VERIFICATION STATEMENT

In accordance with ISO 14034:2016
Environmental Technology Verification

Technology & Company Information		
Technology Name	**Company**	**Technology Type & Application**
Solar thermal-catalytic reactor	Dimensional Energy https://dimensionalenergy.com/	Catalytic conversion of concentrated CO_2 for the production of syngas

Verification Parameter	Verified Performance
Operational Scale	13.8 kg CO_2/day
CO_2 Embodied in Product	5.54 kg CO_2/day, 1.30 kg CO_2/kg product gas
Product Gas Production	4.25 kg/day, 0.31 kg product gas/kg CO_2 input
CO_2 Conversion Efficiency	40.2 % input CO_2 converted to product gas
H_2 Usage	1.23 kg/day, 0.29 kg/kg product gas
Energy Usage	212 kJ/day, 50.0 kJ/kg product gas
Water Usage	0 kg/day, 0 kg/kg product gas

Verifier Information			
Verification Body	**Lead Verifier**	**Verification Body Accrediation**	**Verification ID**
350solutions, Inc. https://350solutions.com	Bill Chatterton	ANAB Cert. AI-2618 for ISO:IEC 17020-2012 / ISO 14034-2016	VS-CXP-A-05

Issue Date: April 15, 2021

350 VERIFIED
ISO 14034

ANAB ACCREDITED ISO/IEC 17021 INSPECTION BODY

ENVIRONMENTAL TECHNOLOGY VERIFICATION STATEMENT

Technology Name:	Solar thermal-catalytic reactor
Technology Type:	Catalytic conversion of concentrated CO_2 to produce syngas
Application:	Syngas Production
Company:	Dimensional Energy https://dimensionalenergy.com/
Verification Body:	350Solutions, Inc. - ISO/IEC 17020:2012 and ISO 14034 Environmental Technology Verification, Certificate Number AI-2619
Lead Verifier:	Bill Chatterton, 350Solutions, Inc.

TECHNOLOGY DESCRIPTION

The Dimensional Energy system demonstrated solar thermal syngas production using a ~2.7 m^2 parabolic mirror on a 2-axis solar tracker. The mirror focuses sunlight into Dimensional Energy's concentrated solar chemical reactor with minimum balance of plant and feed gas flow controls. The sunlight is converted to thermal energy, heating the reactor to above the catalyst's minimum operating temperature. H_2 and CO_2 feed gases are mixed in a 2:1 molar ratio at around 1 to 2 bar pressure and fed through the chemical reactor. The chemical reaction is reverse water-gas shift (RWGS): $CO_2 + H_2 \rightarrow CO + H_2O$. Upon exit, the hot product gas mixture (CO, H_2, H_2O, CO_2) goes through a heat exchanger with incoming reactant gases to pre-heat them. As product gases cool, water condenses and is removed in a knockout pot. The actual demonstrated output was syngas with ratio approximately 3.1 to 1 (H_2 to CO) that contained CO_2 and low amounts of water vapor. The entire process was automated through a PLC and proprietary software program. During all operations during the demonstration, a small stream of the syngas mixture was routed to a control/analytical building where it was fed into a micro-gas chromatograph system to obtain gas composition.

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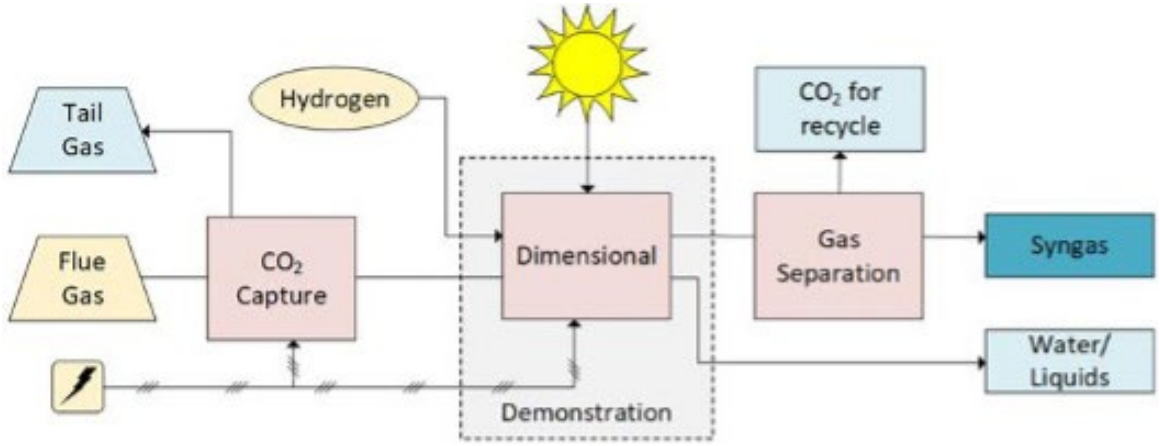

Figure 1. Dimensional Energy Block Flow Process Summary

The demonstration was conducted using compressed CO_2 from a gas vendor as process feedstock. Typically, the syngas generated by the conversion process would be further processed for use as an intermediate. Separation of CO_2 and other post processing was not included in the demonstration however, due to COVID-19 impacts on equipment production and staffing. The final steps planned would have included removal of unreacted CO_2, drying to produce pure syngas, and subsequent compression for a mini-Fischer Tropsch (FT) reactor. Post processing models are not ISO 14034 verified here but are available from Dimensional Energy upon request.

VERIFICATION DESCRIPTION

The verification process applied here was based on 350Solutions' Standard Operating Procedure (SOP) QSP-350-223-01: "ISO 14034 Environmental Technology Verification", the ISO Technical Committee 207 draft guidance document "Environmental technology verification — E.T.V — Guidance to implement ISO 14034", and a technology specific Verification Plan. The objectives and approaches used for this verification were designed to apply these principles and processes to Dimensional's application for performance verification as presented under the NRG-COSIA Carbon XPRIZE competition. The verification provides Dimensional Energy and potential users of the technology with an independent assessment and verification of performance of the technology.

The verification included four primary tasks including administrative and technical application reviews, development of verification objectives and plans, verification of technology performance claims and reporting. The primary objective of the project was to verify the performance claims made by Dimensional with respect to operation of the solar thermal catalytic technology. Dimensional's performance claims specified in the application for verification include:

Performance Claim 1 – Operational Scale: Operational scale is defined as the average daily rate of CO_2 fed into the conversion system during operations and represents the operational scale during the XPRIZE competition demonstration. Performance results are verified within the range of relevant operating conditions that were evident during this demonstration.

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Performance Claim 2 – CO_2 Embodied in Product: CO_2 embodied in product is defined as the utilization of CO_2 input that is converted into useful product – in this case product gas (raw syngas without separations or post processing). It is reported as the average daily rate of CO_2 fed into the conversion system during operations that is converted into product, as well as the amount of CO_2 required to produce a kg of product. Performance results are verified within the range of relevant operating conditions that were evident during this demonstration.

Performance Claim 3 – Product Gas Production: The average daily rate of product gas during the demonstration period and within the range of operating conditions. Product gas composition was also verified by gas chromatography and reported gas quality is expressed as component mole percent and in units of $MW_{thermal}$/metric ton.

Performance Claim 4 –CO_2 Conversion Efficiency: Defined as the fraction of CO_2 converted as the mass ratio of CO_2 input and CO_2 output embodied in the product gas, expressed as a percentage. The performance claim is presented as the daily average conversion efficiency during the demonstration within the operational conditions defined during the period. The reported efficiency does not include losses associated with CO_2 capture or product separation processes. The conversion of the gas was determined by on-site gas chromatography analysis.

Performance Claims 5 through 7 – Energy, H_2, and Water Usage per kg CO_2 in Product: For every kg of CO_2 that was converted into product gas, the conversion system required solar thermal energy, supplemental power, and H_2 feed gas to complete the conversion process. Solar thermal energy use is proprietary and not reported here. The supplemental electrical and H_2 inputs were normalized to output and verified. Note that water use is included as a performance claim to verify that the Dimensional Energy conversion system requires no water use.

Other parameters examined and verified during the demonstration included total system run time and system availability. Both were evaluated by verifying the number of operating hours during the fixed demonstration period and the total number of hours in that period under a set of operational conditions.

After initial reviews of the technology and following the Verification Plan, performance verification was specified using independent performance data generated during the verification at the Wyoming Integrated Test Center (ITC) in the Fall of 2020. Using data that was determined to be relevant and of sufficient quality to support verification, 350Solutions assessed the performance of the technology. The verification also statistically examined variability and confidence intervals in the supporting data used to verify performance claims including comparative sample analytical results and analytical variability.

VERIFICATION OF PERFORMANCE

Table 1 provides a list of the performance claims as they relate specifically to the Dimensional Energy demonstration conducted at ITC. The summary includes the claimed or targeted team performance for each verification parameter, and columns for in-field verified values and associated uncertainties.

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Table 1 – Dimensional Energy Verified Performance

Verification Parameter	Verification Value
Operational Scale, kg CO_2/day	13.8 ± 0.51
CO_2 embodied in product, kg CO_2/day (kg CO_2/kg product gas)	5.54 ± 1.03 (1.30 ± 0.24)
Product gas production, kg/day (kg product gas /kg CO_2 input)	4.25 ± 0.86 (0.31 ± 0.06)
CO_2 conversion efficiency, %	40.2 ± 8.1
H_2 Usage, kg/day (kg/kg product gas)	1.23 ± 0.01 (0.29 ± 0.002)
Energy Usage, kJ/day (kJ/kg product gas)	212 ± 18.2 (50.0 ± 4.3)
Water Usage, kg/kg product gas	0

Table 2 presents the non-proprietary operating conditions under which the verification parameters were observed during the demonstration period. Because the conversion reaction is solar thermal driven, valid operations were achievable only when ambient temperatures and solar insolation were sufficient to maintain the required (proprietary) reactor temperature. These operating conditions have direct correlation to system performance and should be considered in conjunction with the verified performance. When adequate insolation and temperatures were not available, Dimensional logged the system as 'available, non-productive'.

Table 2 – Dimensional Energy Verification Operating Conditions

Operating Parameters	Observed Average Value	Observed Range
CO_2 input flow rate (kg/day)	13.8	0 – 28.0
H_2 input flow rate (kg/day)	1.21	0 – 2.40
Ambient temperature	25°F and above	
Insolation	250 W/m2 and above	

The basis for the verification was a continuous operational period of 30 days from September 18 through October 17, 2020. During this period data was collected on process operations using on-site datalogging, PLC systems, and manual records. Total system operations and operating characteristics for which data was reviewed and verified are summarized in Table 3.

Table 3 - Operational Period

Verification Period Characteristic	Observed Value
Number of days with productive operation	28
Daily average hours of productive operation	5.3*
Total hours of productive operation	160
Process availability during specified operating conditions	85%

**Note that nearby structural components at the ITC demonstration site cast afternoon shadows on the demonstration unit and thereby reduced the daily operational period of sufficient insolation by up to 4 hours per day.*

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Primary findings with respect to verified performance claims indicate that:

- Compressed and purified CO_2 and H_2 from gas vendors were used to simulate reactor feed gases during the demonstration. Feed gas CO_2 and H_2 had gas vendor certified purities of 99.0% and 99.9%, respectively;
- Operational scale defined as CO_2 input rate was verified at 13.8 ±0.5 kg CO_2/day during the demonstration period;
- CO_2 embodiment in product gas was verified at 5.54 ±1.0 kg CO_2/day during the demonstration period, or 1.30 kg/kg product gas produced;
- Verified conversion efficiency of CO_2 input gas to product gas averaged 40.2% ±8.1%;
- Availability was determined based on 23 days valid operations, 5 days partial and 2 non-operational days due to ambient conditions. As such, system availability is estimated for the demonstration period as 85%for the period.
- Building structures adjacent to the demonstration site at ITC cast afternoon shade on the system and limited the daily operational period by up to 4 hours per day.
- Average product gas composition as mol % dry basis was: CO = 24.2. H_2 = 75.7, and CH_4 = 0.12. An average 1.92 kg/day water was condensed from the process gas.
- The product gas had an average verified H_2:CO ratio of 3.13, and an average energy value of 9.56 $MW_{thermal}$/tonne.

The calculation of the performance targets from the measurements that were made on the Dimensional demonstration system are subject to a degree of uncertainty. 350Solutions developed an estimate of the uncertainty of the verification parameters, where appropriate.

DATA QUALITY

350Solutions, an ANAB accredited ISO/IEC 17020:2012 inspection body for ISO 14034 ETV, was contracted by XPRIZE to provide independent verification of the Dimensional Energy CO_2 Conversion technology. The verification process applied was based on 350Solutions' Standard Operating Procedure QSP-350-223-01: "ISO 14034 Environmental Technology Verification", the ISO Technical Committee 207 draft guidance document *"Environmental technology verification — E.T.V — Guidance to implement ISO 14034"*, and a technology specific Verification Plan. The objectives and approaches used for this verification were designed to apply these principles and processes, along with the requirements of the NRG-COSIA Carbon XPRIZE competition, to Dimensional's verification of performance claims. Following ISO 14034 guidance, the data quality assessment included:

- Data quality assessment for the specified performance claims;
- Assessment of ancillary data quality (operations, relevance, representativeness);
- Performer competence (testing and analytical providers);
- Sampling and analytical procedures (repeatability, accuracy, measurement equipment calibration and quality checks); and
- Data management and processing.

Assessment of the quality of data used to verify technology performance was based on three primary components:

- Conformance with the requirements of ISO Standards 14034 and 17025.
- Assessment of the scientific approaches and statistical analyses – specifically, evaluation of measurement uncertainty in laboratory and field demonstration test results, and the statistical analyses of measurement uncertainty.
- The quality of reference field testing and laboratory procedures and results.

In broad terms, the operational and performance data provided by Dimensional to verify performance with respect to the performance claims were found to be acceptable for verification. Sound scientific approaches and statistical analyses are detailed in the Verification Report and demonstrate that the quality of data and data analyses support verification of the performance claims. Assessment of data quality for the product gas analytical results was verified acceptable based on verification of the following data quality assessments:

- Review and verification of acceptable operating procedures and methods,
- Satisfactory verifier observation of facilities, equipment, and operations,
- Review and observation of performer competence (qualifications and training policies),
- Sampling and analytical procedures (repeatability, accuracy, measurement equipment calibration and quality checks), and
- Satisfactory data management and processing.

Certificates of Conformance to vendor specifications for CO_2 and H_2 feed gas purity were provided by the gas vendors. Quantification of energy consumption was conducted using power meters verified as revenue grade quality (rated ± 1% accuracy without NIST traceable calibration).

With the exception of post-processing of the dilute syngas product, all of the findings of the data quality review support verification of the performance claims and conform to the requirements of the standards.

Detailed results of the verification are presented in the Final Report titled *Environmental Technology Verification Report – Dimensional Energy, VR-CXP-A-05,* (350Solutions 2021). The report can be made available to the interested parties upon request to Dimensional Energy.

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