its primary focus in early stages of the development, but recent advancements in commercial applications have increased the importance of networking at relevant industry events like trade shows and clean tech events. Among these are the Rice Alliance Clean-tech Forum, as well as the Globe and Americana conferences. CUT also plans to participate in the COSIA Carbon X-Prize as this opportunity offers valuable funding and exposure to other groups working in a similar field. Furthermore, many of our industry partnerships have resulted from reaching out to companies online by presenting project information and connecting either in person or by correspondence. This effort is expected to continue as relationships developed through this means have created valuable progress.

CUT's CEO, Apoorv Sinha, is also a member of the Energy Futures Lab fellowship. This fellowship is a conglomeration of valuable and ambitious professionals with extensive backgrounds in the energy industry or possess a portfolio of experience that relates to environmental sustainability. The expertise of these individuals is valuable and will be consulted regularly on a case-to-case basis.

University Collaborations

The positive benefits of leveraging expertise from our academic network is unprecedented. Establishing consortium-like groups who specialize in various chemistry and engineering fields has been vital in revealing the applications of our product and expansion of our technology portfolio. Although the management of CUT has been the driving force behind strategizing the progression of our technologies, the level of experience that is offered by university professionals adds an invaluable amount of credibility to our test results. These key players and their contributions, as well as their associated institutions are as followed:

University of Calgary: Dr. Viola Birss and Dr. Jason Young, Department of Chemistry

- Dr. Birss and Dr. Young played a major role in the literature review associated with establishing a low-energy alternative to the mechano-chemical exfoliation process. Once this method was proven in concept and a prototype was built, their expertise was utilized in optimizing this process to achieve maximum CO_2 sequestration.

University of Waterloo: Dr. Pu Chen, Dr. Alireza Yazdi

- Although Dr. Chen and Dr. Yazdi played a supplementary role in product characterization, they made major contributions to this project by demonstrating the production of graphene oxide and reduced-graphene oxide by further exfoliating CUT's CNPs. As a result of their keen involvement, testing in market applications for GO and rGO related avenues has been handle almost exclusively by this group. These avenues include; concrete, lithium-sulphur batteries, solar photovoltaic cells, and drug delivery. Testing each of these applications has shown optimistic results thus far and we expect both Dr. Chen and Dr. Yazdi to be continually involved in the future.

University of Toronto: Dr. Hani E. Naguib, Sean Lin, Muhammad Anwer, Smart and Adaptive Polymers Lab (SAPL) and Alireza Dehgan, Karl Peterson, and Yan Chan, Department of Civil Engineering

- The gentlemen at SAPL have been at the forefront of our market application testing for our products in polymers. All test results presented above have been accumulated in the SAPL and have been focused on properties like tensile strength, Young's Modulus, thermal conductivity, electrical conductivity, and colourant compatibility. The effect of CNPs on HDPE in particular, have some of the largest market applications thus far implied through materials testing. Both CUT and SAPL recognize the significance of these results and plan on a long term engagement to further validate CNP use in polymers.
- Alireza, Karl, and Yan have collaborated with us in an effort to test the effect of GO as an additive in various mortar composites in order to reveal market applications for cement. For each tested admixture, the compressive strength increased in GO blends by approximately 40%. For the next phase of mortar mixes, results with different AEA and CNP dosages will analyzed to find the level at which similar air contents and microstructure are achieved when compared to the control mixtures.

University of British Columbia: Dr. Nemkumar Banthia, Department of Civil Engineering

- Dr. Banthia has been extensively involved in the developing a blend of concrete that utilizes the effects of metallic oxides and phosphates to increase the compressive strength and chloride penetration of concrete. Initial testing proved optimistic, with one blend in particular, and future engagement will be required to refine this towards market use. Furthermore, the data gathered through investigations with Dr. Banthia has translate directly into an engagement with Old Castle Precast, a major concrete company who has engaged with CUTs parent company, zEroCor, in developing an innovative quick-dry blend.

Carlton University: Dr. Abd-El Halim & Dr. Yasser Hassan

- Dr. Halim and Dr. Hassan have been an integral part of exploring our market applications in asphalt. Testing conducted at Carlton has shown that our CNPs assist in maintaining consistent asphalt performance through a wide range of climate conditions seen in Alberta. They have identified a specific blend that has maintained an appropriate tensile strength ratio and volume of air voids when compared against the control. This blend will be further optimized in future testing so that its marketing potential may be explored.

University of Saskatchewan: Dr. Mehdi Nemati

- A full engagement with Dr. Nemati has no yet been discussed. However, he is responsible for some of our preliminary results in the gas adsorption capabilities of CUT's CNPs with regards to ammonia, and in comparison to activated carbon and titanium oxide adsorbents.

University of Alicante: José Miguel Martín Martìnez

- CUT began an engagement with Dr. Miguel in October 2015 to investigate the potential use of its nanoparticles in self-healing polymers and adhesives. Dr. Miguel is a global expert in the field of advanced adhesives for use in the construction, retail and other commercial industries. He is currently working on 8 active projects with commercial partners in Europe and is testing CUTs nanoparticles and graphene derivatives for use in adhesives. Samples were sent from CUT for testing in March 2016 and expects to have preliminary results on the performance of these nanoparticles by the end of summer, 2016.

Next Steps

Carbon Upcycling Technologies (CUT) has grown significantly over the course of two years. From what started out as a proof of concept for a CO_2 sequestration process that produced 0.5 grams of an ambiguously valuable product, CUT has undergone multiple scaling phases and attained promising experimental results for its nanoparticles in market related testing. The start up has proven consistent and reliable production of carbon nanoplatelets ranging from a few nanometers to single atom layers, all through a carbon-negative process. This has been supplemented by third-party validation in various industries ranging from high-volume concrete and polymer sectors to advanced sectors like lithium-sulfur batteries and drug delivery.

4 successfully scaled prototypes firmly support the ability of this technology to produce increasing amounts CNPs cost effectively. Even at a weekly production of 800 grams, CUT is struggling to meet demands for testing within university consortiums and market related partners.

CUT management has strategized that their next steps will entail:

- At least two phases of scale up to keep up with product demand in various industry sectors
- Continued market testing in the concrete, polymer, coatings sectors where market partners have been identified
- Continued testing with Lithium-Sulfur batteries and engagement with a large battery manufacturer
- Engaging with market partners for beta-testing and initial commercialization in the asphalt, drug delivery, physical adsorbents, gas adsorption markets
- Continued engagement with more University partners for further optimization of the CO_2 sequestration process, both through the reduction of time and energy required for maximum CO_2 uptake
- Further testing with various low-grade feedstock for potential use in CUT's proprietary process
- Second round of presentations and follow ups with already-contacted venture capital groups
- Establishing contact with various private and governmental groups globally, such as the Rocky Mountain Institute & the Carbon War Room, for feedback on product development and initial rollout.