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Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a),(b) or (b-bis)

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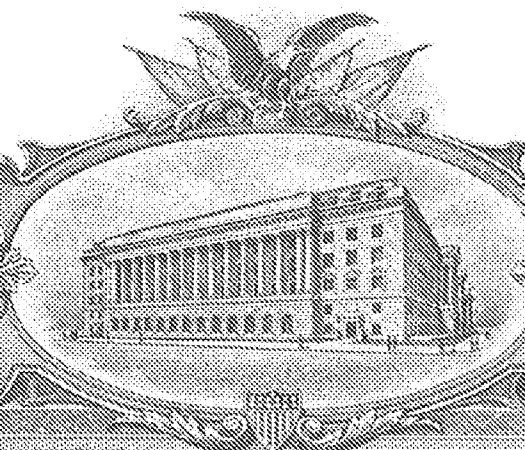
Application number: 63349890

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THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

July 06, 2023

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE UNDER 35 USC 111.

APPLICATION NUMBER: 63/349,890
FILING DATE: *June 07, 2022*

THE COUNTRY CODE AND NUMBER OF YOUR PRIORITY APPLICATION, TO BE USED FOR FILING ABROAD UNDER THE PARIS CONVENTION, IS *US63/349,890*



Certified by

Kathi

Under Secretary of Commerce
for Intellectual Property
and Director of the United States
Patent and Trademark Office

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	P296928.US.01_515365-7
		Application Number	
Title of Invention	SYSTEMS AND METHODS FOR QUANTITATIVE ASSESSMENT AND MONITORING OF THE SOURCE, RESIDENCE TIME, AND SATURATION CONDITIONS OF HYDROGEN IN NATURAL GAS AND OTHER SUBSURFACE FLUIDS AND QUANTIFICATION AND VERIFICATION OF CARBON DIOXIDE		
The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76. This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.			

Secrecy Order 37 CFR 5.2:

☐	Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)
--------------------------	---

Inventor Information:

Inventor	1				Remove	
Legal Name						
Prefix	Given Name	Middle Name	Family Name	Suffix		
	Thomas		Darrah			
Residence Information (Select One) ☒ US Residency ☐ Non US Residency ☐ Active US Military Service						
City	Dublin	State/Province	OH	Country of Residence	US	
Mailing Address of Inventor:						
Address 1	c/o Koloma, Inc.					
Address 2	7251 Sawmill Road, Suite 100					
City	Dublin	State/Province	OH			
Postal Code	43016	Country i	US			
Inventor	2				Remove	
Legal Name						
Prefix	Given Name	Middle Name	Family Name	Suffix		
	Colin		Whyte			
Residence Information (Select One) ☒ US Residency ☐ Non US Residency ☐ Active US Military Service						
City	Dublin	State/Province	OH	Country of Residence	US	
Mailing Address of Inventor:						
Address 1	c/o Koloma, Inc.					
Address 2	7251 Sawmill Road, Suite 100					
City	Dublin	State/Province	OH			
Postal Code	43016	Country i	US			
Inventor	3				Remove	
Legal Name						
Prefix	Given Name	Middle Name	Family Name	Suffix		
	Jacob		Harrington			
Residence Information (Select One) ☒ US Residency ☐ Non US Residency ☐ Active US Military Service						

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City	Dublin	State/Province	OH	Country of Residence ⁱ	US
Mailing Address of Inventor:					
Address 1	c/o Koloma, Inc.				
Address 2	7251 Sawmill Road, Suite 100				
City	Dublin	State/Province	OH		
Postal Code	43016	Country ⁱ	US		
All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the Add button.					Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below. For further information see 37 CFR 1.33(a).			
☐ An Address is being provided for the correspondence Information of this application.			
Customer Number	153511		
Email Address	ip.docket.slc@dorsey.com	Add Email	Remove Email

Application Information:

Title of the Invention	SYSTEMS AND METHODS FOR QUANTITATIVE ASSESSMENT AND MONITORING OF THE SOURCE, RESIDENCE TIME, AND SATURATION CONDITIONS OF HYDROGEN IN NATURAL GAS AND OTHER SUBSURFACE FLUIDS AND QUANTIFICATION AND VERIFICATION OF CARBON DIOXIDE SEQUESTRATION IN SUBSURFACE FORMATIONS		
Attorney Docket Number	P296928.US.01_515365-7	Small Entity Status Claimed	☒
Application Type	Provisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)	5	Suggested Figure for Publication (if any)	

Filing By Reference:

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

Application number of the previously filed application	Filing date (YYYY-MM-DD)	Intellectual Property Authority or Country

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	P296928.US.01_515365-7
	Application Number	
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Publication Information:

☐	Request Early Publication (Fee required at time of Request 37 CFR 1.219)
☐	Request Not to Publish. I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application has not and will not be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32). Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.			
Please Select One:	☒ Customer Number	☐ US Patent Practitioner	☐ Limited Recognition (37 CFR 11.9)
Customer Number	153511		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, 365(c), or 386(c) or indicate National Stage entry from a PCT application. Providing benefit claim information in the Application Data Sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78. When referring to the current application, please leave the "Application Number" field blank.			
Prior Application Status		Remove	
Application Number	Continuity Type	Prior Application Number	Filing or 371(c) Date (YYYY-MM-DD)
Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the Add button.			Add

Foreign Priority Information:

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55. When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX)¹ the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(i)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

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		Remove	
Application Number	Country ⁱ	Filing Date (YYYY-MM-DD)	Access Code ^j (if applicable)
Additional Foreign Priority Data may be generated within this form by selecting the Add button.			Add

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013. ☐ NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.	
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Authorization or Opt-Out of Authorization to Permit Access:

When this Application Data Sheet is properly signed and filed with the application, applicant has provided written authority to permit a participating foreign intellectual property (IP) office access to the instant application-as-filed (see paragraph A in subsection 1 below) and the European Patent Office (EPO) access to any search results from the instant application (see paragraph B in subsection 1 below).

Should applicant choose not to provide an authorization identified in subsection 1 below, applicant **must opt-out** of the authorization by checking the corresponding box A or B or both in subsection 2 below.

NOTE: This section of the Application Data Sheet is **ONLY** reviewed and processed with the **INITIAL** filing of an application. After the initial filing of an application, an Application Data Sheet cannot be used to provide or rescind authorization for access by a foreign IP office(s). Instead, Form PTO/SB/39 or PTO/SB/69 must be used as appropriate.

1. Authorization to Permit Access by a Foreign Intellectual Property Office(s)

A. Priority Document Exchange (PDX) - Unless box A in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the State Intellectual Property Office of the People's Republic of China (SIPO), the World Intellectual Property Organization (WIPO), and any other foreign intellectual property office participating with the USPTO in a bilateral or multilateral priority document exchange agreement in which a foreign application claiming priority to the instant patent application is filed, access to: (1) the instant patent application-as-filed and its related bibliographic data, (2) any foreign or domestic application to which priority or benefit is claimed by the instant application and its related bibliographic data, and (3) the date of filing of this Authorization. See 37 CFR 1.14(h)(1).

B. Search Results from U.S. Application to EPO - Unless box B in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the EPO access to the bibliographic data and search results from the instant patent application when a European patent application claiming priority to the instant patent application is filed. See 37 CFR 1.14(h)(2).

The applicant is reminded that the EPO's Rule 141(1) EPC (European Patent Convention) requires applicants to submit a copy of search results from the instant application without delay in a European patent application that claims priority to the instant application.

2. Opt-Out of Authorizations to Permit Access by a Foreign Intellectual Property Office(s)

☐ A. Applicant **DOES NOT** authorize the USPTO to permit a participating foreign IP office access to the instant application-as-filed. If this box is checked, the USPTO will not be providing a participating foreign IP office with any documents and information identified in subsection 1A above.

☐ B. Applicant **DOES NOT** authorize the USPTO to transmit to the EPO any search results from the instant patent application. If this box is checked, the USPTO will not be providing the EPO with search results from the instant application.

NOTE: Once the application has published or is otherwise publicly available, the USPTO may provide access to the application in accordance with 37 CFR 1.14.

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	P296928.US.01_515365-7
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Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant	1	Remove	
If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section. Clear			
☒ Assignee	Legal Representative under 35 U.S.C. 117	Joint Inventor	
Person to whom the inventor is obligated to assign.		Person who shows sufficient proprietary interest	
If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:			
Name of the Deceased or Legally Incapacitated Inventor:			
If the Applicant is an Organization check here. ☒			
Organization Name	Koloma, Inc.		
Mailing Address Information For Applicant:			
Address 1	7251 Sawmill Road, Suite 100		
Address 2			
City	Dublin	State/Province	OH
Country	US	Postal Code	43016
Phone Number		Fax Number	
Email Address			
Additional Applicant Data may be generated within this form by selecting the Add button. Add			

Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

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Assignee	1			
Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication. An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.				
				Remove
If the Assignee or Non-Applicant Assignee is an Organization check here.				☐
Prefix	Given Name	Middle Name	Family Name	Suffix
Mailing Address Information For Assignee including Non-Applicant Assignee:				
Address 1				
Address 2				
City		State/Province		
Country i		Postal Code		
Phone Number		Fax Number		
Email Address				
Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button.				Add

Signature:

NOTE: This Application Data Sheet must be signed in accordance with 37 CFR 1.33(b). However, if this Application Data Sheet is submitted with the **INITIAL** filing of the application and either box A or B is not checked in subsection 2 of the "Authorization or Opt-Out of Authorization to Permit Access" section, then this form must also be signed in accordance with 37 CFR 1.14(c).

This Application Data Sheet **must** be signed by a patent practitioner if one or more of the applicants is a **juristic entity** (e.g., corporation or association). If the applicant is two or more joint inventors, this form must be signed by a patent practitioner, **all** joint inventors who are the applicant, or one or more joint inventor-applicants who have been given power of attorney (e.g., see USPTO Form PTO/AIA/81) on behalf of **all** joint inventor-applicants.

See 37 CFR 1.4(d) for the manner of making signatures and certifications.

Signature	/Nathan Orme/		Date (YYYY-MM-DD)	2022-06-07
First Name	Nathan	Last Name	Orme	Registration Number
				68918
Additional Signature may be generated within this form by selecting the Add button.				Add

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	P296928.US.01_515365-7
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This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

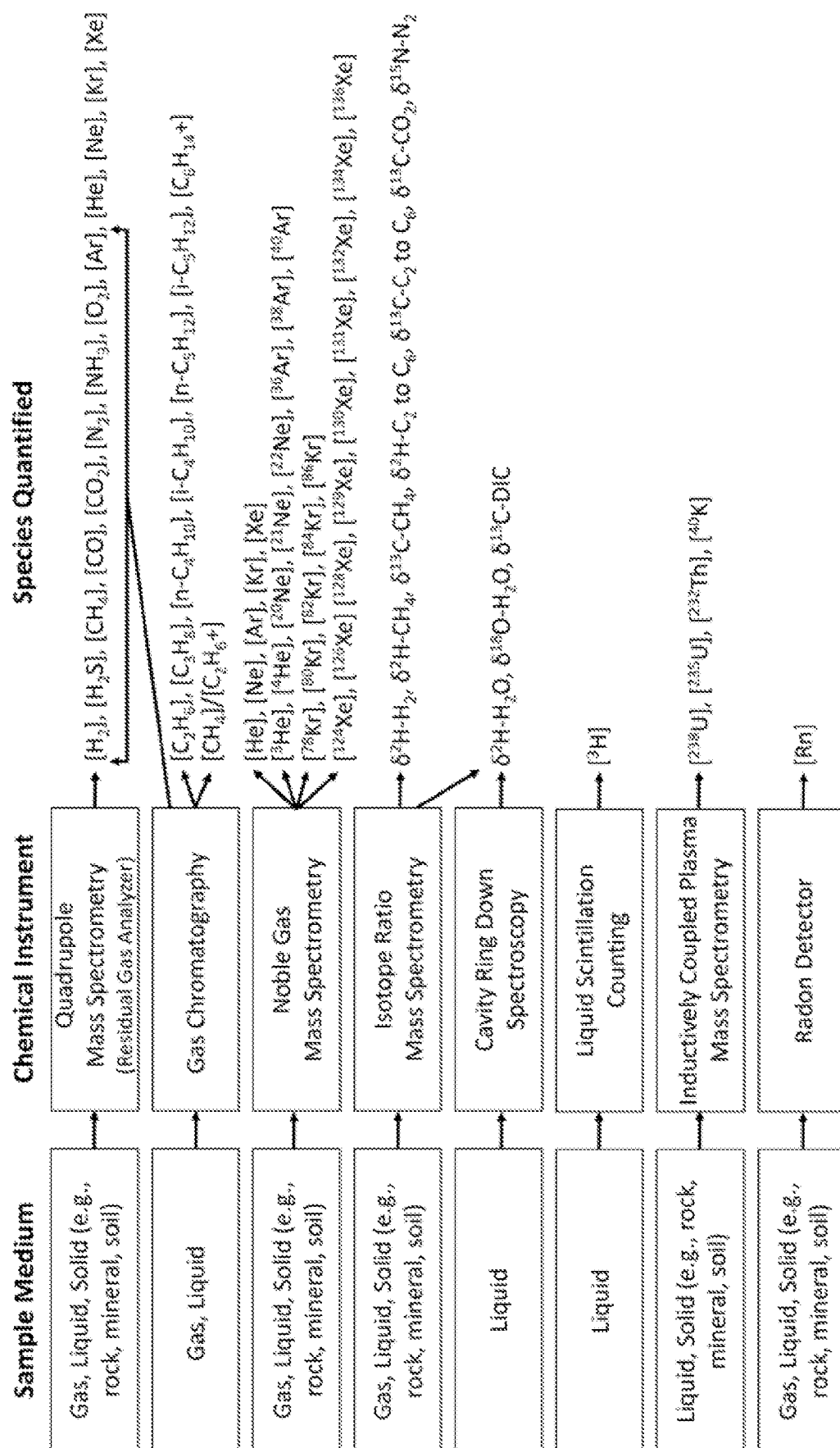


FIG. 1

Work Flow

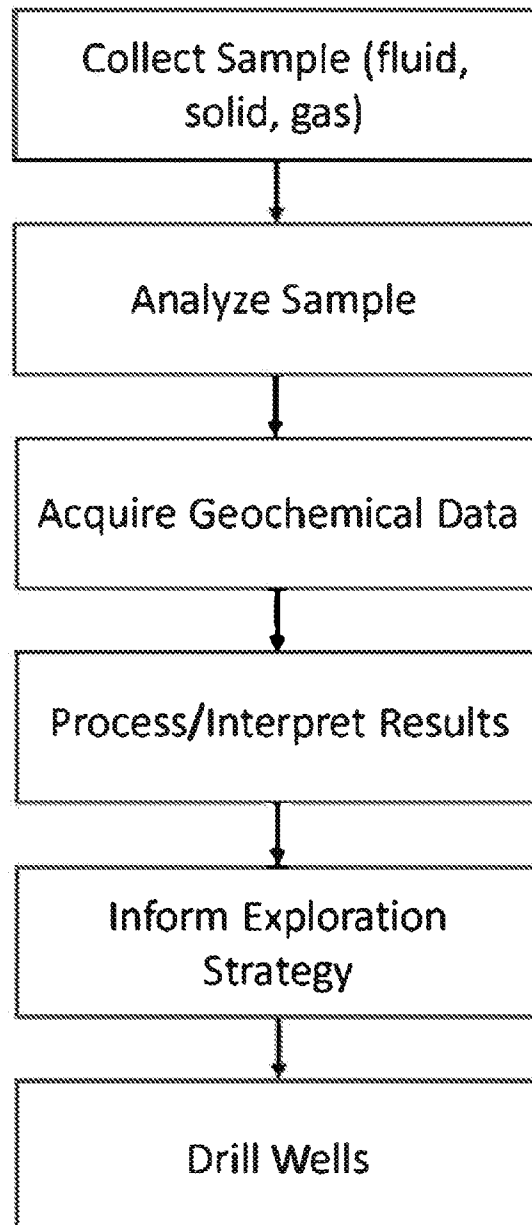


FIG. 2

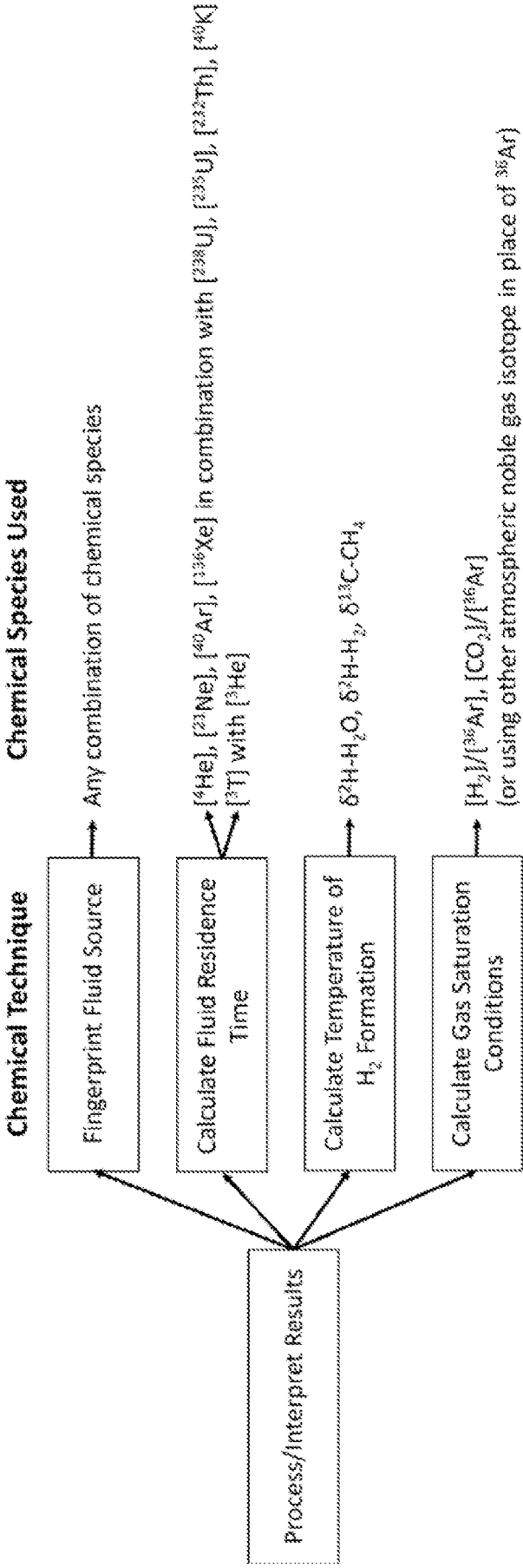


FIG. 3

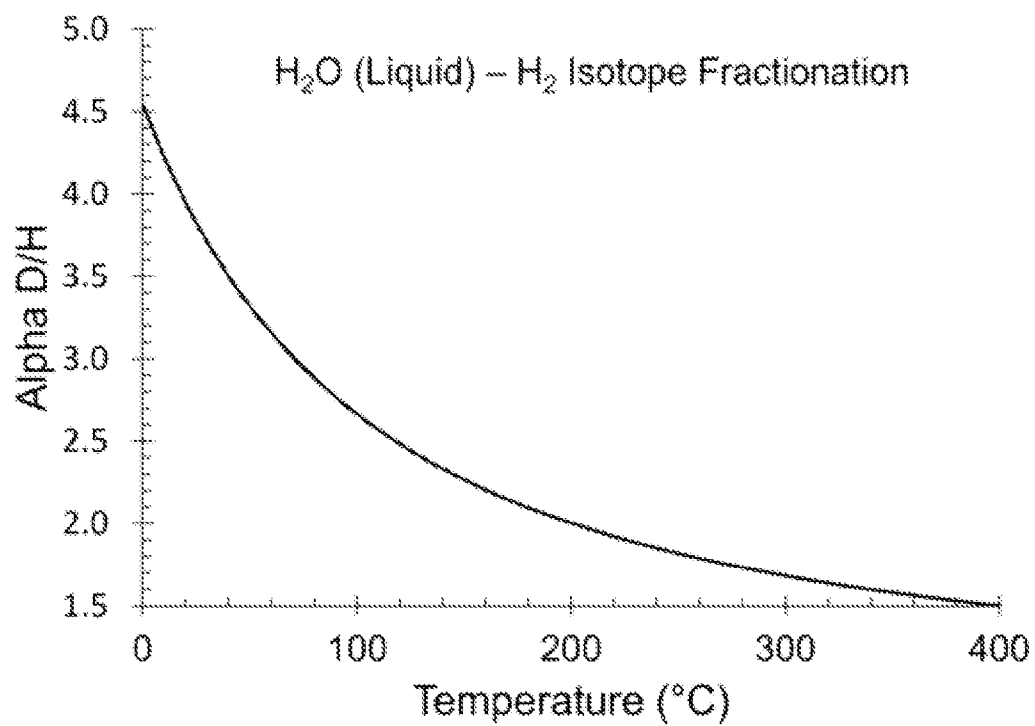


FIG. 4

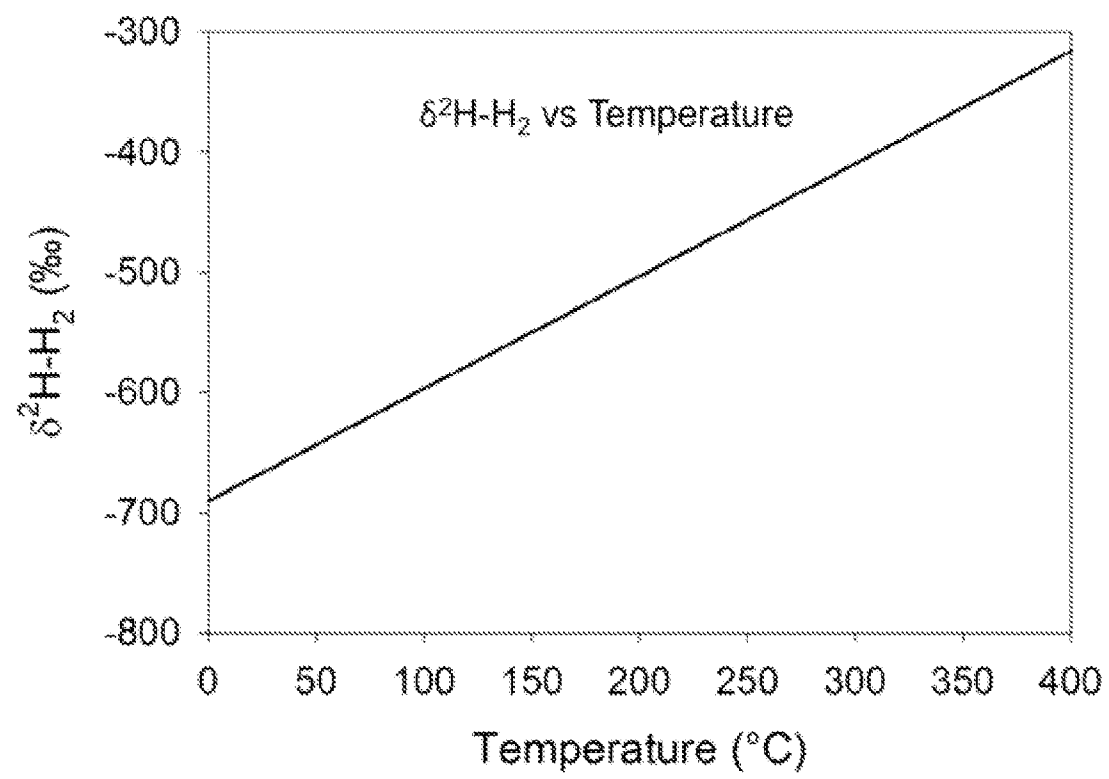


FIG. 5

Electronic Acknowledgement Receipt

EFS ID:	45897596
Application Number:	63349890
International Application Number:	
Confirmation Number:	8841
Title of Invention:	SYSTEMS AND METHODS FOR QUANTITATIVE ASSESSMENT AND MONITORING OF THE SOURCE, RESIDENCE TIME, AND SATURATION CONDITIONS OF HYDROGEN IN NATURAL GAS AND OTHER SUBSURFACE FLUIDS AND QUANTIFICATION AND VERIFICATION OF CARBON DIOXIDE SEQUESTRATION IN SUBSURFACE FORMATIONS
First Named Inventor/Applicant Name:	Thomas Darrah
Customer Number:	153511
Filer:	Nathan Michael Orme/Eve Stark
Filer Authorized By:	Nathan Michael Orme
Attorney Docket Number:	P296928.US.01_515365-7
Receipt Date:	07-JUN-2022
Filing Date:	
Time Stamp:	18:09:38
Application Type:	Provisional

Payment information:

Submitted with Payment	yes
Payment Type	CARD
Payment was successfully received in RAM	\$ 150
RAM confirmation Number	E202267110073967
Deposit Account	506181
Authorized User	Eve Stark
The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows: 37 CFR 1.16 (National application filing, search, and examination fees) 37 CFR 1.17 (Patent application and reexamination processing fees)	

37 CFR 1.19 (Document supply fees)
37 CFR 1.20 (Post Issuance fees)
37 CFR 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Application Data Sheet	20220607_P296928US01_515365-7_USProv-ADS.pdf	1256091	no	9
			0c0cf10736fc2aef05e0113824bf8b7d4b4618ea		
Warnings:					
Information:					
2	Drawings-only black and white line drawings	20220607_P296928US01_515365-7_USProv-Drawings.pdf	1255174	no	5
			185652eb05bfaf8bdc997083f0e53fbbe6b4e425		
Warnings:					
Information:					
3	Specification	20220607_P296928US01_515365-7_USProv-Specification.pdf	363215	no	46
			f7375c023ddf2588a59e042365275c2a124972e5		
Warnings:					
Information:					
4	Fee Worksheet (SB06)	fee-info.pdf	38064	no	2
			c54b28071a3784d2a177f5b365085da47fc_e74f1		
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New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

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UNITED STATES PROVISIONAL PATENT APPLICATION

of

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for

**SYSTEMS AND METHODS FOR QUANTITATIVE ASSESSMENT AND
MONITORING OF THE SOURCE, RESIDENCE TIME, AND SATURATION
CONDITIONS OF HYDROGEN IN NATURAL GAS AND OTHER SUBSURFACE
FLUIDS AND QUANTIFICATION AND VERIFICATION OF CARBON DIOXIDE
SEQUESTRATION IN SUBSURFACE FORMATIONS**

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TECHNICAL FIELD

[0001] Embodiments of the present disclosure relate generally to the fields of geology, exploration geology, petroleum geology, geochemistry, geophysics, energy exploration, energy extraction, energy storage, carbon capture, carbon utilization, or carbon or natural gas storage. Some embodiments disclose methods of subsurface exploration for natural resources, including subsurface hydrogen exploration and storage of carbon dioxide in subsurface reservoirs. More particularly, the present disclosure relates to systems and methods for determining the source, residence time, and saturation conditions of hydrogen, quantifying or certifying the proportion of hydrogen derived from no-carbon, low-carbon, or other sources, quantifying and verifying the sequestration of carbon dioxide in subsurface formations as a fluid or in mineralized form, determining and quantifying the eligibility of hydrogen for proposed United States Internal Revenue Service 45X production tax credit programs, various Low Carbon Fuel Standards, or other hydrogen production tax credit or subsidy programs, and determining and quantifying the eligibility of carbon dioxide storage for the United States Internal Revenue Service 45Q tax credit programs.

[0002] This section is intended to introduce various aspects of the technical field, which may be associated with embodiments described in this disclosure. Thus, the forgoing discussion in this section provides a framework for better understanding the disclosure, and is not to be viewed as an admission of prior art.

SUMMARY

[0003] Embodiments are directed to systems and methods that enable successful natural hydrogen exploration. This disclosure presents the systems and methods that enable identification and characterization of the source, residence time, and saturation conditions of hydrogen or carbon dioxide in order to determine if mixtures of fluids containing hydrogen or

carbon dioxide can be explored for, recovered, and/or stored safely and economically in the subsurface. In some embodiments, a method for analyzing a molecular composition can include analyzing at least one of hydrogen molecules, hydrocarbon gases, noble gases, carbon dioxide, nitrogen, or mixtures of natural gases of varying composition to determine the source of hydrogen or natural gas or to determine and verify the source of carbon dioxide in a subsurface formation.

[0004] In some embodiments, a method for analyzing the molecular composition of hydrogen or other gas mixtures can include analyzing the molecular composition to assess or determine a proportion of hydrogen or carbon dioxide derived from sources including geologic hydrogen (“gold hydrogen”), coal, steam methane reformation, pyrolysis, and electrolysis; quantifying the proportion of hydrogen or carbon dioxide derived from various sources; and validating and certifying the proportion of hydrogen derived from various sources. In some embodiments, a method of analyzing an isotopic composition of various compounds within a fluid can include analyzing at least one of hydrogen molecules, hydrocarbon gases, noble gases, carbon dioxide, nitrogen, or mixtures of natural gases of varying composition to determine the source of hydrogen, carbon dioxide, or natural gas; analyzing water to determine the feedstock for hydrogen formation by electrolysis of water; analyzing at least one of methane or other hydrocarbon gases to determine the feedstock for hydrogen formation by pyrolysis of methane or other hydrocarbon gas feedstocks, or by steam methane reforming of methane or other hydrocarbon gas feedstocks; and analyzing carbon dioxide or other compounds (e.g., hydrocarbon molecules, noble gases) or their isotopic compositions to determine the source of carbon dioxide or natural gas.

[0005] In some embodiments, a method for analyzing an isotopic composition can include analyzing hydrogen or carbon dioxide to assess or determine the proportion of hydrogen or carbon dioxide derived from at least one of geologic hydrogen, coal, steam methane reformation, pyrolysis, electrolysis, or other sources; analyzing hydrogen or carbon dioxide to quantify the proportion of hydrogen or carbon dioxide derived from at least one of geologic hydrogen, coal, steam methane reformation, pyrolysis, electrolysis, or other sources; validating and certifying the proportion of hydrogen derived from geologic hydrogen, coal, steam methane reformation, pyrolysis, electrolysis, or other no-carbon, low-carbon, or high-carbon sources; and qualifying the hydrogen for the US IRS 45X production tax credit; and validating and certifying the

proportion of carbon dioxide stored in a subsurface reservoir in the form of the storage including as a gas or supercritical fluid in pore space or by mineralization for the US IRS 45Q sequestration tax credit.

[0006] In some embodiments, a method for determining a source of hydrogen or carbon dioxide in various fluids can include evaluating fluids sourced from at least one of natural gas pipelines, hydrogen pipelines, oil pipelines, water pipelines, railcars, trucks, storage tanks, subsurface gas reservoirs, subsurface gas storage reservoirs, or other subsurface formations, or industrial facilities. A method for quantifying or apportioning the source of hydrogen or carbon dioxide in various fluids can include quantifying or apportioning the source of hydrogen in fluids sourced from at least one of natural gas pipelines, hydrogen pipelines, oil pipelines, water pipelines, railcars, trucks, storage tanks, subsurface gas reservoirs, subsurface gas storage reservoirs, or other subsurface formations, or industrial facilities. A method for certifying the source of hydrogen in various fluids can include certifying the source of hydrogen in fluids sourced from at least one of natural gas pipelines, hydrogen pipelines, oil pipelines, water pipelines, railcars, trucks, storage tanks, subsurface gas reservoirs, subsurface gas storage reservoirs, or other subsurface formations, or industrial facilities.

[0007] In some embodiments, a method for determining a source of hydrogen or carbon dioxide can include evaluating fluids collected at a surface region including springs, surface seeps, or a subsurface reservoir for the purposes of exploration of oil, natural gas, carbon dioxide, or hydrogen; during drilling for oil, natural gas, carbon dioxide, or hydrogen, including measurement while drilling or drill-stem test operations; downhole or surface pressure-volume-temperature (PVT) tests; evaluating fluids collected at the surface or in the subsurface for the purposes of production of oil, natural gas, carbon dioxide, or hydrogen; monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, or hydrogen in subsurface reservoirs or subsurface caverns; storage of oil, natural gas, carbon dioxide, or hydrogen in surface tanks, subsurface tanks, or other industrial facilities; and monitoring and evaluation of the presence of leaks or fugitive, stray, or other gas emissions in boreholes, oil, natural gas, carbon dioxide, or hydrogen wells, pipelines, water wells, surface seeps, springs, or other storage facilities.

[0008] In some embodiments, a method for determining the residence time of hydrogen, carbon dioxide, or other natural gas mixtures, in at least one of various surface or subsurface fluids, including water, natural gas, carbon dioxide, or other subsurface fluids, can include

analyzing the concentration of helium or other noble gases including neon, argon, krypton, xenon, or radon elemental and isotopic concentrations. A method for determining the residence time of hydrogen or carbon dioxide can include analyzing fluids collected at the surface or the subsurface for the purposes of exploration, drilling, production, or monitoring of oil, natural gas, carbon dioxide, hydrogen, or mixtures thereof or of various fluids; analyzing fluids collected at the surface or in the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, hydrogen, or other various fluid mixtures in subsurface reservoirs, subsurface caverns, surface tanks, subsurface tanks, or other industrial facilities; or analyzing fluids collected at the surface or in the subsurface for the purposes of monitoring and evaluation of the presence of leaks or fugitive, stray, or other gas emissions in boreholes, oil, natural gas, carbon dioxide, or hydrogen wells, pipelines, water wells, surface seeps, springs, or other storage facilities.

[0009] In some embodiments, a method for determining the timing of natural hydrogen formation by serpentinization or pyritization reactions can include calculating the timing of recrystallization of magnetite, ilmenite, hematite, pyrite, or other iron-containing minerals, sediments, or whole rock at the surface or in the subsurface using cores, cuttings, outcroppings, or other rock samples, by analyzing the U, Th, and K concentrations and mineral composition in combination with the noble gas content (e.g., ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar , ^{40}Ar) in magnetite, ilmenite, hematite, pyrite, or other iron-containing minerals, sediments, or whole rocks at the surface or in the subsurface using cores, cuttings, outcroppings, or other rock samples.

[0010] In some embodiments, a method for determining the gas saturation of hydrogen or carbon dioxide in subsurface fluids; determining the gas to water ratio of hydrogen or carbon dioxide in subsurface fluids; determining the gas to water ratio to inform reservoir modelling, estimated ultimate recoverable (EUR), or other resource estimates or production calculations; or determining qualification for the US IRS 45Q tax credit program can include analyzing the molecular composition of fluids, including hydrogen and other molecular gases (e.g., H_2 , N_2 , NH_3 , CO , CO_2), elemental gases (e.g., noble gases: He, Ne, Ar, Kr, Xe), or isotopes of gases (e.g., $\delta^2\text{H-H}_2$, $\delta^2\text{H-CH}_4$, $\delta^{13}\text{C-CH}_4$, $\delta^{13}\text{C-CO}_2$, $\delta^{15}\text{N-N}_2$, ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar , ^{40}Ar , and their derivative isotopic ratios), water (e.g., $\delta^2\text{H-H}_2\text{O}$, $\delta^{18}\text{O-H}_2\text{O}$, ^3H), or other dissolved constituents ($\delta^{13}\text{C-DIC}$).

[0011] In some embodiments, a method comprising determining the gas saturation and gas to water ratio with respect to hydrogen or carbon dioxide in at least one of fluids collected at the surface (e.g., springs, surface seeps) or in the subsurface for the purposes of exploration of oil, natural gas, carbon dioxide, hydrogen, or other natural gases; fluids collected at the surface (e.g., springs, surface seeps) or in the subsurface for the purposes of drilling (e.g., measurement while drilling, drill-stem test (DST), downhole or surface pressure-volume-temperature (PVT) tests) of oil, natural gas, carbon dioxide, hydrogen, or other natural gases; fluids collected at the surface (e.g., springs, surface seeps) or in the subsurface for the purposes of production of oil, natural gas, carbon dioxide, hydrogen, or other natural gases; fluids collected at the surface (e.g., springs, surface seeps) or in the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, hydrogen, or other natural gases in subsurface reservoirs; fluids collected at the surface (e.g., springs, surface seeps) or in the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, hydrogen, or other natural gases in subsurface caverns; fluids collected at the surface (e.g., springs, surface seeps) or in the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, hydrogen, or other natural gases in surface tanks, subsurface tanks, or other industrial facilities; or fluids collected at the surface (e.g., springs, surface seeps) or in the subsurface for the purposes of monitoring and evaluation the presence of leaks or fugitive, stray, or other gas emissions of carbon dioxide or hydrogen in boreholes, oil, natural gas, carbon dioxide, or hydrogen wells, pipelines, water wells, surface seeps, springs, or other storage facilities can include analyzing the molecular composition of fluids, including hydrogen and other molecular gases (e.g., H₂, N₂, NH₃, CO, CO₂), elemental gases (e.g., noble gases: He, Ne, Ar, Kr, Xe), or isotopes of gases (e.g., $\delta^2\text{H-H}_2$, $\delta^2\text{H-CH}_4$, $\delta^{13}\text{C-CH}_4$, $\delta^{13}\text{C-CO}_2$, $\delta^{15}\text{N-N}_2$, ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar , ^{40}Ar , and their derivative isotopic ratios), water (e.g., $\delta^2\text{H-H}_2\text{O}$, $\delta^{18}\text{O-H}_2\text{O}$, ^3H), or other dissolved constituents ($\delta^{13}\text{C-DIC}$).

[0012] Features from any of the disclosed embodiments may be used in combination with one another without limitation. In addition, other features and advantages of the present disclosure will become apparent to those of ordinary skill in the art through consideration of the following detailed description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The drawings illustrate several embodiments of the invention, wherein identical reference numerals refer to identical or similar elements or features in different views or embodiments shown in the drawings.

[0014] FIG. 1 is a list of analytical chemical instrumentation, the types of samples that can be analyzed with each instrument, and the elements and compounds that can be measured that are relevant to determining hydrogen and carbon dioxide sources, residence times, gas saturations, and temperatures of hydrogen formation, according to embodiments.

[0015] FIG. 2 is a general workflow relating to the collection of fluids or solid samples, chemical analyses, geochemical data acquisition, interpretation of the samples, and utilization during exploration that guides the drilling of new wells, according to an embodiment.

[0016] FIG. 3 illustrate chemical techniques and chemical species that may be used during the processing and interpretation of chemical results relating to determining hydrogen and carbon dioxide sources, residence times, gas saturations, and temperatures of hydrogen formation, according to embodiments.

[0017] FIG. 4 is a graph of the degree of fractionation (i.e., alpha or the fractionation factor) between hydrogen isotopic compositions of liquid water ($\delta^2\text{H-H}_2\text{O}$) and molecular hydrogen ($\delta^2\text{H-H}_2$) as a function of temperature in the paired liquid water-molecular hydrogen system that occurs during the serpentinization process.

[0018] FIG. 5 is a graph of the relationship between the isotopic composition of molecular hydrogen ($\delta^2\text{H-H}_2$) and temperature of hydrogen formation during the serpentinization process.

DETAILED DESCRIPTION

[0019] Embodiments disclosed herein are related to systems and methods for identifying and characterizing the source, residence time, and saturation conditions of hydrogen or carbon dioxide, or determining if mixtures of fluids containing hydrogen or carbon dioxide can be recovered economically from subsurface formations. Embodiments disclosed herein describe, quantify, and verify the abundance of hydrogen or carbon dioxide stored in subsurface formations and the type of storage of carbon dioxide, for example, in the form of a fluid or as a mineral precipitate. Systems and methods are disclosed herein that enable identification and characterization of the source, residence time, and saturation conditions of hydrogen or carbon

dioxide in order to determine if mixtures of fluids containing hydrogen or carbon dioxide can be explored for, recovered, and/or stored safely and economically in the subsurface.

[0020] Although the present specification focuses on hydrogen, carbon dioxide, or other mixtures of fluids, it is understood that the techniques disclosed herein are not so limited and can find application in the identification, quantitative assessment, and qualification of other subsurface materials, including other gases, minerals and gems, as well as materials found in large structures such as foundations, dams, hydroelectric facilities, and nuclear facilities, to name a few.

[0021] In the production of natural resources from formations within the earth, a well or borehole is drilled into the earth to the location where the natural resource is believed to be located. Similarly in the sequestration of greenhouse gases in formations within the earth, a well or borehole is drilled into the earth to the location where the greenhouse gas will be injected, located and sequestered. These natural resources may be hydrogen; helium; carbon dioxide; dihydrogen sulfide; methane or other hydrocarbon gases; a dihydrogen sulfide reservoir; a hydrogen reservoir; a helium reservoir; a carbon dioxide reservoir; a natural gas reservoir; a reservoir rich in dihydrogen sulfide; a reservoir rich in hydrocarbons; a reservoir rich in helium; the natural resource may be fresh water; brackish water; brine; it may be a heat source for geothermal energy; or it may be some other natural resource, ore deposit, mineral, metal, or gem that is located within the ground.

[0022] These resource-containing formations may be a few hundred feet, a few thousand feet, or tens of thousands of feet below the surface of the earth, including under the floor of a body of water, for example, below the sea floor or beneath other natural resources, for example, below aquifers. In addition to being at various depths within the earth, these formations may cover areas of differing sizes, shapes and volumes.

[0023] Typically, and by way of general illustration, in drilling a well an initial borehole is made into the earth, for example, the surface of land or seabed, and then subsequent and smaller diameter boreholes are drilled to extend the overall depth of the borehole. In this manner as the overall borehole gets deeper its diameter becomes smaller; resulting in what can be envisioned as a telescoping assembly of holes with the largest diameter hole being at the top of the borehole closest to the surface of the earth.

[0024] Thus, by way of example, the starting phases of a subsea drill process may be explained in general as follows. Once the drilling rig is positioned on the surface of the water over the area where drilling is to take place, an initial borehole is made by drilling a 36" hole in the earth to a depth of about 200 - 300 feet below the seafloor. A 30" casing is inserted into this initial borehole. This 30" casing may also be called a conductor. The 30" conductor may or may not be cemented into place. During this drilling operation a riser is generally not used and the cuttings from the borehole, for example, the earth and other material removed from the borehole by the drilling activity are returned to the seafloor. Next, a 26" diameter borehole is drilled within the 30" casing, extending the depth of the borehole to about 1,000 – 1,500 ft. This drilling operation may also be conducted without using a riser. A 20" casing is then inserted into the 30" conductor and 26" borehole. This 20" casing is cemented into place. The 20" casing has a wellhead secured to it. (In other operations an additional smaller diameter borehole may be drilled, and a smaller diameter casing inserted into that borehole with the wellhead being secured to that smaller diameter casing.) A BOP (blow out preventer) is then secured to a riser and lowered by the riser to the sea floor; where the BOP is secured to the wellhead. From this point forward all drilling activity in the borehole takes place through the riser and the BOP.

[0025] It should be noted that riserless subsea drilling operations are also contemplated.

[0026] For a land-based drill process, the steps are similar, although the large diameter tubulars, 30" – 20" are typically not used. Thus, and generally, there is a surface casing that is typically about 13 3/8" diameter. This may extend from the surface, for example, wellhead and BOP, to depths of tens of feet to hundreds of feet. One of the purposes of the surface casing is to meet environmental concerns in protecting ground water by preventing surface casing ventflow to groundwater aquifers or prevent surface casing ventflow of greenhouse gases or flammable gases to groundwater aquifers or the atmosphere. The surface casing should have sufficiently large diameter to allow the drill string, production equipment such as electronic submersible pumps (ESPs), and circulation mud to pass through. Below the casing one or more different diameter intermediate casings may be used. (It is understood that sections of a borehole may not be cased, which sections are referred to as open hole.) These can have diameters in the range of about 9" to about 7," although larger and smaller sizes may be used, and can extend to depths of thousands and tens of thousands of feet. Inside of the casing and extending from a pay zone, or production zone of the borehole up to and through the wellhead on the surface is the production

tubing. There may be a single production tubing or multiple production tubings in a single borehole, with each of the production tubing endings being at different depths.

[0027] Fluid communication between the formation and the well can be greatly increased by the use of hydraulic fracturing or other stimulation techniques. The first uses of hydraulic fracturing date back to the late 1940s and early 1950s. In general, hydraulic fracturing treatments involve forcing fluids down the well and into the formation, where the fluids enter the formation and crack, for example, by forcing the layers of rock to break apart or fracture. These fractures create channels or flow paths that may have cross sections of a few microns, to a few millimeters, to several millimeters in size, and potentially larger. The fractures may also extend out from the well in all directions for a few feet, several feet, and tens of feet or further. The fractures may be kept open by using a proppant (e.g., various sized sand or other mineral grains) that are forced down the well with the fracturing fluid in a single operation. It should be remembered that the longitudinal axis of the well in the reservoir may not be vertical: it may be on an angle (either sloping up or down) or it may be horizontal. The section of the well located within the reservoir, i.e., the section of the formation containing the natural resources, can be called the pay zone.

[0028] As used herein, unless specified otherwise, the terms “hydrogen exploration and production,” “carbon dioxide exploration and production,” “helium exploration and production,” “dihydrogen sulfide exploration and production,” “exploration and production activities,” “E&P,” and “E&P activities,” and similar such terms are to be given their broadest possible meaning, and include surveying, geological analysis, chemical assessment, well planning, reservoir planning, reservoir management, drilling a well, workover and completion activities, hydrogen production, flowing of hydrogen from a well, collection of hydrogen, secondary and tertiary recovery from a well, the management of flowing hydrogen from a well, carbon dioxide injection, carbon dioxide sequestration, carbon dioxide mineralization, dihydrogen sulfide injection, dihydrogen sulfide sequestration, dihydrogen sulfide mineralization, and any other upstream activities.

[0029] As used herein, unless specified otherwise, the terms “sulfur mineralization,” “sulfur sequestration,” “sulfur mitigation,” “carbon dioxide mineralization,” “carbon dioxide sequestration,” “carbon dioxide mitigation,” “carbon mineralization,” “carbon sequestration,” “carbon mitigation,” and similar such terms are to be given their broadest possible meaning, and

include surveying, geological analysis, well planning, reservoir planning, reservoir management, drilling a well, workover and completion activities, sulfur injection, dihydrogen sulfide injection, carbon injection, carbon dioxide injection, the management of flowing sulfur, dihydrogen sulfide, carbon, carbon dioxide to a well, and any other upstream activities.

[0030] As used herein, unless specified otherwise, the term “earth” should be given its broadest possible meaning, and includes the ground, all natural materials, such as rocks, and artificial materials, such as concrete, borehole casing, piping, or fill, that are or may be found in the ground.

[0031] As used herein, unless specified otherwise "offshore" and "offshore drilling activities" and similar such terms are used in their broadest sense and would include drilling activities on, or in, any body of water, whether fresh or salt water, whether manmade or naturally occurring, such as for example rivers, lakes, canals, inland seas, oceans, seas, such as the North Sea, bays and gulfs, such as the Gulf of Mexico. As used herein, unless specified otherwise the term "offshore drilling rig" is to be given its broadest possible meaning and would include fixed towers, tenders, platforms, barges, jack-ups, floating platforms, drill ships, dynamically positioned drill ships, semi-submersibles and dynamically positioned semi-submersibles. As used herein, unless specified otherwise the term "seafloor" is to be given its broadest possible meaning and would include any surface of the earth that lies under, or is at the bottom of, any body of water, whether fresh or salt water, whether manmade or naturally occurring.

[0032] As used herein, unless specified otherwise, the term “production tax credit”, “hydrogen production tax credit”, “45X”, “U.S. IRS 45X”, “U.S. IRS 45X production tax credit” “hydrogen production payments”, “hydrogen stimulus”, “Low Carbon Fuel Standards”, “LCFS”, or other similar terms should be given its broadest possible meaning would include any production tax credit or production payments issued in the United States, by an individual state, or abroad.

[0033] As used herein, unless specified otherwise, the term “borehole” should be given its broadest possible meaning and includes any opening that is created in the earth that is substantially longer than it is wide, such as a well, a well bore, a well hole, a micro hole, a slimhole and other terms commonly used or known in the arts to define these types of narrow long passages. Wells would further include exploratory, discovery, production, abandoned, reentered, reworked, recirculation, and injection wells. They would include both cased and

uncased wells, and sections of those wells. Uncased wells, or section of wells, also are called open holes, boreholes, open boreholes, open bores, or open hole sections. Boreholes may further have segments or sections that have different orientations, they may have straight sections and arcuate sections and combinations thereof. Thus, as used herein unless expressly provided otherwise, the "bottom" of a borehole, the "bottom surface" of the borehole and similar terms refer to the end of the borehole, i.e., that portion of the borehole furthest along the path of the borehole from the borehole's opening, the surface of the earth, or the borehole's beginning. The terms "side" and "wall" of a borehole should be given their broadest possible meaning and include the longitudinal surfaces of the borehole, whether or not casing or a liner is present, as such, these terms would include the sides of an open borehole or the sides of the casing that has been positioned within a borehole. Boreholes may be made up of a single passage, multiple passages, connected passages, (e.g., branched configuration, fishboned configuration, duallateral configuration, trilateral configuration, quadrilateral configuration, pitchfork configuration, pinnate configuration, or comb configuration), and combinations and variations thereof. Boreholes are generally formed and advanced by using mechanical drilling equipment having a rotating drilling tool, for example, a bit. For example, and in general, when creating a borehole in the earth, a drilling bit is extending to and into the earth and rotated to create a hole in the earth. To perform the drilling operation, the bit must be forced against the material to be removed with a sufficient force to exceed the shear strength, compressive strength or combinations thereof, of that material. The material that is cut from the earth is generally known as cuttings or drill cuttings, for example, waste, which may be chips of rock, dust, rock fibers and other types of materials and structures that may be created by the bit's interactions with the earth. These cuttings are typically removed from the borehole by the use of fluids, which fluids can be liquids, foams or gases, or other materials know to the art.

[0034] As used herein, unless specified otherwise, the term "drill pipe" is to be given its broadest possible meaning and includes all forms of pipe used for drilling activities; and refers to a single section or piece of pipe. As used herein the terms "stand of drill pipe," "drill pipe stand," "stand of pipe," "stand" and similar type terms should be given their broadest possible meaning and include two, three or four sections of drill pipe that have been connected, for example, joined together, typically by joints having threaded connections. As used herein the terms "drill string," "string," "string of drill pipe," string of pipe" and similar type terms should be given their

broadest definition and would include a stand or stands joined together for the purpose of being employed in a borehole. Thus, a drill string could include many stands and many hundreds of sections of drill pipe.

[0035] As used herein, unless specified otherwise, the terms “formation,” “reservoir,” “pay zone,” and similar terms, are to be given their broadest possible meanings and would include all locations, areas, and geological features within the earth that contain, may contain, or are believed to contain, hydrogen, carbon dioxide, helium, dihydrogen sulfide, or natural gas.

[0036] As used herein, unless specified otherwise, the terms “field,” “oil field,” “gas field” and similar terms, are to be given their broadest possible meanings, and would include any area of land, sea floor, or water that is loosely or directly associated with a geologic formation, and more particularly with a resource containing formation, thus, a field may have one or more exploratory and producing wells associated with it, a field may have one or more governmental body or private resource leases associated with it, and one or more field(s) may be directly associated with a resource containing formation.

[0037] As used herein, unless specified otherwise, the terms “conventional hydrogen,” “conventional carbon dioxide,” “conventional helium,” “conventional dihydrogen sulfide,” “conventional natural gas,” “conventional,” “conventional production” and similar such terms are to be given their broadest possible meaning and include hydrogen, carbon dioxide, helium, or dihydrogen sulfide that are trapped in stratigraphic units or structures in the earth. Generally, in these conventional formations the hydrogen, carbon dioxide, helium, dihydrogen sulfide, or natural gas have migrated in permeable, or semi-permeable formations to a trap, or area where they are accumulated. Typically, in conventional formations a non-porous, relatively impermeable layer is above, or encompassing the area of accumulated hydrogen, carbon dioxide, helium, dihydrogen sulfide, or natural gas in essence trapping the hydrogen, carbon dioxide, helium, dihydrogen sulfide, or natural gas in the accumulation. Conventional reservoirs have been historically the sources of the vast majority of hydrogen, carbon dioxide, helium, and dihydrogen sulfide observed. As used herein, unless specified otherwise, the terms “unconventional hydrogen,” “unconventional carbon dioxide,” “unconventional helium,” “unconventional dihydrogen sulfide,” “unconventional natural gas,” “unconventional,” “unconventional production” and similar such terms are to be given their broadest possible

meaning and includes hydrogen, carbon dioxide, helium, dihydrogen sulfide, or natural gas that are held in impermeable rock, or which have not migrated to traps or areas of accumulation.

[0038] As used herein, unless specifically stated otherwise, the term “gold hydrogen” should be given its broadest possible meaning, and generally refers to hydrogen produced from the subsurface by drilling hydrogen-bearing reservoir or drilling and stimulating iron-rich rock, mafic rock, pyrite, iron-rich sandstone, or iron-rich sediments with or without fracturing or other forms of mechanical stimulation that can provide an abundant source of low emission, low cost, fully dispatchable energy.

[0039] As used herein, unless specifically stated otherwise, the term “element” should be given its broadest possible meaning, and generally refers to each of more than one hundred chemical substances that cannot be chemically interconverted or broken down into simpler substances and are primary constituents of matter, each which can be distinguished by its atomic number, i.e., the number of protons in the nuclei of its atoms.

[0040] As used herein, unless specifically stated otherwise, the term “molecule” should be given its broadest possible meaning, and generally refers to a group of atoms bonded together, representing the smallest fundamental unit of a chemical compound that can take part in a chemical reaction.

[0041] As used herein, unless specifically stated otherwise, the term “isotope” should be given its broadest possible meaning, and generally refers to each of two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence differ in relative atomic mass, but not in chemical properties. Isotopes can be stable in that they do not experience radioactive decay, or they can be radioactive in that they decay to other isotopes over time, with time constants referred to as decay constants that can be used to calculate half-lives).

[0042] As used herein, unless specifically stated otherwise, the term “isotopic ratio” should be given its broadest possible meaning, and generally refers to the relative proportions or abundances of isotopes of the same element (e.g., $^2\text{H}/^1\text{H}$, $^{13}\text{C}/^{12}\text{C}$ or $^{18}\text{O}/^{16}\text{O}$). Among other things, the isotope ratio can be used to provide information on the origin of chemical species, the processes that influence them after their formation, physicochemical conditions under which they are formed.

[0043] As used herein, unless specifically stated otherwise, the term “measurement” should be given its broadest possible meaning, and generally refers to the act of measuring something. Examples of geochemical measurements for elements, molecules, isotopes, and isotope ratios described above can be performed with various chemical instruments for methods including chromatography, mass spectrometry, spectroscopy, or other chemical measurement techniques.

[0044] As used herein, unless specifically stated otherwise, the term “chemical instrument” should be given its broadest possible meaning, and generally refers to a device or tool used for scientific purposes, including the study of natural, laboratory-based, and theoretical purposes.

[0045] As used herein, unless stated otherwise, room temperature is 25°C. And, standard temperature and pressure is 25°C and 1 atmosphere.

[0046] Generally, the term “about” as used herein unless specified otherwise is meant to encompass a variance or range of $\pm 10\%$, $\pm 5\%$, $\pm 2\%$ the experimental or instrument error associated with obtaining the stated value, and preferably the larger of these.

[0047] As used herein unless specified otherwise, the recitation of ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate value falling within the range. Unless otherwise indicated herein, each individual value within a range is incorporated into the specification as if it were individually recited herein.

[0048] The term “CO_{2e}” is used to define carbon dioxide equivalence of other, more potent greenhouse gases, to carbon dioxide (i.e., methane and nitrous oxide) on a global warming potential basis of 100 years, based on IPCC AR5 methodology. The term “carbon intensity” is taken to mean the lifecycle CO_{2e} generated per unit mass of a product.

[0049] Carbon dioxide is widely recognized as a greenhouse gas (GHG), and the continued accumulation of carbon dioxide and other GHGs in the atmosphere are expected to cause problematic changes to global ecosystems and contribute to myriad other problems, such as ocean acidification and sea level rise. The two primary causes of carbon emissions globally are the use of fossil fuels for power generation and transportation.

[0050] Given the risks of carbon dioxide emissions, significant work has gone into finding replacements to existing high carbon energy sources, or ways to decarbonize existing energy sources. However, many of these low carbon alternatives have been uneconomic or not dispatchable enough to replace the current options.

[0051] As used herein, unless specified otherwise, the terms “storage”, “gas storage”, “hydrogen storage”, “carbon storage”, and similar terms, are to be given their broadest possible meanings and would include all locations, areas, and geological features within the earth in which hydrogen, carbon dioxide, helium, dihydrogen sulfide, mixtures of natural gas, or other fluids can be injected or otherwise placed into the subsurface either for days, weeks, months, years, or longer, or permanently.

[0052] As used herein, unless specified otherwise, the terms “sequestration” and similar terms, are to be given their broadest possible meanings and would include the act of injecting or otherwise placing gases, liquids, other fluids, or mixtures thereof in any and all locations, areas, and geological features within the earth. Sequestration can be in the gases (e.g., carbon dioxide or dihydrogen sulfide gas), liquid (e.g., supercritical carbon dioxide or dihydrogen sulfide), or solid phases (e.g., various forms of carbonate or sulfide minerals).

[0053] As used herein, unless specified otherwise, the terms “mineralization” or “permanent storage” and similar terms, are to be given their broadest possible meanings and would include the storage of chemical species (e.g., carbon dioxide, dihydrogen sulfide, or other chemicals) in solid phases, mineral precipitates, or in various forms of carbonate or sulfide minerals) either above the surface or in the subsurface.

[0054] As used herein, unless specified otherwise, the term “carbon sequestration tax credit”, “carbon dioxide sequestration tax credit”, “carbon mineralization tax credit” “carbon tax credit”, “carbon storage tax credit”, “carbon mineralization tax credit”, “45Q”, “U.S. IRS 45Q”, “U.S. IRS 45Q carbon storage tax credit”, “U.S. IRS 45Q carbon tax credit”, or other similar terms should be given its broadest possible meaning and would include any carbon tax credit or carbon offset payment issued in the United States or abroad.

[0055] The term “sulfur equivalents” of “SO_x” is used to define dihydrogen sulfide or sulfur dioxide offset equivalence of sulfur emissions. The term “sulfur intensity” is taken to mean the lifecycle SO_x generated per unit mass of a product.

[0056] Sulfur, in various forms, including but not limited to dihydrogen sulfide, sulfur dioxide, sulfuric acid, and sulfate, is widely recognized as a toxic and harmful atmospheric pollutant and the deposition of sulfur in soil, waterways, and other environments are expected to cause problematic changes to global ecosystems and contribute to myriad of other problems, such as acid rain, soil acidification, deforestation, ocean acidification, and other toxic impacts.

The primary causes of dihydrogen sulfide emissions globally are related to petroleum and natural gas extraction and refining, pulp and paper manufacturing, rayon textile production, waste disposal, landfills, water and sewage treatment facilities, and general waste disposal. Additionally, natural factors such as volcanoes, hot springs, thermal vents, geysers, fumaroles, “sour” natural gas fields, biodegraded oil fields, and geothermal power plants also constitute major naturally occurring sources of dihydrogen sulfide.

[0057] Given the risks of dihydrogen sulfide and other forms of sulfur emissions, significant work has gone into sulfur removal technologies, the development of low sulfur fuels, or ways to desulfurize existing energy sources and processes. However, many of these low sulfur alternatives themselves create cost prohibitions, are uneconomic, or limit the dispatchability of energy sources.

[0058] Based on the risks of sulfur emissions, the U.S. EPA (IRC 45H) has created a cap-and-trade sulfur credit program for offset, sulfur abatement, and sequestration. The U.S. IRS 45Q tax credit program is a similar tax credit program for carbon dioxide sequestration.

[0059] In power generation, the alternatives to the highly reliable, low cost, but high emission sources (gas and coal) are either dispatchable and expensive (e.g., nuclear, hydroelectric, green hydrogen, or blue hydrogen), or inexpensive and intermittent (e.g., solar and wind, green hydrogen in some cases). There is only one existing source that is both lower cost and dispatchable, and that is geothermal. However, geothermal resources are limited, many of the economically productive geothermal resources have already been developed and are nearing end of life, and many geothermal resources are already in decline. As such, the growth outlook for geothermal energy resources is limited without significant technical advances.

[0060] Green hydrogen (hydrogen produced from water without the utilization of fossil fuels), which is generated by electrolysis powered from either solar, wind, hydroelectric, renewable natural gas combustion, or geothermal energy can be a reliable source of no-carbon or low-carbon energy when coupled with storage, but high capital cost, intermittent production due to intermittent energy sources or high cost of energy when grid connected, and the high cost and low availability of suitable hydrogen storage resources limits applicability. In addition, electrolysis consumes significantly more energy to produce the hydrogen than what is stored in the hydrogen, resulting in a low round trip efficiency in the system.

[0061] Blue hydrogen faces a similar set of problems to green hydrogen: it takes a low cost, high emission fuel source like coal or natural gas, and by adding expensive and parasitic carbon capture facilities, converts this low-cost-high-emission source of energy into a high-cost-low-emission source. Thus, even though large volumes of hydrogen can be formed in processes that subsequently prevent greenhouse gas emissions from reaching the atmosphere, the newly developed hydrogen resource is not cost competitive with other forms of energy derived from fossil fuels. Additionally, the challenges around finding carbon sequestration resources that can be used to permanently store the captured carbon from these processes result in limited opportunities to deploy these technologies today.

[0062] Natural hydrogen (or “gold hydrogen”), produced from the subsurface by drilling into and producing from a formation with hydrogen gas contained in pore- or fracture-space via conventional gas production methods (e.g., perforation of a target reservoir allowing fluids to flow up a tubing string or steel casing) or by drilling into and stimulating iron-rich rock, mafic rock, pyrite, iron-rich sandstone, or iron-rich sediments with or without fracturing or other forms of mechanical stimulation can provide an abundant source of low emission, low cost, fully dispatchable energy.

[0063] Each of these energy sources and their inherent advantages and limitations are also relevant to transportation. When considering transportation fuels, by far the major sources of fuel are diesel and gasoline, both derived from crude oil production. Additionally, in recent years, electric vehicles have been gaining market share, but the cost for electric vehicles is still more expensive than fossil fueled equivalents and limitations exist regarding cost, recharge time, and primary resources for battery and energy storage. Given the weight of batteries, electric long-haul trucking is also challenged, and most long-haul truck manufacturers are in search of affordable, low carbon options such as hydrogen-fueled trucking.

[0064] Natural hydrogen produced by drilling into hydrogen-rich reservoirs or drilling to stimulate enhanced hydrogen production would be an answer to the low- or negative-carbon, low cost, reliable transportation problem for long-haul trucking and potentially other forms of transportation. As for other types of transportation, natural hydrogen as a compressed or liquified product, or as a feedstock for synthetic liquid fuel (“efuels”), would be a reliable low cost, low or negative-carbon solution. Additionally, natural hydrogen could be combined with nitrogen to produce a carbon free ammonia product, which is being widely discussed as a potential

replacement for bunker fuel for shipping and as a feedstock for synthetic fertilizer manufacturing.

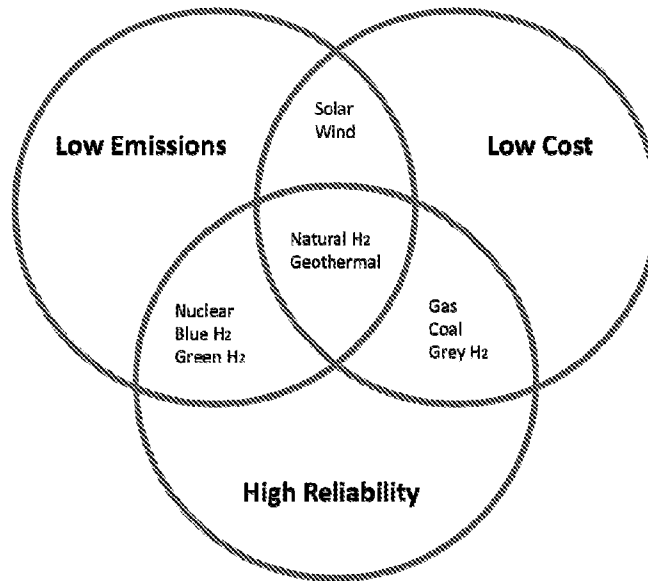
[0065] Direct Emissions Reduction: Because there are no direct carbon dioxide emissions from the combustion or typical use of hydrogen, the reduction in carbon dioxide emissions is a function of what the hydrogen is replacing. In many cases, low-carbon (or negative-carbon) hydrogen would be replacing hydrogen from steam methane reforming (SMR) as a chemical feedstock for ammonia production, oil refining, and other chemical manufacturing. In some cases, low carbon (or negative carbon) hydrogen may replace natural gas, diesel fuel, gasoline, or jet fuel as a heat source or transportation fuel.

[0066] In the case of ammonia production and refining, natural gas is used to produce hydrogen via steam methane reformation reactions, which is used as a chemical feedstock in both the refining process and the ammonia production process. Today, more than 95% of hydrogen is produced using natural gas in steam methane reformers (SMRs). The carbon intensity of hydrogen production using SMRs without carbon capture is 10.4 tonnes of carbon dioxide emitted for each tonne of hydrogen produced. As such, direct replacement of natural hydrogen for hydrogen manufactured by SMR processes results in a carbon dioxide reduction of 10.4 tonnes CO₂/tonne H₂.

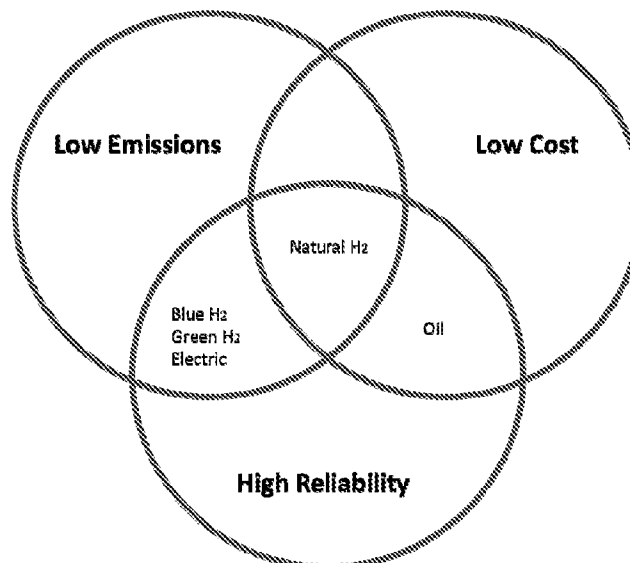
[0067] In power generation with gas turbines, hydrogen must displace the energy (btu) equivalent of natural gas. The energy density of hydrogen is 290 btu/cf or 51,682 btu/lb. By comparison, the energy density of natural gas is 983 btu/cf or 20,267 btu/lb, while the carbon intensity of natural gas is 52.91 kg CO₂/mmbtu CH₄, or 54.87 kg CO₂/mcf CH₄, or 3.5 kg CO₂/kg CH₄.

[0068] Because hydrogen is 2.6 times more energy dense per unit mass than natural gas, only 40% of the gross tonnage of fuel is required to achieve the same energy output. As such, burning one tonne of hydrogen for power generation reduces natural gas consumption by about 2.6 tonnes, and thus carbon dioxide emissions by 9.1 tonnes.

[0069] The realization of abundant natural hydrogen can achieve significant reductions in equivalent carbon emissions.



[0070] **Power source Cost, Emissions, and Reliability.**



[0071] **Transportation fuel Cost, Emissions, and Reliability.**

[0072] Naturally occurring hydrogen (sometimes also called geological hydrogen, native hydrogen, natural hydrogen, gold hydrogen) can be considered a potential energy source for transition to no-carbon or low-carbon fuel. Geochemical, geophysical, and other tools can be used to prospect for and characterize oil and hydrocarbon gases in the subsurface. In some embodiments, systems and methods can identify and characterize the source, residence time, and

saturation conditions of hydrogen or determine if mixtures of fluids containing hydrogen can be recovered economically from the subsurface through: a) oil and gas exploration, drilling, and production; b) natural hydrogen exploration, drilling, and production; c) tracking and verification of the source of naturally occurring hydrogen when sold as negative- or low-carbon hydrogen (“green premium”). Through this process, hydrogen that qualifies for proposed federal (e.g., the production tax credit: United States Internal Revenue Service 45Q tax credit program) and existing state incentive programs (e.g., Low Carbon Fuel Standards or LCFS, or other hydrogen credit, incentive, or subsidy programs) can be achieved. Systems and methods disclosed herein provide for quantitative assessment and monitoring of the source of hydrogen, the residence time of hydrogen and other fluids in the subsurface, and the proportion of hydrogen in pore spaces in a subsurface formation. The systems and methods disclosed herein include making and utilizing measurements of molecular gases (e.g., H₂, N₂, CO, CO₂); elemental gases (e.g., noble gases: He, Ne, Ar, Kr, Xe); or isotopes of gases (e.g., $\delta^2\text{H-H}_2$, $\delta^2\text{H-CH}_4$, $\delta^{13}\text{C-CH}_4$, $\delta^{13}\text{C-CO}_2$, ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar , ^{40}Ar , and their derivative isotopic ratios), water ($\delta^2\text{H-H}_2\text{O}$, $\delta^{18}\text{O-H}_2\text{O}$, ^3H), or other dissolved constituents ($\delta^{13}\text{C-DIC}$) sampled directly or indirectly from subsurface fluids, springs, fumaroles, subsurface discharges, other natural samples, or fluids injected by industrial processes. Further solutes, gases, water, isotopes, or materials may be measured and analyzed according to the techniques disclosed herein.

[0073] Beyond the introduction of negative- or low-carbon hydrogen (e.g., natural hydrogen) and other forms of low carbon energy, another mechanism to mitigate carbon dioxide emissions to the atmosphere can include subsurface carbon dioxide storage, either as a gas, a gas dissolved in aqueous fluids (e.g., water or brine), or as supercritical carbon dioxide. The potential to sequester carbon dioxide in these or other forms in subsurface formations (e.g., in pore spaces within sandstone reservoirs or within mafic rocks following mineralization reactions) enables lower carbon emission production of hydrogen from fossil fuels (e.g., steam methane reformation), commonly termed “blue hydrogen”, or the direct use of fossil fuels when the process is paired with carbon capture, utilization, or storage (i.e., CCUS). The systems and methods that enable successful quantification and verification of secure carbon dioxide storage either as a gas, a gas dissolved in aqueous fluids (e.g., water or brine), a supercritical carbon dioxide, or in mineralized form can be limited.

[0074] The systems and methods described herein quantify and verify the abundance of carbon dioxide stored in subsurface formations and the type of storage such as in the fluid or mineral form. The systems and methods disclosed herein can determine the quantity of carbon dioxide that can be claimed for United States Internal Revenue Service 45Q tax credit program or other regulatory tax credits or payment programs, including LCFS) for subsurface carbon sequestration. In the scenario of permanent carbon storage by subsurface mineralization, these systems and methods can be used to directly quantify and verify the proportion of carbon dioxide permanently sequestered in the mineral phase enabling a higher return (currently \$50/ton) when qualifying for the United States Internal Revenue Service 45Q tax credit, LCFS, or other programs.

[0075] The systems and methods disclosed herein can apply to identification of natural hydrogen or mixtures of fluids containing natural hydrogen collected from the subsurface by the use of a borehole, a well, a pump, downhole sampling technique, a surface casing vent, along a well annulus, seep, ovoid, bay, fairy circle, spring, groundwater well, or in soil gases; identification of natural hydrogen or mixtures of fluids containing natural hydrogen produced from the subsurface by the use of a borehole, a well, a pump, a surface casing vent, along a well annulus, groundwater well; determination of the genetic source of natural hydrogen or mixtures of fluids containing natural hydrogen in subsurface formations; quantification and verification of gas composition to determine eligibility for the United States Internal Revenue Service 45X hydrogen production tax credit program or other low carbon fuel standard (LCFS) programs; determination of the temperature conditions (geothermometry) of natural hydrogen or mixtures of fluids containing natural hydrogen in subsurface formations; determination of the residence time of natural hydrogen or mixtures of fluids containing natural hydrogen in the subsurface; the timing of natural hydrogen formation; verification of no-carbon or low-carbon hydrogen inputs and offtakes of natural gas in pipelines; verification of no-carbon or low-carbon hydrogen inputs and offtakes of natural gas transported by other means (e.g., trucking, railcar, cryogenic tanks); identification of prospective leaks or fugitive or stray gas investigations involving hydrogen in groundwater or other water ways; quantification and verification of storage of natural hydrogen in subsurface reservoirs, formations, caverns, or other facilities; quantification and verification of the subsurface sequestration, storage, or mineralization of carbon dioxide fluids in porous or fractured reservoirs; quantification and verification of carbon mineralization; and quantification

and verification of subsurface carbon dioxide sequestration as a means of demonstrating eligibility for United States Internal Revenue Service 45Q tax credit, LCFS, or other tax credit programs.

[0076] The use of chemical instruments to measure elements, molecules, isotopes, or isotopic ratios by visual inspection, quantitative analysis, or supervised or unsupervised computer-assisted machine learning can enable the identification and characterization of the source, residence time, or saturation conditions of hydrogen or carbon dioxide in the subsurface or at the surface. In particular, in an embodiment, analysis of the combination of these chemical species can be used to determine if mixtures of fluids containing hydrogen or carbon dioxide can be recovered economically from the subsurface through oil and gas exploration, drilling, and production techniques as well as natural hydrogen or carbon dioxide exploration, drilling, and production techniques. FIG. 1 is a list of analytical chemical instrumentation, the types of samples that can be analyzed with each instrument, and the elements and compounds that can be measured that are relevant to determining hydrogen and carbon dioxide sources, residence times, gas saturations, and temperatures of hydrogen formation, according to embodiments.

[0077] Further, the methods and systems disclosed herein can be used for assessment of the integrity of subsurface storage of hydrogen or carbon dioxide; identification and tracking of cross-formational loss of hydrogen or carbon dioxide to other formations; identification and tracking of carbon dioxide migration during carbon sequestration or enhanced oil recovery operations; identification, verification, and tracking of the mineral sequestration of carbon in the subsurface following injection for enhanced oil recovery, carbon sequestration; quantification and verification of secure carbon dioxide storage either as a gas, a gas dissolved in aqueous fluids (e.g., water or brine), a supercritical fluid, in mineralized form, or other means, and combinations and variations of these. Additionally, the systems and methods disclosed herein can track and verify the source of hydrogen (e.g., natural hydrogen, electrolytic hydrogen, or pyrolytic hydrogen) when sold as no-carbon or low-carbon hydrogen (“green premium”) and track and verify chemical species for which hydrogen is used as a feedstock.

[0078] FIG. 2 is a general workflow relating to the collection of fluids or solid samples, chemical analyses, geochemical data acquisition, interpretation of the samples, and utilization during exploration that guides the drilling of new wells, according to an embodiment. Some or

all of the blocks shown in FIG. 2 may be utilized in one or more embodiments. Aspects of the blocks are disclosed herein.

[0079] The embodiments disclosed herein enable identification and characterization of the source, residence time, and saturation conditions of hydrogen or carbon dioxide, which enable identification and verification of the integrity of subsurface storage of hydrogen or carbon dioxide; identification and tracking of cross-formational loss of hydrogen or carbon dioxide to other formations; identification and tracking of carbon dioxide migration during carbon sequestration or enhanced oil recovery operations; identification, verification, and tracking of the mineral sequestration of carbon in the subsurface following injection for enhanced oil recovery or carbon sequestration; quantification verification of secure carbon dioxide storage either as a gas, a gas dissolved in aqueous fluids (e.g., water or brine), a supercritical fluid, in mineralized form, or other means, and combinations and variations of these. Embodiments of these systems and methods can track and verify the source of hydrogen when sold as no-carbon or low-carbon hydrogen (“green premium”), and track and verify chemical species for which hydrogen is used as a feedstock. FIG. 3 illustrate chemical techniques and chemical species that may be used during the processing and interpretation of chemical results relating to determining hydrogen and carbon dioxide sources, residence times, gas saturations, and temperatures of hydrogen formation, according to embodiments.

[0080] The methods herein provide an enhanced technique for use in exploration for occurrences of hydrogen or carbon dioxide, monitoring and quantification of the storage of these gases, tracking of carbon dioxide during storage or enhanced oil recovery, and assessment and quantification of carbon sequestration by mineralization in the subsurface. The techniques herein can include the use of chemical instruments (e.g., mass spectrometer, gas chromatograph, residual gas analyzer, flame ionization, or the like) to measure chemical species that can be quantified to establish the source, migration, residence time, saturation conditions, chemical reactions, and other fluid histories of hydrogen or carbon dioxide at the surface or in the subsurface. In some embodiments, the relationships between the chemical species can be assessed by visual inspection, quantitative analysis, or supervised or unsupervised computer-assisted machine learning to determine the occurrence and quantify the presence of hydrogen or carbon dioxide in the subsurface.

[0081] The systems and methods used herein generally utilize existing chemical data sourced from publications, laboratory reports, technical briefs, as well as other sources or newly acquired chemical data sourced from the analyses of samples that can be obtained through oil and gas exploration, drilling, and production; natural hydrogen exploration, drilling, and production; carbon dioxide exploration, drilling, and production; natural gas, hydrogen, or carbon dioxide storage; groundwater exploration, drilling, and production; from surface water, surface seeps, springs, or soil; or from air. The chemical data can be compared to the data from the chemical characterizations disclosed herein, such as to make any of the determinations disclosed herein.

[0082] In some embodiments, a combination of the elemental, molecular, and isotopic composition of fluids, including gas, water, oil, and mixtures from a particular site (e.g., location, depth, geological formation) can be measured using chemical instruments to enable the identification and characterization of the source, residence time, and saturation conditions of hydrogen or carbon dioxide in order to determine if mixtures of fluids containing hydrogen or carbon dioxide can be safely and economically recovered from or stored in the subsurface. A combination of one or more of molecular gases (e.g., H_2 , N_2 , NH_3 , CO , CO_2), elemental gases (e.g., noble gases: helium, neon, argon, krypton, xenon, radon), or isotopes of gases (e.g., δ^2H - H_2 , δ^2H - CH_4 , δ^2H - C_2H_6 , $\delta^{13}C$ - CH_4 , $\delta^{13}C$ - CO_2 , $\delta^{15}N$ - N_2 , ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar , ^{40}Ar , and other noble gases and their derivative isotopic ratios), water (e.g., δ^2H - H_2O , $\delta^{18}O$ - H_2O , ^3H), or other dissolved constituents (DIC concentrations and the $\delta^{13}C$ -DIC, where DIC is dissolved inorganic carbon), can identify the origins, residence times, equilibration temperatures of formation, and gas saturation conditions of fluids such as naturally-occurring hydrocarbons (e.g., CH_4) and other gases (e.g., N_2 , CO_2 , H_2S , H_2). The above criteria can be applied in the methods and systems disclosed herein to identify the source, residence times, equilibration temperatures of formation, and gas saturation conditions of hydrogen or carbon dioxide in subsurface reservoirs.

[0083] Hydrocarbon gases are formed naturally by inorganic or biological processes that each result in distinct molecular and stable isotopic signatures of methane (e.g., δ^2H - CH_4 , $\delta^{13}C$ - CH_4) and higher molecular weight hydrocarbon species (e.g., δ^2H - C_2 , $\delta^{13}C$ - C_2). Thermogenic hydrocarbons (e.g., oil, shale gas) are formed from the thermocatalytic cracking of organic matter and result in δ^2H - CH_4 generally greater than -250‰ and $\delta^{13}C$ - CH_4 generally between -55 and -25‰. As thermal maturity of the organic matter increases, the stable isotopic signatures of

carbon and hydrogen in the produced hydrocarbons become more positive in predictable fashions. In contrast, microbial methane (e.g., coalbed methane) is formed from methanogenic archaea utilizing the reduction of CO₂ or fermentation of acetate in the shallow subsurface, which result in $\delta^{13}\text{C-CH}_4$ values generally less than -55‰ and $\delta^2\text{H-CH}_4$ values generally greater than -250‰ but less than -100‰. Abiotic methane is the result of Sabatier reactions between H₂ and CO₂ at elevated (about 150°C or more) temperatures and is often observed in geothermal systems, which result in isotopically heavy $\delta^{13}\text{C-CH}_4$ (greater than about -30‰) and $\delta^2\text{H-CH}_4$ (greater than about -400‰).

[0084] Hydrogen can be formed by inorganic or biological processes. The isotopic composition of hydrogen generated by either mechanism displays molecular or isotopic characteristics that can be used to determine the source of hydrogen. For example, like microbial methane, hydrogen produced by biological species (e.g., microbes) is associated with highly elevated levels of dissolved inorganic carbon and dissolved inorganic carbon that is isotopically enriched (e.g., $\delta^{13}\text{C-DIC}$ greater than about -10‰) relative to that produced from CO₂ dissolution or the oxidation of organic matter (e.g., $\delta^{13}\text{C-DIC}$ commonly ranging from -30‰ to -15‰). Hydrogen produced by microbes also displays hydrogen isotopic compositions that are significantly depleted in deuterium relative to protium (i.e., $\delta^2\text{H-H}_2$ less than about -750‰).

[0085] Hydrogen produced by inorganic processes displays a predictable relationship with temperature and the original source of water from which hydrogen is derived. FIG. 4 is a graph of the degree of fractionation (i.e., alpha or the fractionation factor) between hydrogen isotopic compositions of liquid water ($\delta^2\text{H-H}_2\text{O}$) and molecular hydrogen ($\delta^2\text{H-H}_2$) as a function of temperature in the paired liquid water-molecular hydrogen system that occurs during the serpentinization process. Similar graphs for other hydrogen-forming reactions (e.g., pyritization) that quantify the degree of fractionation between a given reactant and the hydrogen product (e.g., dihydrogen sulfide and hydrogen) are also conceived of as part of embodiments. Because hydrogen can be formed by the reduction of water by a variety of mechanisms (e.g., serpentinization), there is a strong temperature-fractionation relationship for H₂O-H₂ systems. For example, thermochemical calculations show that in reducing conditions (e.g., low oxygen fugacity) fractionation factors between oxygen and hydrogen during the olivine-water or pyroxene-water interactions (i.e., serpentinization) are well calibrated from temperatures ranging from about 20°C to 700°C. As a result, if the $\delta^2\text{H-H}_2\text{O}$ and $\delta^2\text{H-H}_2$ values of a given water-H₂

(gas) pair can be measured, or if the $\delta^2\text{H-H}_2$ values of a fluid containing hydrogen can be measured while the isotopic composition of the original water can be reasonably assumed (such as if the $\delta^2\text{H-H}_2\text{O}$ value is known, e.g., based on local porewater isotopic values or seawater isotopic values), the temperatures of gas formation can be calculated based on measuring the $\delta^2\text{H-H}_2$ and calculating the temperature-dependent degree of fractionation relative to the original hydrogen-carrying molecule (i.e., water in the case of serpentinization). These calculated temperatures can be compared to local geothermal gradients to determine the genetic source of the hydrogen gas and by comparison to a range of parameters (e.g., concentration of other gases, concentration of dissolved inorganic carbon, mineralogy) in other approaches to determine a mechanism responsible for the formation of hydrogen (e.g., serpentinization compared to pyritization). FIG. 5 is a graph of the relationship between the isotopic composition of molecular hydrogen ($\delta^2\text{H-H}_2$) and temperature of hydrogen formation during the serpentinization process. Similar graphs for other hydrogen-forming reactions (e.g., pyritization) that quantify the degree of fractionation between a given reactant and the hydrogen product (e.g., dihydrogen sulfide and hydrogen) are also conceived of as part of embodiments. A small amount of re-equilibration between ambient H_2O and H_2 can be expected above 100°C suggesting in higher temperature regimes, these calculated temperatures may represent a minimum. Whether plotted manually, with a computer, or by other form of graphing or statistical tool, graphs of $\delta^2\text{H-H}_2$ can be plotted relative to either water isotope data ($\delta^2\text{H-H}_2\text{O}$) or calibration lines of anticipated temperature based on the thermodynamics of equilibrium between water and newly generated hydrogen gas assuming or determining a fractionation factor between the two species that is dependent on mineralogy, porewater chemistry, and temperature.

[0086] Hydrogen can also be produced by biologically-mediated (i.e., bacterial production) or other inorganic processes, including magma oxidation, basalt alteration, magmatic degassing, cataclasis, pyritization (“metal-sulfide precipitation”), lava crystallization, radiolysis, graphitization, and lava-seawater interactions. For those reactions that involve interactions with water (e.g., magma oxidation, basalt alteration, low-temperature weathering, magma crystallization, lava-seawater interactions), there is a similarly predictable, temperature-dependent relationship between the original source of water and the derived hydrogen. In this case, the same process described for serpentinization can be applied and used to determine the source of hydrogen. For other mechanisms, similar thermodynamic relationships exist between

the original hydrogen-containing molecule, such as dihydrogen sulfide in pyritization (“metal-sulfide precipitation”), methane or other heavier molecular weight hydrocarbons in graphitization, water in radiolysis or cataclasis, or hydroxyls in radiolysis or cataclasis, and the evolved hydrogen. For example, thermodynamic calculations show that fractionation factors between dihydrogen sulfide and hydrogen formed during the olivine-dihydrogen sulfide or pyroxene-dihydrogen sulfide reaction (i.e., pyritization (“metal-sulfide precipitation”)) are well-calibrated according to temperature ranging from about 20°C to 700°C. As a result, if the $\delta^2\text{H-H}_2\text{S}$ and $\delta^2\text{H-H}_2$ values of a given $\text{H}_2\text{S-H}_2$ (gas) pair can be measured, or if the $\delta^2\text{H-H}_2$ values of a fluid containing hydrogen can be measured while the isotopic composition of the original dihydrogen sulfide can be reasonably assumed, the temperatures of gas formation can be calculated based on measuring the $\delta^2\text{H-H}_2$ and calculating the temperature-dependent degree of fractionation relative to the original hydrogen-carrying molecule. These calculated temperatures and a range of parameters can be used to determine the mechanism responsible (i.e., genetic source) for the formation of hydrogen (e.g., pyritization compared to serpentinization), especially when compared to other geochemical parameters (e.g., concentration of other gases, concentration of dissolved inorganic carbon, mineralogy) and the source rock of the hydrogen gas based on a comparison to the local geothermal gradient. Whether plotted manually, with a computer, or by another form of graphing or statistical tool, graphs of $\delta^2\text{H-H}_2$ can be plotted relative to either the isotopic composition of the hydrogen-carrying molecule (e.g., $\delta^2\text{H-H}_2\text{S}$) or calibration lines of anticipated temperature based on the thermodynamics of equilibrium between the hydrogen-carrying molecule and newly generated hydrogen gas by assuming or determining a fractionation factor between the two species that is dependent on mineralogy, porewater chemistry, and temperature.

[0087] Hydrogen can also be produced by various synthetic processes, including steam methane reforming, electrolysis, pyrolysis, and others. For those reactions, there is a similarly predictable, temperature-dependent relationship between the original source of the hydrogen-carrying molecule (e.g., water, methane) and the hydrogen derived by these processes. As a result, the same thermodynamic calculations and measurements can be applied and used to determine the source of hydrogen and delineate the process used to synthesize hydrogen formation. Thus, these same geochemical parameters can be used to determine the mechanism responsible (i.e., genetic source) for the formation of hydrogen (e.g., steam methane reforming,

electrolysis, and pyrolysis, as compared to various forms of natural hydrogen) especially when compared to other geochemical parameters (e.g., concentration of other gases). Whether plotted manually, with a computer, or by another form of graphing or statistical tool, graphs of $\delta^2\text{H-H}_2$ can be plotted relative to either the isotopic composition of the hydrogen-carrying molecule (e.g., $\delta^2\text{H-H}_2\text{S}$) or calibration lines of anticipated temperature based on the thermodynamics of equilibrium between the hydrogen-carrying molecule and newly generated hydrogen gas assuming a fractionation factor between the two species that is dependent on mineralogy, porewater chemistry, and temperature. These methods can be used to identify and apportion natural hydrogen (“gold hydrogen”) from other synthetic forms of hydrogen.

[0088] Other characteristics, such as the concentration of methane compared to the concentration of hydrogen (e.g., $[\text{CH}_4]/[\text{H}_2]$), can help identify the origin of natural hydrogen. In general, as the temperature increases, the kinetic rate of the Sabatier reaction can convert more hydrogen to methane in the presence of ambient gaseous or dissolved carbon dioxide. During this process, the newly formed methane, or abiogenic methane, can have unique isotopic compositions such as $\delta^{13}\text{C-CH}_4$ greater than about -20‰. As a result, a generally positive correlation between $[\text{CH}_4]/[\text{H}_2]$ and $\delta^2\text{H-H}_2$ or $\delta^{13}\text{C-CH}_4$ values can be taken as an indication of increasing and/or decreasing temperature of gas formation. Whether plotted manually, with a computer, or by other form of graphing or statistical tool, graphs of these data can be used to determine temperature and resolve the mixing of multiple sources or generations of gas.

[0089] Noble gases (He, Ne, Ar, Kr, Xe) and their isotopes are chemically inert and can be considered to be in low but well-constrained abundances in the atmosphere, hydrosphere, and subsurface. As a result, noble gases are particularly useful for understanding fluid origins, residence times, and gas saturation conditions. Generally, noble gases have three primary sources: the atmosphere, the mantle, and the crust through radioactive decay of uranium, thorium, and potassium. The origin of hydrogen can be refined when comparing the helium, neon, and argon isotopic composition of gases and the $[\text{He}]/[\text{Ne}]$ or $[\text{He}]/[\text{Ar}]$ ratios. Mantle-derived noble gas isotopes (e.g., ^3He) are primordial and have been trapped in the mantle since the accretion of the Earth. Because of the exceptionally low natural abundance and production of ^3He in the crust, ^3He can be used as an unambiguous indication of mantle-derived fluids in water, natural gases, or other fluids.

[0090] The most dominant geologic process that produces natural hydrogen is the serpentinization of iron-rich minerals such as olivine and pyroxene, which are minerals most-commonly found in mantle-derived mafic and ultramafic igneous rocks (e.g., basalt, gabbro, and peridotite). Olivine and pyroxene minerals also contain trapped ^3He , therefore a fluid rich in hydrogen produced from serpentinization may be enriched in ^3He relative to other crust-derived or microbially-derived hydrogen-rich fluids. This is most often observed in geothermal environments but has also been seen in intracontinental settings where mafic and ultramafic igneous rocks have intruded and elevated natural hydrogen has been found. Further, while carbon dioxide has many sources in the crust (e.g., microbial respiration, dissolution of calcium carbonates, post-mature kerogen), mantle-derived fluids have characteristic $\delta^{13}\text{C}\text{-CO}_2$ (about -2‰ to -8‰) and $[\text{CO}_2]/[^3\text{He}]$ ratios (about 1×10^9 to 10×10^9). Mantle-derived helium displays a $[\text{He}]/[\text{He}]$ of up to about 6 to $8R_A$ (where R_A is the $[\text{He}]/[\text{He}]$ in air or 1.384×10^{-6}) or higher in mantle plume environments, while the helium isotopic ratio in the atmosphere is about $1R_A$ and the helium isotopic ratio of crustal gases is about $0.02R_A$. Together, these geochemical signatures can be used as evidence for identifying the source of naturally occurring hydrogen in the subsurface. In most crustal systems, the relative contributions of each component can be resolved using a combination of helium, neon, argon, or other noble gas isotopes and various ratios of helium or other noble gases to other atmospheric noble gases (e.g., He/Ne, He/Ar, He/Kr, He/Xe, or to specific isotopes of one of these elements).

[0091] Systems and methods for determining the source of hydrogen can include determining the temperature of hydrogen formation. Determining the formation mechanism and thermal conditions (“genetic source”) of hydrogen provides better informed exploration strategies, as well as the ability to track the fate of fugitive hydrogen, monitor hydrogen production, or identify a “fingerprint” of natural hydrogen that can be used to track its utilization in various commercial processes; the latter of which is relevant for evaluating if it qualifies for and certifying the use of this hydrogen for low-carbon fuel standards (LCFS), 45X production tax credit, or other low-carbon hydrogen policies. For example, determining the thermal conditions may allow explorationists to identify the source rock, depth of key fluid reactions, the depth to drill, or affiliated formations at which hydrogen is formed. Accurately determining the source may be important in evaluating the likelihood that hydrogen formed at a specific depth would migrate into a specific reservoir or be emplaced below a specific seal and/or in estimating

the volume of gas that would accumulate in a given 3-dimensional trap. This source fingerprint may be important for various efforts to apportion the source of gas, identify chemicals derived that use this or other forms of hydrogen as a feedstock, or track its downstream utilization or environmental fate. Importantly, this same approach can be used to qualify, monitor, and track “gold” hydrogen and verify or authenticate its qualification for the proposed United States Internal Revenue Service 45X production tax credit, various low-carbon fuel standards (LCFS) programs, and other low-carbon hydrogen programs.

[0092] The concentration and stable isotopes of carbon dioxide (i.e., $\delta^{13}\text{C-CO}_2$) and dissolved inorganic carbon ($\delta^{13}\text{C-DIC}$) and various ratios of carbon dioxide to other gases can also be used to determine and track the genetic source of carbon dioxide at the surface or in the subsurface.

[0093] Atmospheric noble gas isotopes (e.g., ^{20}Ne , ^{36}Ar , ^{84}Kr) may dissolve into surface and groundwater as a function of Henry’s Law of solubility based on temperature, pressure, and salinity with relative ratios and fractionation factors varying according to mass ($^{20}\text{Ne} < ^{36}\text{Ar} < ^{84}\text{Kr}$). As a result, the dissolved atmospheric noble gas abundances are predictable and are only altered by physical processes such as gas-water solubility fractionation. Solubility fractionation can occur if gas comes in contact with a volume of water, such as natural hydrogen accumulating in previously water-filled pore space in a mafic rock or a volume of gas buoyantly migrating through the water-saturated crust, at which point less soluble (e.g., ^{20}Ne) isotopes preferentially enter the gas phase while more soluble isotopes (e.g., ^{84}Kr) remain in the liquid phase. Further, because the abundances of atmospheric noble gas isotopes are unchanging upon entry into the sediment porewaters at burial or groundwater system, the noble gas abundances can serve as proxies for the ratios of $(\text{Gas}_{\text{volume}})/(\text{Water}_{\text{volume}})$ or relative hydrogen gas saturation or water saturation conditions in the reservoir. If the depth (e.g., formation depth in a borehole) and pressure (e.g., hydrostatic pressure or over-pressured conditions (pressures exceeding hydrostatic pressure) at reservoir formation) from which collected samples are known, the ratio of hydrogen to atmospheric noble gases (e.g., $\text{H}_2/^{36}\text{Ar}$ or $\text{H}_2/^{20}\text{Ne}$) can therefore be used to calculate hydrogen saturation in the reservoir (e.g., subsurface formation). This technique allows indirect evaluation of hydrogen saturation conditions because the expected abundance of any atmospheric gas is able to be calculated by estimating the atmospheric pressure, temperature, and salinity of subsurface fluids (e.g., seawater in pore fluids) recharged during sediment deposition,

groundwater recharge, other or forms of porewater infiltration. As hydrogen gas is formed, initially low volumes of hydrogen gas will dissolve into porewaters with an initially low ratio of hydrogen to atmospheric gases (e.g., $[H_2]/[^{36}Ar]$, where ^{36}Ar is chosen as an example because nearly all of the ^{36}Ar in any sample is derived entirely from atmospheric (e.g., air-saturated water) inputs without influence from radioactive decay) and the relative solubility of H_2 and Ar with respect to water are similar. As the hydrogen saturation or percent hydrogen in a given pore fluids increases, the $[H_2]/[^{36}Ar]$ increases since the absolute volume of ^{36}Ar is fixed at the time of recharge in a given volume of water according to pressure, temperature, and salinity. Even if the partial pressure of hydrogen and other gases increases to the point where it exceeds the hydrostatic pressure-controlled saturation conditions of water at a given depth, because the relative solubilities of hydrogen and argon are similar, the $[H_2]/[^{36}Ar]$ can record the relative volume of each phase independent of whether the components are measured in the gas phase, dissolved in porewaters, or mixtures of both. By directly measuring these two components (or other ratios such as $[H_2]/[N_2]$, $[H_2]/[Ne]$, $[H_2]/[Kr]$, or $[H_2]/[Xe]$, or specific isotopes of any of these) and calculating the expected concentration of the air-saturated water component (e.g., $[^{36}Ar] = 920 \times 10^{-6}$ cc/kg at one atmosphere of pressure, $15^\circ C$, in a salinity equivalent to seawater (i.e., salinity equals 35 per mil)), the relative proportion of a given pore space that is filled with hydrogen or the hydrogen gas to water ratio can be calculated. Some embodiments may include utilizing the abundances of methane and other natural hydrocarbon gases to atmospheric noble gas isotopes as proxies for the ratios of $(Gas_{volume})/(Water_{volume})$ or relative hydrocarbon gas saturation or water saturation conditions in the reservoir.

[0094] In some embodiments, systems and methods can include determining the relative proportion of hydrogen gas (or methane or other gases) in subsurface pore fluids or “hydrogen gas saturation conditions.” Techniques for estimating the relative proportion of hydrogen gas in a given volume of pore space water can determine the economic viability of a prospect for a variety of reasons. For example, gas saturation conditions may be important for constraining the approximate depth of hydrogen gas (or methane or other gases) in the subsurface, for building estimated ultimate recovery (EUR) estimates for subsurface hydrogen production, for estimating the gas recovery conditions in reservoir models used to estimate gas recovery/decline curves, or for estimating the likelihood of water breakthrough and ultimately the probability of successfully recovering hydrogen from a given prospect.

[0095] In some embodiments, the approach described above with respect to carbon dioxide can be used to determine the saturation conditions of carbon dioxide in various subsurface formations. The carbon dioxide gas to water ratio can be used to prepare reservoir models, estimate carbon dioxide storage capacity in a given reservoir, anticipate water displacement, and act as a mechanism for monitoring and determining if the relative proportion of carbon dioxide gas and water remain constant when considering the partial dissolution of carbon dioxide into porewaters. In some embodiments, the technique can be specifically important when quantifying the proportion of carbon dioxide that qualifies for the United States Internal Revenue Service 45Q tax credit program or other similar tax or payment programs in the US or abroad, and verifying for what level of 45Q tax credit a given carbon sequestration approach qualifies. For example, carbon dioxide storage in pore spaces, whether as a gas or supercritical fluid currently qualifies for a \$35/ton tax credit, while carbon mineralization, including permanent storage, qualifies for a \$50/ton tax credit. In the former, the $[\text{CO}_2]/[^{36}\text{Ar}]$ can be monitored in an injected fluid, while changes in the $[\text{CO}_2]/[^{36}\text{Ar}]$ (because ^{36}Ar is conservative) can be used to directly quantify the proportion that is either mineralized or dissolved as inorganic carbon mass, which can be monitored by direct measurement of dissolved inorganic carbon.

[0096] In some embodiments, noble gas isotopes derived from the radioactive decay of ^{235}U (e.g., ^4He), ^{238}U (e.g., ^4He , ^{136}Xe), ^{232}Th (^4He), and ^{40}K (^{40}Ar) in the crust, termed “crustal” or “radiogenic” gases, provide an understanding of both the fluid origin and residence times. Additionally, ^{21}Ne is produced indirectly when the α particles (^4He) expelled during the decay of U and Th strike an ^{18}O atom within an oxygen-saturated mineral, which occurs at relatively fixed rates (1 in every 22.2 million decays). The diffusional release of these isotopes from mineral grains to pore space in the subsurface are a function of temperature, for example the closure temperatures of $^4\text{He}^*$ (where * denotes the proportion from radioactive decay), $^{21}\text{Ne}^*$, $^{40}\text{Ar}^*$, and $^{136}\text{Xe}^*$ are less than about 15°C , about 94°C , about 240°C , and much greater than 500°C , respectively, in quartz with varying other well-constrained temperature profiles in other mineral phases.

[0097] Crustal noble gases can benefit the characterization of natural hydrogen in two fundamental ways. The first stems from crustal noble gases produced by the decay of U, Th, and K and known rates that can be determined by directly measuring the concentration of parent isotopes (e.g., ^{235}U , ^{238}U , ^{232}Th , ^{40}K) and using the half-life of radioactive decay. By measuring

the diffusional release constants of the noble gas products of decay (e.g., $^4\text{He}^*$, $^{21}\text{Ne}^*$, $^{40}\text{Ar}^*$, $^{136}\text{Xe}^*$) by techniques such as step heating experiments of reservoir, source, or other rock matrices, cuttings, or cores and comparing the inferred rates of diffusional loss to the abundance of key noble gas products of radioactive decay measured in hydrogen gas, carbon dioxide gas, natural gas, or other mixtures of hydrogen or other species with other gases (e.g., methane, nitrogen), or other porewaters, the residence time or age of a given fluid can be determined. This residence time estimate can be useful to distinguish the source of hydrogen. The estimation of age or residence time can constrain what structural or stratigraphic traps may have been present and in what configuration they were in during the time of hydrogen migration. For example, hydrogen produced 1 billion years ago could not fill a reservoir if the reservoir was only deposited 700 million years ago. In contrast, for example, hydrogen produced 2 million years ago could fill a reservoir if the reservoir was deposited 250 million years ago. As a result, the development of a hydrogen system (in the sense of the oil and gas industry phrase “petroleum system”) that was present could have accumulated hydrogen during its formation/migration.

[0098] A second beneficial characterization technique derived from crustal noble gases relates to samples of source rock retrieved from the surface, such as outcrops, or subsurface (e.g., cuttings or cores from drilled wells). Magnetite, hematite, pyrite, and other forms of iron, as well as minerals such as magnesite and other carbonates, are mineral byproducts of key reactions that form geological hydrogen (e.g., hydrogen is formed by serpentinization and pyritization reactions). By directly measuring the U, Th, and K concentration in samples of source rock and also measuring the abundance of crustal noble gases that have accumulated in magnetite, hematite, pyrite, and other forms of iron mineral grains, or other minerals (e.g., magnesite, carbonates), one can quantify the amount of time that has elapsed since the mineral formed during the various reactions that generate hydrogen (e.g., serpentinization, pyritization), which can be used to derive the timing of hydrogen generation. This approach can be used to determine key characteristics about the timing of mineralization and when comparing apparent ages derived from $^4\text{He}^*$, $^{21}\text{Ne}^*$, and $^{40}\text{Ar}^*$, the thermal conditions and age of subsequent re-mineralization events for various natural hydrogen source rocks can be determined.

[0099] In some embodiments, for classification of H_2 , one or more of a suite of geochemical analyses can be conducted on a fluid sample(s). Fluid samples can be taken from a well at one or more depths or may be taken from the surface. Adequate sample containers for gas samples

include refrigeration-grade copper tubes sealed with brass, steel, aluminum, or other forms of refrigeration clamps, seamless stainless-steel cylinders, Isotubes®, gas-tight septum vials, or the like. Acceptable water sample containers include refrigeration-grade copper tubes sealed with brass, steel, aluminum, or other forms of refrigeration clamps, Isoflasks®, gas-tight vials, or the like. The fluid may be extracted from the sample container on a vacuum line and, if necessary, may be sonicated for about 30 minutes to ensure complete transfer of dissolved gases from the extraction vessel to the sample inlet line. The sample may also be extracted using a gas-tight syringe or flushed from the sample vessel into a sample preparation line using a carrier gas (e.g., helium, argon). Major gas/dissolved gas components (e.g., H₂, N₂, NH₃, CO, CO₂, C₁-C₆+) can be measured by one or more of a Residual Gas Analyzer (RGA) Quadrupole Mass Spectrometer, a Gas Chromatograph (GC) fitted with a Flame Ionizing Detector (FID) and Thermal Conductivity Detector (TCD), or other suitable analytical equipment and techniques. Noble gases and their stable isotopes can be measured by a residual gas analyzer or gas source mass spectrometer, such as following purification of an aliquot of the sample or other suitable technique. The stable isotopic composition of gas molecules (e.g., $\delta^2\text{H-H}_2$, $\delta^2\text{H-CH}_4$, $\delta^{13}\text{C-CH}_4$, $\delta^2\text{H-C}_2\text{H}_6$, $\delta^{13}\text{C-C}_2\text{H}_6$, $\delta^{13}\text{C-CO}_2$, $\delta^{15}\text{N-N}_2$) can be measured by an isotope ratio mass spectrometer (IRMS), cavity ring down spectroscopy, or other suitable method. If necessary, the IRMS can be used to measure the stable isotopes of hydrogen and oxygen in water (i.e., $\delta^2\text{H-H}_2\text{O}$, $\delta^{18}\text{O-H}_2\text{O}$). Any other technique disclosed herein may be utilized to measure isotopes in fluid samples.

[00100] Determining the characteristics of hydrogen, carbon dioxide, or any other material in a subsurface geological formation may include retrieving a fluid sample from a borehole or well. The borehole or well may be drilled for the characterization if necessary. The sample may be collected at the surface, such as from a water or other fluid source at the surface.

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a subsurface geological formation may include retrieving a mineral or rock sample from a cutting, borehole, or well. The borehole or well may be drilled for the characterization if necessary. The sample may also be collected at the surface, such as from an outcropping at the surface.

[00102] In an embodiment, a method for locating a fluid sequestration or production site for fluids (e.g., hydrogen, methane or other natural gases, carbon dioxide, water, or the like) may

utilize any of the methods for analyzing material disclosed herein. The method includes obtaining information regarding one or more of, a molecular composition of a fluid including one or more of hydrogen, methane or other natural gases, or carbon dioxide; a gas saturation and gas to water ratio with respect to hydrogen, methane or other natural gases, or carbon dioxide; residence time of hydrogen or carbon dioxide in the fluid; mass of water; a concentration of helium and other noble gases and isotopic concentrations of the helium or other noble gases; a source of hydrogen, carbon dioxide, or natural gas; quantifying or apportioning the source of hydrogen in natural gases; certifying the source of hydrogen in natural gases; and analyzing an isotopic composition of the fluid, as disclosed herein. The method includes providing the information to an exploration planner. The exploration planner may include one or more of a driller, an engineering firm, or a natural resources exploration company. Providing the information to an exploration planner may include transferring one or more of electronic or paper files including the information to the exploration planner. The method includes one or more of planning a well, planning a field, or producing hydrogen with the information. For example, the planner may receive the information and use the information to plan a well site for connecting to a subterranean formation at a location. The planner may receive the information and use the information to plan a field of multiple well sites at a location. The planner may receive the information and use the information to plan the location of equipment to utilize the fluid (e.g., hydrogen or natural gas) from the subterranean formation. The planner may receive the information and use the information to plan the location of equipment to sequester fluid (e.g., hydrogen or carbon dioxide) in the subterranean formation. The method may include collecting sample fluid from a subterranean formation, such as via a well, for chemical analysis.

[00103] The methods disclosed herein may be performed using a system for determining information including one or more characteristics of water, hydrogen, methane or other natural gases, carbon dioxide, or noble gases. The system includes chemical analysis equipment. The chemical analysis equipment may be configured to determine information about the fluid. The information may include one or more of the characteristics determined using any of the analytical methods disclosed herein. For example, the information may include one or more of a molecular composition of a fluid including one or more of hydrogen, methane or other natural gases, or carbon dioxide; a gas saturation and gas to water ratio with respect to hydrogen, methane or other natural gases, or carbon dioxide; residence time of hydrogen or carbon dioxide

in the fluid; mass of water; a concentration of helium and other noble gases and isotopic concentrations of the helium or other noble gases; a source of hydrogen, carbon dioxide, or natural gas; quantifying or apportioning the source of hydrogen in natural gases; certifying the source of hydrogen in natural gases; or analyzing an isotopic composition of the fluid. For example, the chemical analysis equipment may include one or more of an isotope ratio mass spectrometer, a cavity ring down spectroscopy apparatus, a residual gas analyzer, a quadrupole mass spectrometer, a gas chromatograph, a gas chromatograph fitted with a flame ionizing detector and thermal conductivity detector, or any other chemical analysis equipment suitable for the analytic techniques disclosed herein. The system includes one or more computing devices operably coupled to the one or more pieces of chemical analysis equipment, the one or more computing devices being configured to electronically communicate the information to a remote computing device. The one or more computing devices may include a desktop computer, a laptop computer, a tablet computer, a smartphone, or the like. The system may include one or more wells for obtaining fluids for test samples, such as from a subterranean formation. The system may include fluid sampling equipment, such as any of the sampling equipment disclosed herein. The system may include a remote computing device, such as a computing device located at a different location than a well site, a chemical analysis site or the like. The remote computing device may be operably coupled to or couplable to (e.g., via an internet connection) the one or more computing devices. The remote computing device may be located at a third party location, such as at the exploration planner.

[00104] It is noted that there is no requirement to provide or address the theory underlying the novel and groundbreaking production rates, performance or other beneficial features and properties that are the subject of, or associated with, embodiments of the present inventions. Nevertheless, various theories are provided in this specification to further advance the art in this important area, and in particular in the important area of hydrogen, dihydrogen sulfide, carbon dioxide, and helium exploration, production, and downstream conversion or utilization. These theories put forth in this specification, and unless expressly stated otherwise, in no way limit, restrict or narrow the scope of protection to be afforded the claimed inventions. These theories may not be required or practiced to utilize the present inventions. It is further understood that the present inventions may lead to new, and heretofore unknown theories to explain the conductivities, fractures, drainages, resource production, chemistries, and function-features of

embodiments of the methods, articles, materials, devices and system of the present inventions; and such later developed theories shall not limit the scope of protection afforded the present inventions.

[00105] The invention may be embodied in other forms than those specifically disclosed herein without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting. The various embodiments of devices, systems, activities, methods and operations set forth in this specification may be used with, in or by, various processes, industries and operations, in addition to those embodiments of the Figures and disclosed in this specification. The various embodiments of devices, systems, methods, activities, and operations set forth in this specification may be used with: other processes industries and operations that may be developed in the future: with existing processes industries and operations, which may be modified, in-part, based on the teachings of this specification; and with other types of gas recovery and valorization systems and methods. Further, the various embodiments of devices, systems, activities, methods, and operations set forth in this specification may be used with each other in different and various combinations. Thus, for example, the configurations provided in the various embodiments of this specification may be used with each other. For example, the components of an embodiment having A, A' and B and the components of an embodiment having A'', C and D can be used with each other in various combination, e.g., A, C, D, and A. A'' C and D, etc., in accordance with the teaching of this specification. Thus, the scope of protection afforded the present inventions should not be limited to a particular embodiment, configuration or arrangement that is set forth in a particular embodiment, example, or in an embodiment in a particular Figure.

CLAIMS

What is claimed is:

1. A method for analyzing a molecular composition, the method comprising:
analyzing at least one of hydrogen molecules, hydrocarbon gases, noble gases, carbon dioxide, nitrogen, or mixtures of natural gases of varying composition to determine the source of hydrogen or natural gas or to determine and verify the source of carbon dioxide in a subsurface formation.
2. A method for analyzing the molecular composition of hydrogen or other gas mixtures, the method comprising:
analyzing the molecular composition to assess or determine a proportion of hydrogen or carbon dioxide derived from sources including geologic hydrogen, coal, steam methane reformation, pyrolysis, and electrolysis;
quantifying the proportion of hydrogen or carbon dioxide derived from the sources; and
validating and certifying the proportion of hydrogen or carbon dioxide derived from the sources.
3. A method of analyzing an isotopic composition, the method comprising:
analyzing at least one of hydrogen molecules, hydrocarbon gases, noble gases, carbon dioxide, nitrogen, or mixtures of natural gases of varying composition to determine the source of hydrogen or natural gas;
analyzing water to determine the feedstock for hydrogen formation by electrolysis of water;
analyzing at least one of methane or other hydrocarbon gases to determine the feedstock for hydrogen formation by pyrolysis of methane or other hydrocarbon gas feedstocks or by steam methane reforming of methane or other hydrocarbon gas feedstocks; and
analyzing carbon dioxide to determine the source of carbon dioxide or natural gas.
4. A method for analyzing an isotopic composition, the method comprising:
analyzing hydrogen or carbon dioxide to assess or determine the proportion of hydrogen or carbon dioxide derived from at least one of geologic hydrogen, coal, steam methane reformation, pyrolysis, electrolysis, or other sources;

analyzing hydrogen or carbon dioxide to quantify the proportion of hydrogen or carbon dioxide derived from at least one of geologic hydrogen, coal, steam methane reformation, pyrolysis, electrolysis, or other sources;

validating and certifying the proportion of hydrogen derived from geologic hydrogen, coal, steam methane reformation, pyrolysis, electrolysis, or other no-carbon, low-carbon, or high-carbon source;

qualifying the hydrogen for the US IRS 45X production tax credit and various Low Carbon Fuel Standards, or other existing or future hydrogen tax credit, incentive, or subsidy programs; and

validating and certifying the proportion of carbon dioxide stored in a subsurface reservoir and the form of the storage including pore space or mineralization.

5. A method for determining a source of hydrogen or carbon dioxide in natural gases, the method comprising:

evaluating fluid samples from at least one of natural gas pipelines, hydrogen pipelines, oil pipelines, water pipelines, railcars, trucks, or industrial facilities.

6. A method for quantifying or apportioning the source of hydrogen in natural gases, comprising:

quantifying or apportioning the source of hydrogen in fluids in at least one of natural gas pipelines, hydrogen pipelines, oil pipelines, water pipelines, railcars, trucks, or industrial facilities.

7. A method for certifying the source of hydrogen in natural gases, the method comprising:

certifying the source of hydrogen in at least one of natural gas pipelines, hydrogen pipelines, oil pipelines, water pipelines, railcars, trucks, and industrial facilities.

8. A method for determining a source of hydrogen or carbon dioxide, the method comprising:

evaluating fluids collected at a surface region including springs and surface seeps or a subsurface reservoir for one or more of:

exploration of oil, natural gas, hydrogen, carbon dioxide, helium, or other gases;

drilling for oil, natural gas, hydrogen, carbon dioxide, helium, or other gases including measurement while drilling, drill-stem test, pressure-volume-temperature (PVT), or other forms of testing;

evaluating fluids collected at the surface or in the subsurface for the purposes of production of oil, natural gas, hydrogen, carbon dioxide, helium, or other gases;

monitoring and evaluation of the storage of oil, natural gas, hydrogen, carbon dioxide, helium, or other gases in subsurface reservoirs or subsurface caverns;

storage of oil, natural gas, hydrogen, carbon dioxide, helium, or other gases in surface tanks, subsurface tanks, or other industrial facilities; and

monitoring and evaluation the presence of leaks or fugitive, stray, or other gas emissions in boreholes, oil, natural gas, or hydrogen wells, pipelines, water wells, surface seeps, springs, or other storage facilities.

9. A method for analyzing the concentration of helium and other noble gases including neon, argon, krypton, xenon, or radon elemental and isotopic concentrations, comprising:

analyzing to determine the residence time of hydrogen in at least one of subsurface fluids, water, carbon dioxide or other subsurface fluids; and

analyzing the timing of recrystallization of magnetite, ilmenite, hematite, other iron-containing minerals, or other mineral forms such as magnesite and carbonates to derive the timing of hydrogen generation in the subsurface using cores, cuttings, outcrop, or other rock samples.

10. A method for determining the residence time of hydrogen or carbon dioxide, the method comprising:

analyzing fluids collected at a surface region or from the subsurface for the purposes of exploration, drilling, production, monitoring of oil, natural gas, hydrogen, or carbon dioxide;

analyzing fluids collected at the surface or from the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, or hydrogen in subsurface reservoirs, subsurface caverns, surface tanks, subsurface tanks, or other industrial facilities;

analyzing fluids collected at the surface or from the subsurface for the purposes of monitoring and evaluation of the presence of leaks or fugitive, stray, or other gas emissions in

boreholes, oil, natural gas, or hydrogen wells, pipelines, water wells, surface seeps, springs, or other storage facilities; and

analyzing cores, cuttings, outcrop, or other rock samples to measure the U, Th, K, and mineral composition and crustal noble gas content in magnetite, ilmenite, hematite, other iron-containing minerals, or other mineral forms such as magnesite and carbonates to derive the timing of hydrogen generation in the subsurface.

11. A method for analyzing the mass of water, the molecular composition of fluids including hydrogen and other molecular (H_2 , N_2 , NH_3 , CO , CO_2) or elemental (noble gases: helium, neon, argon, krypton, xenon, radon) gases, and isotopes of gases (e.g., δ^2H-H_2 , δ^2H-CH_4 , $\delta^{13}C-CH_4$, $\delta^2H-C_2H_6$, $\delta^{13}C-C_2H_6$, $\delta^{13}C-CO_2$, $\delta^{15}N-N_2$, ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar , ^{40}Ar , or other noble gases and their derivative isotopic ratios), water (δ^2H-H_2O , $\delta^{18}O-H_2O$), or other dissolved constituents ($\delta^{13}C-DIC$), the method comprising:

determining the gas saturation of hydrogen, methane or other natural gases, or carbon dioxide in subsurface fluids;

determining the gas to water ratio of hydrogen, methane or other natural gases, or carbon dioxide in subsurface fluids;

determining the gas to water ratio to inform reservoir modelling calculations; and

determining qualification for the US IRS 45Q tax credit or other carbon management programs.

12. A method comprising determining the gas saturation and gas to water ratio with respect to hydrogen, methane or other natural gases, or carbon dioxide in:

a. fluids collected at the surface (e.g., springs, surface seeps) or from the subsurface for the purposes of exploration of oil, natural gas, carbon dioxide, hydrogen, or other gases;

b. fluids collected at the surface (e.g., springs, surface seeps) or from the subsurface for the purposes of drilling (e.g., measurement while drilling, drill-stem test) for oil, natural gas, carbon dioxide, hydrogen, or other gases;

c. fluids collected at the surface (e.g., springs, surface seeps) or from the subsurface for the purposes of production of oil, natural gas, carbon dioxide, hydrogen, or other gases;

d. fluids collected at the surface (e.g., springs, surface seeps) or from the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, hydrogen, or other gases in subsurface reservoirs;

e. fluids collected at the surface (e.g., springs, surface seeps) or from the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, hydrogen, or other gases in subsurface caverns;

f. fluids collected at the surface (e.g., springs, surface seeps) or the subsurface for the purposes of monitoring and evaluation of the storage of oil, natural gas, carbon dioxide, hydrogen, or other gases in surface tanks, subsurface tanks, or other industrial facilities; and

g. fluids collected at the surface (e.g., springs, surface seeps) or from the subsurface for the purposes of monitoring and evaluation the presence of leaks or fugitive, stray, or other gas emissions of gases, including carbon dioxide or hydrogen, in boreholes, oil, natural gas, or hydrogen wells, pipelines, water wells, surface seeps, springs, or other storage facilities.

13. Any of the methods disclosed herein.

14. Any of the methods of disclosed herein for determining a molecular composition of fluids including hydrogen and other molecular gases (H_2 , N_2 , NH_3 , CO , CO_2), elemental gases (noble gases: He , Ne , Ar , Kr , Xe) and isotopes of gases (e.g., δ^2H-H_2 , δ^2H-CH_4 , $\delta^{13}C-CH_4$, $\delta^{13}C-CO_2$, $\delta^{15}N-N_2$, ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar , ^{40}Ar , and their derivative isotopic ratios), water (δ^2H-H_2O , $\delta^{18}O-H_2O$), or other dissolved constituents ($\delta^{13}C-DIC$).

15. The method of claim 14 further comprising using the determined molecular composition to:

determine a proportion of hydrogen, methane or other natural gases, or carbon dioxide derived from sources including geologic hydrogen, coal, steam methane reformation, pyrolysis, and electrolysis;

quantify a proportion of hydrogen, methane or other natural gases, or carbon dioxide derived from the sources;

validate and certifying the proportion of hydrogen derived from the sources;

determine the source of hydrogen or natural gas;

determine the feedstock for hydrogen formation by electrolysis of water; or

determine the feedstock for hydrogen formation by pyrolysis of methane other hydrocarbon gas feedstocks or by steam methane reforming of methane other hydrocarbon gas feedstocks.

16. A method for locating a fluid storage or production site, the method comprising:
obtaining information regarding one or more of,

a molecular composition of a fluid including one or more of hydrogen, methane or other natural gases, or carbon dioxide;

a gas saturation and gas to water ratio with respect to hydrogen, methane or other natural gases, or carbon dioxide;

residence time of hydrogen or carbon dioxide in the fluid;

mass of water;

a concentration of helium and other noble gases and isotopic concentrations of the helium or other noble gases;

a source of hydrogen, carbon dioxide, or natural gas;

quantifying or apportioning the source of hydrogen in natural gases;

certifying the source of hydrogen in natural gases; and

analyzing an isotopic composition of the fluid;

providing the information to an exploration planner; and

one or more of planning a well, planning a field, or producing hydrogen with the information.

17. The method of claim 16, wherein the exploration planner includes one or more of a driller, an engineering firm, or a natural resources exploration company.

18. The method of claim 16, wherein providing the information to an exploration planner includes transferring electronic files including the information to the exploration planner.

19. The method of claim 16, wherein the fluid includes one or more of water, hydrogen, methane or other natural gases, carbon dioxide, or noble gas(es) obtained from a subsurface formation.

20. A system for determining information including one or more characteristics of water, hydrogen, methane or other natural gases, carbon dioxide, or noble gases, the system comprising:

chemical analysis equipment configured to determine the information including one or more of,

a molecular composition of a fluid including one or more of hydrogen, methane or other natural gases, or carbon dioxide;

a gas saturation and gas to water ratio with respect to hydrogen, methane or other natural gases, or carbon dioxide;

residence time of hydrogen or carbon dioxide in the fluid;
mass of water;
a concentration of helium and other noble gases and isotopic concentrations of the helium or other noble gases;
a source of hydrogen, carbon dioxide, or natural gas;
quantifying or apportioning the source of hydrogen in natural gases;
certifying the source of hydrogen in natural gases; and
analyzing an isotopic composition of the fluid;
one or more computing devices operably coupled to the one or more pieces of chemical analysis equipment, the one or more computing devices being configured to electronically communicate the information to a remote computing device.

21. The system of claim 20, further comprising the remote computing device operably coupled to or couplable to the one or more computing devices.

22. The system of claim 20 wherein the chemical analysis equipment includes one or more of an isotope ratio mass spectrometer, a cavity ring down spectroscopy apparatus, a residual gas analyzer, a quadrupole mass spectrometer, a gas chromatograph, a gas chromatograph fitted with a flame ionizing detector and thermal conductivity detector.

22. A system configured to perform any of the methods disclosed herein.

23. Any of the systems disclosed herein.

ABSTRACT

Embodiments are directed to analyzing the molecular composition of hydrogen molecules, hydrocarbon gases, noble gases, carbon dioxide, nitrogen, water, mixtures of natural gases of varying composition, and other fluids and gases to determine a source of hydrogen or natural gases and/or determine and verify sources of carbon dioxide in a subsurface zone; to determine the residence time of hydrogen or natural gases in fluids from a subsurface zone; to determine the gas-water ratio, gas saturation, or water saturation conditions of hydrogen, natural gas, or carbon dioxide in fluids from a subsurface zone.