Pilot Scale Demonstration & Independent Verification of Carbon Utilization Technologies for the NRG COSIA Carbon XPRIZE

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ABSTRACT

The NRG COSIA Carbon XPRIZE is a global competition to develop technologies for converting CO_2 from power plants and industrial facilities into valuable products. The pilot scale demonstration required teams to operate at a 200 kg/day CO2 input, with evaluation of capture and conversion efficiency, product market and value, land and water resource use, and life cycle emissions. Technology verification procedures were implemented to confirm technology performance and impact claims. Independent verification was valuable providing consistent, repeatable results in evaluating technologies which had not reached commercial maturity – with 40% of teams having verified CO_2 conversion within 30% of claimed, and an average total CO_2 conversion efficiency of 53%.

Keywords: measurement, verification, ISO 14034, carbon, utilization, carbon dioxide

1 INTRODUCTION

Green technology has seen over $279.8 billion in new investment in 2018, with an anticipated $7.4 trillion expected on renewable energy alone in the next two decades[1]. At the same time, only marginal improvements in emissions have been made, with estimated reductions in global Carbon Dioxide (CO_2) emissions of only 1.6% forecast in 2019 and less than 1% in 2020[2]. With a growing need for carbon emissions reduction, increasing numbers of technology developers are proposing systems which claim to reduce environmental impact while generating economic returns. Offering a large cash prize as an incentive and a venue to demonstrate these new technologies, the NRG COSIA Carbon XPRIZE is designed to focus attention on these new technologies and products and supercharge the rate of adoption and acceptance of CO_2 derived materials in the marketplace. The Carbon XPRIZE does this in three key ways:

1. Increasing the required scale of demonstration over three rounds of competition on an aggressive timeline.
2. Requiring consistent ongoing, and verifiable operation of each demonstration, including a continuous run, to evaluate the maturity and reliability of each technology.
3. Providing developers with a venue to test their technologies in an industrial context using industrial flue gas as feedstock.

The Carbon XPRIZE competition involves a demonstration and independent verification approach intended to validate the technology claims and reduce risk to investment and market growth. To give all ideas of merit an equal opportunity, the Carbon XPRIZE developed a three-phase competition with requirements and complexity that increase with each phase, and with substantial financial rewards (totaling $20 million) for successful teams at the end of each phase. Awards are determined by a panel of expert judges, recruited by but independent of XPRIZE.

The competition began with a call for proposals with detailed technology and company profiles which were evaluated for technical and business viability. Forty-seven teams submitted full proposals, using a variety of technology approaches and producing a wide range of materials derived from CO_2. Twenty-seven teams were invited by the judges to advance to the second phase of competition where physical demonstration was required. In this round, teams were required to demonstrate technologies at a rate of 200 $kgCO_2/d$. Twenty-one of these teams provided data from pilot-system operations.

In the third and final phase of competition (ongoing at the time of writing), teams are required to scale up their technologies to a CO_2 consumption rate of at 2-5 tons CO_2 per day at one of two test centers which provide industrial flue gas from coal and natural gas electricity generation.

Teams who successfully operate their technologies using this flue gas as a feedstock will be eligible for one of two $7.5M grand prizes – one for each type of flue gas utilized.

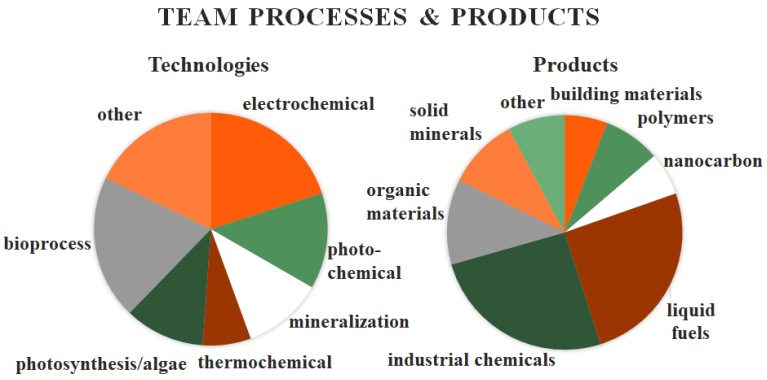

Figure 1: Technology types and product distribution

Criteria	Performance Threshold for Competition	Scoring
CO_2 Converted	Convert ≥30% of CO_2 in flue gas	50%
Net Value	N/A	50%
Water Consumed	Water used is ≤ 4000 L/tonne CO_2 converted	Pass/Fail
Land Footprint	Round 3 scale < 2330 m^2	Pass/Fail
CO_2 Emissions Assessment	Reasonable case for technology to be carbon neutral or better, or achieve measureable relative emissions reductions	Pass/Fail

Table 1: Evaluation criteria for Carbon XPRIZE

2 CARBON UTILIZATION TECHNOLOGIES & PRODUCTS

The Carbon XPRIZE competition attracted technology approaches representing a wide variety of products derived from CO_2 via a diverse set of technology pathways (Figure 1). These included products that are drop-in replacements for petroleum-derived fuels and chemicals – methanol, carbon monoxide, dimethyl ether; products tha substitute petroleum derived products or are altogether new – biodegradable thermoplastics, carbon nanotubes; and materials and products serving the construction industry, such as ready-mixed and pre-cast concrete.

3 EVALUATION CRITERIA

In the pilot demonstration rounds of the Carbon XPRIZE, all teams are evaluated on the same criteria: three environmental impact screening criteria, and two scores addressing performance and net value of products on a normalized basis. The underlying data supporting these criteria must meet minimum specifications for data volume, data quality, and validity**.**

Total CO_2 converted was based on a complete carbon material balance, including monitoring of:

- CO_2 input from real or simulated flue gas via input flow rate and CO_2 concentration;
- Carbon content of feedstocks;
- Carbon content of products;
- Carbon contained in any wastes or emissions.

Net value score was based on measurement of:

- All inputs and their usage rates, including all feedstocks (chemicals, aggregates, and water) and energy inputs, both thermal and electrical;
- The economic value and market size of all inputs, products, byproducts, and wastes;
- Carbon content of inputs and products

In conjunction with the material and energy flows, the Carbon XPRIZE also provided standardized value and market size information for all inputs and outputs, known as Standard Data Sets (SDS)[3], with product specifications (i.e. purity and composition) associated with each input or output. These values were determined based on publicly available market data from 2015, accounting for market volatility. Utilizing the value and the market size information from the SDS, teams computed their overall net value score, a normalized indicator of the potential value of the product for its defined market, enabling comparison of disparate products ability to both generate economic returns and consume significant volumes of CO_2. A 'total score' incorporating net value, market, and conversion capability was then calculated to aid in comparing the teams.

Within these criteria, XPRIZE sought to monitor and verify critical parameters to ensure accurate and reproducible score calculations were delivered to the judges for consideration. In order to ensure consistency across the many different technologies demonstrated in the competition, standardized test methods, analytical techniques, and verification protocols needed to be implemented.

4 VERIFICATION METHODOLOGY

Carbon utilization technology development is in its early stages, with a variety of technical approaches. As a result, standard analyses and protocols for techno-economic analysis (TEA), lifecycle emissions analysis (LCA), and product quality specifications had not yet matured across all approaches and products. It was also XPRIZE's intent to focus the evaluation of teams on specific factors (such as CO_2 Conversion efficiency), and explicitly exclude other factors (such as the capital costs of each system) that would have been included in a full LCA or TEA. For this reason, XPRIZE implemented an evaluation approach via its rules, regulations, performance expectations and scoring criteria that enabled comparison of differing technologies and

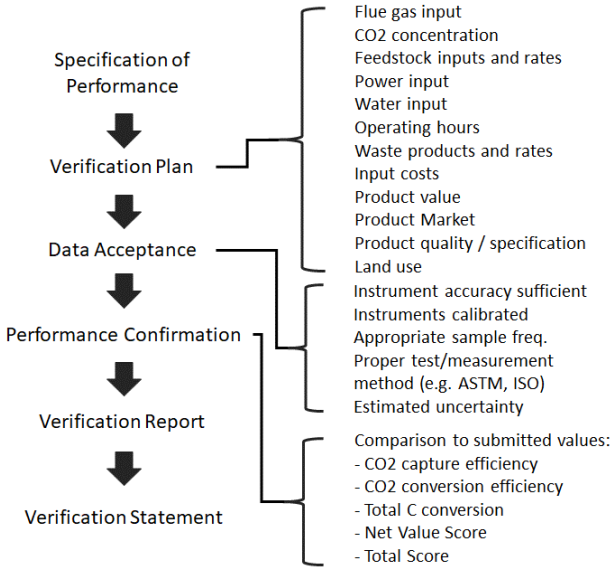

Figure 2: Carbon XPRIZE M&V process

products, while ensuring consistency and data quality. Independent verification of the data was required as a key step in the competition process, ensuring that technology performance was properly evaluated and documented.

Measurement and Verification approaches were developed and implemented based on the ISO 14034 environmental technology verification standard. ISO 14034 provides general guidelines for data requirements, the verification process, and qualifications of independent verifiers. The standard is appropriate when evaluating technologies that are innovative, have a potential environmental added value, and for which product certification or technology evaluation protocols do not yet exist. It has the flexibility to incorporate aspects of lifecycle analyses, techno-economic analysis, standard test methods, and other approaches to address the needs of interested stakeholders, and is flexible enough to be used across a variety of technology and product classes.

The approach incorporates the development of a verification plan, which identifies the specific parameters of interest to stakeholders, data required to evaluate these parameters, operating parameters and conditions under which the technology will be evaluated, and data quality requirements, such as instrument calibrations, measurement frequency, instrument challenges, and data validation. Where appropriate, for specific technologies or products, existing test methods may be specified, such as ASTM C31/39 standards for concrete compressive strength. A summary of the process is provided in Figure 2, with primary measurements and data streams for the Carbon XPRIZE specified during the Verification Plan and the verified performance parameters calculated from this data for final performance confirmation indicated.

Each team generated data for submission to the Carbon XPRIZE competition, providing original claims for technology performance, impacts, and scoring. Testing was duplicated during on-site field validation visits. Performance claims made by each team were then confirmed, unconfirmed, or not verified if data was not available.

5 RESULTS

Primary results from the pilot scale demonstration indicate a wide range of performance characteristics for the technologies demonstrated in the Carbon XPRIZE semi-finals. Although 21 technologies were observed for verification, 16 teams had field-verified results. A summary of carbon conversion values for each is provided in Figure 3. The verified total carbon conversion capacity (capture and conversion) for the competing technologies ranged from 0.1% to 93%, with the top three performers above 80% overall conversion to products and 50% of the teams achieving a verified conversion greater than the 30% competition requirement. In addition to carbon conversion, results for other key criteria are provided in Table 2.

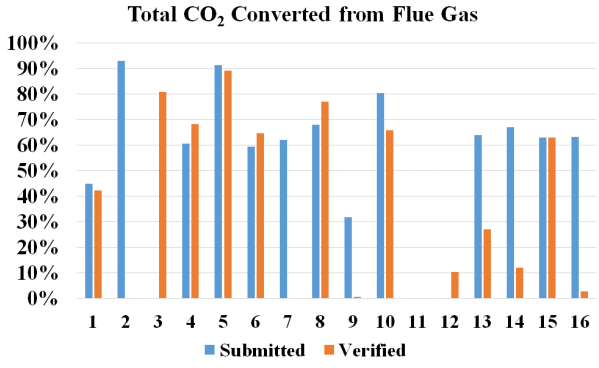

Figure 3: Submitted and verified results comparison

Parameter	High	Low	Mean (*Median)
CO_2 capture from flue gas (%)	95.9%	77.0%	86.4%
CO_2 conv. (%)	100.0%	0.1%	53.4%
CO_2 in product ($kgCO_2/kgProduct$)	2.042	0.001	0.663
Water use (L/tCO_2)	128000	4.55	1948*
Land Use (m^2)	1932	24	480
Scale (Kg/d)	621143	0.0035	200*

Table 2. Range of Verified Performance.

As is expected with an array of innovations at various stages of development, some technologies were ready for operation at the required scale, performing above target requirements and meeting required competition criteria. However, other technologies could not perform at required levels of CO_2 conversion, or did not meet screening criteria, such as the water usage requirement. It should also be noted that some technologies could not achieve the scale of operation or could not provide valid data for the required 24 hour operating period. Results indicate the varying stages of development of these technologies.

6 VERIFICATION IMPACT

Figures 3 and 4 indicate that, in many cases, there are distinct differences between submitted data and field verified data. Note that, at first glance in Figure 3, many of the technologies appear to convert a large portion of the flue gas CO_2 based on submitted data. After independent verification, some technologies are observed achieving higher conversion with great certainty in their claims, while others did not exhibit the promised performance. Figure 4 provides examples of two different technologies which were verified through field observation. Example 1 exhibits reproducibility of results and adherence to the Carbon XPRIZE competition and Verification Plan requirements. Alternatively, example 2 shows results that are uncertain, with potential issues including poor instrumentation, core technology performance issues, invalid assumptions, reliability problems, or operational issues.

In terms of technology verification performance, the percentage of technologies that met their claimed performance values within +/- 5% was generally less than

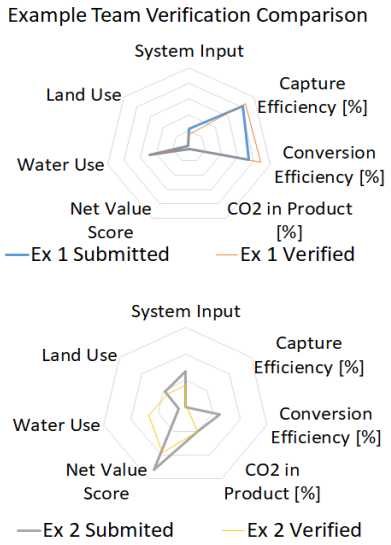

Figure 4: plot of submitted and verified values for 2 teams

20% (with the exception of system input, for which over 30% of teams performed as claimed). The percentage of teams within 30% of their submitted values for key performance criteria increases to over 50% for system input scale, and >32% for conversion and market value. It should be noted that 50% of teams exhibited greater than 30% difference from their submitted conversion efficiency values – a key performance criteria. Also, note that a significant number of teams either did not submit or could not have verified market value, net value, or water use (>44%).

It is important to note that a poor verification result does not necessarily discount the merit of the idea. Poor verification simply demonstrates that the current implementation does not provide sufficient to warrant further scale-up at the time of verification. More development, data, or attention to detail is required to show improved confidence and reduce risk

Alternatively, a successful verification provides a level of assuredness that repeatable results can be expected from the technology, that the technology has reached maturity at the demonstrated scale, and proper operation, testing, and quality assurance methods are utilized. Verified technologies can therefore be compared directly with other verfiied technologies and can be considered candidates for further development and potential investment.

Key Competition Criteria	**Submittal vs Verified Accuracy**			
	±<5%	*±5-30%*	*±>30%*	*N/V*
System Input	31%	25%	19%	25%
Conversion Efficiency	19%	19%	50%	13%
Market Value	13%	19%	25%	44%
Net Value Score	0%	25%	31%	44%
Water Use	13%	6%	19%	63%

Table 3: percentage of teams within range of verified values

These results support the need for independent verification of technology performance for this competition, and for innovative technologies in general. A staged approach to development and evaluation is also validated, ensuring appropriate maturity at each stage before pursuing further development and enabling selection of competitors with the potential to perform at the next stage of competition.

7 FUTURE EFFORTS

The 2nd round of competition was completed at the close of 2017, with 10 finalist teams announced in Spring of 2018. Finalist teams are required to perform technology demonstration at a target scale of 2-5 t/day CO_2 input, with 150 days of operational data, using flue gas provided at one of two test centers co-located with power plants: the Alberta Carbon Conversion Technology Centre in Calgary provides a natural gas-derived flue gas, and the Integrated Test Center in Gillette, Wyoming provides coal-derived flue gas. The described verification process will be used to evaluate finalists in late 2019, with award expected in 2020.

8 CONCLUSIONS

The development and implementation of carbon utilization technologies holds the potential for significant impact on mitigation of climate change. The NRG COSIA Carbon XPRIZE was established to support these innovations and identify, through demonstration and standard evaluation approaches, technologies that have the potential to scale to achieve global impact on greenhouse gas emissions. The pilot scale demonstration program, at 200kg/d CO_2 input, demonstrated that technologies vary widely in stages of development, and with varying ranges of performance and environmental and econimic imact potential.

With a lack of standards for evaluation and specific evaluation requirements, XPRIZE implemented independent technology verification with standard methods to support the identification of the most impactful and ready technologies. Independent technology verification was deemed a necessity based on the need for a consistent and high quality evaluation spanning a diverse set of technologies. Verified quality data enabled selection of top potential candidates for prize awards and participation in the final large scale technology demonstration.

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