Engineering Practice

Integrating the ISO 14034 standard as a platform for carbon capture and utilization technology performance evaluation

Tim Hansen1,*, Kevin McCabe1, Bill Chatterton1 and Michael Leitch2

1350Solutions, Inc., 1053 E. Whitaker Mill Rd, Suite 115, Raleigh, NC 27604, USA
2XPRIZE Foundation, 800 Corporate Pointe, Suite 350, Culver City, CA 90230, USA
*Corresponding author. E-mail: tim@350solutions.com

Abstract

Independent testing and verification of emerging technologies are vital parts of the technology-commercialization process. With the rapid development of carbon capture and utilization (CCU) technologies, where existing standards and certifications do not exist, independent verification approaches and guidelines can provide a means to obtain credible information for an emerging market. The ISO 14034:2016—Environmental Management: Environmental Technology Verification (ETV) standard can serve as a foundational platform to ensure the consistency, quality and credibility of data on CCU technology performance, enabling direct comparisons between technologies and reducing risk to decision-makers regarding potential investment, future deployment and ultimate impacts of CCU innovations. Applying the fundamental principles of ISO 14034 to the evaluation of nine finalist CCU technologies competing in the NRG COSIA Carbon XPRIZE ensured that data used to evaluate competitors was of high quality, consistent across technologies and met the information needs of the XPRIZE and competition judges responsible for selecting winners. The approaches outlined here, including verification parameters and verification tasks for both XPRIZE-specific technology evaluations and full CCU technology evaluation by an accredited entity in conformance with the ISO 14034 standard, provide insight into the potential benefits—methodological consistency, high-quality data, independent oversight, methodological flexibility and broad applicability—and limitations—technology readiness and applicability, verification and instrumentation costs and lack of specificity—of the approach in an application for the evaluation of emerging technologies. Further application of the ISO 14034 standard and principles, developed through a consensus approach that incorporates other developing guidelines, can drive consistency and credibility for technology-performance evaluations across the CCU sector, ultimately leading to reduced risk and improved market access for new innovations.
Introduction

With increasing pressure to curb industrial CO₂ emissions, carbon capture and utilization (CCU) technologies have emerged as an opportunity to produce a variety of important commodities with lower carbon footprints, in addition to consuming CO₂ directly. Independent testing and verification of emerging technologies are vital parts of the technology-commercialization process, providing credibility for technologies as they approach the commercial phases of the technology-development cycle.

The CCU industry has grown rapidly in recent years: corporate and venture capital investments in CCU technologies, including sequestration technologies (i.e. CCUS), have exceeded $460 million over the last four quarters, with Q1, 2021 including >$250 million in investment [1]. Strategic funding by the US Department of Energy (DOE) for CO₂-utilization development projects, as well as the advancement of large, heavily funded global competitions, such as the $20 million NRG COSIA Carbon XPRIZE, have pushed technology companies to develop and, most importantly, rapidly scale CO₂-capture and -utilization technologies. As increasing numbers of technology developers propose innovations with claimed abilities to capture and use CO₂ at significant levels, independent verification approaches can provide needed credible information to an emerging market.

Alongside the development of CCU technologies, methodologies for evaluating the technologies and verifying their performance claims are also being developed, with several approaches emerging for evaluating CCU technologies in several different contexts. The US DOE has developed CO₂-emissions life-cycle assessment (LCA) guidelines as well as techno-economic assessment (TEA) guidance for projects implemented using DOE funding [2]. The Global CO₂ initiative has developed technical, economic and LCA guidelines for CCU technologies, with protocols provided publicly [3]. Finally, the XPRIZE Foundation developed specific rules, regulations, and measurement and verification approaches associated with the NRG COSIA Carbon XPRIZE competition [4]. Each of these efforts shares a common set of goals: to understand the carbon balance of CCU systems to ensure that the carbon-mitigation benefits are established; to understand the technical performance of the candidate technology as well as any technical barriers that hamper performance; and to understand the economic potential and risks that may influence the ability of a technology to attract investment and scale. Although the underlying goals are similar, the approaches of existing guidelines differ, and often require customization and modification for each CCU technology type to ensure that they are applicable—i.e. biological, chemical and mineralization processes may all have different critical
performance factors that should be evaluated in addition to primary criteria, such as carbon-conversion performance. With the rapid evolution of CCU technologies, it becomes difficult to apply such assessments consistently. In addition, as interest in low-carbon and carbon-removal technologies increases, efforts to document the impacts of technology implementation are also developing, with an even wider set of potential standards and protocols being introduced—40 registries and retailers of carbon-offset credits have been identified [5]—but a lack of transparency and robust accounting has made the determination of quality carbon offsets ‘virtually impossible’ [6].

Although more protocols for evaluating CCU technologies have recently been introduced, each one considers its own approach and consensus regarding consistent performance metrics, data quality, baselines, product performance and life-cycle carbon emissions is lacking, mainly because of the novelty of the CCU technology market and the readiness level of most CCU technologies. In addition, most approaches do not focus on a critical core issue—data quality, which can dictate the ultimate utility of the results of a technology evaluation, whether for technology investment decisions or for certifying carbon-removal credits, for example. There is a strong need to ensure that credible, high-quality data are used as the basis for every evaluation. Developing a consensus approach to CCU technology evaluations is critical such that apples-to-apples comparisons can be completed by purchasers, investors and others who want to be able to ensure that the most viable technologies are implemented and their ultimate benefits observed on a broad scale.

The ISO 14034:2016—Environmental Management: Environmental Technology Verification (ETV) standard [7] can serve as a foundational platform to ensure the consistency, quality and credibility of data on CCU technology performance, enabling direct comparisons between technologies and reducing the risk to decision-makers regarding potential investment, future deployment and ultimate impacts of CCU innovations. It may also be used as a tool to develop and build consensus regarding approaches for completing environmental-technology evaluations. The NRG COSIA Carbon XPRIZE utilized the verification approach established in ISO 14034 as a foundation for its assessments of the nine technologies [8] that participated in the Finals of the competition during 2019 and 2020. The fundamental principles of ISO 14034 were applied to ensure that the evaluation of competitors was of high quality, consistent across technologies and met the information needs of the XPRIZE judges responsible for selecting winners.

Further application of this approach can drive consistency and credibility across the entire sector, reduce the probability of technology failure or poor investment return and help to ensure that this burgeoning industry does not meet the fate of other large cleantech process technology investments of the recent past that overpromised and under-delivered, causing a rapid decline in investment and market growth [9, 10].

### 1 The ISO 14034 standard

The ISO 14034:2016 ETV standard establishes globally accepted verification principles, testing practices, data-quality requirements and capabilities required to ensure that technology-performance claims are valid, credible and supported by independent, high-quality test data and third-party review. The standard also facilitates a market-driven approach to technology-performance verification. Stakeholder groups and communities of interest can collaborate in defining appropriate performance parameters and verification requirements, reflecting their particular market needs. The consensus platform also enables the international recognition of verifications, enabling global market entry.

While the need for high-quality information occurs throughout the technology-development cycle, the ISO 14034 standard was written specifically to facilitate the verification of technologies that are commercial or approaching the commercial-ready phases of development (typically for technology readiness levels (TRLs) from 6 to 9) [11]. This pre- or early commercial demonstration can provide a clear picture of the performance and benefits of the technology in its planned commercial application, with an emphasis on the performance of the fully integrated technology, including core technology, balance of plant and ancillary systems, on a commercially relevant scale. Note, however, that the core principles of ISO 14034 can apply to technology assessments across the full range of TRLs—from proof-of-concept through to commercial deployment—and provide the benefits of improved credibility based on high data quality throughout the technology-development life cycle.

ISO 14034 implements several key requirements based on a set of fundamental principles specified in the standard, including [7]:

- **Principle—transparency and credibility:**
  
  Technology verifiers are independent third parties—meeting the requirements of ISO/IEC 17020:2012 Conformity assessment—Requirements for the operation of various types of bodies performing inspection [12];
  
  verifiers are technically competent and qualified as required by ISO 17020;
  
  verification results are made publicly available, documenting observed performance based on verified data;

- **Principle—factual basis:**
  
  Performance assessment is based on direct measurements and data—not models and estimates—that are collected in accordance with various quality requirements, including ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories [13];
• **Principle—sustainability:**
technologies evaluated under ISO 14034 must have a positive environmental impact;
technologies are also evaluated for potential secondary environmental impacts, such as wastes, water usage or other factors;

• **Principle—flexibility:**
verifications, including specific parameters evaluated, can be customized to meet the needs of stakeholders or interested parties;
performance claims of technology developers can be adjusted as data are reviewed and verified.

For transparency, perspective and understanding of the application of ISO 14034, it is also important to note what ISO 14034-based ETV is not:

• ISO 14034 ETV is not a labelling system that requires technologies to meet a predefined set of criteria to achieve certification;
• ISO 14034 ETV is not pass-or-fail certification of technologies—it provides credible data to enable decision-making;
• ISO 14034 ETV does not compare technologies, although the information resulting from ETV will enable purchasers and decision-makers to make needed comparisons.

A summary of the ISO 14034 ETV process is provided in Fig. 1, with major requirements and activities summarized in Table 1. Initial reviews and discussions focus on the technology design, development status and its claimed performance, as stated by the technology developer. Stakeholders are engaged to ensure that the performance metrics and parameters that will be evaluated are relevant and meet the information needs, to the extent possible, of those interested in the technology.

As noted in Fig. 1, the actual testing and collection of data are completed outside of the verification process, with data collected by the technology developer and independent test labs or facilities. The verifier inspects and audits all data, test procedures, equipment and/or labs to ensure that data are complete, valid, representative and of high quality, meeting the requirements of ISO 17025 or similar applicable standards.

### 2 ISO 14034 implementation for CCU technologies in the NRG COSIA Carbon XPRIZE

#### 2.1 Background
CCU technology is an excellent candidate for application of the ISO 14034 ETV process. CCU is a field consisting of novel technologies, most of which are in stages ranging from proof-of-concept (TRL 3 to 6) to pre-commercial (TRL...
Table 1: ISO 14034 verification process: major requirements and activities

| Verification step          | Performer                      | Major requirement                                                                 |
|---------------------------|--------------------------------|-----------------------------------------------------------------------------------|
| Application               | Technology developer and/or     | - Performance parameters suggested by sponsor/developer                             |
|                           | sponsor                        | - Performance claims specified for each parameter                                   |
|                           |                                | - Environmental impact of technology documented by tech developer                   |
| Application               | Verifier                       | - Review performance parameters and claims:                                        |
|                           |                                |   • ensure claims are scientifically sound                                         |
|                           |                                |   • determine appropriate existing evaluation standards, if any (i.e. ASTM, etc.)   |
|                           |                                |   • contact stakeholders and/or review existing evaluation approaches and modify verification parameters to meet market needs |
|                           |                                | - Ensure environmental impact is positive and claim is scientifically justifiable   |
|                           |                                | - Ensure technology developer is a legal entity, has intellectual-property rights   |
| Verification planning/protocol | Verifier                      | - Develop protocol that specifies verification parameters, data sources, data requirements (QA/QC, quantity, validity, representativeness) |
|                           |                                | - Preliminary review of available data in preparation for verification              |
| Testing                   | Tech developer/sponsor         | - Collect data and complete calculations to adequately demonstrate technology performance: |
|                           |                                |   • data may be existing from prior testing, but must meet all verification quality requirements (e.g. ISO 17025 accreditation of test labs) |
|                           |                                |   • data may be collected after completion of verification protocol to ensure compliance with requirements |
| Verification               | Verifier                       | - Perform detailed audit of critical measurements and associated instrumentation, data produced, calculations of performance parameters and uncertainty, including, where appropriate: |
|                           |                                |   • on-site inspection of instrumentation and equipment                              |
|                           |                                |   • inspection of calibration records, QA/QC, data-validation procedures            |
|                           |                                |   • observation of technology operation and data collection                         |
|                           |                                |   • independent sampling for analysis                                              |
|                           |                                |   • utilization of independent measurement equipment to cross-check data            |
| Reporting                 | Verifier                       | - Develop verification statement—summary of technology performance and verification results                                      |
|                           |                                | - Post Verification Statement publicly                                             |
|                           |                                | - Develop Verification Report with Verification process details and record of verification activities |

7 to 9), with no existing consensus standard or protocol for analysis. CCU technologies generally claim to provide a positive environmental benefit due to the ability to capture and remove CO₂ from industrial gas streams, such as power-plant flue gas, and utilize the CO₂ to make useful products, potentially sequestering the CO₂ and impacting the overall level of CO₂ in the atmosphere. As CCU technologies develop, there is a growing need to understand
and document demonstrated performance of specific technologies to ensure that technologies hold the promise they claim and ensure that investment is made in effective solutions to mitigate climate change. Although primarily focused on pre- or early commercial technologies, the ISO 14034 standard can have significant benefits in a growing technology sector, such as CCU, by establishing consistent metrics and data requirements throughout the technology-development life cycle.

The NRG COSIA Carbon XPRIZE was developed to drive the innovation and scale-up of CO₂-utilization technologies and their CO₂-derived materials and products. The Carbon XPRIZE accomplished this by offering a $20 million prize purse to incentivize development, requiring increasing scale and technical maturity over 5 years and three rounds of competition, and requiring verified operation and data on each process to evaluate the performance, maturity and reliability of each technology. It is critical that programmes like the Carbon XPRIZE utilize credible, quality data in their award-adjudication process. The focus of the competition evaluation was on the ability of teams to scale up in terms of both size and TRL, and the focus of the evaluation on the overall integrated system performance at the industrial pilot scale made the ISO 14034 methodology well suited to meet the XPRIZE-verification needs.

### 2.2 Approach

For the Carbon XPRIZE, the ISO 14034 standard and its third-party verification requirements and quality principles were applied in two ways: (i) an evaluation of specific XPRIZE competition parameters related to technology performance and competition scoring and (ii) a fully ISO 14034-conformant verification of technology performance (completed without consideration of specific XPRIZE requirements or limitations). Both approaches required similar sets of data and inputs for verification, enabling simultaneous completion of verification for both XPRIZE-specific and ISO 14034-conformant processes. This experience demonstrated the flexibility and utility of the standard as a foundational platform whose principles and processes can be used in almost any environmental-technology evaluation but can also result in issuance of an ISO 14034-accredited verification statement.

The Carbon XPRIZE established a specific set of rules, regulations and criteria by which technologies would be evaluated and rated as part of the adjudication process. Those requirements were developed with input from a variety of stakeholders and documented in the Carbon XPRIZE Rules & Regulations [14]. Stakeholders included a variety of participants including members of the XPRIZE judging panel, XPRIZE staff, researchers in the CCU area, technical experts and others, who all provided input regarding the state of technology development, the performance targets that technologies can currently achieve and the potential impacts of new innovations that should be considered. In addition, performance targets were established for each round of the competition, as summarized in Table 2 for the competition Finals.

The performance parameters for XPRIZE-specific CCU technology verifications were established based on the specific rules, requirements and targets, as well as established schedules and due dates. Evaluation parameters included some that were important within the confines of the competition but not meaningful in the broader market and CCU stakeholder community (such as specific scoring metrics used to rank the teams in the competition). In contrast, the ISO 14034-conformant approach considered the requirements of the XPRIZE competition, as well as requirements and data needs of other users or stakeholders, and as specified in technical evaluation guidelines for CCU technologies, such as the DOE TEA Guidance. As a result, the performance parameters of interest and reporting units for ISO-compliant technology verifications align with more than just the XPRIZE competition requirements and are potentially comparable to other CCU technologies evaluated outside the confines of the Carbon XPRIZE—a benefit for all data users. A comparison of the primary verification parameters selected for the XPRIZE-specific verification approach and the separate ISO CCU verifications is provided in Table 3. As noted in Table 3, ISO-compliant technology verifications reported the primary critical metrics regarding the technology performance, in units that enable comparison to other assessments that follow the DOE TEA guidelines, and because they are required to be published under ISO 14034, provide transparency regarding the performance of the system. Although similar metrics were used for the XPRIZE verifications, results focused on competition requirements and metrics that were utilized in judging, with many not

### Table 2: XPRIZE competition requirements

| Criteria                      | Performance threshold to compete                                                                 | Scoring weight                  |
|-------------------------------|--------------------------------------------------------------------------------------------------|---------------------------------|
| CO₂ converted                 | Must convert at least 30% of the CO₂ in the flue gas stream                                      | 50% of points                   |
| Net value                     | None                                                                                             | 50% of points                   |
| Water consumed                | Must consume <4 cubic metres of water per metric ton of CO₂ converted                            | Pass/fail screening             |
| Land footprint                | Must have a total land footprint less than ~2320 square metres (25 000 square feet) at Round 3 scale | Pass/fail screening             |
| CO₂ emissions assessment      | Teams must make a reasonable case that their technology has the potential to be carbon-neutral or better, or achieve measurable relative emissions reductions, now and/or in the future | Pass/fail screening             |
relevant to most stakeholders. However, both evaluations utilized the fundamental data-quality requirements associated with ISO 14034 to ensure that data regarding each technology and metric were of high quality or, if not, were transparent by providing uncertainty and statistical analysis for each metric in both cases.

The verification approach for the CCU technologies demonstrated for the NRG COSIA Carbon XPRIZE was multiphased due to the long duration of operations, large quantity of data and the need to ensure data quality and credibility throughout the demonstration period. The three phases of verification required different verification activities and targets for each phase:

**Phase 1:** An initial site inspection and process-observation site visit, to be conducted on-site preferably or remotely if necessary due to coronavirus travel restrictions;

**Phase 2:** Continuous remote monitoring via direct access of digital records supplemented with periodic data requests and standardized team-submitted performance summary reports;

**Phase 3:** A final site visit.

Table 4 summarizes specific activities associated with the verification approach.

### 3 ISO 14034 implementation experience, benefits and lessons learned

The implementation of the ISO 14034 ETV standard for the evaluation of the performance of CCU technologies provided a foundational approach to ensure high-quality data on the performance of these developing technologies. There is significant value in the approach, as it provided important benefits, in both ISO 14034-conformant, accredited technology verifications as well as in general practice for the evaluation of new CCU innovations.

During the implementation of the ISO 14034 process in the evaluation of CCU technologies for the NRG COSIA Carbon XPRIZE, some specific considerations and limitations of the application of the standard were identified. Some of these limitations or considerations were noted during the pre-verification process in which candidate technologies and their existing instrumentation, data-collection and analytical-testing approaches were reviewed, with several gaps identified that required improvements. In addition, during completion of both the XPRIZE-centric and ISO 14034-compliant technology verifications, verification staff, XPRIZE staff and technology developer teams identified issues with the verification approaches, such as technology readiness and its impact on data quality and availability, as discussed below:

(i) Instrumentation and analytical costs: High-quality data can come at a higher cost due to a preference for increased accuracy requirements, digital logging capability, as well as a requirement under ISO 14034 and 17025 for traceable calibrations of instrumentation, which often increase cost. However, with improved instrumentation, additional benefits may be realized. For example, using a properly calibrated and data-logged

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**Table 3:** Performance parameters for XPRIZE and ISO14034-compliant CCU technology verifications

| Performance parameter                                      | XPRIZE verified metric | ISO-compliant verified metric |
|-------------------------------------------------------------|------------------------|-------------------------------|
| Operational size (tonne CO₂/d)                             | (tonne CO₂/d input)    | (tonne/d CO₂ input; kg CO₂ input/kg product) |
| Runtime total (hours)                                      | ✓                      | ✓*                           |
| Runtime continuous (hours)                                 | ✓                      | ✓*                           |
| Continuous run availability (%)                            | ✓                      | ✓*                           |
| CO₂-capture efficiency (%)                                 | ✓                      | ✓*                           |
| CO₂ conversion (%)                                         | ✓                      | ✓*                           |
| Overall conversion (%)                                     | ✓                      | ✓*                           |
| Final net value score (unitless)                           | ✓                      | ✓*                           |
| Cost of inputs ($/d)                                       | ✓                      | ✓*                           |
| Product value ($/d)                                        | ✓                      | ✓*                           |
| CO₂ embodied in product/CO₂ utilization (mass CO₂/mass product) | ✓                      | ✓*                           |
| Product rate (mass/day or mass product/mass CO₂ input)     | (Embedded in net value score) | ✓*                           |
| Inputs required (mass/day or mass input/mass product)      | (Embedded in net value score) | (Critical material inputs, i.e. hydrogen, cement, graphite) |
| Energy usage—electricity, natural gas/thermal               | (MJ/d; MJ/kg CO₂ utilized) | (kwh/d; kwh/kg product) |
| Water use (m³/tonne CO₂)                                   | ✓                      | ✓*                           |
| Land use (m²)                                               | ✓                      | ✓*                           |
| Scale penalty                                              | ✓                      | ✓*                           |
| Other technology-specific performance parameters           | ✓                      | ✓*                           |

*Reported for operational and verification context based on verified data.
| Task # | Verification tasks                                                                                                                                                                                                 | Requirement                                                                                                                                                                                                 | Phase |
|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| 1.0   | Review team performance reports submitted to date                                                                                                                                                                      | Data support claims and meet verification protocol specifications                                                                                                                                         | x     |
| 2.0   | Update documents, drawings and specifications obtained during verifiability assessment                                                                                                                              | Process diagrams and process & instrumentation diagrams (P&IDs) support claimed performance and instrumentation to measure critical parameters                                                        | x     |
| 3.0   | Opening meeting and process walk-through                                                                                                                                                                            |                                                                                                                                                                                                            | x     |
| 4.0   | Witness operations to verify general integrity and conformance with XPRIZE rules and regulations                                                                                                                  | Ensure all inputs and outputs are identified during operation. Ensure critical measurements and instrumentation are as stated                                                                             | x     |
| 5.0   | Verify measurement points/instruments against P&ID and instrument list                                                                                                                                             | Ensure all data are reviewed and validated, and calculations of final parameters can be traced to raw data                                                                                             | x     |
| 6.0   | Verify traceability from raw data through to data collection, processing/reduction, validation, analysis and reporting steps. This includes verifying correct use of unit conversions, corrections (e.g. for ambient conditions) and physical/chemical constants as well as checks for simple errors and omissions | Ensure instruments and analysers are properly calibrated, with NIST or other similar traceability, where possible                                                                                      | x     |
| 7.0   | Verify required calibrations and quality assurance/quality control (QA/QC) checks are performed and recorded                                                                                                        | Determine if deviations have any material impact on reported performance parameters                                                                                                                        | x     |
| 8.0   | Verify that the impact on data quality of any noted calibration, QA/QC or process deviations is properly accounted for and reflected in reported results                                                                 | Data are representative of process operation (i.e. no upsets, instrument dropouts, operations outside stated operating conditions)                                                                    | x     |
| 9.0   | Verify that reported results are based on valid data that are representative of actual process performance                                                                                                         | Ensure the product is a marketable, saleable product (e.g. meets purity specifications, performance specifications or other standards); review product analysis, compliance with product standards (e.g. ASTM C39 for concrete compressive strength, International Methanol Producers and Consumers Association (IMPCA) standard for methanol) and analyses were performed by independent lab with appropriate credentials (e.g. ISO 17025 accreditation) | x     |
| 10.0  | Verify product quality                                                                                                                                                                                                | Ensure provided data and calculations meet XPRIZE targets and data-quality requirements, and data processing and calculations are done correctly                                              | x     |
| 11.0  | Verify team scoring approach and calculations are consistent with XP R&R and guidelines                                                                                                                             |                                                                                                                                                                                                            | x     |
| 12.0  | Verify CO₂ input rate                                                                                                                                                                                               |                                                                                                                                                                                                            | x     |
| 13.0  | Verify achieved carbon conversion versus R3 requirement                                                                                                                                                                |                                                                                                                                                                                                            | x     |
| 14.0  | Verify validity of approach and measurements used to determine ‘mass CO₂ embodied in product’                                                                                                                        |                                                                                                                                                                                                            | x     |
| 15.0  | Verify correct Standards Data Sets (SDS) values used in XPRIZE score calculations                                                                                                                                     |                                                                                                                                                                                                            | x     |
| 16.0  | Verify actual material and energy input rates against SDS values and reported values                                                                                                                                  |                                                                                                                                                                                                            | x     |
Coriolis flow meter instead of a low-cost rotameter with intermittent visual or manual recording not only provides credibility, but can also enable better process control, detailed troubleshooting, post-mortems and analysis, especially for technologies still being optimized. It should also be stated that the highest-quality instrumentation is not required for every measurement. There are many factors that can determine the influence of a specific measurement on a final performance parameter. Careful design, planning and assessment of measurement accuracy on reported parameters can result in an instrumentation strategy that provides both needed accuracy and optimized cost. Analytical costs may also potentially increase, as ISO 14034 requires test labs to demonstrate compliance with applicable ISO 17025 requirements. This may come in the form of accreditation or through a more time-consuming review of lab documentation and quality procedures by a verifier. However, there are many independent commercial labs with competitive costs that are ISO 17025-accredited, so impacts may be low, even when compared to inexpensive on-site analytical efforts.

(ii) Verification costs: With independent third-party verification comes the requirement to contract a qualified, preferably accredited, third-party verifier. This inherently requires additional costs. Costs are dependent on the needs of the project, the complexity of the technology, the amount of parameters and data, and other factors. However, the costs for verification are typically a small fraction of the costs to develop, fabricate, install, commission and operate a pilot or early commercial demonstration. Verification costs can be managed by ensuring that the technology is ready for verification and that the data sets and data-reduction tools are well organized, and easy to follow and comprehend.

(iii) Verification protocol flexibility: This is both a benefit and a drawback. Because of the flexibility in the ISO 14034 approach to verification to meet different stakeholder needs and requirements, it is possible for technologies in the same category, such as CCU, to be evaluated in different ways, emphasizing different performance parameters, depending on the need. This can be observed in the differences between the XPRIZE-specific verification and the ISO 14034-accredited verifications. Caution should be taken to ensure that verifications are as globally beneficial as possible. However, each technology type or process may require specific additional metrics or analyses that should be customized for that technology type and be consistent across evaluations of that technology type. Similar research findings have been identified when evaluating the applicability of TEA approaches for CCU technologies, with flexibility and consistency often at odds with the wide variety of different approaches that occur in a novel technology-development space [15]. This issue highlights an opportunity for further development of CCU-specific evaluation standards, ideally integrating the principles of ISO 14034 to, at a minimum, ensure that the data produced in technology testing and evaluation are of a high enough quality to serve as inputs into a quality, consistent TEA or LCA approach.

(iv) Technology readiness and applicability: ISO 14034 was designed primarily for technologies that are at a stage of development in which the process is well established, the design is not changing significantly and the technology is near the commercial or early commercial stage (generally, TRL 7 to 9). However, the fundamental principles, which focus in large part on data quality, can be applied to any technology at any stage. But attempting a comprehensive verification too early can be inefficient. Technologies that have not been fully optimized and are still in scale-up and development can have significant process variability that can provide large uncertainty in reported performance, even if the measurements are of high quality. Technology developers who are still focusing on their core technology also may not have developed a balance of plant with sufficiently mature instrumentation or data-collection equipment in place to facilitate an accredited verification process. That said, approaching the ongoing evaluation of a new innovation with data quality and specific evaluation metrics

| Task # | Verification tasks | Requirement | Phase |
|-------|-------------------|-------------|-------|
| 17.0  | Verify product output rate against specifications and reported values | | x x |
| 18.0  | Finalize Data Transfer Connection with 350Solutions data acquisition system (DAS) | Provide continuous access to field data; provide independent measurements to cross-check data | x |
| 19.0  | Periodic remote monitoring of continuous data set | | x x |
| 20.0  | Complete verification. Generate verification report and statement, present summary of major findings | | x |
associated with an ISO 14034-based approach—within the limitations of cost and effort appropriate to the development stage—can help to improve technology-development processes and benefit developers by ensuring that the best-quality data can be obtained at each stage of development to enable proper decision-making at each step, whether by investors, technology developers or others.

(v) Full accredited ISO 14034 verification is not always applicable: ISO 14034—for transparency—requires publication of results, making it difficult to apply in situations in which significant proprietary information is being collected from technology developers and used in proprietary calculations, such as scoring methods and rankings. These data may not be publicly released, preventing full implementation of the ISO 14034 verification process. Nevertheless, ISO 14034 provides a solid foundation upon which evaluation methodologies can be customized.

The observed benefits of implementation of the ISO 14034 process in the evaluation of nine CCU technologies for the NRG COSIA Carbon XPRIZE include:

(i) Methodological consistency: The fundamental approach enables the development of verification protocols for a specific technology category, such as CCU, that define performance parameters, measurement and instrumentation specifications, and other criteria to ensure that consistent approaches are utilized across the technology category, even for fundamentally different technologies. This enables direct comparisons among technologies, such as those that participated in the Carbon XPRIZE.

(ii) Methodology flexibility and broad application: The fundamental approach of ISO 14034, with its focus on data quality, can ensure that good engineering and measurement practices are applied in technology demonstrations consistently. This approach can be implemented whether an ISO 14034-conformant verification is being completed by an accredited verifier or an entity prefers to solely implement the ISO 14034 fundamental practices to ensure credible, high-quality data as a result of their demonstration or evaluation. The flexibility also enables application of the principles of the standard at various TRLs, and for different markets and information needs. However, despite the ability to apply the principles of ISO 14034 at all TRL levels and ensure the best data quality possible, as well as utilize consistent metrics for evaluation, a full, accredited ISO 14034 verification should still be completed for near-commercial technologies (i.e. TRL 6 to 9).

(iii) High-quality data: Because of the fundamental focus on data quality, the ISO 14034 approach ensures that the final verified performance is based on rigorous measurements and testing, and is determined by qualified personnel with no bias. ISO 14034-based verification provides a true picture of the technology performance under the specific set of operating conditions observed. Additionally, because of the focus on quality and credible instrumentation and measurement, the bounds on uncertainty of data are reduced, providing additional confidence and credibility.

(iv) Independent oversight: Independent oversight and verification by a third party ensure that there is no bias in evaluation and that data are not selected or ‘cherry-picked’ to show only the best performance. In addition, third-party oversight has the benefit of helping to identify errors and omissions in approaches to evaluation, whether they be in overall process evaluation, such as not accounting for specific inputs and outputs, or identifying issues in data validation and reduction. A qualified second set of eyes is valuable.

Moving forward, the continued development of evaluation protocols for CCU technologies should consider the implementation of ISO 14034 as a foundational platform. The data-quality benefits of implementing ISO 14034 as well as the credibility it can bring can prove valuable in the development process and technology market. However, as the ISO 14034 process suggests, the stakeholders and interested parties—researchers, policy-makers, investors, funding agencies, technology developers and others—should also work together to pursue approaches that unify metrics used for assessing CCU technologies. This is critical to ensure that this emerging market does not become a confusing collection of inconsistent and incomparable information that can create confusion and inhibit market uptake of CCU technologies. An ISO 14034-based approach can ensure that the technology performance itself, as well as system economics and life-cycle carbon emissions—which can utilize high-quality data from ISO 14034 verifications as inputs—provide the best-quality data and credibility possible. Consensus protocols should provide requirements for overall evaluation of CCU technologies a ‘generic’ CCU protocol, as well as specific approaches, assessments and testing requirements for technology categories; and ‘technology-specific’ CCU protocols, to ensure that adequate data are available to compare technologies across categories as well as within specific technology types. By defining these requirements now and being transparent about them, those developing technologies can plan for verification by specifying appropriate instrumentation, data-collection methods and approaches to ensure that their technologies are ready for verification when appropriate. Each protocol should also establish criteria for qualifications that should be met in order to seek a full verification, including such specifications as the appropriate TRL level.

4 Conclusions
The ISO 14034 standard provides a foundation to ensure that high-quality data regarding the performance and
impact of environmental technologies are obtained and independently verified by qualified third parties. Its application to evolving technologies in the rapidly developing CCU industry, as demonstrated for the NRG COSIA Carbon XPRIZE, can have significant benefit in improving credibility and quality of data. The methodology established by the ISO standard was shown to provide the quality and consistency required by the evaluation process, along with the flexibility to accommodate a variety of technologies and applications. However, the standard must be applied carefully, with considerations for costs and market needs, TRL and consistency with other evaluation approaches.

Primary considerations for the successful implementation of ISO 14034 for CCU and other environmental technologies are:

- pre-plan for data collection and consider data, sampling and analytical plans as part of process design;
- implement good engineering practices in process and instrumentation design;
- ensure that the technology is ready for verification—near-commercial and fully integrated;
- consider the needs of the market—what data and information do stakeholders need?

In an emerging technology market, such as CCU, the ISO 14034 standard can serve as a foundation to the development of consensus technology-evaluation approaches, to ensure consistency, comparability and quality across evaluations and provide high-quality data for decision-makers and interested parties.

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**Conflict of interest statement**

None declared.

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