U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Hydrogen Emissions and Environmental Impacts Workshop

2024 Workshop Summary Report

Hydrogen and Fuel Cell Technologies Office

Office of Energy Efficiency and Renewable Energy

U.S. Department of Energy

September 16-17, 2024

(This page intentionally left blank)

Preface

Prepared by: U.S. Department of Energy/Office of Energy Efficiency and Renewable Energy/Hydrogen and Fuel Cell Technologies Office

Acknowledgments

The Hydrogen Emissions and Environmental Impacts Workshop was organized by the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy, along with the European Commission Joint Research Centre.

The following people and organizations are acknowledged for their contributions to the workshop and in the preparation of this report:

- The European Commission Joint Research Centre (Beatriz Acosta Iborra, Alessandro Arrigoni, and Laura Bravo Diaz) for their input in conceiving and organizing the workshop, as well as additional contribution and feedback during the revisions of this report.

- The University of California, Irvine for co-sponsoring the workshop.

- The following speakers and organizations that they represent for their contributions to the workshop, many of whom also provided valuable feedback in revision of this report:

  - Ramon Alvarez, Environmental Defense Fund (EDF)
  - Kandilarya Barakat, U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration
  - Matteo Bertagni, Politecnico di Torino
  - William Buttner, National Renewable Energy Laboratory (NREL)
  - Daniel Cherney, ExxonMobil Technology & Engineering
  - Amgad Elgowainy, Argonne National Laboratory (ANL)
  - Lee Gardner, Canadian Nuclear Laboratories (CNL)
  - Cullen Hall, GenH2
  - Didier Hauglustaine, Laboratory for Sciences of Climate and Environment (LSCE)
  - William Hoagland, Element One, Inc.
  - Hendrik Louw, Republic of South Africa
  - John Patterson, University of California, Irvine
  - Fabien Paulot, National Oceanic and Atmospheric Administration (NOAA)
  - Barry Prince, Fabrum
  - Linta Reji, University of Chicago
  - Matteo Robino, Snam
  - Munjal Shah, National Renewable Energy Laboratory (NREL)
  - David Stevenson, University of Edinburgh
  - Rossella Urgnani, Warrant Hub
  - Ruishu Wright, National Energy Technology Laboratory (NETL)

The organizers would like to thank all the meeting participants for providing meaningful feedback and engaging in valuable discussions. The organizers would also like to thank the moderators, scribes, and facilitators for their assistance during the workshop: Beatriz Acosta Iborra, Marc Melaina, Mark Richards, Ethan Hecht, Jamie Holladay, Hendrik Louw, Christine Watson, Haboon Osmond, Zakaria Hsain, Miranda Helena Miranda, and John Patterson.

The organizers would additionally like to thank the International Partnership for Hydrogen and Fuel Cells in the Economy's Hydrogen Emissions Impacts Analysis Task Force members for their critical review of this report.

Nomenclature or List of Acronyms

ANL	Argonne National Laboratory
ARIES	Advanced Research on Integrated Energy Systems
ARPA-E	Advanced Research Projects Agency-Energy
BOG	Boil-off gas
BOGM	Boil-off gas management
BTU	British Thermal Units
CCS	Carbon capture and storage
CFD	Computational Fluid Dynamics
CH_4	Methane
CNL	Canadian Nuclear Laboratories
CI	Climate intensity
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EDF	Environmental Defense Fund
EC	European Commission
EERE	Office of Energy Efficiency and Renewable Energy
EU	European Union
FCEVs	Fuel cell electric vehicles
GHG	Greenhouse gas
GML	NOAA Global Monitoring Laboratory
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GWP	Global warming potential
H_2	Hydrogen gas
H_2O	Water

HFTO	Hydrogen and Fuel Cell Technologies Office
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
JRC	Joint Research Centre
kg	kilogram
LCA	Life-cycle assessment
LH_2	Liquid hydrogen
LSCE	Laboratory for Sciences of Climate and Environment
m	meter
MT	metric ton
N_2	Nitrogen gas
NETL	National Energy Technology Laboratory
NOAA	National Oceanic and Atmospheric Administration
NO_x	Mono-nitrogen oxides
NREL	National Renewable Energy Laboratory
-OH	Hydroxy or Hydroxyl group
O_2	Oxygen gas
O_3	Ozone
PHMSA	U.S DOT Pipeline and Hazardous Materials Safety Administration
ppb	parts per billion
ppm	parts per million
R&D	Research and development
ROM	Reduced order models
SAW	Surface acoustic wave sensor
SMR	Steam methane reforming
TF	Task Force
UCI	University of California, Irvine
WP	Work packages

Executive Summary

On September 16-17, 2024, the Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE) at the U.S. Department of Energy (DOE), in collaboration with the European Commission (EC), held an in-person workshop at McDonnel Douglas Engineering Auditorium in the University of California, Irvine (UCI). The workshop objectives included the following: coordinate efforts among international governments, industry, and environmental stakeholders to understand and mitigate potential atmospheric impacts of hydrogen releases; share the latest advances in climate science, modeling and detection, mitigation, and measurement technologies; and identify remaining R&D gaps and priorities for next steps.

Representatives from DOE-HFTO, the EC, and the Republic of South Africa kicked off the workshop by providing an overview of research being funded in coordination with IPHE to advance understanding of hydrogen emissions and atmospheric impacts, and to develop detection and measurement technologies suitable for low-level hydrogen releases. Subsequently, UCI, the National Oceanic and Atmospheric Administration (NOAA), Snam, Politecnico di Torni, and the University of Chicago gave presentations describing current estimates of the global warming potential (GWP) of hydrogen. Key areas of uncertainty impacting hydrogen's GWP estimates include the mechanisms of soil bacterial uptake of hydrogen, and sensitivity of soil uptake to changes in moisture and temperature.

Presenters from the University of Edinburgh, Laboratory for Sciences of Climate and Environment (LSCE), Environmental Defense Fund (EDF), and Argonne National Laboratory (ANL) presented analyses of the net implications of hydrogen emissions in future scenarios. Environmental impacts were shown to be highly dependent on the method of hydrogen production and delivery, and on the timescale of a given analysis (e.g. GWP-20 vs. GWP-100). Economic impacts of hydrogen losses, particularly in the case of liquefaction, were identified as being strong drivers to mitigate losses in a mature economy. The first day ended with a breakout session consisting of four moderated groups discussing next steps, gaps, and future R&D work needed in the area of hydrogen's GWP modeling.

The second day of the workshop continued discussions on R&D in hydrogen emissions with a comprehensive presentation from ExxonMobil Technology & Engineering on the role of hydrogen in decarbonization, air quality, energy security, domestic manufacturing and domestic resource development. The presenter additionally identified key requirements to assess hydrogen emissions across the entire value chain, such as robust measurement and detection technologies, improved standardized design, and analytics to locate and quantify emissions sources. Presenters from the National Renewable Energy Laboratory (NREL) and Element One, Inc. followed up with presentations on the latest advances in hydrogen sensor and detection technologies for both indoor and outdoor applications, including hydrogen release and sensor testing capabilities at NREL. The U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) and National Energy Technology Laboratory (NETL) then presented on pipeline-specific R&D currently being funded to address hydrogen releases.

Warrant Hub, NREL, and EDF presented current and planned research projects focused on modeling of hydrogen releases from facilities. Data from these modeling efforts will both help inform both climate models of atmospheric behaviors of hydrogen and help facilities pinpoint the location of potential hydrogen leaks. Since estimates show that a large source of future hydrogen releases may be due to the release of boil-off gas in liquid hydrogen systems, the Canadian Nuclear Laboratories (CNL), Fabrum, and GenH2 presented on reduction and potential elimination of liquid hydrogen boil-off gas through management systems or technologies such as active refrigeration or recombination.

The final breakout session focused on discussions of proposed terminology for categorizing hydrogen emissions, high priority R&D areas for detection and measurement technologies, specific challenges and gaps, and near and long-term next steps.

Key takeaways from the workshop include:

- International collaboration on atmospheric data of hydrogen levels is needed to support climate models, including collaboration with NOAA's Global Monitoring Laboratory for atmospheric data sampling worldwide.
- A data collection method and repository need to be developed for sources of anthropogenic hydrogen emissions.
- More research is needed on uncertainties in the microbial uptake of hydrogen in soil (the largest sink for atmospheric hydrogen): more data on the amount of uptake, the mechanisms of the microbial consumption of hydrogen, and how the uptake of hydrogen and the microbes themselves are impacted by moisture and temperature changes.
- Agreement on a consistent GWP of hydrogen is needed. Estimates from climate models have varied[1], and uncertainties particularly around soil uptake can impact the value.
- Once agreement is attained on the GWP of hydrogen, incorporation of hydrogen's GWP into models that are widely used for life cycle analysis, such as R&D GREET, would improve social cost accounting of hydrogen. Further, development of government policies that incentivize reduction in hydrogen emissions would enable deployment of best practices within industry.
- Consistency is needed on key terminology used within research and analysis (e.g. leak, emissions, etc.). In the time since the workshop, the IPHE's Hydrogen Emissions and Environmental Analysis (HEIA) Task Force (TF) has launched an initiative to develop a common understanding of terminology by reviewing different definitions used by various organizations involving hydrogen emissions and their impact on climate change (such as atmosphere, hydrogen concentration, short-lived climate forcers, fugitive emissions, leak, etc.) The task force expects to publish a public document on commonly-agreed upon terminology in the near-term.
- Monitoring equipment for hydrogen releases, limits of hydrogen detection technologies, and liquid hydrogen boil-off mitigation options are improving, but more R&D is needed to reduce energy and financial cost of detection and mitigation technologies, as well as assess monitoring requirements across the hydrogen value chain (for example, if mitigation options have a high energy cost, the emissions included in supplying additional energy may surpass the smaller impact of hydrogen in the atmosphere).
- Analysis of project siting methods may reduce hydrogen losses (such as co-location of production and end-use.)

This workshop summary report provides additional information on hydrogen emission and environmental impacts from expert presentations and breakout group discussion. This report, the detailed agenda, speaker information, and the presentation materials can be found at: Hydrogen Emissions and Environmental Impacts Workshop | Department of Energy.

[1] Recent estimates for the indirect global warming potential for hydrogen, assuming GWP_{100} metrics, include 5 +/- 1 (Derwent et al, 2020) and 11.6 +/- 2.8 (Sand et al, 2023.)

Table of Contents

List of Tables

1 Presentations

All workshop presentations were split between two days, each day with its own topic. Day 1 focused on hydrogen behavior and climate modeling of atmospheric hydrogen and Day 2 focused on hydrogen detection, mitigation, and measurement technologies.

Table 1. Workshop speakers

Topic Area	Speakers
Welcome & Overview of Workshop Objectives	Christine Watson, U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office
International Activities on Hydrogen Emissions	Beatriz Acosta Iborra, European Commission Joint Research Centre Christine Watson, U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office Hendrik Louw, Republic of South Africa/IPHE
Measurement and Modeling of Atmospheric Hydrogen Levels	John Patterson, University of California, Irvine Fabien Paulot, National Oceanic and Atmospheric Administration
Sources and Sinks of Atmospheric Hydrogen	Matteo Robino, Snam Matteo Bertagni, Politecnico di Torino Linta Reji, University of Chicago
GWP Modeling and Climate Impacts of Increased Hydrogen Production and Use	David Stevenson, University of Edinburgh Didier Hauglustaine, Laboratory for Sciences of Climate and Environment Ramon Alvarez, Environmental Defense Fund Amgad Elgowainy, Argonne National Laboratory
Detection and Quantification Technologies	Daniel Cherney, ExxonMobil Technology & Engineering William Buttner, National Renewable Energy Laboratory William Hoagland, Element One, Inc.
Pipeline Leak Detection	Kandilarya Barakat, U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration Ruishu Wright, National Energy Technology Laboratory
Modeling and Measurement	Rossella Urgnani, Warrant Hub

	Munjal Shah, National Renewable Energy Laboratory Ramon Alvarez, Environmental Defense Fund
Mitigation Technologies	Lee Gardner, Canadian Nuclear Laboratories Barry Prince, Fabrum Cullen Hall, GenH2

The following sections summarize the presentation highlights and breakout sessions. Copies of the speaker presentations can be found on the Workshop Proceedings webpage: Hydrogen Emissions and Environmental Impacts Workshop | Department of Energy. An overview of the workshop speakers and topics is presented in Table 1.

Note that the terminology used in this report (loss, emissions, release, leak, etc.) reflects that used by the individual speakers and may be inconsistent across the presentations. The development of a common set of definitions and terms used to describe hydrogen emissions and environmental impacts was identified through the breakout sessions as a major near-term need, which IPHE plans to address within the coming year.

1.1 Welcome and Overview

The Hydrogen Emissions and Environmental Impacts Workshop began with a welcome and overview of objectives from Christine Watson (U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office [HFTO]), followed by presentations from Beatriz Acosta Iborra (European Commission [EC] Joint Research Centre [JRC]), Christine Watson, and Hendrik Louw (Republic of South Africa/International Partnership for Hydrogen and Fuel Cells in the Economy [IPHE]) on international governmental activities.

Beatriz Acosta Iborra shared an overview of research initiatives at the EC targeting environmental impacts of hydrogen emissions. She started her presentation by sharing a summary report of the 2022 Clean Hydrogen Joint Undertaking Expert Workshop on the Environmental Impacts of Hydrogen, which was co-organized by the EC and the U.S. Department of Energy. The workshop triggered the launch of several activities for research on hydrogen emissions impacts. She then discussed two ongoing Horizon Europe funded projects: 1) HYDrogen economy benefits and Risks: tools development and policies implementation to mitigate possible climAte impacts (HYDRA) and 2) Studying the climate impacts of large-scale hydrogen usage (HYway). She then shared a Clean Hydrogen Partnership project: pre-Normative Research on Hydrogen Releases Assessment (NHyRA) which aims to assess potential hydrogen releases along the entire hydrogen value chain. The JRC recently published Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe, addressing the question, "What is the most environmentally sustainable option of delivering of 1 MT/y of renewable H_2 to a single industrial customer via a direct transport pathway (via ships or pipelines)?" The publication evaluated the climate change potential impact of delivery options and found that options more prone to losses (such as liquid and compressed hydrogen) exhibit the lowest potential global warming impact, therefore more research is needed to reduce these losses. She ended her presentation by highlighting the JRC.C1 High Pressure Gas Testing Facility (GASTEF) in Europe that has capabilities for hydrogen fatigue cycling and permeation testing of pipelines and high pressure components.

Christine Watson provided an overview of U.S. Department of Energy activities addressing hydrogen emissions, starting with the U.S. energy landscape and key goals. The Administration goals include a net-zero emissions economy by 2050 with 50-52% reduction by 2030 and 100% carbon-pollution-free electric sector by 2035. Furthermore, she discussed examples of policies and activities such as the Bipartisan Infrastructure Law and the Inflation Reduction Act. Then, she discussed the U.S. National Clean Hydrogen Strategy and Roadmap. The strategy consists of three parts: 1) target strategic, high-impact end uses, 2) reduce the cost of clean hydrogen, and 3) focus on regional networks. Then, she discussed the HFTO Safety Codes and Standards subprogram, which supports R&D on hydrogen safety technology, such as sensors. To address lack of climate data on hydrogen, HFTO funded NOAA with $2.2 million over three years to develop a more robust understanding of the hydrogen biogeochemical cycle, including its sensitivity to anthropogenic emissions, climate change, and land use. Additionally, HFTO has funded many activities to detect and quantify hydrogen releases (National lab R&D [examples include R&D for Safety, Codes and Standards: Hydrogen Behavior, NREL Hydrogen Sensor Testing Laboratory, Component Failure R&D], $8.6 million in funding opportunities to develop ppb-level sensors (including Sensing Hydrogen Losses at 1 ppb-Level for Hydrogen-Blending Natural Gas Pipelines, Real-Time Ionic Liquid Electrochemical Sensor for Highly Sensitive and Selective Hydrogen Detection and Quantification, The Electrical Hydrogen Sensor Technology with a Sub-Minute Response Time and a Part-per-Billion Detection Limit for Hydrogen Environmental Monitoring), Small Business Innovation Research (SBIR) projects on quantification (Multi-Gap Fabry Perot Fiber Optic Sensor For Real-Time and Cumulative Leak Detection and Quantification and Low Cost Hydrogen Monitor for Continuous Quantification of Facility Emissions), a Technology Commercialization Fund project to develop ppb-level sensors, and a Cooperative Research and Development Agreement (CRADA) between NREL and industry to explore wide area monitoring detection technologies. She then went over the recently announced ARPA-E H2SENSE projects which aim to integrate three major components (sensor, sampling mode, and emissions modeling) for hydrogen emissions detection and quantification. Finally, she presented HFTO activities to address hydrogen losses and recovery along the value chain, including conclusions from a recent workshop on hydrogen infrastructure priorities. She then shared opportunities for involvement; interested parties can participate in HyCReD, apply to the Hydrogen Shot Fellowship, or join the Center for Hydrogen Safety.

Hendrik Louw shared an overview of IPHE. IPHE is a global government-to-government partnership to accelerate hydrogen and fuel cell deployments. Its four practical actions: monitor, enable, provide, and share. He shared the new task force on Hydrogen Environmental Impact Assessment to provide a deeper understanding of hydrogen in the atmosphere and its impact on climate change, and mentioned a recently released IPHE position paper on the topic. He concluded that business-as-usual is not sufficient given energy, climate and societal drivers; it is crucial for governments to facilitate efficient and effective intentional hydrogen markets and to facilitate efficient and effective intentional collaborations and coordination beyond IPHE members.

1.2 Measurement and Modeling of Atmospheric Hydrogen Levels

John Patterson (University of California, Irvine) discussed the reconstruction and interpretation of historical hydrogen levels from measurements in polar ice. He started by discussing the biogeochemical cycle of hydrogen and modern atmospheric hydrogen distribution. Stored ice cores are not able to be used for hydrogen because, unlike most gases, hydrogen can dissolve into and diffuse through the ice matrix. Despite this, he was able to reconstruct the 20th century atmospheric history of hydrogen from firn air measurements, firn being the layer of densifying snow that sits on top of the ice sheet. He demonstrated how firn air measurements relate to atmospheric histories by sharing a simulation of carbon dioxide (CO_2) in firn air at Megadunes. Active research regarding historical 20th century changes in hydrogen biogeochemistry was shared as well. Recently field research involving drilling a new ice core at Summit Station, Greenland occurred during the summer of 2024, and included development of a custom field analytical system and measurement of new ice cores. Main takeaways from his research are that atmospheric H_2 levels over Antarctica increased by ~60% over the 20th century, and levels over Greenland increased by ~30% since 1950; general trends in atmospheric H_2 over the 20th century are explained by changing anthropogenic emissions and increasing production from atmospheric methane (CH_4); reconstructed 20th century H_2 levels show a surprising reversal in the interpolar difference that is difficult to explain by perturbing only one climate budget term; and new measurements of H_2 from a

Greenland ice core show preindustrial levels of 250-300 ppb, in rough agreement with reduced production from CH_4 and no anthropogenic emissions. The reversal in the reconstructed interpolar difference could have important ramifications for the scientific understanding of the cycling of hydrogen in the modern atmosphere. He concluded his presentation by sharing future directions for this research including development of a bipolar record by drilling a new ice core in Antarctica, understanding the biogeochemical implications of the reconstructions, and analyzing measurements of the deuterium content of hydrogen in Greenland firn air for better constraints on biogeochemistry.

Fabien Paulot (National Oceanic and Atmospheric Administration [NOAA]) discussed the observational constraints on the hydrogen budget. He started with an overview of the hydrogen budget and its recent developments. Recent work on NOAA GML H_2 observations has included addressing biases caused by drift in the standard and instrument non-linearity, and NOAA GML flask air H_2 dry air mole fraction for 70 sites (2009-2021) was recently publicly released. He then went through an evaluation of NOAA GFDL chemistry-climate model compared to that of Ehhalt et al. (2009), showing that anthropogenic activities account for ~40% of the overall H_2 source. The BASE model failed to capture an observed increase in H_2 from 2010 to 2019, due to an increase at all sites and the model balancing an increase H_2 from CH_4 with decreasing anthropogenic H_2. Therefore, anthropogenic emissions may not have declined over the last 10 years and updating anthropogenic emissions to 2% (and increasing) may eliminate the model bias.

1.3 Sources and Sinks of Atmospheric Hydrogen

Matteo Robino (Snam) provided an overview of the pre-Normative Research on hydrogen Releases Assessment (NHyRA). The NHyRA project has 15 partners from 9 countries, with a duration of 36 months (January 2024-December 2026), and a budget of 3.5 million euros. NHyRA will focus on the assessment of potential hydrogen releases along the entire hydrogen value chain. As knowledge on the amount of anthropogenic hydrogen in the atmosphere is scarce in literature, it is of utmost importance to improve capabilities to quantify small and large releases and to have validated methodologies and techniques for measuring or calculating releases. Goals of the project include: 1) creation of an inventory for anthropogenic hydrogen releases, 2) development and validation of methodologies for detecting and quantifying hydrogen releases, 3) hydrogen releases quantification and definition scenarios considering different time horizons (e.g., 2030, 2050), and 4) providing recommendations and mitigation strategies to international standard bodies for reducing identified hydrogen releases.

Matteo Bertagni (Politecnico di Torino) discussed global hydrogen cycle dynamics in the energy transition. He gave an overview of the global hydrogen cycle, indirect climate impacts of hydrogen, and the relationship between H_2 and CH_4 budgets. He then discussed the role of bacteria in soil uptake of hydrogen. The first measurement of soil uptake of hydrogen was in the 1970s and the first isolation of high-affinity H_2-oxidizing bacteria was in 2010. Current global calculations of soil uptake of hydrogen have high uncertainties and are poorly parameterized. The goals of this research project are to develop a mechanistic model based on hydroclimatic drivers, assess the crucial role of soil moisture and its temporal fluctuations, and quantify the uptake potential and limitations. Research challenges remain in understanding temporal dynamics and sensitivity to moisture; distribution of rainfall in time and semi-arid regions are potential hotspots but these are challenging to be modeled. The soil sink is critical to mitigate H_2's climatic impacts and hydrology exerts both physical and biological controls on the soil sink, but despite our advancements, there are still significant uncertainties in the soil sink representation, especially in semi-arid regions.

Linta Reji (University of Chicago) further discussed constraining the soil microbial hydrogen sink under moisture variability. She reiterated that soil uptake is the largest sink for atmospheric hydrogen and is also the most uncertain term in the global hydrogen budget. In global budget estimates, soil sinks are typically scaled up to match the magnitude of uncertainty around hydrogen emission sources, rather than calculated based on data. For more precise modeling, more data is needed through observations, characterization of microbes, and characterization of abiotic controls on hydrogen uptake. The relationship between soil moisture and microbial uptake is strongly non-linear, and there are sparse measurements available. In this project, three soil types (sandy loam, silty loam, and loamy sand) were collected from temperate ecosystems, and then used in experiments to determine moisture controls on hydrogen uptake. Results showed that the soil hydrogen sink is highly sensitive to moisture variability, uptake occurs under very dry moisture conditions, and diverse microbes encode high-affinity uptake of hydrogen gases. Ongoing work in this project includes improving H_2 models by focusing on a mechanistic model of soil H_2 uptake and spatial and temporal upscaling.

1.4 GWP Modeling and Climate Impacts of Increased Hydrogen Production and Use

David Stevenson (University of Edinburgh) opened the session on global warming potential (GWP) modeling with a detailed discussion of how hydrogen indirectly impacts Earth's climate. Hydrogen is not a direct greenhouse gas, but it reacts with hydroxyl groups (-OH) leading to increases of tropospheric ozone and stratospheric water vapor. The resulting reduction of OH concentration also lengthens methane's lifetime. By altering atmospheric levels of oxidants, hydrogen in the atmosphere affects aerosol formation and clouds. Quantifying the net climatic impacts of these changes can be done using the GWP climate metric. GWP integrates the impact of an emission on radiative forcing over a specified time horizon. Adding an instantaneous H_2 pulse to a model shows increasing CH_4 over ~3 years, which then decays according to CH_4's perturbation lifetime of ~12 years. Similarly, adding an H_2 pulse increases O_3 which then decays according to H_2's perturbation lifetime of ~2 years. The differences between step change experiments and pulse experiments were discussed. The use of GWP_{100} (100 year time horizon model) of H_2 was discussed, as well as sources of uncertainty in H_2's GWP_{100}: model range from various studies showing GWP_{100} as ~12 ± 6; methodology (pulse vs step changes; transient shapes); ongoing, effective radiative forcing calculations (including cloud adjustments, (the UKESM model suggests this could be a large effect); soil sink; hydrogen's atmospheric lifetime; background composition (different NO_x levels are shown as small effects in UKESM) location of emissions (land vs sea; southern vs northern hemisphere); chemistry (e.g. HCHO chemistry); and aerosol effects. Hydrogen climate impact also depends on production methods, the release rate of hydrogen, and distribution methods. In summary, the climate effect of released hydrogen depends on production, distribution, and end usage, and impacts air quality and stratospheric ozone, and is only partly characterized by the GWP.

Didier Hauglustaine (LSCE) discussed the climate benefit of blue hydrogen. A clear benefit for climate arises from a transition to a hydrogen economy. The European Commission requires that the production of low-carbon hydrogen results in "at least" 70% less greenhouse gas than the liquid fossil fuel benchmark, which means a maximum of 3.38 kg CO_{2e} per kg of hydrogen. Investigating different scenarios of hydrogen production, preliminary results show a renewable hydrogen carbon footprint increasing by a factor of 2-3 depending on the hydrogen leakage rate. For steam methane reforming (SMR), an approximately 3x emissions reduction was estimated to be feasible with SMR with CCS. Pyrolysis was estimated to be capable of a lower carbon footprint when using renewable electricity. Considering these pathways, a clear benefit for climate arises from a transition to a hydrogen economy. For a H_2 leakage rate of 1-3%, the climate benefits of hydrogen use still appear to outweigh climate impacts.

Continuing to build on the importance of hydrogen climate impact assessments, Ramon Alvarez (EDF) discussed maximizing climate benefits of hydrogen systems. He stated that hydrogen's warming potency is stronger than CO_2 per mass, but hydrogen is short-lived. Key sources of uncertainty in the models include the magnitude of the soil sink and changing future OH concentrations driven by other OH-influencing emissions. He then summarized key milestones in the >20 year history of the science concerning H_2's climate implications. Results of a recent study conducted by EDF examined the importance of including overlooked factors in climate impact assessments of the transition from fossil fuel to hydrogen technologies (examining hydrogen and methane losses in particular). Original LCA from the Hydrogen Council shows all hydrogen pathways consistently achieve >75% climate benefits in the long-term. Including the effect of high hydrogen emissions can reduce intended near-term climate benefits by up to 25%. High hydrogen (10%) and methane release rate (2.1%) may lead to an increase in near-term warming in some cases. High hydrogen (10%) and extremely high methane release rates (5.4%) may lead to an increase in near-term warming by up to 50%.

There is an opportunity to ensure investment in hydrogen projects worldwide yields the climate benefits being sought – and avoid unintended climate consequences by accurately accounting for hydrogen's climate impact, keeping hydrogen and methane emissions to a minimum, producing green hydrogen using additional renewable electricity, and deploying high efficiency, permanent carbon capture. He then discussed published estimates of hydrogen currently emitted ranging from < 1% to 20%, from either fugitive emissions (e.g., leakage, permeation, and diffusion) or operational releases (e.g., residual, venting, purging, and boil-off) at facilities producing or using hydrogen. There is currently no empirical data on the extent of hydrogen emissions from existing infrastructure because instrumentation capable of measuring small leaks and site-wide emissions (ppb level) is only now becoming available. He then shared an overview of a collaborative H_2 field campaign involving EDF, several universities, and industry participants to measure H_2 emissions measurement from operating hydrogen infrastructure. Other future steps for EDF include advocating for including the latest science in assessments of clean hydrogen's climate impacts for better decision-making and determining mitigation strategies, working on additional greenhouse gas (GHG) assessments comparing clean hydrogen with fossil fuels and other clean alternatives.

Amgad Elgowainy (Argonne National Laboratory [ANL]) discussed modeling and environmental and economic assessment of the hydrogen value chain. Today, approximately 10 million metric tons of hydrogen are produced in the U.S. annually, mainly from steam methane reforming of natural gas. With DOE support, ANL has been developing the R&D Greenhouse gases, Regulated Emissions, and Energy use in Technologies (R&D GREET) LCA model since 1995 with annual updates and expansions, which is free to download. The R&D GREET's suite of models and tools and its use by DOE were shared. R&D GREET's sustainability metrics include energy use, criteria air pollutants, GHG, and water consumption. R&D GREET covers current and emerging hydrogen technologies and applications. LCA of H_2 production via CH_4 reforming was discussed. ANL evaluated studies of methane leakage of natural gas supply chains for R&D GREET. The LCA of H_2 production via water electrolysis was also shared. The climate intensity (CI) for H_2 production via electrolysis depends on the following three major factors: CI for used electricity, energy intensity of electrolyzer, and credits for byproduct O_2 export if valorized. Hydrogen delivery involves energy intensive processes such as compression, liquefaction, storage, and trucking. The cost of hydrogen delivery and refueling for fuel cell electric vehicles (FCEVs) is strongly driven by onboard storage requirements and the hydrogen supply chain. Liquid hydrogen supplied stations can handle faster fills with lower cost compared to gaseous hydrogen supplied stations. Energy use and CO_2 emissions are critical for environmental sustainability of H_2 liquefaction. Additionally, H_2 liquefaction plants have been recently announced to serve the growing H_2 market, although the process of H_2 liquefaction is energy and cost intensive. Finally, ammonia as a fertilizer, fuel, and H_2 carrier was discussed. The concluding remarks included that hydrogen is very different from natural gas with respect to production volume, most natural gas emissions occur in the field during recovery, gaseous hydrogen delivery losses are unknown but believed to be small, and liquid hydrogen delivery has significant losses in the early market due to boil-off, particularly in scenarios where liquid hydrogen is underutilized. R&D GREET model does not currently include hydrogen losses in estimating greenhouse gas emissions of hydrogen systems, although these losses may be added in future years given better estimates of loss rates and the GWP of hydrogen.

1.5 Detection and Quantification Technologies

On the second day, Daniel Cherney (ExxonMobil Technology & Engineering) opened the workshop with a comprehensive discussion of the role of hydrogen in a net-zero emissions future along with the importance of addressing hydrogen emissions ExxonMobil supports the development of infrastructure design standards and emissions detection technologies; emissions along the value chain are not well quantified, and analytics are needed for locating/sizing an emissions source. Hydrogen is present in the atmosphere at ~550 ppb and has been measured for decades. Hydrogen cannot be detected remotely, unlike CH_4: hydrogen measurements currently require point-wise air samples, and commercial sensors for safety have ~10 ppm minimum detection limit and require analytics for source sizing/locating. Sensing in a manufacturing facility can be done with conventional sensors for safety but ability to do site-level quantification is still lacking. Pipelines can be particularly challenging because of the “sniff, not see” challenge. Technology measurement gaps are driving DOE funding to promote sensor development, but testing will be needed to verify claims of sensitivity and accuracy. ExxonMobil has a new collaboration with the University of Texas - Austin to do quantitative, precisely controlled releases to validate different technologies. R&D opportunities include pushing detection limits to ppb levels, increasing portability and precision (response time and recovery time), minimizing user interaction, addressing interferents, making areal coverage easier & less expensive with lower limit of detection sensors, and advancing modeling/inversions for size & location.

William Buttner (National Renewable Energy Laboratory [NREL]) discussed NREL’s detection and quantitation of hydrogen emissions role and status of detection technology program. The program involves the NREL Sensor Laboratory (hydrogen detection technology development and deployment), component testing and reliability (reliability of hydrogen systems and components), and supporting hydrogen codes and standards. The NREL Hydrogen Safety Research and Development (HSR&D) Program was established to facilitate the safe and efficient utilization of hydrogen. The NREL Component Reliability R&D Program supports hydrogen infrastructure reliability, mitigating the occurrences and impact of component failures. Regarding hydrogen detection, the term “sensor” can have different meanings among stakeholders within the hydrogen community. He explained the differences between a sensing element, a sensor, and a detection apparatus: the practical definition is a hydrogen sensor provides quantitative information the presence and amount of hydrogen; a sensing element is the interaction with stimuli and transduction into electrical signal; and a detection apparatus is the analyzer. He then gave an overview of hydrogen releases, such as operational hydrogen releases and unintended releases (e.g., leaks/out of normal events). Gas sensors/detectors are one of the most common strategies for the direct detection and empirical characterization of hydrogen releases. The NREL Sensor Laboratory has a unique sensor testing and deployment capability with the Safety Sensor Test Apparatus (SSTA) and access to the Advanced Research on Integrated Energy Systems (ARIES) facility. The SSTA enables metrological performance assessment of hydrogen sensors; topical studies/custom applications; supports developers, end-users, and R&D with partners in industry, research institutions, and regulatory groups; and emerging technologies and markets in support of H_2@Scale and the Regional Clean Hydrogen Hubs. ARIES offers on-site hydrogen production and utilization resources, available for H_2 release studies, including as a test bed for sensor deployment and release studies. The Sensor Laboratory has testing capability to validate hydrogen sensors with sub-ppm and detection limits, which provides tools to validate hydrogen behavior models and to quantify hydrogen releases within a facility. He then discussed DOE’s commitment to develop sensors and detection technologies for hydrogen releases. Ultrasonic leak detection for hydrogen and modelling of hydrogen releases profiles were mentioned. Also, strategies for quantifying hydrogen emissions were touched on. Assurances of safety is critical for community acceptance, and he discussed activities to support training of next generation engineers, scientists, and technologists. In summary, hydrogen has a critical role to decarbonize energy and manufacturing industries, hydrogen releases arise from a variety of mechanisms (process, design features, “leaks”) that contribute to total hydrogen releases, detection methodologies will be critical to detect and quantify hydrogen emissions, and DOE is committed to develop the tools to model and mitigate the impact of hydrogen releases.

Continuing the discussion on hydrogen emissions monitoring, William Hoagland (Element One, Inc.) discussed leak detection strategies. Focusing first on hydrogen and then on hydrogen sulfide and other hazardous gases, Element One is a supplier of the next generation of very low-cost gas detectors. He emphasized the importance of hydrogen leak detection due to safety, economics, environmental, and codes. Safety concerns with hydrogen include personal safety, public safety and acceptance, and asset protection. He shared lessons learned from methane: for example, methane leaks made the energy transition much harder and “dirtier” than it needed to be, so as the next energy transition comes, we must ensure hydrogen leaks do not cause similar problems. Current leak detection technologies include sniffers, which are labor intensive and functional for initial leak testing but not sufficient for long-term leak prevention. Soapy water or sniffers are too labor intensive for continual monitoring for loose fittings. Other current leak detection technologies include area monitors, ultrasonic detectors, and flame detectors. Area monitors are currently standard, reasonable for indoor use, and required in most cases, but they regularly fail to detect outdoor leaks and are not able to locate leak points. Ultrasonic detection is improving, but still has challenges such as false positives and missed leaks. Flame detectors have blind spots and false positives as well. He then gave an overview of differences in strategies for indoor and outdoor leak detection, between visual and remote hydrogen leak detection, and sources being intentional/venting vs unintentional leaks. Element One's DetecTape reaction was shown and simple mechanism explained: the closer the sensor is to the leak, the more reliable the response will be. Tape/sensors are exposed to 100% gas concentration regardless of conditions. Widely populating sensors at potential leak points greatly reduces the chance that hydrogen will escape to the atmosphere without first passing over a sensor. The presentation ended by emphasizing the need for successful emissions reduction through solutions that are low cost, easily adaptable for various applications, complementary to other proposed solutions, and designed with industry in mind.

1.6 Pipeline Leak Detection

Kandilarya Barakat (U.S. Department of Transportation, Pipeline and Hazardous and Materials Safety Administration [PHMSA]) opened a special session looking at pipeline leak detection in particular. PHMSA's R&D mission is to sponsor research and development projects focused on providing near-term solutions for the nation's pipeline transportation system that will improve safety, reduce environmental impact, and enhance reliability. The R&D focus areas are liquefied natural gas safety, underground natural gas storage safety, pipeline anomaly detection/characterization, pipeline leak detection, pipeline threat prevention, repair/rehabilitation, design and materials, and alternative fuels research to address climate change. Regarding ongoing hydrogen pipeline research, there are 11 active projects totaling \$10.6 million in PHMSA funding and \$2.5 million in cost sharing. As for ongoing carbon dioxide pipeline research, there are two active projects totaling \$1.5 million in PHMSA funding + \$380K in cost sharing. She then discussed the Pipeline Safety 2023 R&D Forum. The purpose of the two-day R&D Forum was for public, government, and industry pipeline stakeholders to identify technology and knowledge gaps within certain topic areas. The Forum identified five gaps for CO_2: CO_2 specification, equation of state refinement for CO_2 pipelines, refining fracture control models for CO_2 pipelines, validating and applying dispersion modeling for CO_2 releases, and non-metallic materials compatibility for CO_2 service. The four identified gaps for hydrogen were coating and liners development, updating and validating welding standards of hydrogen transmission and distribution lines, evaluating of existing pipeline repair and maintenance technologies for hydrogen and hydrogen-natural gas blends, and recommended guidance for engineering assessment for hydrogen pipelines. Various research announcements and current and future planning initiatives were shared. The next R&D Forum is planned for Fall 2025.

Ruishu Wright (National Energy Technology Laboratory [NETL]) continued the discussion on pipeline leak detection by discussing advanced sensors for real-time pipeline monitoring. She touched on several state-of-the-art hydrogen sensors and each sensor's physical changes, advantages, and disadvantages. Three synergistic sensor platforms (distribution optical fiber sensors, passive wireless surface acoustic wave (SAW) sensors, and advanced electrochemical sensors) are being developed at NETL with complementary cost, performance, and geospatial characteristics are being developed with an emphasis on pipeline integrity and gas leak monitoring. She discussed optical fiber sensors for pipeline and subsurface infrastructure monitoring, along with distributed optical fiber interrogator development. Multiple distributed optical fiber sensing platforms have been developed to enable structural health monitoring of pipeline and other infrastructure. She also discussed distributed temperature and strain sensing, which measures strain and temperature along the pipeline in a spatially distributed manning using one single optical fiber. Distributed acoustic sensing and ultra-sensitive acoustic sensor were touched on too. Spatially distributed acoustic vibrations are measured along the pipeline in kilometer-range. She shared fiber optic acoustic sensing results of flow rate, leak detection, and third-party intrusion detection. Furthermore, AI-enhanced distributed optical fiber sensor network was explained and how fiber optic technology integrated with advanced analytics. including pattern and feature recognition can convert large data sets to actionable information. Other topics were discussed such as corrosion sensing, early on-set detection, optical fiber methane sensing, and optical fiber hydrogen selective sensors. Other technologies discussed included: passive wireless SAW sensors and SAW hydrogen sensors for high temperatures, conducting oxide coated SAW sensors for hydrogen sensing at high temperatures, advanced electrochemical sensor for water content and corrosion rate monitoring, electrochemical hydrogen permeation sensors, and fast Raman gas analyzers for real-time gas analysis of H_2, N_2, and O_2.The presentation ended by summarizing the need to monitor low-concentration CH_4 and H_2 leaks in real time to mitigate greenhouse gas emissions and ensure safe operations using the flammable gases. Quantification of gas emissions from pipelines and oil and gas infrastructure is needed for evaluation of global warming impacts. Multiple complementary sensor technologies developed at NETL can monitor pipeline gas leaks to build an in-situ, multi-parameter, distributed, and cost-effective sensor network. A wide range of sensing materials are being developed to achieve high sensitivity, selectivity, and fast response, including metal-organic frameworks, polymers, and nanocomposite. Predictive and early detection of pipeline structural and equipment failures can inform timely maintenance and mitigate risks and gas emissions, and artificial intelligence-enhanced sensor network with ubiquitously embedded sensors will ultimately achieve desired visibility across the energy infrastructure.

1.7 Modeling and Measurement

Rossella Urgnani (Warrant Hub) gave an overview of the EU-funded HYDRA project “Hydrogen Economy Benefits and Risks: Tools Development and Policies Implementation to Mitigate Possible Climate Impacts” (GA number 101137758), coordinated by Isella Vicini founder and CEO of beWarrant. beWarrant is a Belgian consultancy company offering a methodological and strategic approach for the successful implementation of EU-funded European research and innovation projects. Besides beWarrant, HYDRA foresees the participation of Warrant Hub (beWarrant Italian sister company), CARTIF, AUTOMA, the Italian National Research Council, Politecnico di Torino, CERTH, Lancaster University, and Universidad de Valladolid. The HYDRA project is dedicated to examining the implications of widespread hydrogen adaption as a carbon-free energy source. It aims to assess climate and environmental impacts associated with large-scale hydrogen deployment, utilizing market analysis, atmospheric modeling, and the development of a leakage monitoring tool. The overarching goal is to inform policymakers and stakeholders about the long-term implications of hydrogen adoption while contributing new scientific knowledge to the research community and promoting awareness of the need for sustainable energy vectors. HYDRA’s objectives are the following: analyze hydrogen technologies diffusions, develop improved monitoring tools for detecting hydrogen leakages, study the impacts of large-scale deployment of hydrogen technologies in the mid-to-long term, assess the socio-economic and environmental effects on the energy sectors resulting from the penetration of hydrogen, develop policy briefs and mitigation guidelines for the sustainable development of the hydrogen economy, promote networking, and communicate the project results to stakeholders. HYDRA’s structure involves six work packages (WPs): project management (WP1); state-of-the-art knowledge of hydrogen polices, market analysis, and emissions estimation (WP2); hydrogen leakage monitoring system design, implementation, and validation (WP3); scenarios of a future hydrogen economy (WP4); hydrogen economy benefits and risks, mitigation strategies, and guidelines for policymaking (WP5); dissemination, communication, and exploration (WP6). HYDRA’s expected impacts are providing energy, socio-economic, and emissions scenarios; assessing the climatic impacts of the hydrogen economy, developing a monitoring system to detect and prevent hydrogen leakages to increase safety of hydrogen technologies, updating the LCA methodology to take into account potential environmental impacts of hydrogen technologies; and assessing risks and benefits of a large-scale hydrogen economy.

Mungal Shah (NREL) discussed modeling of hydrogen dispersion. Monitoring for safety purposes focuses on smaller scales, economic impacts, and local regulations. Monitoring for environmental purposes focuses on larger scales, global warming impacts, and broad environmental regulations. Sensing and monitoring technologies used in production, storage, transportation, and end use cases include mass spectrometry, thermal conductivity, electrical conductivity, metal oxide sensors, etc. He then discussed hydrogen dispersion modeling, which includes weather data, sensor related data, computational fluid dynamics (CFD) data, and site-specific data. There are several ongoing efforts for small scale monitoring and large-scale monitoring, including hydrogen dispersion modeling at NREL ARIES where controlled release scenarios can be performed. He then discussed stages of hydrogen leak modeling and the wind-dependent nature of hydrogen dispersion. Future work and planned activities include Reynolds-averaged Navier–Stokes based CFD simulations, high fidelity simulations in OpenFOAM, exploration of reduced order models (ROM) for >100m for large scale dispersion, development of ARIES CFD/ROM based leak source predictor models, development of ARIES as a testbed for hydrogen sensor testing and validation, and building out of dataset/digital twins to benchmark other academic and partner institutions for hydrogen dispersion.

Ramon Alvarez (EDF) discussed quantifying hydrogen emissions in the context of the collaborative field measurement campaign that EDF is organizing with academic researchers and industry (introduced in Day 1). The campaign seeks to quantify hydrogen emissions from existing facilities involving production, conversion and storage, distribution, and end uses of hydrogen. It will be divided into two major studies, one for production facilities, transfer and industrial uses in North America and Europe, and a second focused on fueling stations and hydrogen vehicles. The campaign is utilizing new fast-response and high-sensitivity technology capable of determining site-level emissions. The field-deployable hydrogen quantification system relies on chemical oxidation of hydrogen to water to quantify changes in ambient hydrogen concentrations. Using these measurements, H_2 emissions from a facility can be estimated using tracer releases or plume inversion methods. He shared a demonstration of the planned quantification methods at Colorado State University and a sample dataset from a prior study of methane emissions from midstream natural gas facilities. He then shared results from using both tracer release and plume inversion to quantify H_2 emissions. Finally, he described planned methods for direct measurement of hydrogen emissions from fueling stations and vehicles.

1.8 Mitigation Technologies

Lee Gardner (Canadian Nuclear Laboratories [CNL]) discussed hydrogen recombiners and hydrogen emissions reduction. He gave an overview of CNL and Atomic Energy of Canada Limited. He then shared the hydrogen technologies branch of CNL, which involves systems, infrastructure, and technology assessments; hydrogen-based clean fuels production technologies; safety fundamentals, behaviors, and application; and materials interaction and storage technologies. He then gave an overview of applications of hydrogen recombiners: providing a complementary and alternative hydrogen removal solution for ventilation or flaring, reducing hydrogen emissions, using the heat of reaction from hydrogen and O_2, and converting H_2 to H_2O. CNL developed wetproof catalyst materials used in several hydrogen recombiner technologies, such as passive and active and trickle-bed recombiners. He discussed in-depth the features of hydrogen recombiner catalysts, such as low temperature and low hydrogen concentrations required for start-up, suitability for use in high humidity, high temperatures, and radiation environments, recombination of other combustible gases, but with the limitations of hydrogen being a potential ignition source and the catalysts being susceptible to poisoning by volatile organic compounds and other chemicals. There are four types of test facilities and models available for hydrogen recombination: hydrogen safety test facility (pressure vessel to study flammability limits, combustion behavior, and catalyst performance), recombiner test channel (testing to simulate passive recombiner operation, ventilation duct operation, an active recombiners), active hydrogen recombiner (forced flow hydrogen recombiner testing), and CFD passive recombiner model (modelling in COMSOL). The next steps for use of hydrogen recombiners for hydrogen mitigation include exploration of the use of active recombiners in liquid hydrogen boil-off, investigation of hydrogen recombiner catalyst activity at low hydrogen concentrations, investigation of active recombiners integrated in ventilation systems, and demonstrations with partners toward the use hydrogen recombiners for non-nuclear applications (hydrogen emission reduction, low level continuous hydrogen release).

Barry Prince (Fabrum) discussed liquid hydrogen boil-off gas (BOG) management systems. He gave an overview of Fabrum and its activities related to cryogenics, hydrogen refueling stations, and composite storage, including Fabrum's proprietary technology for liquid hydrogen, including pulse tube cryocoolers such as PTC330 and PTC1000He then discussed the importance of boil off gas management (BOGM) for hydrogen. BOGM is essential for both economic and environmental reasons. Losses from cryogenic hydrogen tanks are greater than what might be expected from liquid nitrogen or liquid natural gas due to the low density of hydrogen. He explained various hydrogen BOGMs such as pressure transfer, gravity transfer, pump transfer, no transfer, and liquefaction on site. He then discussed Fabrum's BOGM system solution, which can remove ~500W of heat at 25K and reliquefy 100 kg of liquid hydrogen (LH_2) per day at saturation or sub-cool storage causing a reduction in pressure. It reduces venting losses by 100 kg/day at 15kWH/kg. Fabrum's BOGM system is packaged in a 20' shipping container, retrofitted to existing storage and simply needs offtake and return ports, and a modular scalable system. Each unit saves 36,500 kg LH_2 per annum and payback is less than one year per unit. He concluded by stating that BOGM systems will be critical for an economically and environmentally viable LH_2 supply chain. One of the more challenging areas to be addressed is the boil off generated during LH_2 transfers between storage vessels, and Fabrum's BOGM systems based on their proprietary cryocooler technology can offer an attractive means for addressing BOG.

Cullen Hall (GenH2) discussed hydrogen loss mitigation with active refrigeration. He started his presentation by listing the advantages of liquid hydrogen, covering aspects like safety, value and control, transport liquid hydrogen to gaseous hydrogen ratio, and increased energy storage capacity with dramatically less footprint and weight. He then discussed the challenges with liquid hydrogen, such as normal evaporation rate, compression, filling and dispensing losses, and super-saturated liquid. For on-road tanker transfer and storage for hydrogen refueling stations, existing liquid hydrogen methods estimate 13 - 20% transfer loss (tanker transfer to tank), ~1% storage loss daily, ~10% transfer loss from tank to dispensing interface, making the total operational losses from 16 - 31% for vehicle filling processes. He then went through a cost benefit analysis based on transit buses. He finished his presentation by talking about GenH2's cryogenic controlled storage, inspired by NASA Integrated Refrigeration and Storage (IRaS), that has capability for 0% transfer loss from tanker to tank,0% daily storage loss with active refrigeration, and a 0% transfer loss to dispensing interface. He then shared photos and results from NASA's Cryogenics Test Laboratory at Kennedy Space Center where NASA's IRaS system is now in service, demonstrating that controlled storage can enable zero-loss tanker offload.

2 Breakout Sessions

On both days, attendees were divided into four groups for parallel breakout session discussions following the speaker presentations. On Day One, the breakout session focused on hydrogen behavior and climate science. On Day Two, the breakout session focused on detection, mitigation, and measurement technologies. Both breakout sessions had assigned discussion questions. Participants wrote ideas on large flip-pad notes, and then voted using sticky dots on which ideas they thought were the highest priorities.

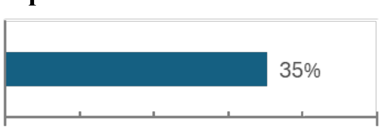
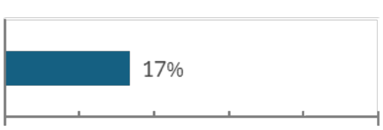
2.1 Day 1 Breakout Sessions

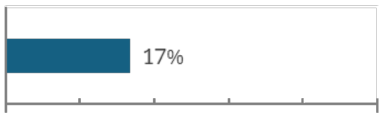
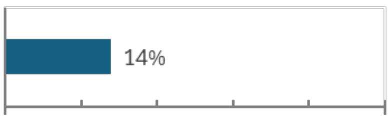
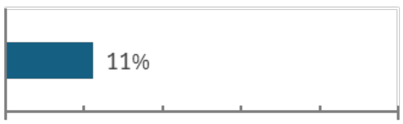
Discussion questions on Day 1 focused on hydrogen behavior and climate science:

- What are the most important opportunities for model development collaboration or data sharing that should be pursued in the near-term? What major gaps, if any, exist within current hydrogen GWP modeling frameworks?
    - What specific future R&D work needs to be done to address uncertainties? Who should do it, and what should be the role of industry, government, and community/environmental groups?
- How can GWP models be used to inform decision-makers involved in addressing technical challenges or policy mechanisms? What additional capabilities are needed to better inform either technical requirements or policy mechanisms?

Results of the breakout session voting, including percent of votes for cards receiving two or more votes are tabulated below. The most-voted priorities included improvements to how data is collected through the development of a new data repository with a focus on the largest sources of anthropogenic emissions, enhancing soil science and modeling with R&D on how soil conditions (temperature and moisture) affect hydrogen uptake, improvement of climate and LCA models to inform decision-makers, and improved sharing and collection of data.

Table 2. Results of Day 1 Breakout Session, including percent of votes for cards receiving 2 or more votes.

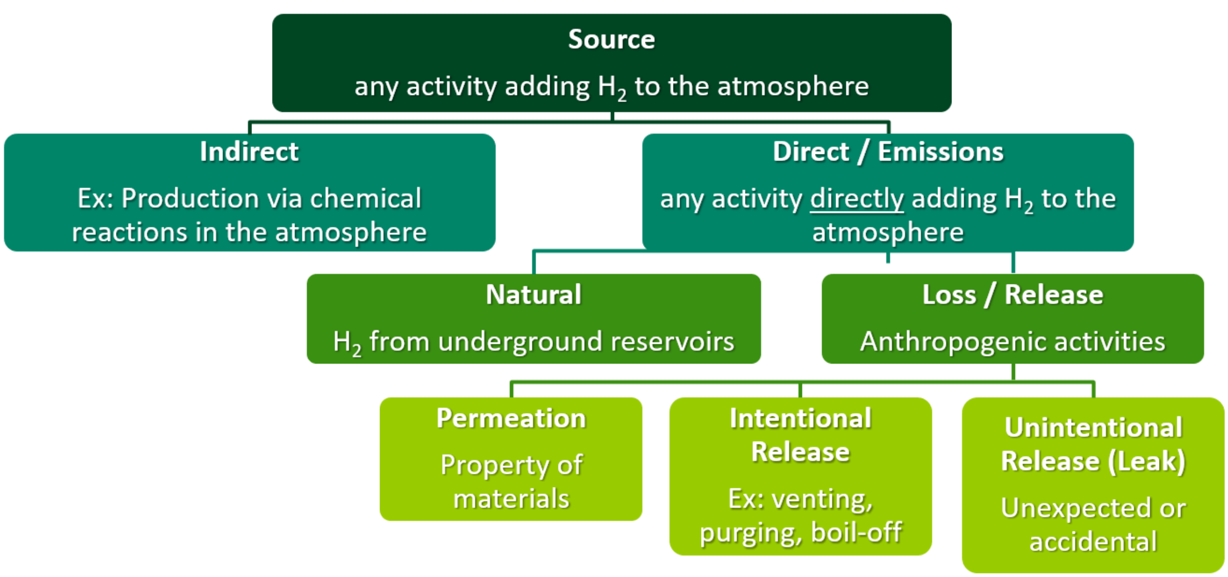
Improve how data is collected  	• Data repository that is streamlined, public, transparent, and tailored to particular groups (18%) • Repository that is private, anonymous, and not subject to U.S. Freedom of Information Act (FOIA) requirements (11%) • Include mechanisms to incentivize industrial collaboration, such as policies, cost-share reporting waivers, etc. (6%)
Prioritizing which data are collected  	• Focus on largest sources of anthropogenic emissions (8%) • Explore new metrics that account for the low molecular weight of H_2 (6%) • Expand global monitoring to include isotopes of hydrogen (2%)

Enhancing soil science and modeling 	• Increased data on how soil conditions (temperature, moisture) affect H_2 uptake (8%) • Improve land surface models based on additional soil microbe data (8%) • Need global network of soil microbe data (2%)
Better models to inform decision-makers 	• Climate and LCA models should be the basis of funding, credits, and social cost accounting (6%) • Improve incorporation of GWP results into formal models, including R&D GREET (5%) • Exploration of additional H_2 production and decarbonization pathways (4%)
Improve collaboration on data sharing 	• Improved sharing and collection of data (9%) • Better sharing and collaboration on H_2 emission sources (2%)
Additional priorities 	• Establish global history of atmospheric H_2 on millennial time scales (3%) • Lack of industrial collaboration and research (2%) • Model H_2 influence on warming with emissions as driver instead of concentrations (2%)

2.2 Day 2 Breakout Sessions

The theme of the second breakout session was detection, mitigation, and measurement technologies. The discussion questions are listed below.

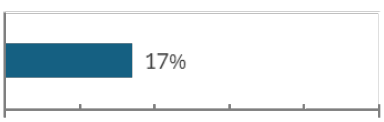
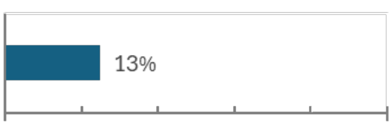
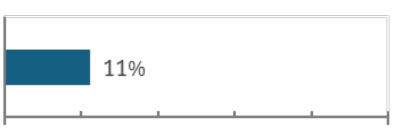
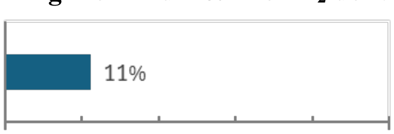
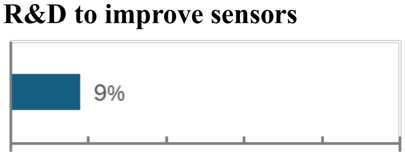
- The below terminology was presented based on the definitions proposed in the 2022 JRC Workshop Report. Do you have any feedback or comments on the proposed terminology and definitions for leakage, emissions, releases, etc.?

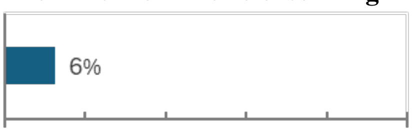
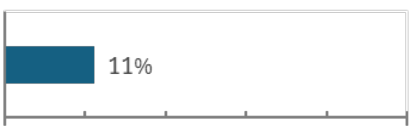


- What are two highest priority gaps in R&D that were identified today? What future work needs to be done to address uncertainties and remaining technology gaps?
- What are the biggest challenges with monitoring emission facility-wide? What are incremental steps that can be made to address these challenges?
- What are the major low-hanging fruit opportunities to manage mitigation efforts in the near-term? How and how quickly can these be addressed in the near-term?
- Since boil-off is by far the largest source of anthropogenic hydrogen released into the atmosphere, how soon are boil-off mitigation or recovery technologies needed?

Results of the breakout session voting, including percent of votes for cards receiving 2 or more votes are tabulated below. The most-voted priorities included the need to assess monitoring requirements based on technology available and comparison of energy and financial costs of mitigation options, evaluations of different sensors and mitigation technologies for use across the hydrogen value chain, new large-scale projects to define an emissions baseline to inform future policy decisions, R&D on loss mitigation in hydrogen delivery scenarios, advances in sensor and detection R&D, identification of process and siting methods to reduce hydrogen losses, R&D on wide area monitoring and modeling, and mitigation of methane releases.

Table 3. Results of Day 2 Breakout Session, including percent of votes for cards receiving 2 or more votes.

Assessing monitoring requirements 	• Quantify emissions with high reliability and with as few sensors as possible (8%) • Comprehensive comparison (of mitigation options) of financial and energy intensity (6%) • LCA on mitigation methods to see if they add more GHGs (3%)
Supply chain R&D and evaluations 	• Sensors/Monitoring: Fit for different uses and purposes (distribution, delivery) (5%) • Evaluation of real loss rate of H_2 in supply chain (7%) • Detection of leakage at pipeline (2%)
Improve H_2 emissions baseline 	• Initiate large-scale projects to measure hydrogen now with current technology, to guide decisions in 2030 (9%) • Improved data on current t baseline emissions from existing supply chains (2%)
Mitigation and R&D for H_2 delivery 	• R&D on mitigation in H_2 delivery modes (5%) • R&D on mitigation of leakage from LH_2 delivery (3%) • Minimize H_2 losses in distribution and transfers (3%)
R&D to improve sensors 	• Sensors & quantification with portable and low-cost hardware (6%) • Need for reliable, low-cost, lightweight sensors (3%)

Mitigation at concept phase 	• Mitigation through co-location of production and demand, where possible (4%) • Identify where H_2 can and should be deployed (4%)
Prioritize wide-area monitoring 	• Large-area monitoring and sensing (8%)
Improved simulation of H_2 behavior 	• Dispersion modeling for leak quantification (4%) • Modeling plumes in complex environments (2%)
Prioritize methane release mitigation 	• Mitigate methane releases in other industries (refining, ammonia, etc.) (6%)
Additional priorities 	• Technology test-beds for H_2 infrastructure components to prove out reliability of mitigation methods and technologies (4%) • Public education and communication on H_2 (safety and leaks) (4%) • R&D on technology to detect and mitigate emissions at the same time (3%)

3 Conclusions

This workshop had a very high level of interest, with participation from 55 attendees from 9 countries. The workshop achieved its objectives to bring together industry partners, international government stakeholders, and environmental stakeholders to understand and discuss how to mitigate potential atmospheric impacts of hydrogen release; share the latest advances in hydrogen's climate science, hydrogen modeling and detection, mitigation, and measurement technologies; and to identify remaining R&D gaps and priorities for next steps. The high level of engagement from external stakeholders confirms their confidence in hydrogen as an important part of the energy economy. The participation of speakers in the breakout sessions was especially valuable as many questions and discussions arose from the content of their presentations.

The lead organizer for this event, Christine Watson, is grateful for the support of the co-organizing team and for the active engagement from presenters, attendees, moderators, and scribes.

Appendix I

This appendix provides a summary of the workshop agenda.

Day 1: Hydrogen Behavior and Climate Science

08:00 – 08:30 Breakfast

08:30 – 08:35 Welcome & Overview of Workshop Objectives

- Christine Watson (U.S. DOE HFTO)

08:35 – 09:00 International Activities on Hydrogen Emissions

- Beatriz Acosta Iborra (EC JRC)
- Christine Watson (U.S. DOE HFTO)
- Hendrik Louw (Republic of South Africa / IPHE)

09:00 – 10:00 Morning Session #1: Measurement and Modeling of Atmospheric Hydrogen Levels

- John Patterson (UCI)
- Fabien Paulot (NOAA)

10:00 – 10:15 Break

10:15 – 12:00 Morning Session #2: Sources and Sinks of Atmospheric Hydrogen

- Matteo Robino (Snam) – virtual
- Matteo Bertagni (Politecnico di Torino) - virtual
- Linta Reji (University of Chicago)

12:00 – 13:00 Lunch

13:00 – 14:30 Afternoon Session #1: GWP Modeling and Climate Impacts of Increased Hydrogen Production and Use

- David Stevenson (University of Edinburgh)
- Didier Hauglustaine (LSCE) – virtual
- Ramon Alvarez (EDF)
- Amgad Elgowainy (ANL)

14:30 – 14:45 Break

14:45 – 16:00 Afternoon Session #2: Breakout Session

16:00 – 16:30 Concluding Remarks

Day 2: Detection, mitigation, and measurement technologies

08:00 – 08:30 Breakfast

08:30 – 10:00 Morning Session #1: Detection and Quantification Technologies

- Daniel Cherney (ExxonMobil Technology & Engineering)
- William Buttner (NREL)
- William Hoagland (Element One, Inc.)

10:00 – 10:10 Break

10:10 – 11:00 Morning Session #2: Pipeline Leak Detection

- Kandilarya Barakat (U.S. DOT PHMSA) - virtual
- Ruishu Wright (NETL)

11:00 – 12:30 Morning Session #3: Modeling and Measurement

- Rossella Urgnani (Warrant Hub) - virtual
- Mungal Shah (NREL)
- Ramon Alvarez (EDF)

12:30 – 13:30 Lunch

13:30 – 15:00 Afternoon Session #1: Mitigation Technologies

- Lee Gardner (CNL)
- Barry Prince (Fabrum) – virtual
- Cullen Hall (GenH2) - virtual

15:00 – 15:15 Break

15:15 – 16:00 Afternoon Session #2: Breakout Session

16:00 – 16:30 Concluding Remarks

Appendix II

This appendix provides a list of participants.

Participant Name	Company/Organization
Beatriz Acosta Iborra	European Commission Joint Research Centre
Dr. Olumide (Olu) Adeoye	U.S. Department of Energy / ORISE
Katherine Anderson	Brint Tech
Carsten Beyer	NOW GmbH
Louis Brzuzy	Shell New Energies
William Buttner	National Renewable Energy Laboratory
Daniel Cherney	ExxonMobil Technology & Engineering
Olivia Clifton	ExxonMobil Technology & Engineering
Beverly Coleman	Chevron
Richard Craig	Compressed Gas Association
Amgad Elgowainy	Argonne National Laboratory
Sean Fackler	Indrio Technologies Inc
Karin Fickerson	SoCalGas
Elisabeth Freese	Carnegie Institution for Science
Matthew Gacek	Southwest Research Institute
Lee Gardner	Canadian Nuclear Laboratories
Toni Haubitz	NOW GmbH
Ethan Hecht	Sandia National Laboratories
William Hoagland	Element One, Inc.
Jamelyn Holladay	Pacific Northwest National Laboratory
Zakaria Hsain	U.S. Department of Energy / ORISE
Shan Hu	Iowa State University
Erik Kamrath	NRDC
Eladio Knipping	EPRI
Hendrik Louw	DFFE / IPHE
Deepika Malhotra	Pacific Northwest National Laboratory
Akiteru Maruta	Technova Inc
Kanechika Matsui	NEDO
Marc Melaina	Boston Government Services (Contractor to U.S. Department of Energy)
Miranda Miranda	University of California, Irvine
Chris Moore	GTI Energy
Kenji Nagai	NEDO
Tho Nguyen	University of Georgia
Haboon Osmond	U.S. Department of Energy (Contractor)
John Patterson	University of California, Irvine
Fabien Paulot	NOAA
Linta Reji	University of Chicago
Irving Rettig	Environmental Defense Fund
Robert Rhew	University of California, Berkeley
Mark Richards	U.S. Department of Energy

Morgan Rote	Environmental Defense Fund
Eric Saltzman	University of California, Irvine
Munjal Shah	National Renewable Energy Laboratory
Vatsal Shah	Shell Global Solutions (US) Inc
Hadia Sheerazi	RMI (Rocky Mountain Institute)
Shane Siebenaler	Southwest Research Institute
David Stevenson	The University of Edinburgh
Rito Sur	Indrio Technologies Inc.
Christine Watson	U.S. Department of Energy
Kevin Woo	ENTRUST Solutions Group
Ruishu Wright	National Energy Technology Laboratory
Yaofan Yi	Chevron
Katsumi Yokomoto	Kyushu University
Xiangqun Zeng	University of Missouri Columbia

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

For more information, visit:
energy.gov/eere/fuelcells/