Case No. PUR-2022-00125
Sponsor: ("ENVIRONMENTAL RESPONDENT")
Exhibit No. 1

Witness: ANDRÉS F. CLARENS
Bailiff: JABARI T. ROBINSON

Summary of the Direct Testimony of Andrés F. Clarens

The Company proposes a project that entails two phases: (1) rehabilitating five of the seven digesters at the Western Virginia Water Authority's Roanoke Regional Water Pollution Control Plant (currently in progress), and (2) constructing and operating an RNG facility and blending the RNG into the natural gas in the Company's distribution system. The Company seeks the Commission's approval for recovery of costs under the 2022 Virginia Energy Innovation Act ("VEIA"), which requires eligible biogas projects to result in "a reduction in methane or carbon dioxide equivalent emissions."

The Company anticipates the vast majority of emissions reductions will come from rehabilitating the existing digesters at the wastewater treatment plant. However, these estimates are inflated. The Company has also overestimated reductions due to replacing diesel with RNG for vehicles. Finally, the Company has failed to account for *increases* in emissions from the project – specifically, fugitive emissions from biogas upgrading, emissions from flaring during the RNG Facility's downtime, and emissions from RNG transmission, storage, and distribution. My testimony provides a more accurate accounting of the emissions reductions, while identifying where missing information in the Application prevents a full understanding of the Project's impact on emissions. I conclude that the Company has not shown the Project is "reasonably anticipated" to result in the greenhouse gas emissions reductions required under the new law.

I recommend that the Commission: (1) deny the Application so that the Company can resubmit with more complete and accurate factual support for the Project's reasonably anticipated emissions reductions, as specified in my testimony; and (2) require that future applications for approval under Virginia Code Section 56-525 consider the full lifecycle of RNG generation and include the information specified in my testimony.

COMMONWEALTH OF VIRGINIA

STATE CORPORATION COMMISSION

APPLICATION OF ROANOKE GAS COMPANY *For approval of a certificate of public convenience and necessity to construct, own, and operate a digester gas conditioning system and for a rate adjustment clause designated Rider RNG and related tariff provisions pursuant to Chapters 10.1 and 30 of Title 56 of the Code of Virginia*	)	Case No. PUR-2022-00125

DIRECT TESTIMONY OF

ANDRÉS F. CLARENS

ON BEHALF OF

ENVIRONMENTAL RESPONDENT

October 21, 2022

<u>ATTACHMENTS</u>

Attachment AFC-1	(Curriculum Vitae)
Attachment AFC-2	(Carbon Accounting of the Proposed Biogas Project)
Attachment AFC-3	(Bakkaloglu et al., 2022, Methane Emissions Along Biomethane and Biogas Supply Chains Are Underestimated, One Earth)
Attachment AFC-4	(Discovery Cited in Report)

Q1. PLEASE STATE YOUR NAME, PRESENT POSITION, AND ROLE WITH THE ENVIRONMENTAL RESPONDENT.

A1. My name is Andrés Clarens. I am a Professor of Civil and Environmental Engineering in the department of Engineering Systems and Environment at the University of Virginia. My expert testimony in this proceeding is on behalf of Appalachian Voices ("Environmental Respondent").

Q2. PLEASE SUMMARIZE YOUR EDUCATIONAL BACKGROUND AND WORK EXPERIENCE.

A2. I received a Bachelor's in Science (B.S.) in Chemical Engineering from the University of Virginia in 1999, a Master's in Science in Engineering (M.S.E.) in Environmental Engineering from the University of Michigan in 2004, and a doctorate (Ph.D.) in Civil and Environmental Engineering and Natural Resources and Environment from the University of Michigan in 2008. From 2008 to 2014, I was an Assistant Professor of Civil and Environmental Engineering at the University of Virginia. From 2014 to 2020, I continued working at the University of Virginia as an Associate Professor in Civil and Environmental Engineering and became a tenured professor there in September 2020 in Engineering Systems and Environment. I have also worked as an Environmental Engineer for the United States Peace Corps (1999-2001) and Tetra Tech, Inc. (2001-2002).

Q3. HAVE YOU PREVIOUSLY FILED TESTIMONY WITH THE COMMISSION?

A3. No, I have not.

Q4. WHAT IS THE PURPOSE OF YOUR TESTIMONY IN THIS PROCEEDING?

A4. The purpose of my direct testimony is to address the following topics:

1. *The Applicant's accounting of greenhouse gas (GHG) emissions.* The Application states that the proposed RNG Facility is expected to result in an overall emissions reduction of approximately 13,700 MT CO_2e annually, a 63 percent reduction in GHG emissions compared to the 2021 baseline (Application Vol. 3, Direct Testimony of Becky Luna p. 3). I was asked to analyze this accounting, consider how any relevant factors not considered in the Application might impact the Project's emissions, and – to the extent there were deficiencies in the Company's accounting – provide my own accounting of the likely change in emissions reductions due to the proposed project. My testimony includes a more thorough accounting of the change in expected greenhouse gas emissions due to the proposed Project, which indicates that the much-lower figure of 3,744 MT CO_2e/year is more accurate than the Company's emissions reductions estimate but is still too high because it does not quantify all sources of increased emissions due to the Project.
2. *The realistic impact of the digester rehabilitation on GHG emissions.* The Application identifies the largest source of projected emissions reductions as preventing fugitive biogas emissions (Application Vol. 3, Direct Testimony of Becky Luna, Table 3, p. 6), and claims that this would be achieved primarily by rehabilitating the wastewater treatment plant's current digesters (Application Vol. 3, Direct Testimony of Becky Luna, p. 7). I was asked to assess the reasonableness of this expectation and what the emissions reductions (or increases) anticipated from more realistic leakage rate estimates.

I have included my analysis, conclusions, and recommendations in the report attached to my testimony as Exhibit 2.

Q5. DOES THIS CONCLUDE YOUR TESTIMONY?

A5. Yes, it does.

Attachment AFC-1

Andres F. Clarens

Department of Engineering Systems and Environment
University of Virginia
Charlottesville, VA

web: engineering.virginia.edu/faculty/andres-f-clarens
e-mail: andres@virginia.edu

Education

Ph.D. Civil and Environmental Engineering and Natural Resources & Environment
University of Michigan, 2008
Dissertation: *Carbon Dioxide Based Metalworking Fluids*
Ph.D. advisors:

- Kim F. Hayes, Professor, Civil and Environmental Engineering
- Steven J. Skerlos, Professor, Mechanical Engineering
- Gregory A. Keoleian, Professor, Natural Resources and Environment

M.S.E. Environmental Engineering
University of Michigan, 2004

B.S. Chemical Engineering
University of Virginia, 1999
Thesis: *A Hybrid Approach to Phosphorus Modeling in Stratified Lakes*

Experience

Professor - University of Virginia Engineering Systems and Environment	September 2020-present
Associate Director - University of Virginia Environmental Resilience Institute	September 2017-present
Associate Professor - University of Virginia Civil and Environmental Engineering	August 2014- September 2020
Visiting Professor – National Technical University, Argentina Environmental Engineering	February 2016- May 2016
Visiting Professor – Utrecht University, Netherlands Geosciences, Environmental Hydrogeology	August 2015- December 2015
Assistant Professor – University of Virginia Civil and Environmental Engineering,	January 2008- August 2014
Graduate student research assistant – University of Michigan, Civil and Environmental Engineering, Ann Arbor, MI.	September 2002- December 2007
Environmental Engineer – Tetra Tech, Inc., Fairfax, VA	October 2001-August 2002
Environmental Engineer – United States Peace Corps, Dominican Republic	July 1999-July 2001

Substantial Honors and Awards

- **Earth Leadership Program** - Fellow — 2022
- **United States Fulbright Fellow** – National Technical University of Argentina — 2016

- **National Academies of Science, Arab American Frontiers of Science, Engineering and Medicine** - Participant 2014
- **National Science Foundation CAREER Award** 2013-2018
- **Department Teaching Award** – UVa Civil and Environmental Engineering 2013
- **American Chemical Society Petroleum Research Fund Young Investigator** Award 2010-2012
- **Fund for Excellence in Science and Technology** – UVa Vice President for Research Office Junior Faculty Award (w/ L. Colosi) 2010-2011
- **University of Virginia Teaching Fellow** - One of six junior professors selected to develop teaching via yearlong program 2010-2011
- **Finalist and 1st runner up** - ConocoPhillips Penn State Energy Prize for game-changing technology in energy 2009
- **NASA/Virginia Space Grant Young Investigator** Award 2009
- **Distinguished Academic Achievement Award** - Given annually to one University of Michigan CEE Graduate Student 2007
- **1st Place Presentation** - Design and Manufacturing Session, Michigan Research Symposium 2006
- **3M Prize for Outstanding Achievement in Industrial Ecology** 2006
- **Outstanding Student Leader Award** - University of Michigan Annual Awards Program, Honorable Mention 2006
- **2nd Place, Student Poster Competition** - Association of Environmental Engineering and Science Professors Conference 2005
- **1st Place, Student Poster Competition** - International Society of Industrial Ecology Conference 2005
- **Leader 1st place team** - EPA People, Prosperity, and The Planet Design Competition 2005
- **1st Place Technical Paper Competition** - Society of Hispanic and Professional Engineers Conference 2005
- **EPA STAR Fellow** - Recipient of Graduate Fellowship 2004-2007
- **1st Place Presentation** - Design and Manufacturing Session, Michigan-KAIST Research Symposium 2004
- **Graduate Student Award in Environmental Chemistry** – American Chemical Society 2004
- **Spirit of Martin Luther King Award** - Given by the University of Michigan, College of Engineering 2004

Graduate students directed

Ph.D.

- **Shibo Wang**

Entered – Sept. 2007
M.S.E. – 2009
Qualifying Exam – May 2010
Proposal defense – Feb. 2012
Ph.D. defense – Jan. 2013: *"The role of interfacial phenomena in leakage from geologic carbon sequestration site"*
First job – Postdoctoral research fellow, Lawrence Berkeley National Laboratory

- **Eleazer Resurreccion** (co-advised with Lisa Colosi (CEE))
Entered – Sept. 2008
MS defense – May 2010 "*Comparative Life Cycle Assessment of Algae Cultivation Methods*"
Qualifying Exam – Jan. 2011
Proposal defense – June 2012
Ph.D. defense – May 2013: "*Characterizing Synergisms between Algae-Mediated Wastewater Polishing and Energy Production*"
First job – McKnight Postdoctoral Fellow, University of Minnesota - Duluth

- **Conrad 'Alec' Gosse**
Entered – Sept. 2009
MS defense – May 2010: "*Incorporating Greenhouse Gas Emissions into Pavement Management Decisions*"
Qualifying Exam – Aug. 2010
Proposal defense – Feb. 2012
Ph.D. defense – October 2013: "*Environmentally Preferable Streets*"
First job – Commonwealth Computer Research

- **Xiaowei Liu**
Entered – Sept. 2008
Qualifying Exam – Jan. 2011
Proposal defense – July 2012
Ph.D. defense – May 2014: "*Climate Impacts of Next Generation Biofuels Produced from Algae*"
First job – Postdoctoral Research Scholar - Desert Research Institute (Univ. of Nevada System)

- **Brian Weaver**
Entered – Sept. 2009
Qualifying Exam – Jan. 2011
Proposal defense – Sept. 2012
Ph.D. defense – September 2014: "*Gas Expanded Lubricants*"
First job – Postdoctoral Research Fellow, ROMAC, MAE, Univ. of Virginia

- **Zhiyuan Tao**
Entered – Sept. 2012
Qualifying Exam – Jan. 2014
Proposal defense – April 2015
Ph.D. defense – April 2017: "*Storing and Securing Carbon Dioxide in Depleted Shale Formations*"
First job – Energy Analyst for Boston Consulting Group – Shanghai, PRC

- **Rodney Wilkins**
Entered – Sept. 2013
Qualifying Exam – Jan. 2015
Proposal defense – June 2017
Ph.D. defense – June 2018: "Alternatives for Hydraulic Fracturing Fluids in Unconventional Shale Gas Wells"
First job – Independent Consultant, Waynesboro, VA

- **Bo Liang**
Entered – Sept. 2011

Qualifying Exam – Jan. 2013
Proposal defense – Sept 2018
Ph.D. defense – 2018: "The Role of Wettability, Surface Roughness, and Rock-Fluid Interactions on Multiphase Flow Dynamics in Geologic Carbon Storage"
First job – Schlumberger Energy Service, Houston, TX

- **Dan Plattenberger**

Entered – Sept. 2014
Qualifying Exam – Jan. 2015
Proposal defense – July 2018
Ph.D. defense – July 2019: "Synthesis and Application of Crystalline Calcium Silicate Hydrate Phases"
First job – National Renewable Energy Laboratory

- **Jeff Bennett**

Entered – Sept. 2017
Qualifying Exam – April 2018
Proposal defense – September 2019
Ph.D. defense – April 2021: "Trade-offs between emissions, cost and resilience in emerging technologies supporting deep decarbonization of the electric grid"
First job – Carbon Solutions

- **Jay Fuhrman**

Entered – Sept. 2017
Qualifying Exam – January 2019
Proposal defense – May 2020
Ph.D. defense – April 2021: "Integrated Assessment Modeling of Direct Air Capture for Negative CO2 Emissions"
First job – Joint Global Change Research Institute – Pacific Northwest National Laboratory

- **Coleman Tolliver (Principal Advisor Beth Opila)**

Entered – Sept. 2019
Qualifying Exam – September 2021

- **Tawfeeq Gdeh**

Entered – Sept. 2020

- **Suzanne Nguyen**

Entered – Sept. 2021

- **Wade Fritzeen** (co-advised with Lisa Colosi (ESE))

Entered – Sept. 2021

MS

- **Chloe Fauvel**

Regional Dimensions of Deep Decarbonization Plans
Expected May 2022

- **Joseph Sansalone**

Life Cycle Implications of Cement Decarbonization Processes
Expected May 2022

- **Tyler Brown**
Feasibility of Using Reactive Nanoparticles to Control Leakage in Geologic Carbon Storage
May 2018

- **Mark Santana**
Beneficial Use of Coal Combustion Fly Ash: Evaluating the Environmental Implications
August 2009
Went on to receive a Ph.D. at the University of South Florida

Other MS students continued on to Ph.D. and are listed above.

MSE

- **Lyu Xiaotong**
Entered – Sept. 2013
Graduated – May 2018

Undergraduate student theses supervised

Maddie Robinson, Nicole Beachy, Jackson Sompayrac, Aidan Jacobs, Hana Sexton
Quantifying the Impact of Fugitive Emissions on Facilities Upgrade Decisions in the Built Environment
May 2022

Thomas Anderson, Daniel Collins, Harrison Hurst, Chloe Fauvel, Nina Mellin, Bailey Thran
Predictive Tools for Load Management at UVA to Support State-Wide Decarbonization
May 2021

Colin Kim
Geospatial Analysis of CO_2 Fracturing and CO_2 Storage Potential in the Marcellus Shale
December 2018

Sarang Patel
Pseudowollastonite Concrete
December 2018

Elie Seff
Using Integrated Assessment Modeling to Compare Negative Emissions Technologies
December 2018

Heena Shah
Geospatial Analysis of CO_2 Fracturing and CO_2 Storage Potential in the Marcellus Shale
December 2018

Tyler Brown
Using artificial intelligence to achieve deep reductions in power consumption at UVa
December 2017

Andres Clarens

Carly Cocke
Pseudowollastonite based cements
December 2017

Claire Trevasian
Improving the resilience and sustainability of the Puerto Rican Power sector using distributed generation
December 2017

Dustin Weir
Pseudowollastonite based cements
December 2017

Henry Cornell
Leapfrogging energy technology in the Argentinian Power Sector
December 2016

George Kohlroser
Nanostructured patterns on glass surfaces for manufacturing microfluidic devices
December 2016

Kendra Patrick
Wollastonite carbonation in glass bead columns
December 2016

Amy Linderman
Synthetic Rocks with Pore Structures
May 2014

Lauren Hunter
Fluid Flow Through 3-D Printed Porous Rocks
May 2014

Andrew Cole
Fluid Flow Through 3-D Printed Porous Rocks
May 2014

Nik McGruder (Chemical Engineering)
Experimental Study of Migration and Entrapment of CO_2 Leakage from Geologic Sequestration Sites
May 2014

Stewart Walker
Properties of carbon dioxide bubble rise through porous geologic media, in environmental engineering
May 2013

Garrett Rapp
Measuring Buoyancy-Driven Subsurface CO_2 Behavior
May 2013

Andres Clarens

Ari Daniels
Bicycle route choice modeling: objectively predicting where cyclists will ride
May 2013

Kasey Harvey
Opportunities for Carbon Sequestration in Hydraulically Fractured Wells
May 2013

Ian Edwards
Wettability phenomena at the CO_2-brine-mineral interface: Implications for geologic carbon sequestration
May 2013

Adam Shepard
Metalworking Fluids Unit Process Life Cycle Inventory
May 2012

Zhuosong Wang
Gas-Expanded Lubricant Formation and Phase Behavior in Tilting-Pad Journal Bearings
May 2012

Brian Tison
Gas Expanded Lubricants
May 2011

Jasmine Copeland
Contact Angles Effects in Predicting Bubble Rise in Geologic Carbon Sequestration
May 2011

Matthew Shufflebarger
Red Mud Bricks Enhanced with Carbon Sequestration
May 2009

Visitors and postdoctoral fellows supervised

Postdoctoral Fellows:

Sanjeev Kumar
Ph.D. (2018) – Civil Engineering – Malaviya National Institute of Technology
Previous Post-doctoral Fellow – Nanyang Technological University
February 2020 – present

Shreekar Pradhan
Ph.D. (2016) – Economics – University of Tennessee
October 2019 – January 2021

Flo Liang
Ph.D. (2016) – Geology – Penn State University
September 2016 – 2018

Pragnya Eranki
Ph.D. (2012) – Chemical Engineering – Michigan State University
February 2013 – February 2014

External research grants and contracts

Supporting the Transition to Sustainable Aviation Systems in the Commonwealth of Virginia — 9/21-8/22
Sponsor: Virginia Transportation Research Council
PI: L. Colosi, co-PI: A. Clarens, J. Lambert
Total Award Amount: $100,000 (AFC portion: $30,000)
No. of Students Supported: 1
Academic year support: 0

Climate Restoration Initiative — 6/21-5/22
Sponsor: Jefferson Trust
PI: K. McGlathery, co-PI: A. Clarens, L. Szeptycki
Total Award Amount: $110,000 (AFC portion: $25,000)
No. of Students Supported: 1
Academic year support: 0

Modeling the path toward decarbonization in heavy industry — 1/21-12/23
Sponsor: Alfred P Sloan Foundation
PI: A. Clarens, co-PI: S. Doney, B. Shobe, H. McJeon (UMD)
Total Award Amount: $600,000 (AFC portion: $300,000)
No. of Students Supported: 1 (1 post-doc in Clarens lab)
Academic year support: 1

Reinventing CEMENT: Carbonation-Enabled Mineralization to Engender Novel Technology — 9/19-8/22
Sponsor: Department of Energy ARPA-E Open
PI: A. Clarens, co-PI: B. Opila, R. Shahsavari (Rice)
Total Award Amount: $1,318,828 (AFC portion: $800,000)
No. of Students Supported: 1 (1 post-doc in Clarens lab)
Academic year support: 1

Characterizing the reactivity and industrial ecology of pseudowollastonite to enable high-performance building materials from waste streams — 7/18-6/21
Sponsor: National Science Foundation
PI: A. Clarens
Total Award Amount: $300,000
No. of Students Supported: 1
Academic year support: 1

The Promise and Pitfalls of Negative Carbon Emissions – A Regional Case Study of the Chesapeake Bay Watershed — 1/19-12/19
Sponsor: 3 Cavaliers
PI: A Clarens; Co-PIs: S. Doney, W. Shobe

Andres Clarens

Total Award Amount: $60,000
No. of Students Supported: 0 (1 post-doc in Clarens lab)
Academic year support: 0

Green to Grey Tradeoffs in Negative Emissions Technologies — 1/19-12/19
Sponsor: UVa Environmental Resilience Institute Collab
PI: S. Doney; Co-PIs: A Clarens, W. Shobe
Total Award Amount: $30,000
No. of Students Supported: NA
Academic year support: 1

Rebuilding America's Infrastructure — 10/18-9/21
Sponsor: U.S. Department Of Education - Post Secondary Ed.
PI: Lisa Colosi Peterson, co-PIs: Band, Clarens, Culver, Goodall, Lambert, Louis, Quinn, J. Smith
Total Award Amount: $348,840 (AFC portion: $50,000)
No. of Students Supported: 1
Academic year support: 0

Pan-University Environmental Resilience Institute — 9/16-8/19
Sponsor: UVa Strategic Investment Fund
PI: Karen McGlathery co-PI: A. Clarens
Amount: $2,000,000 (AFC portion: $150,000)
No. of Students Supported: NA
Academic year support: 1

GAANN: Resilient Infrastructure: Designing for America's Future — 9/17-8/20
Sponsor: U.S. Department of Education
PI: L. Colosi-Peterson co-PIs: A. Clarens, T. Culver, D. Chen, J. Goodall
Amount: $600,000 (AFC portion: $100,000)
No. of Students Supported: 1
Academic year support: 1

Engineering fractures and pores to selectively control fluid flow in porous media — 7/16-7/17
Research Innovation Grants – UVa SEAS
Amount: $76,000
No. of Students Supported: 1
Academic year support: 1

Targeted Mineral Carbonation to Enhance Wellbore Integrity — 10/15-9/18
Sponsor: Department of Energy, National Energy Technology Laboratory
PI: A. Clarens, co-PI: Jeff Fitts (Princeton - CEE)
Amount: $700,000 (AFC portion: $400,000)
No. of Students Supported: 1 (+1 post-doc)
Academic year support: 1

Andres Clarens

Social and environmental implications of the shale gas boom on transportation systems: The Atlantic Coast Pipeline and its implications for Virginia and beyond — 1/16-12/16
Sponsor: 4VA Grant Program
PI: A. Clarens, co-PI: Rider Foley (STS)
Amount: $40,000
No. of Students Supported: 0.25
Academic year support: 0

UVa Resilience Fellows — 1/16-12/16
Sponsor: Vice President for Research
PI: A. Clarens
Amount: $10,000
No. of Students Supported: 0.25
Academic year support: 0

Anticipating the Environmental Impacts of Unconventional Fossil Fuel Development in Argentina — 3/16-5/16
Sponsor: U.S. Fulbright Foundation
PI: A. Clarens
Amount: $15,000
No. of Students Supported: 0
Academic year support: 2

Partnership to analyze multiphase transport in porous media with applications to carbon-neutral energy technologies (Supplement ERC-NSF CAREER Awards) — 6/15-12/15
Sponsor: National Science Foundation
PI: A. Clarens
Amount: $15,000
No. of Students Supported: 0
Academic year support: 1

Biomass productivity technology advancement towards a commercially viable, integrated algal biomass production unit — 10/13-9/15
Sponsor: Department of Energy
PI: C. Behnke (Sapphire Energy), co-PIs: J. Moreno, Y. Poon, B. Saydah, S. Warner, D. Venardos, N. Baliga, L. Laurens, P. Savage, A. Clarens, L. Colosi
Amount: $5 M (UVa portion: $50,000)
No. of Students Supported: 1
Academic year support: 0
Summer Support: 0 month

Improving transportation sustainability by mining existing data from traffic cameras — 6/1/13-5/31/14
Sponsor: Jefferson Trust – Big Data Initiative
Co-PIs: A. Clarens and S. Acton
Amount: $45,000 (AFC portion: $20,000)
No. of Students Supported: 1

Andres Clarens

Academic year support: 0
Summer Support: 0 month

CAREER: Understanding the physicochemical and systems-level processes that would enable sustainable CO_2 sequestration in shales — 6/1/13-5/31/18
Sponsor: National Science Foundation
PI: A. Clarens
Amount: $414,392
No. of Students Supported: 1
Academic year support: 0
Summer Support: 1 month

Systems Analysis for the Bio-Jet Fuel Industry in Virginia — 12/1/12-6/31/13
Sponsor: Virginia Center for Transportation Research and Innovation
PI: A. Clarens; co-PI: L. Colosi, J. Lambert
Amount: $60,859 (AFC portion: $40,000)
No. of Students Supported: 1
Academic year support: 0
Summer Support: 1 month

Nucleus: Redesign of Introduction to Green Engineering — 6/1/13-5/30/14
Sponsor: UVA Teaching Resource Center
PI: A. Clarens
Amount of Award: $10,000
Academic year support: 0
No. of Students Supported: 0
Summer Support: 1 month

Life cycle analysis in a carbon market context — 2/1/13-1/31/14
Sponsor: Embori Group LLC
PI: A. Clarens
Amount: $33,038
No. of Students Supported: 1
Academic year support: 0
Summer Support: 0 month

Gas expanded lubricants: Energy efficiency and increased reliability in power production using tunable fluids — 6/1/13-5/31/14
Sponsor: Department of Commerce
PI: A. Clarens
Amount: $40,000
No. of Students Supported: 1
Academic year support: 0
Summer Support: 0 month

Life cycle analysis of natural gas fired power production with carbon capture and enhanced oil recovery — 5/1/13-10/31/13
Sponsor: Bipartisan Policy Center
PI: A. Clarens
Amount: $44,576
No. of Students Supported: 1

Academic year support: 0
Summer Support: 0 month

A Partnership for Multiscale Experimental Study of CO_2 Leakage and Vertical Flow in Geologic Carbon Sequestration — 10/1/11-9/31/14
Sponsor: National Science Foundation
PI: A. Clarens
Amount: $446,062
No. of Students Supported: 1
Academic year support: 0
Summer Support: 1 month

GRDS: Characterizing Estrogenicity in Life Cycle Assessment (Supplement) — 9/1/12-8/31/13
Sponsor: National Science Foundation
PI: L. Colosi; co-PI: A. Clarens.
Amount: $40,000
No. of Students Supported: 1
Academic year support: 0
Summer Support: 0 month

Conceptual Model for Conducting Climate Change Vulnerability and Risk Assessments of Transportation Infrastructure Hampton Roads, Virginia Implementation Pilot — 10/1/10-9/31/11
Sponsor: Federal Highway Administration
PI: B. Smith, co-PIs: A. Clarens, J. Lambert, Y. Haimes, K. Hill, S. Chase. AFC took lead preparing proposal and is co-directing this grant with J. Lambert.
Amount: $300,000 (AFC portion: $60,000)
No. of Students Supported: 1
Academic year support: 0
Summer Support: 1 month

A Meta-Model for Life Cycle Assessment of Algae-to-Energy Systems — 9/31/11-8/31/13
Sponsor: National Science Foundation
PI: L. Colosi; co-PIs: A. Clarens, M. White. AFC, MAW, and LMC contribute equally to this work.
Amount: $205,299 (AFC portion: $60,000)
No. of Students Supported: 1
Academic year support: 0
Summer Support: 1 month

Gas Expanded Lubricants – Improving Energy Efficiency Using 'Smart' Fluids — 9/1/10-8/31/12
Sponsor: American Chemical Society – Petroleum Research Fund
PI: A. Clarens
Amount: $100,000
No. of Students Supported: 1
Academic year support: 0

Andres Clarens

Summer Support: 1 month

Gas Expanded Lubricants: Improving Wind Turbine Efficiency — 6/1/10-8/30/10
Sponsor: Rodman Scholars
PI: B. Tison (undergraduate working in our group)
Amount: $3,000
No. of Students Supported: 0
Academic year support: 0
Summer Support:0

Estrogen uptake by algae cultivated using municipal wastewater for simultaneous bioremediation and energy production — 6/1/10-5/29/11
Sponsor: UVA Vice President for Research and Graduate Studies: Fund for Excellence in Science and Technology
co-PI's: Andres Clarens and Lisa Colosi. AFC and LMC contribute equally to this work.
Amount: $50,000 (AFC portion: $25,000)
No. of Students Supported: 1
Academic year support: 0
Summer Support:0

Gas Expanded Lubricants: Smart Fluids for Improving Efficiency of Wind Turbines — 6/1/10-5/29/13
Sponsor: National Science Foundation
PI: A. Clarens, co-PI: P. Allaire. AFC directing this work with support from students in ROMAC laboratory.
Amount of Award: $300,000 (AFC portion: $282,000)
No. of Students Supported: 1
Academic year support: 0
Summer Support: 1.5 months

Feasibility of Gas Expanded Lubricants: Improving Turbine Efficiency using 'Smart' Fluids — 12/1/09-11/29/11
Sponsor: ConocoPhillips and Penn State Energy Prize
PI: A. Clarens
Amount of Award: $75,000
No. of Students Supported: 1
Academic year support: 0
Summer Support: 0 month

Gas-Expanded Lubricants: Improving Turbine Efficiency Using 'Smart' Fluids — 7/1/09-6/30/10
Sponsor: Virginia Space Grant Consortium - NASA
PI: A. Clarens
Amount of Award: $10,000
No. of Students Supported: 1
Academic year support: 0
Summer Support: 0

Redesign of Introduction to Environmental Engineering to Focus on Environmental Sustainability — 6/1/10-5/30/11

Sponsor: UVA Teaching Resource Center – University Teaching Fellows
PI: A. Clarens
Amount of Award: $6,000
Academic year support: 0
No. of Students Supported: 0
Summer Support: 1 month

CO_2 sequestration with concurrent synthesis of fatty acid based fuels in a model organism: Chlorella protothecoides — 6/1/08-5/31/09
Sponsor: UVA Collaborative Energy Research Program
PI: A. Clarens, co-PIs: L. Colosi, and M. White. AFC, MAW, and LMC contribute equally to this work.
Amount: $37,999 (AFC portion: $15,000)
No. of Students Supported: 1
Academic year support: 0
Summer Support: 0

Bibliography[1]

Peer-reviewed journal publications

[68] Kim, J. J., Ling, F. T., Plattenberger, D. A., Clarens, A. F., & Peters, C. A.* (2022). Quantification of mineral reactivity using machine learning interpretation of micro-XRF data. *Applied Geochemistry, 136*, 105162. Citations = 0/0[2], IF = 3.52. [Editors' Choice Award]

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- "The impact of interfacial properties on fluid fate and transport during production of hydraulically fractured unconventional gas wells" American Geophysical Union Fall Meeting, Washington, DC. 12/18
- "Machine learning application for mapping calcium mineral precipitates using coupled microscale XRF and XRD" (Given by Catherine Peters) American Geophysical Union Fall Meeting, Washington, DC. 12/18
- "Integration of supercritical CO_2-power cycles to improve grid resilience and sustainability" International Conference on the Management of Energy, Climate and Air for a Sustainable Society, Havana, Cuba. 7/18
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- "Using Peer-Instruction Strategies in Environmental Engineering Education" Association of Environmental Engineering and Science Professors Meeting. Ann Arbor, MI 6/17
- "Targeted permeability control in the subsurface for emerging energy applications" Association of Environmental Engineering and Science Professors Meeting. Ann Arbor, MI 6/17
- "Use of functionalized nanoparticles to selectively control permeability in porous media" Interpore Annual Meeting. Rotterdam, NL. 5/17
- "Targeted Mineral Carbonation to Enhance Wellbore Integrity" Mastering the Subsurface Through Technology, Innovation and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting. 8/16
- "Targeted Control of Subsurface Permeability Using Mineral Carbonation Reactions" Goldschmidt Annual Meeting. Prague, Czech Republic. 8/15

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- "Carbonation of wollastonite in shale formations" Interpore Annual Meeting. Padua, Italy. 5/15
- "Carbonation of wollastonite in a shale matrix" Association of Environmental Engineering and Science Professors Meeting. New Haven, CT 6/15
- "Feasibility of using depleted shales as a repository for permanent storage of CO_2" American Geophysical Union Fall Meeting. San Francisco, CA 12/13
- "Adhesion of CO_2 on Hydrated Mineral Surfaces and Its Implications to Geologic Carbon Sequestration (GCS)" American Geophysical Union Fall Meeting. San Francisco, CA 12/13
- "Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction" Pacific Rim Summit on Industrial Biotechnology & Bioenergy. San Diego, CA 12/13
- "An integrated experimental program to understand leakage from geologic carbon sequestration sites across scales" Association of Environmental Engineering and Science Professors. Golden, CO 7/13
- "Historical land use change emissions: Implications for biofuel accounting" International Symposium on Sustainable Systems and Technology. Cincinnati, OH 5/13
- "Feasibility of using depleted shales as a repository for permanent storage of CO_2" Technical and Community Challenges of Hydraulic Fracturing for Shale Gas. Boulder, CO 8/13
- "An integrated experimental program to understand leakage from geologic carbon sequestration sites across scales" American Geophysical Union Fall Meeting. San Francisco, CA 12/12
- "An integrated experimental program to understand leakage from geologic carbon sequestration sites" ACS - Northeast Regional Meeting. Rochester, NY 10/12
- "Integrating environmental life cycle assessment into infrastructure design and management" ASCE - Workshop on Sustainability Quantification for Building and Infrastructure Design, Engineering and Construction. Ft. Worth, TX 10/12
- "CO_2-Brine Rheology Could Suppress Leakage From Geologic Carbon Sequestration Sites" (Given by Shibo Wang). American Geophysical Union Fall Meeting. San Francisco, CA 12/11
- "Meta-model of Algae Bio-Energy Life Cycles (MABEL)" (Given by Xiaowei Liu) American Center for Life Cycle Assessment Meeting. Chicago, IL. 10/11.
- "Comparative Life Cycle Assessment and Costing of Algae Cultivation Methods" (Given by Eleazer Resurreccion) American Center for Life Cycle Assessment Meeting. Chicago, IL. 10/11.
- "Life cycle impacts of winter maintenance treatments for roadways" American Center for Life Cycle Assessment Meeting. Chicago, IL. 10/11.
- "The top five things that environmental engineers can teach us about algae-to-energy technology" Association of Environmental Engineering and Science Professors Meeting. University of South Florida. 7/11

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- "Safe and effective geologic sequestration of CO_2: Multi-scale experimental studies of formation integrity and leakage" Association of Environmental Engineering and Science Professors Meeting. University of South Florida. 7/11
- "Life cycle assessment of algae-to-energy technologies. International Society for Industrial Ecology" University of California, Berkeley 6/11
- "Evaluating the environmental impact of algae cultivation techniques using life cycle assessment" American Center for Life Cycle Assessment Meeting. Portland, OR. 11/10
- "Feasibility of gas-expanded lubricants for increased energy efficiency in rotating machinery" ASME/STLE International Joint Tribology Conference. San Francisco, CA. 10/10
- "Modeling metalworking fluid penetration in the cutting zone to understand EAL" ASME/STLE International Joint Tribology Conference. San Francisco, CA. 10/10
- "Gas expanded lubricants for increased energy efficiency in power turbines" American Chemical Society National Meeting. San Francisco, CA. 3/10
- "Rheology of CO_2-H_20 mixtures: Implications for understanding leakage in geologic sequestration" American Chemical Society National Meeting. San Francisco, CA. 3/10
- "Identifying the Rate Limiting Steps in Sustainable Algae Production for Bioenergy" American Chemical Society National Meeting. San Francisco, CA. 3/10
- "What can algae farmers learn from environmental engineers?" Association of Environmental Engineering and Science Professors Meeting. University of Iowa. 7/09

Conference posters

- "Integrated Assessment Modeling of Multiple Carbon Dioxide Removal Pathways" (Given by J Fuhrman) American Geophysical Union Fall Meeting. New Orleans, LA 12/21
- "Decarbonizing Cement and Concrete: A Curable Problem" (Given by J Sansalone) American Geophysical Union Fall Meeting. New Orleans, LA 12/21
- "Reconciling Integrated Assessment Estimates of Carbon Removal with Regional-Scale Potential" (Given by C Fauvel) American Geophysical Union Fall Meeting. New Orleans, LA 12/21
- "Environmental Change and Human Security: Strengthening the Scientific Foundations and Bridging the Research-Practitioner Gap" (Given by S Burke) American Geophysical Union Fall Meeting. New Orleans, LA 12/21
- "Assessing the need for direct air capture in the context of the shared socioeconomic pathways " (Given by J Fuhrman) American Geophysical Union Fall Meeting. Virtual 12/20
- "Multimineral Characterization of Shales for Reactive Transport Modeling Based on Micro-XRF Interpretations" (Given by J Kim) American Geophysical Union Fall Meeting. Virtual 12/20

- "Deployment of negative emissions technology under various policy scenarios intended to limit warming or limit CO2 atmospheric stocks" (Given by S Pradhan) American Geophysical Union Fall Meeting. Virtual 12/20
- "Modeling the Potential to Deploy Offshore Compressed Air Energy Storage in the Eastern United States" (Given by J Bennett) American Geophysical Union Fall Meeting. Virtual 12/20
- "Incorporating Extreme Weather Risks into Energy System Modeling" American Geophysical Union Fall Meeting. Virtual 12/20
- "Evaluating the Anticipated Food-Energy-Water Impacts of Direct Air Capture and Other Forms of Negative Emissions Using Integrated Assessment Models" American Geophysical Union Fall Meeting. San Francisco, CA 12/19
- "Comparative Life-Cycle Assessment of Aquatic and Terrestrial Bioenergy with CO2 Capture and Storage" (Given by J. Melara) American Geophysical Union Fall Meeting. Washington, DC 12/18
- "Calcium silicate crystal structure impacts its reactivity with CO_2 and chemistry of reaction products" (Given by D. Plattenberger) American Geophysical Union Fall Meeting. Washington, DC 12/18
- "Bio-organoclay composite materials designed to seal leaking and abandoned natural gas well-bores" (Given by F. Chen) American Geophysical Union Fall Meeting. Washington, DC 12/18
- "Interfacial Impacts on Slickwater Imbibition and Gas Production in the Marcellus Shale" Interpore. New Orleans, LA 5/18
- "Cementing pores and fractures using mineral silicate carbonation in situ" Interpore. New Orleans, LA 5/18
- "Harnessing mineral carbonation reactions to seal fractured shales and sequester carbon" (Given by Tao Zhiyuan) American Geophysical Union Fall Meeting. San Francisco, CA 12/14
- "Estimating the CO_2 sequestration capacity of fractured shale formations using methane production rates: The case of the Utica Shale" (Given by Tao Zhiyuan) American Geophysical Union Fall Meeting. San Francisco, CA 12/14
- "Adhesion of CO_2 on hydrated mineral surfaces and its implications to geologic carbon sequestration" Gordon Research Conference – Flow and Transport in Permeable Media. Lewiston, ME
- "Experimental study of heterogeneity-induced capillary trapping in the context of leakage from geologic carbon sequestration sites" (Given by Bo Liang) American Geophysical Union Fall Meeting. San Francisco, CA 12/14
- "Adhesion at the CO_2/mineral interface" Association of Environmental Engineering and Science Professors. Golden, CO 7/13
- "A novel method for quantifying the greenhouse gas emissions of biofuels based on historical land use change" American Geophysical Union Fall Meeting. San Francisco, CA 12/12

- "Evaluating the role of interfacial properties on controlling buoyancy driven leakage from geologic carbon sequestration sites" Gordon Research Conference on Flow Through Porous Media. Les Diablerets, Switzerland 7/12

- "Methodological shortcomings of life cycle assessment when evaluating emerging energy technologies: The case of algae" Gordon Research Conference on Industrial Ecology. Les Diablerets, Switzerland 7/12

- "Evaluating the role of interfacial properties on controlling buoyancy driven leakage from geologic carbon sequestration sites" NSF – CBET Grantees Meeting. Baltimore MD 6/12

- "Wetting phenomenon of representative minerals in geologic carbon sequestration formations" (Presented by Shibo Wang) 2012 Carbon Capture and Sequestration Meeting. Pittsburgh, PA. 5/12

- "Improved Force Balance For Predicting Vertical Migration of CO_2 from Geologic Sequestration Sites" Carbon Management Technology. Orlando, FL 2/12

- "The wettability of CO_2 on minerals under relevant geologic carbon sequestration conditions and its implications on leakage processes" American Geophysical Union Fall Meeting. San Francisco, CA 12/11

- "Greenhouse Gas Emissions in Pavement Management Systems" American Center for Life Cycle Assessment Meeting. Portland, OR. 11/10

- "Rheology of CO_2-saturated brine solutions: Implications for fluid flow under geologic-storage relevant conditions" 2010 Carbon Capture and Sequestration Meeting. Pittsburgh, PA. 5/10

- "Greenhouse Gas Emissions Associated with Large-Scale Algae Cultivation" 2010 Carbon Capture and Sequestration Meeting. Pittsburgh, PA. 5/10

Invited talks

- "Reinforcing and balancing feedback loops driven by dissolution and precipitation in reactive transport through porous media" Interpore, 6/2021
- "The role of negative emissions in achieving net-zero emissions goals" ICUS XXXVII, Seoul, South Korea, 4/2021
- "Green to Gray Infrastructure Needs to Achieve Deep Decarbonization" Pontificia Javeriana Colombia, Colombia, 12/2020
- "Jumpstarting a New Carbon Economy " Columbia University, NY, NY, 1/2020
- "Reinventing Cement and Negative Emissions Using Alkaline Mining Waste" Peking University China, 8/2019
- "The Energy-Water Nexus and Hydraulic Fracturing: Toward a waterless and carbon neutral future" United States Geological Survey Seminar Series, Reston, VA 4/13/17
- "Targeted control of permeability using carbonate dissolution/precipitation reactions" American Geophysical Union – Fall Meeting, San Francisco, CA 12/12/16

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- "Thinking about the 'engineering' in 'geoengineering'" NC – State CEE Department Seminar 11/18/16
- "CO_2 - shale interactions with implications for fracturing, enhanced gas production, and storage" FEST Seminar Series – Utrecht University, 12/8/15
- "CO_2/shale interactions and their implications for fracturing, enhanced gas production, and storage" Chemical Engineering Seminar, Imperial College London 10/20/15
- "CO_2/shale interactions" Pore Scale Physics Seminar, Royal Dutch Shell, 11/3/15
- "Are hydraulically fractured shales viable repositories for carbon storage?" Purdue University, Environmental and Ecological Engineering, 4/29/15
- "Could hydraulically fractured shale formations be used as repositories for carbon storage?" Frontiers of Geoscience Colloquia, Los Alamos National Lab - Earth and Environmental Sciences Division, 3/9/15
- "Calculating the carbon sequestration capacity of fractured shale formations" – National Energy Technology Laboratory, Department of Energy, 7/22/14
- "Feasibility of using depleted shales as a repository for permanent storage of CO_2" – Princeton – Civil and Environmental Engineering Seminar. Princeton, NJ 4/14/14
- "Climate implications of algae-based bioenergy systems" – American Chemical Society Green Chemistry and Engineering Conference. Bethesda, MD 6/20/13
- "Climate implications of algae-based bioenergy systems" – Cornell University – Civil and Environmental Engineering Seminar. Ithaca, NY 9/20/12
- "Are wastewater treatment plants the next Saudi Arabia?" – Virginia Tech - Environmental and Water Resources Seminar. Blacksburg, VA 4/13/12
- "Limits to Algae Biofuels" – MITRE Corporation – Workshop on Next Generation Energy Technologies 3/28/12
- "Multi-scale experimental studies of CO_2 vertical migration from geologic sequestration sites" – NSF – Sustainable Engineering and Education for Sustainability Workshop, Minneapolis, MN 10/20/11
- "Multi-scale experimental studies of CO_2 vertical migration from geologic sequestration sites" – University of Virginia, Department of Chemical Engineering, Charlottesville, VA 9/15/11
- "Life cycle assessment of algae-to-energy technologies" – National Academies of Engineering – Committee on Sustainable Development of Algal Biofuels, Washington, DC 6/13/11
- "The top five things that life cycle assessment can teach us about algae-to-energy technology" – Scripps Oceanographic Institute – Algal biotechnology seminar series. San Diego, CA 11/3/10
- "Why soils matter for biofuels" – Life cycle evaluation of algae-to-energy - Soil Science Society National Meeting, Long Beech, CA 11/2/10
- "Understanding vertical migration of CO_2 under geologic storage conditions" – University of Virginia, Department of Environmental Sciences Seminar, Charlottesville, VA 9/16/10
- "Identifying the rate limiting steps in bioenergy production from algae" – Carnegie Mellon University, Department of Civil and Environmental Engineering Seminar, Pittsburgh, PA 5/11/10

Andres Clarens

- "Horizons in alternative energy" – Presented to the Axel Johnson Board of Directors. ($3 billion privately owned company) Portsmouth, NH 10/6/09

Patents

- Cementitious materials and methods of making and using thereof
  United States Patent Disclosure (11/15/19)
  Inventors: Clarens, A. F., D. Plattenberger

- Novel Method to Dispose of Carbon, Stabilize Fractured Shale Formations
  United States Patent Disclosure (12/12/14)
  Inventors: Clarens, A. F., T. Zhiyuan, J. Fitts.

- Gas-expanded lubricants
  United States Patent (1/23/18)
  Inventors: Clarens, A. F., P.E. Allaire, A. Younin, S. Wang.

- Metalworking Fluids Delivered in Supercritical Carbon Dioxide
  United States Patent (4/17/08)
  Inventors: Clarens, A. F.; S.J. Skerlos; K.F. Hayes

Professional service

- **Appointed Member** – Advisory Committee (to the Director of NSF) for Environmental Research and Education of the US National Science Foundation. Serving a 3-year appointment (2014-2017). Appointment extended for an additional two years (2017-2019), Chairman (2019-2022)
- **Chair** – Engineering Sustainability 2030 Plan 2021-22
- **Member** – SEAS Working Group on Design of the Common Core 2019
- **Search Committee** – Engineering Systems and Environment Search (3 Positions) 2017-18
- **Appointed Member** – Advisory Committee (AdCom to the Associate Director of NSF for Engineering) for the Engineering Directorate of the US National Science Foundation. Serving a 3-year appointment (2013-2016).
- **Search Committee** – Open Rank Position in Engineering Resilience and Environmental Justice (2020)
- **Assistant Chair for Graduate Studies** - Civil and Environmental Engineering (1/2014 – 5/15)
- **Search Committee** – Dean, School of Engineering and Applied Science, UVa
- **Search Committee** – Environmental Sciences, UVa, Position in Atmospheric Science
- **Faculty advisor** – Engineering Students Without Borders (2010 – 2013)
- **Member** – Committee on Research Distinctiveness, School of Engineering and Applied Science Strategic Planning 2010-2011
- **Member** – President's Committee on Sustainability – School and Department Initiatives Subcommittee (2011 – present)
- **Assistant Chair for Graduate Studies** (interim Fall 2009) - SEAS Graduate Studies Committee
- **Co-chair** – Hoos for Haiti Benefit Concert which raised over $30,000 for disaster relief and rebuilding in Port-au-Prince, Haiti following the massive earthquake (January 2010).
- **Chair for CEE** – SEAS Open House Committee (2008-2011)
- **Facilitator** – SEAS First-Year Common Reading Experience (2009, 2010, 2011, 2012, 2013).
- **Member** – CEE Web-Site Committee (2011)

- **Member** – CEE Space Committee (2011)
- **Member** – University Committee on Fraternities & Sororities (2010)
- **Journal Reviewer** (and number of manuscripts reviewed) – Accounts of Chemical Research (2), ACS Omega (1), ACS Sustainable Chemistry and Engineering (3), Algae Research (1), American Society of Agricultural and Biological Engineers (1), Applied Energy (5), ASME – Journal of Energy Resources Technology (1), Biofuels (1), Bioresource Technology (13), Chemosphere (1), Crystal Growth and Design (1), Colloids and Surfaces A: Physicochemical and Engineering Aspects (1), Energies (1), Energy (6), Energy & Fuels (5), Energy Conversion and Management (1), Energy Policy (1), Environmental Engineering Science (8), Environmental Research Letters (8), Environmental Science and Technology (61), Environmental Science and Technology Letters (7), Environmental Science: Processes & Impacts (1), EOS (1), Frontiers (7), Fuel (6), Fuel Processing Technology (1), Global Change Biology (1), Geomechanics and Geophysics for Geoenergy and Georesources (1), Greenhouse Gases Science and Technology (3), Industrial and Engineering Chemistry Research (4), International Journal of CO_2 Utilization (2), International Journal of Energy and Environmental Engineering (1), International Journal of Greenhouse Gas Control (5), Joule (7), Journal of Cleaner Production (3), Journal of Energy Resources Technology (1), Journal of Engineering Manufacture (1), Journal of Green Building (1), Journal of Industrial Ecology (5), Journal of Infrastructure Systems (3), Journal of Manufacturing Systems (1), Journal of Manufacturing Processes (2), Journal of Transportation Engineering (1), Journal of Water and Climate Change (2), Langmuir (1), Materials (1), Materials Research (1), Nature Communications (1), Nature Energy (2), Philosophical Transactions A (1), PNAS (1), Science of the Total Environment (1), SPE Journal (1), Water Resources Research (5), Water Science and Technology (3)
- **Proposal Reviewer** – National Science Foundation, Environmental Protection Agency, Department of Agriculture, Department of Energy (ARPA-E), ACS-PRF, Fulbright Program
- **Session Organizer and Chair**
    - **Reactive Transport in Real Rocks: From the Pore to the Field Scale** at American Geophysical Union Fall Meeting, Virtual, 12/20
    - **The geochemistry of carbon storage and sequestration** at Goldschmidt Annual Meeting, Prague, Czech Republic, 8/15
    - **New adventures in reactive flow through porous media** at Association of Environmental Engineering and Science Professors 2013 Meeting, Golden, CO 7/13
    - **Modeling Sustainable Systems** at International Symposium on Sustainable Systems and Technology, Cincinnati OH 4/13
    - **Exploring the Multiple Scales of Leakage from Geologic Carbon Sequestration Sites** at American Geophysical Union, International Fall Meeting, San Francisco, CA 12/11
    - **Environmentally Sustainable Manufacturing Processes and Systems** at International Conference on Manufacturing Science and Engineering, ASME, West Lafayette, IN 10/09

Professional Associations

American Chemical Society	2002 - present
International Society of Industrial Ecology	2005 - present
American Association of Environmental Engineering and Science Professors	2005 - present
American Geophysical Union	2010 - present
American Association for the Advancement of Science	2010 - present

Andres Clarens

Foreign Languages

Native Spanish speaker

Interests

- Outdoor sports – backpacking, fly fishing, mountain biking, skiing
- Travel
- Running
- Swimming

Attachment AFC-2

Review of the Application's Claimed Greenhouse Gas Emissions Reductions

Andrés F. Clarens, Ph.D.

Having reviewed the Application,[1] Roanoke Gas Company's ("Roanoke Gas" or "the Company") responses to discovery, and the other documents in Docket PUR-2022-00125, I have reached the following conclusions about the Project. The Company has not shown that the Project is "reasonably anticipated" to result in greenhouse gas emissions reductions, as required for approval under Virginia Code Section 56-525 B. The Company's emissions reduction estimates for fugitive biogas emissions and renewable natural gas ("RNG") vehicles are inflated, and the Company has not adequately accounted for increases in emissions due to the Project. While the greenhouse gas (GHG) inventory that forms the basis for the Application reports a reduction of 13,740 MT CO_2e/year, I have produced a more accurate accounting of the emissions reductions yields estimates of less than 3,744 MT CO_2e/year, and even that much-lower figure may overstate the Project's emission reductions because it does not include all sources of increased emissions. This is a small benefit that represents less than 1% of the total greenhouse gas emissions generated by Roanoke Gas each year in their operations.[2]

My updated assumptions are based on more realistic biogas generation rates at the facility (using numbers provided by the Company) and more representative estimates for leak control from anaerobic digesters (obtained from the United Nations and EPA). However, this updated

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[1] *Application of Roanoke Gas Company, For approval of a certificate of public convenience and necessity to construct, own, and operate a digester gas conditioning system and for a rate adjustment clause designated Rider RNG and related tariff provisions pursuant to Chapters 10.1 and 30 of Title 56 of the Code of Virginia*, Case No. PUR-2022-00125 (Aug. 3, 2022) ("Application").

[2] *See* Roanoke Gas, *About*, https://www.roanokegas.com/about/ (last visited Oct. 21, 2022), and CARBON DIOXIDE EMISSIONS COEFFICIENTS, U.S. ENERGY INFO. ADMIN. (Oct. 2022) eia.gov/environment/emissions/co2_vol_mass.php (10×10^6 decatherms * 10^6 btu/decatherm * 53 kg $CO_2/10^6$ btu * 1 tonne /1000 kg = 530000 MtCO2e).

accounting does not consider a number of additional sources of increased emissions that would likely further erode emissions reduction benefits of the project, including fugitive emissions from biogas upgrading, more accurate estimates of emissions due to flaring during RNG Facility downtime, and emissions due to transmission, storage, and distribution of the RNG.

The only way to have confidence in the Project is for the Commission to require the Company to re-submit its application with more complete and accurate data, including verifiable measurements of biogas throughput in the Western Virginia Water Authority ("the WVWA") facility to produce a transparent validation of the marginal environmental benefits of the Project (which is referred to as "additionality" in the carbon offsets market), measurements demonstrating that the WVWA can achieve the emissions reductions it claims, and a plan for managing leaks from a compressed natural gas transportation fleet. In an updated application, the WVWA should also consider its operations broadly, including what it would take to achieve the stated emissions reductions and how other elements of its operation, specifically its digestate management practices, could undermine the climate benefits of any effort to limit emissions from its operations. Finally, for future projects like this one, the Commission should require applications for approval to consider the full lifecycle of RNG generation.

Table 1. Adjusted GHG Inventory for the project using updated estimates for biogas throughput at the facility, leakage control estimates, and fugitive emissions suggest that the project, as conceived, would have very low, low, or possibly no, environmental benefits. The numbers in this Table are derived from the Company's GHG Inventory Tool (Confidential). Numbers in red are those changed directly as a result of using updated biogas throughput estimates and leakage rates. Numbers in yellow are those that changed indirectly as a result of these changes.

	Application		Adjusted	
Emission Source	2022 Baseline Operations Metric Tons (CO2e/year)	2022 Future Operations Metric Tons (CO2e/year)	2022 Baseline Operations Metric Tons (CO2e/year)	2022 Future Operations Metric Tons (CO2e/year)
Scope 1				
Natural Gas Combustion*	769	2,463	769	2,463
Biogas Combustion (Flare, Boilers)	4,241	272	2,282	139
Biogenic CO_2	4,219	270	2,271	139
CH_4 & N_2O*	22	1.4	12	0.7
Leaked Digester Gas	13,559	904.6	5,690	1,308.6
Tailgas Venting	0	3,503	0	1,794
Scope 1 Subtotal	18,568	7,143	8,741	5,705
Scope 2				
Purchased Electricity	0	603	0	603
Gas Conditioning Skid	0	603	0	603
Scope 2 Subtotal	0	603	0	603
Scope 3 - Emissions				
Natural Gas Production	18	58	18	58
Chemical Production	1.3	27	1.3	27
Iron Hydroxide	1.3	1.3	1.3	1.3
Granulated Activated Carbon	0	25.4	0	25.4
Chemical Transport	2.3	3.2	2.3	3.2
RNG Combustion Vehicles - CH_4 and N_2O**	0	294	0	144
Diesel Combustion Vehicles	4971		2432	
Scope 3 (Emissions) Subtotal	4,993	382	2,454	232
Scope 3 - Offsets				
Avoided Emissions - Boilers	-1,694	0	-912	0
Avoided Purchased Natural Gas	-1,694	0	-912	0
Scope 3 (Offsets) Subtotal	-1,694	0	-912	0
Total Emissions Summary				
Scopes 1, 2, & 3 (Emissions) TOTAL	23,561	8,128	11,195	6,540
Scope 3 (Offsets) TOTAL	-1,694	0	-912	0
NET EMISSIONS	21,867	8,128	10,284	6,540

*Emission source that is included in federal regulations. Applicability of
**Emissions included for comprehension only, not needed for regulatory
†Offsets can be incentivized to mitigate emissions. Offsets are estimated

I. Description of the Project and Application

The Company seeks approval under Chapters 10.1 and 30 of Title 56 of the Virginia Code to construct and operate a RNG facility within the WVWA's Roanoke Regional Water Pollution Control Plant. RNG produced at the plant will be blended with natural gas already in the Company's distribution system. The Company seeks to recover costs under the 2022 Virginia Energy Innovation Act ("VEIA"),[3] a new Virginia law that authorizes cost recovery for "eligible biogas supply infrastructure projects,"[4] defined as follows:

> "Eligible biogas supply infrastructure projects" or "projects" means capital investments in biogas facilities that, alone or in combination with other projects or strategies, offer reasonably anticipated benefits to customers and markets, which benefits mean (i) a reduction in methane or carbon dioxide equivalent emissions from the biogas facility, (ii) an additional source of supply for the natural gas utility, and (iii) a beneficial use for the biogas, and which benefits do not result in the gas delivered to customers failing to meet the natural gas utility's pipeline quality standards.[5]

For the purposes of my review, the most important eligibility criteria is that a project must "offer reasonably anticipated benefits to customers and markets," including that the project must result in "a reduction in methane or carbon dioxide equivalent emissions from the biogas facility."[6] The Commission may only approve a project plan for recovery of "eligible biogas supply infrastructure costs" under Virginia Code Section 56-625 B

> upon a finding that it (i) is in the public interest, (ii) will result in a decrease of methane or carbon dioxide equivalent emissions, and (iii) will result in rates that are just and reasonable, after notice and an opportunity for a hearing in accordance with the provisions of this chapter.[7]

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[3] 2022 Va. Acts chs. 728, 759.
[4] Va. Code § 56-525 A.
[5] Va. Code § 56-625 A.
[6] Va. Code § 56-625 A.
[7] Va. Code § 56-625 B.

The Company's Application describes a project with two phases: (1) rehabilitation of the anaerobic digesters and (2) construction of a gas upgrading facility ("RNG Facility") and transport pipeline to connect the system to the Roanoke Gas Company distribution system. According to the Company's plan, construction of the RNG facility, which would begin in early 2023 if approved,[8] would take place while the rehabilitation of the WVWA's wastewater treatment digesters is being completed.[9] The rehabilitation of the digesters, however, began in 2022 and is scheduled to be completed by August 2023;[10] as such, it is an independent process not under the Company's control[11] and not before the Commission. The Company's Application only asks the Commission to issue an order allowing them to construct and operate the RNG Facility; approve a RAC for the recovery of project costs; and approve tariff provisions related to the Facility and the Company's purchase of RNG.[12]

The vast majority of the claimed emissions reductions will come from rehabilitation of the digesters, which WVWA will complete without the Commission's approval of the Company's construction and operation of the RNG Facility.[13] Only a small portion of the total avoided emissions claimed in the Application will come as a result of the construction and operation of the

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[8] Application Vol. 1, at 5.

[9] Application Vol. 1, at 4.

[10] *See* Western Virginia Water Authority, *Facility Improvements*, https://www.westernvawater.org/wastewater-service/wastewater-treatment/facility-improvements; *see also* Company Response to ER 4-8, included as Attachment 4, at 131 ("Roanoke Gas Company is not involved in the rehabilitation program of the WVWA digesters and therefore does not have a full timeline for the rehabilitation program, however it is the Company's current understanding that rehabilitation is scheduled to be complete by August 2023."); Company Response to Staff Set 7-49, included as Attachment 4, at 135–36.

[11] *See* Company Response to ER Set 4-8, included as Attachment 4, at 131.

[12] Application Vol. 1, at 9.

[13] Company Response to Staff Set 7-49, included as Attachment 4, at 135–36 ("While the digester rehabilitation and RNG upgrading are part of the same project and are being constructed by the same contractor, but under two separate contracts, the anaerobic digesters could be rehabilitated without the construction of the RNG Project."); Company Response to ER Set 4-5, included as Attachment 4, at 130 ("If the Commission does not approve the Company's Application the West Virginia Water Authority will assume ownership.").

RNG Facility,[14] the part of the Project requiring approval by the Commission. By the Company's accounting, the rehabilitation alone, without the RNG Facility, results in emissions reductions of 11,534 MT CO_2e/year,[15] a reduction nearly as high as the Application's total claimed emissions reductions of 13,740 MT CO_2e/year.

Some background information about biogas production is helpful for understanding this Project. Wastewater treatment plants work by consuming dissolved organic material (municipal waste) aerobically (that is, in the presence of oxygen) using bacteria, which grow and die and must be disposed of regularly. The resulting sludge (or accumulated dead bacteria) can be sent to an anaerobic digester where a different kind of bacteria will consume the sludge to form methane and carbon dioxide (biogas). Anaerobic digesters are typically large, sealed vessels that are operated at a slight pressure and elevated temperatures. There are several types of digesters, but the Application describes the digesters at the WVWA facility as concrete containers built between 40-70 years ago with some original plumbing and some degraded walls and seals.[16]

The biogas produced in the digester can be used to fuel boilers that heat the digesters themselves, or it can be used in combined heat and power units to produce electricity and heat, or it can be upgraded and sold into the gas distribution network. Biogas quality varies depending on a number of factors related to the wastewater composition and the digester performance and as a result, when the biogas is of insufficient quality, plants often must flare (burn) their biogas to avoid releasing potent methane into the atmosphere directly.

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[14] Application Vol. 3, at 6 (Testimony of Becky Luna, ex. 1, Table 3).
[15] See Company Response to Staff Set 7-49, included as Attachment 4, at 135–36.
[16] See Company Response to ER Set 3-1(a), Confidential Supplemental Attachment, included as Attachment 4, at 19–21.

There are a few characteristics of wastewater treatment plants that put my interpretation of this Application in context. First, wastewater treatment facilities are large and complex and perform a vital public service with a limited budget. So it is not at all surprising that the data availability on biogas flows is incomplete. Methane is colorless and odorless and has been traditionally very challenging to measure. There have been significant advances in measurement technology in the past few years that would help eliminate uncertainty in many of the numbers in the Application.[17] Second, anaerobic digesters can be tuned up to produce more methane. But mass is always conserved so on some fundamental level, the only way to significantly increase the amount of gas produced at a plant is to treat more wastewater or supplement their flows with high strength wastewater.[18] Third, plants have a rated capacity, but that capacity should be distinguished from the average amount of wastewater that the plant handles. Just because the plant will be upgraded to treat >60 million gallons of water a day does not mean that Roanoke will have that much water available to send to the facility.

Furthermore, even assuming the Company's estimates of emissions reductions from leakage control in the digesters were accurate, recent findings suggest that the management of the digestate at the WVWA plant could eclipse any climate benefits of this Project.[19] The WVWA facility uses open lagoons to manage their biosolids after they are removed from the digesters. Upgrading of these facilities could provide a separate and appreciable opportunity for methane emissions reductions. At present, the facility uses an uncovered lagoon to store digestate. Storage

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[17] J. Tauber, V. Parravicini, K. Svardal & J. Krampe, *Quantifying Methane Emissions from Anaerobic Digesters*, 80 Water, Sci. & Tech. 1654, 1655 (2019), https://iwaponline.com/wst/article/80/9/1654/71591/Quantifying-methane-emissions-from-anaerobic.

[18] B. Morelli et al., *Life Cycle Assessment and Cost Analysis of Anaerobic Co-Digestion of Food Waste at a Medium-Scale Water Resource Recovery Facility-Tucson*, AWWA's 2019 Sustainable Water Management Conference (2019), https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=344856.

[19] *See generally* Semra Bakkaloglu, Jasmin Cooper, & Adam Hawkes, *Methane Emissions Along Biomethane and Biogas Supply Chains Are Underestimated*, 5 One Earth 724 (2022), included as Attachment 3.

of this digestate in these lagoons under anaerobic conditions can produce significant additional methane emissions as the residual organic matter is decomposed. Lagoon storage can be switched to other approaches, such as drying and landfilling, to generate less fugitive emissions. Simply put, a goal of reducing emissions could be more effectively achieved through addressing the uncovered lagoon than by building the proposed RNG Facility.

Before passage of the VEIA, at least as of August 2020, the WVWA planned to rehabilitate its anaerobic digesters and construct and operate its own RNG Facility and inject its upgraded biogas into Roanoke's distribution grid.[20] The WVWA expected the project to allow it to produce and sell environmental attributes (Renewable Identification Numbers, or "RINs") under the Renewable Fuel Standard Program.[21] Now that the WVWA has entered a partnership with Roanoke Gas, the plan is for the two companies to instead use proceeds from the sale of RINs to help offset the RNG Facility Revenue Requirement and split any remaining proceeds evenly between them; Roanoke Gas has indicated it intends to credit 75% of its RIN proceeds to customers and keep 25% for shareholders.[22] While the RFS program requires certain volumes of renewable fuel to "replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel," the Company has not yet clearly indicated how the RNG produced at the Facility will fit into any of these categories.[23]

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[20] See Company Response to ER Set 3-1(a), Confidential Supplemental Attachment, included as Attachment 4, at 19.

[21] *Id.*

[22] Application Vol. 1, at 6.

[23] In response to the Staff's request that Roanoke Gas confirm that the RNG will not be used to "produce compressed natural gas or liquefied natural gas that will be used as renewable transportation fuel and replace diesel combustion in vehicles," the Company only stated that it would not "directly" use the RNG for those purposes, and would instead incorporate them into the distribution system, "which will displace the purchase of traditionally sourced natural gas (avoided gas purchases)." Company Response to Staff Set 7-39, included as Attachment 4, at 134.

II. The Company's Emission Reduction Estimates Are Inflated.

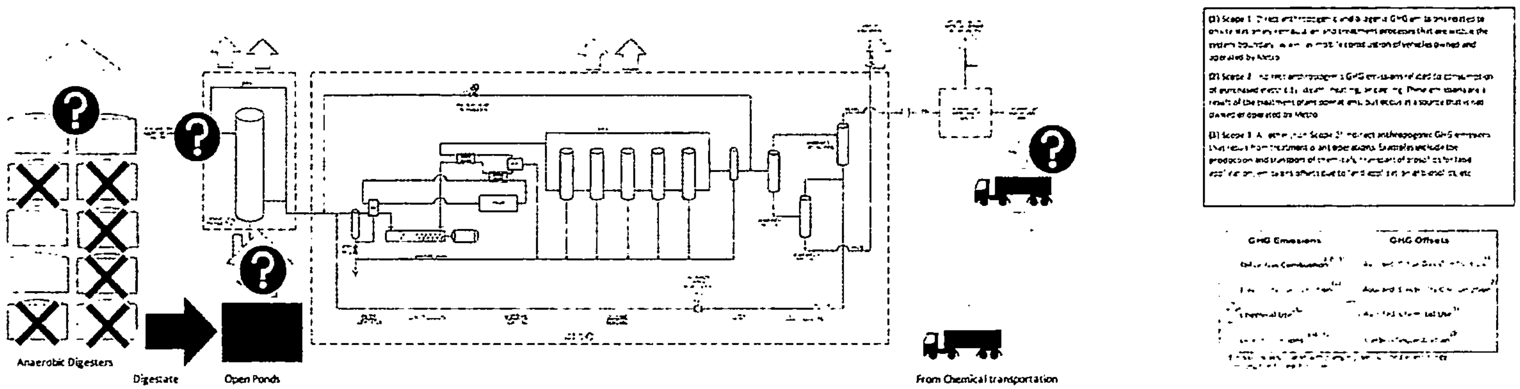

Figure 1. Updated process schematic for the Application highlights a few of the sources of uncertainty in this project. The anaerobic digestion system at the WVWA facility is extensive and six of the digesters are not in service. The emissions from these units are poorly quantified and yet the expected change in their emissions forms the basis for most of the emissions reductions claimed in this Application. The management of digestate represents a major, undiscussed source of emissions. The extent to which the upgrades to the digesters will result in emissions reductions cannot be verified.

The Application attempts to quantify the Project's benefits in terms of Scope 1, 2, and 3 emission reductions, but it overestimates the reductions and fails to count anticipated increases in emissions. Carbon accounting is typically organized by dividing an organization or facility's emissions into three categories. Scope 1 emissions are direct emissions generated on site. For a wastewater treatment plant, this is typically the CO_2 generated from aerobic processes and the CH4 generated by anaerobic processes, as well as nitrous oxide. Scope 2 emissions are those associated with electricity production that occurs offsite. For a wastewater treatment plant these are dominated by the power needed to run aeration units, pumps and other equipment. Scope 3 emissions are all those emissions in the supply chain for which the organization or facility is responsible. For wastewater treatment plants that includes chemicals manufacturing and transportation fuels used by facility vehicles. The Application (1) overstates Scope 1 emissions reductions by overestimating reductions in fugitive biogas emissions; (2) overstates Scope 3 emissions reductions by overestimating reductions due to substituting RNG for diesel in vehicles; and (3) understates various increases in Scope 1 emissions due to the Project. While other aspects of the Company's accounting may be inaccurate, incomplete, or based on faulty data, I have limited my review to the aspects of the accounting most likely to impact the ultimate question of whether the Project, as currently proposed, will result in greenhouse gas emission reductions.

1. The Company's Fugitive Biogas Emissions Reduction Estimates Are Too High.

My evaluation of the Application suggests that the Scope 1 Emissions in the GHG Inventory,[24] specifically the fugitive biogas emissions reduction estimates, are based on numbers that are too high. As a result, the Application's claims of the Project's emissions reductions are

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[24] See Company Response to Staff Set 3-27, Confidential Attachment (Roanoke GHG Inventory Tool), included as Attachment 4, at 1–10.

greatly overestimated (which, by extension, also calls into question whether the Project is ultimately in the public interest). The Company's Scope 1 Emissions estimates are too high because: (1) the baseline biogas throughput of the WVWA plant is lower than the Application suggests, and (2) the percent reduction in emissions that could be expected from digester rehabilitation are overestimated.

a. The Company overestimates the baseline biogas throughput of the WVWA plant.

The Company expressed their leakage rate as a percentage, which is common in the context of methane leaks, but that means that an accurate understanding of the overall throughput of the facility is critical for assessing the emissions reduction potential of the project. The Company's baseline biogas production figures, however, are inflated, leading to a large overestimate in the reduction in total fugitive biogas emissions due to the digester rehabilitation. In other words, the higher the baseline biogas throughput the Company estimates, the higher the fugitive biogas emissions appear to be at the baseline. That overestimate of the baseline fugitive biogas emissions in turn results in an overestimate of the change in fugitive emissions due to the digester rehabilitation.

The Company uses 341 standard cubic feet per minute (scfm) as its input for the baseline annual biogas production,[25] but the historical measured biogas production data do not support an aggregate (sum of biogas going to boilers, flaring, and leakage) flow of 341 scfm (GHG Inventory Tool, 108,000 + 119,534 + 263,205 standard cubic feet per day (scfd)). Technical Memorandum 2 suggests the plant's actual biogas

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[25] See Company Response to Staff Set 3-27, Confidential Attachment (Roanoke GHG Inventory Tool: "Inputs" tab), included as Attachment 4, at 4.

production average is closer to 175 scfm (Technical Memorandum 2 Table 2, 206000 scfd + 22% for leakage). Figure 2, taken directly from Technical Memorandum 2, shows how different the "Measured (original)" and "Measured (corrected)" numbers are, and how close the corrected numbers are to theoretical predictions based on the volatile solids coming into the plant, which are the carbonaceous material that is transformed into biogas in the digesters. The Company argues that there is no discrepancy in these figures because these data were from different time periods, but the Company does not explain why there would be such a large difference in biogas production in different years. The data from 2014-2019[26] are very stable, the population of Roanoke has not increased dramatically,[27] and nothing in the record indicates that plant operations changed significantly in 2020-2021. Using this updated number for biogas throughput of the plant, the carbon benefits of this project are overstated by between 2-3 times—an artificially high baseline production level results in a similarly inflated emissions level, making subsequent *reductions* in emissions look greater than they actually are. As stated in the WVWA's Technical Memorandum No. 2, "[a]fter discussions with WPCP operations and laboratory staff, it was determined that the measured digester gas has been incorrectly reported in each monthly data report as a result of the wrong conversion factor being used to produce an hourly gas production rate from the total gas volume recorded. The reported hourly flow rates were overestimated by a factor of 2.4."[28] The Application suggests that Scope 1 emissions would be reduced by 11,435 MT CO_2e/yr[29] but we

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[26] See Company Response to ER Set 3-1(a), Confidential Supplemental Attachment (Technical Memo 2 Digester Process Evaluation, Figure 2), included as Attachment 4, at 24.

[27] The 2010 census registered a population of 97,032; as of July 2021, Roanoke's population estimate was 98,865. United States Census Bureau, *Dashboard – Roanoke city, Virginia*, https://www.census.gov/quickfacts/fact/dashboard/roanokecityvirginia/PST045221.

[28] *See* Company Response to ER Set 3-1(a), Confidential Supplemental Attachment (Technical Memo 2 Digester Process Evaluation), included as Attachment 4, at 25.

[29] Application Vol. 3, at 6 (Testimony of Becky Luna, Ex. 1, Table 3).

believe that the updated estimate, based on the new biogas throughput at the plant, is closer to 3,036 MT CO_2e/yr.

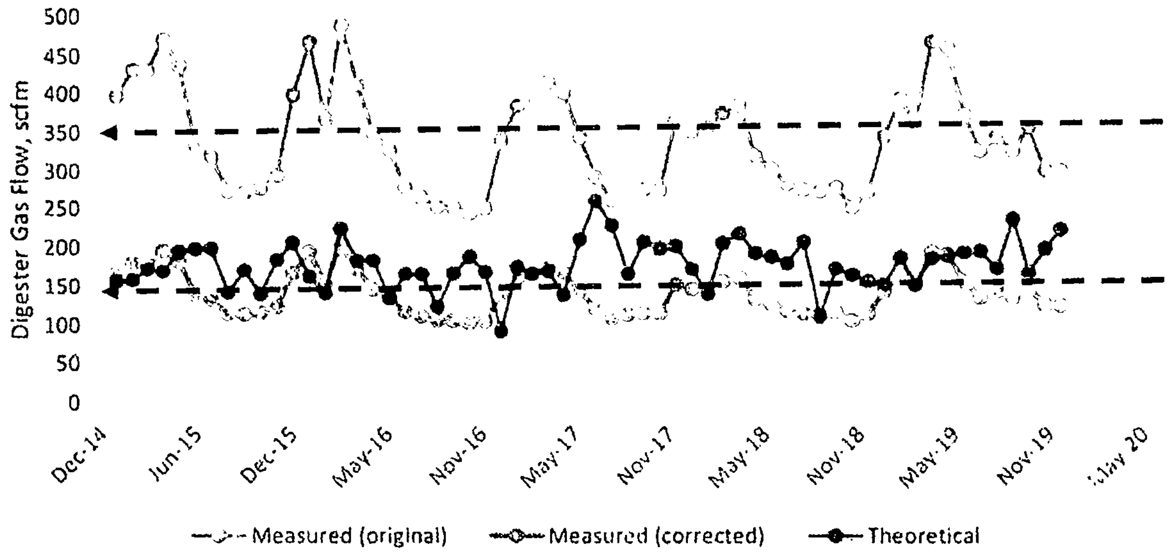

Figure 2. Historical biogas estimates for the plant were incorrect and by using these incorrect numbers the application significantly overstates the proposed benefits of the project in terms of absolute emissions reductions. It is worth noting that the methane emissions at the WVWA facility listed in the report are rough approximations, not measurements.

b. The Company overestimates percent reductions in digester leakage from rehabilitation.

The Application's claimed Project emission reductions rely heavily on achieving a large percent reduction in fugitive biogas emissions from the digesters due to the rehabilitation effort that is currently underway. As discussed below, if the rehabilitation fails to achieve a leakage rate below 5% to 10%, the Project will not result in *any* reduction in greenhouse gas emissions. The WVWA engineers expect a biogas capture rate of 98.6% for their rehabilitated digesters.[30] This

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[30] Application Vol. 3, at 7 (Testimony of Becky Luna, Ex. 1).

means the WVWA expects to achieve a leakage rate below 1.4% in their digesters. Given that the digester rehabilitation effort is not even primarily aimed at reducing leakage, but rather at increasing biogas production,[31] it is surprising that the Company is so optimistic that the rehabilitation will result in such a high level of leakage reduction.

The Company states that the biogas capture rate of 98.6% is based on field testing of two rehabilitated digesters, but the overall project's leakage rate is likely to be higher than 1.4%.[32] The United Nations Framework Convention on Climate Change "Tool 14: Project and leakage emissions from anaerobic digesters" provides several emissions factors for anaerobic digesters. The lowest emissions rate they provide is 2.8% for "Digesters with steel or lined concrete or fiberglass digesters and a gas holding system (egg shaped digesters) and monolithic construction,"[33] and this emissions factor is considered a "best case scenario."

Thus, the Company assumes it can reduce leakage rates by twice as much as what the UN suggests could be considered a "best case" rehabilitation scenario. It is important to mention the increasing marginal costs of emissions abatement—in other words, each additional percent reduction costs more to achieve. Reducing fugitive emissions from 20% to 10% is likely much less challenging and/or expensive than reducing emissions from 2% to 1%. That means if the existing 22% emissions reductions achieve an optimistic rate of 3%, then the Scope 1 emissions should be

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[31] *See, e.g.*, Company Response to Staff Set 7-49, included as Attachment 4, at 135–36 ("Rehabilitation of the anaerobic digesters will result in additional biogas being routed to the biogas upgrading system to produce RNG."); *see also generally* Company Response to ER Set 3-1(a), Confidential Supplemental Attachment (Technical Memo 2 Digester Process Evaluation), included as Attachment 4, at 13–126.

[32] *See* Company Response to ER Set 5-2(a)–(c), included as Attachment 4, at 132–33; *see also* Company Response to ER Set 3-1(a), Confidential Supplemental Attachment (Technical Memo 2 Digester Process Evaluation), included as Attachment 4, at 13–126; Company Response to ER Set 3-1(a)(1), Second Supplemental Attachment (Public), included as Attachment 4, at 127–28; Company Response to ER Set 3-1(a)(2) Second Supplemental Attachment (Public), included as Attachment 4, at 129.

[33] U.N. Framework Convention on Climate Change, *Methodological Tool: Project and Leakage Emissions from Anaerobic Digesters*, at 12 (Sept. 22, 2017).

an additional 2,463 MT CO_2e/yr lower. But if the leakage rate is only reduced to 5% or 10%, then the Scope 1 savings would be 3,080 or 6,161 MT CO_2e/yr lower than reported, respectively. These more conservative leakage abatement estimates are consistent with the IPCC and Technical Memorandum 2. The rehabilitation activities described in Technical Memorandum 2 and in the Company's discovery responses would not have appreciable reductions in leakage.[34] A separate Technical Memorandum 3 describes efforts to add a secondary digester cover, but effectively sealing such old units is challenging, as described above.[35] The activities likely *will* increase biogas generation. But this would effectively represent a shift of biogas from the storage lagoons to the biogas stream, which would represent a climate benefit, but not one that is considered in the calculations reported in the GHG Inventory. The leak abatement calculations in Table 1 correspond to emissions reductions of 75% or a final leakage rate of just over 5%, which corresponds to the performance the United Nations expects of digesters of the type operated at the WVWA.

It is also important to emphasize here that retrofits to these digesters are not guaranteed to produce emissions reductions. Some reductions will be expected given how leaky the existing infrastructure is, but these digesters are quite old and in poor condition, as the Technical Memorandum 2 makes clear.[36] Digesters are large, pressurized vessels that can have low leakage rates when they are new but are difficult to seal after years of service. New digesters would come with warranties and assurances that the planned retrofit will need to match in order to have confidence that the emissions reductions are real. The cost of replacing digesters, however, would be tens of millions of dollars, very likely

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[34] See Company Response to ER Set 5-2(b), included as Attachment 4, at 132–33.

[35] Company Response to ER Set 3-1(a), Confidential Supplemental Attachment (Technical Memo 2 Digester Process Evaluation), included as Attachment 4, at 19.

[36] Company Response to ER Set 3-1(a), Confidential Supplemental Attachment (Technical Memo 2 Digester Process Evaluation), included as Attachment 4, at 19–21.

eclipsing the financial benefits of all other new sources of revenue and credits derived from this effort.[37] In light of this technological uncertainty, it is important to consider how the project engineers will guarantee that the fugitive emissions reductions will be achieved and/or update the Application calculations. Using three more common leakage rates of 3%, 5%, and 10% and then translating those emissions into CO_2 equivalents, shows that all of the remaining climate benefits of this project will be canceled in the likely event that the WVWA engineers cannot reduce leakage below 5-10%. Table 2 provides a sensitivity analysis that explores how much the final emissions reduction target impacts the overall GHG inventory. Notably, the initial emissions rate of 22% is never fully substantiated and would also have a major impact on these estimates. If the plant is leaking more (or less) methane, even by a few percentage points, this could completely erase the environmental benefits of the proposed project.

Table 2. The Scope 1 emissions estimates are highly sensitive to the WVWA's ability to cut fugitive emissions from their plant. The application assumes an unrealistically ambitious cut from 22% leakage to 1.5% leakage. Using three more common leakage rates of 3%, 5%, and 10% and then translating those emissions into CO_2 equivalents shows that all of the remaining climate benefits of this project will be canceled in the likely event that the WVWA engineers cannot reduce leakage below 5-10%. The numbers in this Table are derived from the Company's GHG Inventory Tool (Confidential).

Baseline Biogas Production	263,500	cfd
Baseline Biogas Leakage @22% leakage	108,000	cfd
Baseline Biogas Leakage	13,559	metric tons CO_2e/year
Projected Biogas Leakage @ 10% leakage	6,161	metric tons CO_2e/year
Projected Biogas Leakage @ 5% leakage	3,080	metric tons CO_2e/year
Projected Biogas Leakage @ 3% leakage	2,463	metric tons CO_2e/year
Projected Biogas Leakage @ 1.5% leakage	905	metric tons CO_2e/year

2. The Company Overestimates Emissions Reductions Due to RNG vehicles.

The use of the methane from the digesters as a transportation fuel to offset the emissions from diesel fuel at the facility represents the major source of emissions reductions in the project

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[37] VIC KELSON & BRAD SCHROEDER, WASTE-TO-ENERGY TASK FORCE PHASE 1 REPORT, CITY OF BLOOMINGTON UTILITIES, at 17 (Mar. 6, 2020), https://bloomington.in.gov/sites/default/files/2020-03/20200306%20Waste-to-Energy%20Memo.pdf.

The use of the methane from the digesters as a transportation fuel to offset the emissions from diesel fuel at the facility represents the major source of emissions reductions in the project partnership between the WVWA and Roanoke Gas Company. Compressed natural gas vehicles have a high lifecycle fugitive emissions load, *i.e.*, they leak methane at high rates.[38] These fugitive emissions are not considered in the current accounting of future emissions. Empirical estimates from similar fleets suggest lifecycle emissions reductions of up to 15% relative to diesel baselines.[39] This suggests that the emissions estimates from "RNG" vehicle combustion, which are approximately 2,538 MtCO_2e/yr in the application, are likely much smaller, on the order of 750 MtCO_2e/yr. This overestimate of the emissions reductions that would be achieved by moving to methane powered vehicles could have a major impact on the final GHG Inventory.

3. The Company Has Not Adequately Accounted for Increases in Emissions Due to the Project.

The environmental benefits of wastewater-to-biogas facilities are being studied around the world and the literature is increasingly clear that the full lifecycle of the process must be considered in order to produce a complete understanding of the climate impacts of these projects. In this respect, there are several important aspects of this project to which the Application has not given adequate consideration in the emissions accounting.

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[38] Zhiyi Yuan, et al., *Life Cycle Greenhouse Gas Emissions of Multi-Pathways Natural Gas Vehicles in China Considering Methane Leakage,* 253 Applied Energy 113472 (2019) (https://www.sciencedirect.com/science/article/pii/S0306261919311468?casa_token=QOOhnce9r6AAAAAA:S-5q3fE_yfsWrBfU114CMdFBe_KRI_oKf7qJE5IYW9latyRsoSKMr5TLF7buG5HrHZnT38mH8oI.

[39] Zhiyi Yuan, et al., *Life Cycle Greenhouse Gas Emissions of Multi-Pathways Natural Gas Vehicles in China Considering Methane Leakage,* 253 Applied Energy 113472 (2019) (https://www.sciencedirect.com/science/article/pii/S0306261919311468?casa_token=QOOhnce9r6AAAAAA:S-5q3fE_yfsWrBfU114CMdFBe_KRI_oKf7qJE5IYW9latyRsoSKMr5TLF7buG5HrHZnT38mH8oI.

a. **The Company has completely overlooked fugitive emissions from biogas upgrading.**

As shown in Figure 3, the methane emissions from biogas upgrading are non-trivial and represent a new source of emissions that ranges from 0-6% of total emissions. Each of the upgrading steps creates new opportunities for failure and leakage. The probabilities of these failures increase nonlinearly with the complexity of the upgrading infrastructure.[40] The use of repurposed and existing gas upgrade equipment from another project, as Roanoke Gas Company proposes, for example, could introduce opportunities for leakage.

Additionally, the Company's emissions accounting does not include emissions due to anomalous events. These are equipment or human failures that are common in engineered systems but difficult to predict and can result in significant emissions. For example, someone may mistakenly leave a valve partially open and thus allow methane, a colorless and odorless gas, to leak for an extended period of time. The science is very clear that methane emissions from infrastructure systems are dominated by anomalous events that are correlated with system size and complexity.[41] Anticipating these kinds of events and quantifying their emissions is challenging, but the data are unequivocal that these events dominate the emissions profile.[42] Therefore, calculations should not assume simply that these "super emitting" events do not occur or that they occur at the same rate in the "baseline" and "future condition" states of the project.

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[40] Daniel Zavala-Araiza, et al., *Super-emitters in Natural Gas Infrastructure are Caused by Abnormal Process Conditions*, 8 Nature Communications 1, 6 (Jan. 16, 2017), https://www.nature.com/articles/ncomms14012.

[41] *See, e.g.*, Zachary D. Weller, Steven P. Hamburg, & Joseph C. von Fischer, *A National Estimate of Methane Leakage from Pipeline Mains in Natural Gas Local Distribution Systems*, 54 Env't Sci. & Tech. 8958, 8960 (2020); Ramon A. Alvarez et al., *Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain*, 361 Science 186, 186 (2018).

[42] *See, e.g.*, Company Response to Staff Set 7-49, included as Attachment 4, at 135–36 ("Rehabilitation of the anaerobic digesters will result in additional biogas being routed to the biogas upgrading system to produce RNG."); *see also generally* Company Response to ER Set 3-1(a), Confidential Supplemental Attachment (Technical Memo 2 Digester Process Evaluation), included as Attachment 4, at 13–126.

If the Company had used best practices for this kind of analysis, it would have done two things differently: (1) it would have substantiated estimates with data, to provide confidence about the numbers used in the calculation; and (2) it would have performed a sensitivity analysis, providing ranges for each parameter to understand how uncertainty propagates through the analysis and influences the final estimates.

b. The Company has underestimated emissions due to flaring during RNG Facility downtime.

In a similar vein, the amount of gas that the Company would flare during the RNG Facility's downtime is likely underestimated. The reliability of the upgraded units themselves is a concern that could lead to unplanned releases of methane, high operation costs, and risks to the Roanoke infrastructure downstream. The application assumes that upgrading units will be down for maintenance 5% of the time and indicates the gas will be flared during this maintenance.[43] The Company has not offered verifiable evidence to support its estimate of 5% downtime.[44] And, as the "long tails" (the data points outside of the boxes) in Figure 3 suggest, the emissions due to maintenance downtime can be many times higher than the Company's estimates. All it takes is one anomalous event for the life cycle budget of the system to become overwhelmed. Studies of existing biogas upgrading units are needed to understand how plant operating conditions and real-world factors contribute to these unplanned methane releases.

[43] Company Response to ER Set 3-1(c), included as Attachment 4, at 11.

[44] Company Response to ER 3-1(c)(iii), included as Attachment 4, at 12 ("[B]ased on our conversations with wastewater treatment facilities operating RNG systems, and in our discussion with equipment manufacturers, an assumption of 95% uptime is valid.").

c. The Company has not considered emissions due to transmission, storage, and distribution.

Finally, a major source of new emissions that the Company does not count at all are the fugitive emissions from the Roanoke Gas Company distribution system. Conservative estimates of methane emissions from transmission, storage, and distribution (TSD) are included below in Figure 3. The US gas infrastructure is quite leaky. The extent and source of the leaks varies significantly by location.[45] But estimates are that between 1-3% of methane leaks.[46] Connecting the biogas from the WVWA facility to the Roanoke Gas Company would introduce new places for this biogas to enter the atmosphere. These numbers are not included in the carbon budget and, when considered alongside the reliability concerns described earlier, are another part of the reason that more complex infrastructure is less desirable from a leakage prevention standpoint. Fugitive emissions from the Roanoke Gas Company's pipelines would need to be verified or included in the Scope 1 emissions of the project.

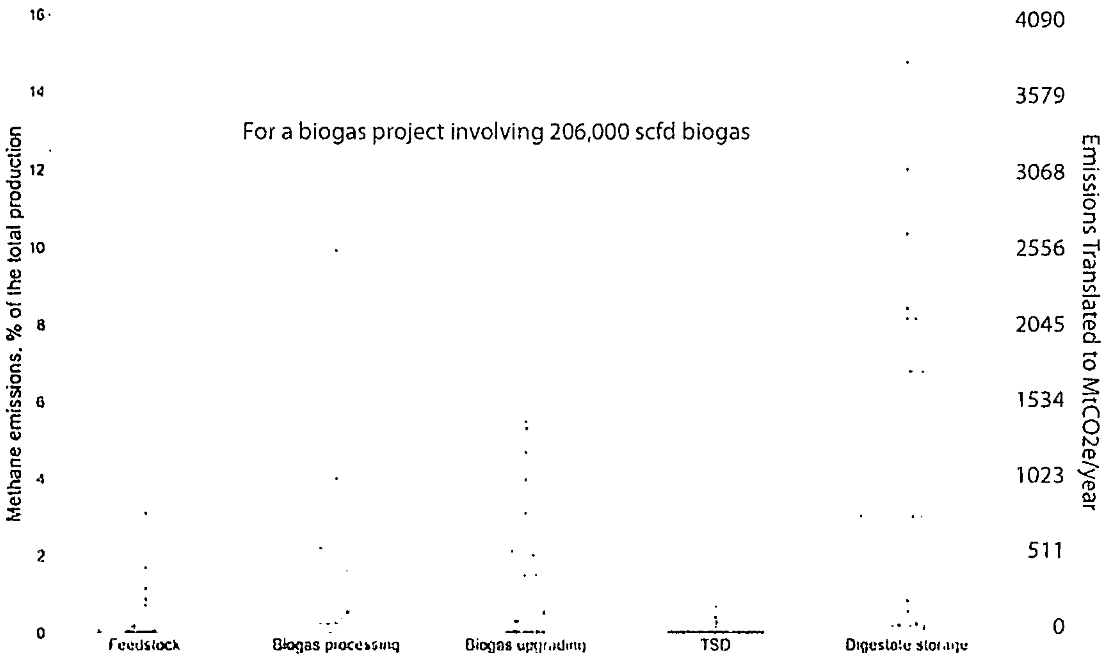

Figure 3.[47] Fugitive emissions from the biogas supply chain are typically much higher than expected. These data were derived from a study of numerous waste and wastewater to biogas facilities representing feedstock (n = 52), biogas processing (n = 95), biogas upgrading (n = 84), TSD (n = 48), and digestate storage (n = 120) stages. The boxes represent the middle 50% of the data – that is, all of the points falling below each box are the lowest 25% of the data, while all of the points falling above the top of the box represent the highest 25% of the data. Points falling above the top of the line extending from the box are outliers, *e.g.*, extreme high values that fall outside the expected range of methane emissions of the facilities studied. The secondary y-axis puts these fugitive emissions in the context of a biogas project of the size being considered here in units of CO_2 equivalents, which can facilitate more direct contextualization of these data.

III. Recommendations

For these reasons, I recommend that the Commission:

1) Deny the Application so that the Company can resubmit with more complete and accurate data and other evidence of the Project's reasonably anticipated reductions in greenhouse gas emissions, including verifiable data on biogas throughput, actual measurements demonstrating that the WVWA can achieve the leakage emissions reductions claimed, and a detailed plan for managing leakage from a compressed natural gas transportation fleet; and

2) Require that future applications for approval under Virginia Code Section 56-525 consider the full lifecycle of the RNG generation, including but not limited to:

- a plan to manage anomalous events that cause additional fugitive methane emissions;
- an estimate of the role of digestate management in lifecycle methane emissions as it relates to quantifying additionality; and

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[45] Environmental Defense Fund, *Local Leaks Impact Global Climate*, https://www.edf.org/climate/methanemaps.

[46] Global Energy Monitor, *The Gas Index*, https://globalenergymonitor.org/projects/the-gas-index/.

[47] Semra Bakkaloglu, Jasmin Cooper, & Adam Hawkes, *Methane Emissions Along Biomethane and Biogas Supply Chains Are Underestimated*, 5 One Earth 724, 727 (2022), included as Attachment 3.

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- a post-approval monitoring plan to periodically and regularly verify that both gas production and leakage match the figures in a Company's application, and to address situations in which more fugitive emissions are detected than were anticipated in an application.

- a post-approval monitoring plan to periodically and regularly verify that both gas production and leakage match the figures in a Company's application, and to address situations in which more fugitive emissions are detected than were anticipated in an application.

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Virginia State Corporation Commission
eFiling CASE Document Cover Sheet

Case Number **(if already assigned)**	PUR-2022-00125
Case Name **(if known)**	Roanoke Gas Company — Application for approval of a certificate of public convenience and necessity to construct, own, and operate a digester gas conditioning system and for a rate adjustment clause designated Rider RNG and related tariff provisions
Document Type	EXTE
Document Description Summary	Public (Redacted) version of the direct testimony and exhibits of Andrés F. Clarens on behalf of Appalachian Voices ("Environmental Respondent") - Part 2

Total Number of Pages	76
Submission ID	26034
eFiling Date Stamp	10/21/2022 4:58:00PM

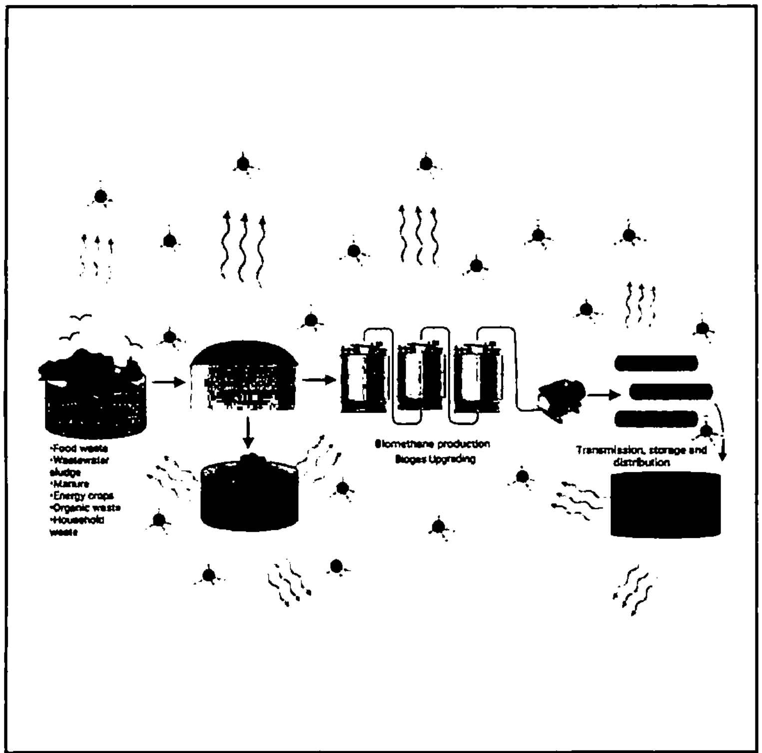
Attachment AFC-3

Article

One Earth

Methane emissions along biomethane and biogas supply chains are underestimated

Graphical abstract



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In brief

Biomethane and biogas have emerged as cleaner alternatives for natural gas, as they generate fewer greenhouse-gas emissions. However, their production and distribution can still result in methane emissions, the magnitude of which remains unclear. Here, we evaluate methane emissions throughout the biomethane and biogas supply chains and show that emissions are greater than previously estimated. The digestate stage generated the most CH_4, and 62% of total emissions were released by just 5% of emitters.

Highlights

- The biomethane and biogas supply chain may emit up to 18.5 Tg CH_4 per year
- Biomethane and biogas emit much less CH_4 than oil and natural gas
- CH_4 loss rates in biomethane and biogas supply chain exceed those in oil and natural gas
- The top 5% of emitters account for 62% of CH_4 emissions

Bakkaloglu et al., 2022, One Earth 5, 724–736
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Article

Methane emissions along biomethane and biogas supply chains are underestimated

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SCIENCE FOR SOCIETY An immediate shift away from coal and oil for energy is necessary to limit rising temperatures but is challenging due to energy needs, particularly in areas like heating and cooling that require substantial energy supply all year round. Natural gas is presently being used as a bridging fuel. It delivers the same performance as coal and oil but has lower CO_2 emissions. However, natural gas releases methane (CH_4), which is a more powerful warming agent than CO_2. Biomethane and biogas have emerged as strong candidates to replace gas and lower CO_2 and CH_4 emissions. However, these replacement fuels are not CH_4 emission free. Indeed, CH_4 is released at various points during production and distribution, but a thorough understanding of where, when, and how much CH_4 is released remains absent. A synthesis and analysis of existing biomethane and biogas CH_4 emission data reveal that CH_4 emissions throughout the supply chains have been underestimated. The majority of CH_4 comes from just a few super-emitters and mainly at the digestate stage. Mitigating CH_4 throughout biomethane and biogas supply chains is urgently needed if we are to limit global warming to 1.5 C.

SUMMARY

Although natural gas generates lower CO_2 emissions, gas extraction, processing, and distribution all release methane, which has a greater global warming potential than CO_2. Biomethane and biogas that use organic wastes as a feedstock have emerged as alternatives to natural gas, with lower carbon and methane emissions. However, the extent to which methane is still emitted at various stages along biogas and biomethane supply chains remains unclear. Here, we adopt a Monte Carlo approach to systematically synthesize the distribution of methane emissions at each key biomethane and biogas supply chain stage using data collected from the existing literature. We show that the top 5% of emitters are responsible for 62% of emissions. Methane emissions could be more than two times of greater than previously estimated, with the digestate handling stage responsible for the majority of methane released. To ensure the climate benefits of biomethane and biogas production, effective methane-mitigation strategies must be designed and deployed at each supply chain stage.

INTRODUCTION

As we move further into the 21st century, energy systems must move away from fossil fuels and grow in renewable energy capacity if Paris Agreement temperature targets are to be met. However, due to challenges in adopting low-carbon technologies, certain areas of global energy systems are difficult to decarbonize. These include heavy industry, transport, and heating and cooling systems, which together account for a significant portion of carbon dioxide (CO_2) emissions.[1] Natural gas has therefore been used as an important alternative fuel, which can offer large-scale energy supply, especially for domestic space heating and hot water needs, electricity generation, and industrial applications, with much lower CO_2 emissions compared with oil and coal. Although replacing oil and coal with natural gas reduces CO_2 emissions, fugitive emissions from the supply chain of natural gas—gas extraction, processing, and distribution—can all release CH_4. Around 39.6 million tonnes of CH_4 were emitted in 2021,[2] representing 61% of oil and gas emissions and 30% of total-energy-sector CH_4 emissions. Since CH_4 has a much stronger global warming potential than CO_2 and is currently responsible for at least one-quarter of global warming, there are strong calls for natural gas use to be reduced by at least 35% by 2050 and 70% by 2100 relative to 2019;[3]

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therefore, alternative clean-energy methods are vital to replace natural gas to limit global warming to 1.5°C.

An alternative method of decarbonizing natural gas is via replacing it with biomethane or biogas, which is a mixture of gases (mostly CH_4 and CO_2) produced from biodegradable materials. Biomethane and biogas production and use have been put forward as part of mitigation efforts,[4] with up to 37 exajoule (EJ)/year of biomass-based gases in Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C (IPCC SR1.5C) scenarios,[5] which limits temperature rises to below 2°C. The International Energy Agency (IEA)[6] reported that global biomethane and biogas production could satisfy nearly 20% of global gas demand if its sustainable potential was fully utilized.[6] Because biomethane is similar to natural gas, it can be easily stored and injected into the existing natural gas infrastructure, potentially providing reliable and affordable energy.[7] At the time of writing, Europe is the world leader in biomethane production by upgrading biogas, followed by the United States, China, and Canada.[8] According to the World Biogas Association (2019), 700 biogas-upgrading plants are operating worldwide, with 195 in Germany (the largest producer), with biogas currently dominating biomethane production. Biomethane and biogas production are expected to grow further, with demand predicted to grow 9-fold by 2040 compared with 2018 levels,[6,9] driven by increases in the volume of organic waste generated by modern societies, changes in waste practices, and the phasing out of fossil fuels aimed at reducing greenhouse gas (GHG) emissions and meeting government targets. Given this host of commitments, investments, and developments, biomethane and biogas could be crucial in helping to establish a clean, reliable, and affordable global energy system.

However, large quantities of CH_4 can still be emitted from the biomethane and biogas supply chains, including digestate handling, anaerobic digesters, upgrading units, feedstock storages and transmission, and storage and distribution stages.[4] CH_4 is a relatively short-lived GHG but has a global warming potential (GWP) 27.2 ± 11 times larger than CO_2 over a 100-year horizon and 80.8 ± 25.8 times larger over a 20-year time horizon for biogenic sources.[10] The importance of reducing CH_4 emissions to meet Paris Agreement[11] targets has been demonstrated by Rogelj et al.,[12] as it is an important GHG in terms of potential overshooting of Paris Agreement targets, where warming exceeds "well below 2°C" and then returns to the target level by 2100,[10] leading to potential tipping points in physical and socio-economic systems. The IPCC (Intergovernmental Panel on Climate Change) Sixth Assessment Report (AR6) (Working Group III)[13] highlighted CH_4 as playing a significant role in determining whether or when 1.5°C is achieved, as reducing CH_4 emissions will offset global temperature increase much more quickly than CO_2, due to its relatively short lifetime and higher GHG potency. The AR6 report also noted that reductions to CH_4 emissions will need to occur more rapidly than CO_2 and that reducing CH_4 (and other non-CO_2 GHG) emissions is essential for lowering warming.[13] As the AR6 scenarios predict biomethane capacity to increase by up to 200-fold between 2020 and 2050,[14] understanding where CH_4 emissions occur and how much is emitted is crucial.

There are some emissions-measurement studies to date focusing on specific biomethane facilities,[4,15–22] which have measured on site (measurement of emissions at each individual point source) and off site (measurement of emissions based on observations made away from the site). These can also be referred to as bottom-up (on-site) and top-down (off-site) studies. These have found that emissions from biomethane facilities can be up to 97 kg h^{-1} CH_4.[4,16–24] However, a comprehensive evaluation by characterizing the distribution of CH_4 emissions at each biomethane and biogas supply chain stage remains unclear.

Here, we bring together the published emissions data from CH_4-measurement studies to assess and synthesize the distribution of emissions from each supply chain stage in order to characterize the emissions profile of the biomethane and biogas supply chain (see experimental procedures and Figure S1 for the selected supply chain route). A Monte Carlo aggregation examines the distribution of supply chain emissions. This allows for the emission profile of biomethane and biogas supply chains to be characterized. We find that, while the biomethane and biogas supply chain emits less CH_4 than the oil and natural gas supply chain, the emission rate is higher. Furthermore, we find that 62% of cumulative emissions are released by just the top 5% of emitters. We also find that methane emissions could be more than two times higher than previously estimated, and the digestate-handling stage contributed to the largest CH_4 emissions along the supply chain. Our results will allow for a greater understanding of how to improve the sustainability of biomethane and biogas production by providing plant operators, investors in the supply chain, and policymakers with information on where improvements can be made in biomethane and biogas supply chains to reduce CH_4 emissions, as well as whether existing or proposed CH_4 regulations are sufficient or need to be revised.

RESULTS

Method summary

To assess overall supply chain emissions, the biomethane supply chain is divided into five major stages: (1) feedstock; (2) biogas production; (3) biogas upgrading; (4) transmission, distribution, and gas storage; and (5) digestate storage. This study was compiled from several published studies and the data from on-site (taken at each individual emission source) and off-site measurements (reported for the entire site). The kernel density estimation (KDE) function was used to assess the characteristics of the data distribution gathered from individual sources for each stage of the supply chain. Following that, a Monte Carlo simulation was performed to estimate total supply chain emissions, which were then compared with the off-site emissions reported from whole-site measurements in previously published studies (see the experimental procedures for further details).

Total supply chain emissions

The cumulative distribution of the supply chain CH_4 emissions is shown in Figure 1A. Median and mean emissions are 40.0–42.3 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (41.1–41.3 at the 95% confidence interval [CI]) and 51.4–52.7 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (52.2–52.4 at the 95% CI), respectively, with a 5[th] percentile of 11.0–16.3 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (15.6–15.7 at the 95% CI) and a 95[th] percentile between 118.2 and 144.0 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (131–133 at the 95% CI) using

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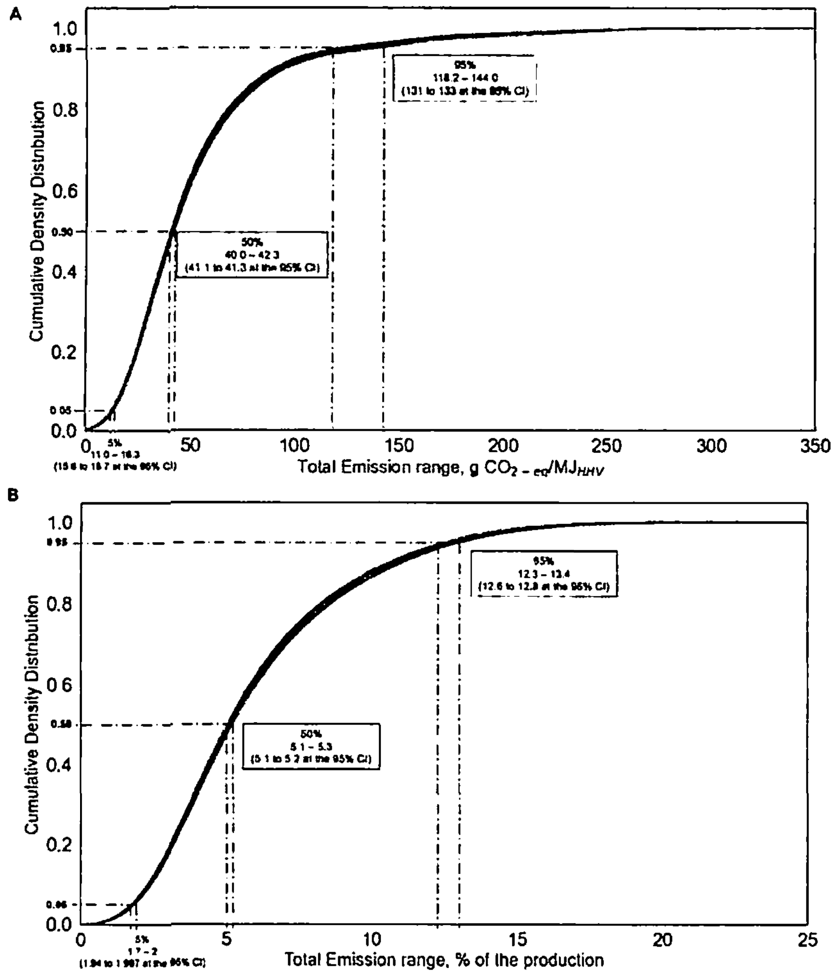

Figure 1. Cumulative distribution of CH_4 emissions from the total supply chain

(A) Cumulative distribution of total supply chain CH_4 emissions for the 10,000 Monte Carlo runs and 100 curves described in the experimental procedures, expressed as g $CO_{2\text{-eq}}/MJ_{HHV}$.

(B) Cumulative distribution of total supply chain CH_4 emissions for the 10,000 Monte Carlo runs and 100 curves, expressed as percentage of total CH_4 production.

The range of 5th, 50th, and 95th percentile estimates are shown as dotted black lines. CI: confidence interval.

GWP_{100} values. Each curve defines the cumulative distribution for a single Monte Carlo simulation and shows that total supply chain emissions range from 2.5 to 343 g $CO_{2\text{-eq}}/MJ_{HHV}$. The emissions distribution is highly upward skewed (Figure 1A), which is indicative of disproportionately high emitting sites referred to as "super-emitters" (see the identification of super-emitters section for details). Our findings are consistent with those observed for oil and natural-gas supply chains.[25–30] Using global biogas and biomethane production of 35 megatonnes of oil equivalent (Mtoe) (1.47×10^{12} MJ) in 2018,[6] our model-based estimate of 2018 biomethane supply chain emissions may account for up to 18.5 teragram (Tg) CH_4 per year (6.4–7.8 Tg CH_4 $year^{-1}$ at the 95th percentile and an average of 2.8–2.9 Tg CH_4 $year^{-1}$), which is more than two times greater than the International Energy Agency's (IEA's) estimate of CH_4 emissions from bioenergy (9.1 Tg in 2021).[2] Our estimate of global biogas and biomethane CH_4 emissions is significantly lower than in the global oil and natural-gas supply chain (82.5 Tg in 2021);[2] on the other hand, it is comparable to the production segment of the US oil and natural-gas supply chain (6.1–7.1 Tg $year^{-1}$)[31] based on site measurements.

The cumulative distribution of emissions as a percentage of total CH_4 produced is shown in Figure 1B. The 5th percentile is 1.7%–2.0% (1.94%–2.0% at the 95% CI) of CH_4 production, and the 95th percentile is 12.3%–13.4% (12.6%–12.8% at the 95% CI) of total gas production. The ranges in minimum, median, mean, and maximum values were fairly consistent across all estimates (Figure 1). While the low and median estimates are nearly identical, the disparity between biomethane and natural gas varies widely in the highest estimates. The median ranged from 5.1% to 5.3% (5.1%–5.2% at the 95% CI), with mean emission rates of 5.90%–6.04% (5.9%–6.0% at the 95% CI) of total CH_4 production, which is higher than natural gas (0.8%–2.2% of CH_4 production).[25,26] Rutherford et al.[31] found CH_4 emissions in the oil and natural-gas-production segment to be 1.3% (1.2%–1.4% at the 95% CI), which is significantly lower than our findings. On the other hand, despite declining gas production, one of the highest reported CH_4 emissions from oil and gas production (Uinta Basin from a multi-year record of in-site observations) reveals a higher emission rate than our results (6%–8%).[32] Although emissions from the biomethane supply chain are comparable to oil and natural-gas production in terms of Tg CH_4 $year^{-1}$, the production-normalized emission rate is considerably higher. This could be due to a variety of factors, including poorly managed production facilities; a lack of attention to the biomethane industry resulting in lower investments for modernization, operation, and monitoring; and employment of highly skilled plant operators[16,21] when compared with oil and natural gas. In addition, poor design and management of feedstock and digestate storage units[33] as well as a limited interest in infrastructure emissions may result in higher emission rates compared with the amount of gas produced. Because oil and natural-gas supply chains have been primarily operated by large companies for decades, they have invested more in leak detection and repair.[34,35] On the other hand, given the growth in biomethane generation due to national decarbonization strategies, more urgent efforts are also needed for the biomethane supply chain to address not only CH_4 emissions but also the sustainability of biomethane.

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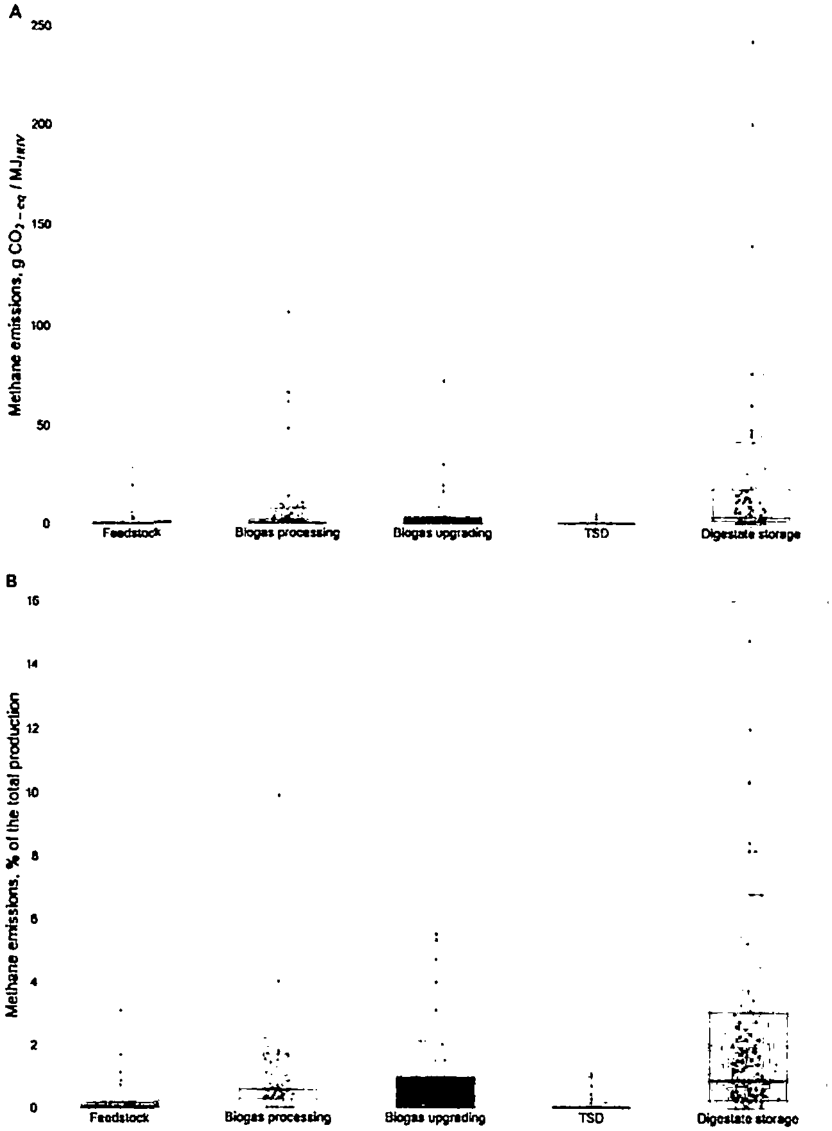

Figure 2. Literature CH_4 emissions from different stages of biomethane supply chain
(A) Emissions range of feedstock (n = 49), biogas processing (n = 100), biogas upgrading (n = 35), TSD (n = 44), and digestate storage (n = 119) stages in g $CO_{2\text{-eq.}}/MJ_{HHV}$.
(B) Emissions range of feedstock (n = 52), biogas processing (n = 95), biogas upgrading (n = 84), TSD (n = 48), and digestate storage (n = 120) stages in terms of total CH_4 emissions as a percentage of the total gas production rate.
Individual estimates are shown as circles in the same color at each stage of the supply chain, with median and 25th and 75th percentile boxes. Sample sizes for each stage are demonstrated in the Figure 3.

Identification of super-emitters

A small proportion of facilities or equipment with disproportionately large emission rates are labeled super-emitters,[36,37] causing the heavy-tailed distribution (see Figure S4). A small number of high emitters may cause under- or overestimations of emissions rates[38] if they have intermittent emissions patterns, insufficient process equipment usage, or inadequate operations and maintenance strategies. In this study, super-emitters have been investigated at various stages across the supply chain, including feeding systems; substrate storage; runoff ponds; pressure relief valves on the anaerobic digesters and gas holders; exhausts and aeration lines of upgrading units; ventilation of units, such as compressors or closed digestate tanks; open digestate storage; and flaring. Within the heavy-tail distribution (Figures 1A and 1B) and the boxplot of each stage's emissions (Figure 2), the mean emission rate is higher than the median because of super-emitters (see Table S1 for details). Since we lack information on on-site CH_4 sources, we identify them as the top 5% of highest emissions based on the cumulative density function of CH_4 emissions, parallel to natural-gas production sites.[29,36,39] The highest 5% of total emissions (199–224.8 g $CO_{2\text{-eq.}}/MJ_{HHV}$) account for 62% (CI: 58%–66%) of cumulative emissions, with a threshold of 211.9 g $CO_{2\text{-eq.}}/MJ_{HHV}$. The characteristics of super-emitters in the biomethane supply chain are similar to those of super-emitters in the oil and natural-gas supply chain (the largest 5% of leaks contribute to 50%–60% of total emissions).[29,36] Since super-emitters are unlikely to remain constant over time, continual monitoring will be required to detect intermittent emission patterns or unpredictable leaks from the biomethane supply chain. Future work is necessary to understand the characteristics of individual super-emitter sites in the biomethane supply chain. The efficiency of mitigation efforts could be improved by investing in the underlying cause of preventable operational conditions at a component level.[30]

Contribution of each supply chain stage

The contribution of each stage of the biomethane supply chain is illustrated in Figure 2A in g $CO_{2\text{-eq.}}/MJ_{HHV}$ and as a percentage of total production in Figure 2B. The distributions are almost identical. Emissions are mainly from digestate storage, followed by production and upgrading stages. Similar results were observed by Reinelt et al.,[17] where the highest emissions are from open digestate storage and pressure-release valves. Similarly, Alvarez et al.[39] found production and gathering units to be the main emission source in the US oil and natural-gas supply chain. Overall, the lowest emissions are exhibited in the transmission, storage, and distribution (TSD) stage, similar to the US oil and natural-gas supply chain.[39]

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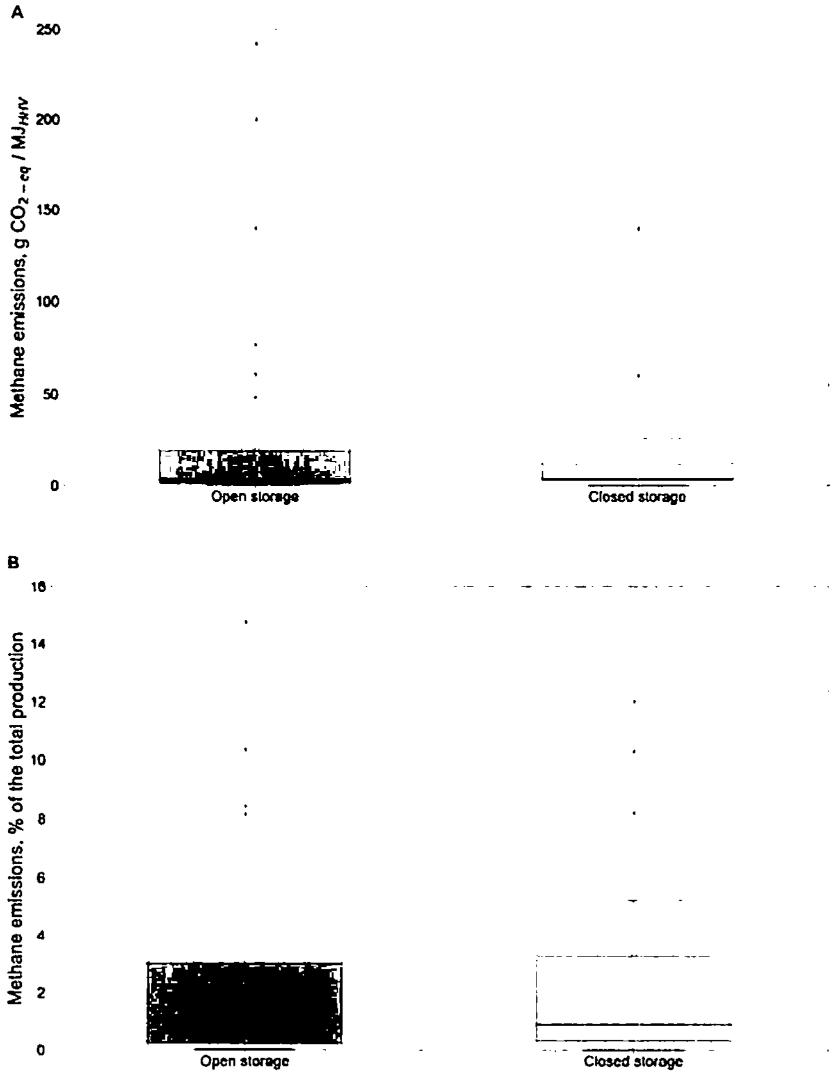

Figure 3. Literature CH_4 emissions of open and closed digestate storage

(A) Emissions from digestate handling from open (n = 98) and closed (n = 21) storage tanks in g CO_{2-eq}/MJ_{HHV}.

(B) In terms of the percentage of total biomethane produced, illustrating emissions from the open (n = 95) and closed (n = 25) storage tanks.

Closed tank emissions originate mainly from leaks of covered material and ventilation of stockpile building.

Of particular note here is that the digestate storage stage is a significant source of CH_4, ranging between 0.05 and 242.1 g CO_{2-eq}/MJ_{HHV} (Figure 2A) or 0.005% and 14.8% of the total biomethane produced (Figure 2B). Sources of emissions are open or covered digestate (liquid and solid) storage tanks and lagoons. The emissions from digestate handling, such as post-composting processes, application of digestate, thickening exhaust, dewatering units, and leaks from centrifuges, were excluded from the biomethane supply chain in this study. Our analysis revealed that CH_4 emissions from this stage are 23% higher than previously reported,[40] while they still form a substantial portion of previous studies.[19,40]

The biogas production stage is the second biggest emission source, ranging from 0.002 to 106.5 g CO_{2-eq}/MJ_{HHV} (Figure 2A) or 0.001% to 9.9% of CH_4 production (Figure 2B). Biogas-production emissions are mainly from the anaerobic digester and hygienization tank. Hygienization tanks represent a relatively small fraction of the emissions from this stage. Emissions from the anaerobic digester are highly variable, depending on fugitive emissions from different cover types and control of venting from pressure-release valves. In addition, Zeng et al.[41] found that the fermentation temperature and quality of the feeding material have an effect on the CH_4 emissions from anaerobic digesters. Following biogas production, estimates of emissions from biogas upgrading are 0.002–72.4 g CO_{2-eq}/MJ_{HHV} (Figure 2A) or 0.001% to 5.5% of CH_4 production (Figure 2B), which are slightly higher than what was reported by Dumont et al.[40] The emissions from the biomethane production stage arise from the exhaust or aeration of units, ventilation ducts, booster pumps, safety valves on upgrading facilities, water or chemical scrubbers, and membranes.

In addition, feedstock emissions, resulting from fugitives and vents from substrate storage, are the fourth highest contributor to the supply chain, accounting for 0.0003 to 28.8 g CO_{2-eq}/MJ_{HHV} (Figure 2A) or 0.0003% to 3.1% of the total CH_4 production (Figure 2B), and represent the smallest proportion of total supply chain emissions. Higher emissions are associated with substrate storage. Dumont et al.[40] reported a larger range in CH_4 emission (0.2%–0.5% of CH_4 production) for feedstock storage.[40] However, their results were based on a smaller dataset than ours, and emissions may have reduced through technology improvements since their study was published.

Digestate-handling approaches

As discussed above, digestate storage is the largest emission source in the biomethane supply chain. This is because of the accumulation of organic material, which leads to CH_4 production from fermentation. According to Döhler et al.,[42] digestate storage may account for nearly 27% of global $CO_{2eq.}$ emissions from anaerobic digestion processes. How digestate is handled has a major impact on emissions, with open digestate storage tanks and lagoons emitting more than closed tanks similar to the results from Paolini et al.[33] (Figure 3). The residual gas potential, digestate temperature, substrate amount, level of filling, and meteorological conditions all have a significant influence on the emission rate from open digestate storage tanks

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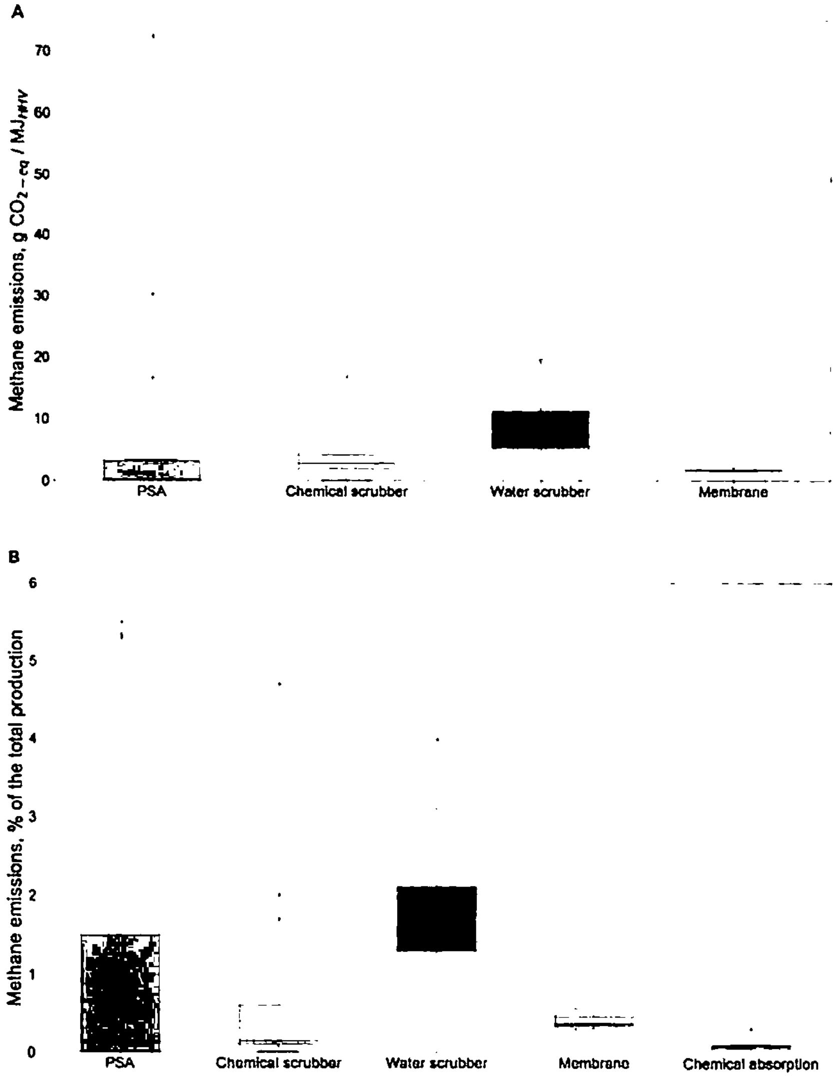

Figure 4. Literature CH_4 emissions from different biogas-upgrading technologies
(A) Emissions from biogas-upgrading technologies in g $CO_{2\text{-eq.}}/MJ_{HHV}$, pressure swing adsorption (PSA) with activated carbon filters (n = 22), water scrubber (n = 4), chemical scrubber (n = 5), and membrane (n = 4).
(B) Emissions from upgrading biogas technologies in terms of the percentage of total biomethane produced, with PSA with activated carbon filters (n = 30), water scrubber (n = 9), chemical scrubber (n = 25), chemical absorption (n = 14), and membrane technologies (n = 6).
Scrubber emissions include chemical (e.g., amine) and water scrubber emissions.

and lagoons.[15,19,43,44] Figure 3 clearly demonstrates that the closed tanks can still emit CH_4, although emissions from closed tanks can be avoided with improved covering materials, effective design, and regular maintenance. The facilities should consider becoming accredited under the Publicly Available Specification (PAS) 110 standards,[45] which recommend coverage of digestate to diminish emissions. Therefore, we recommend using closed digestate storage with vapor-recovery systems directed to the upgrading unit where economically viable to address emissions from this stage. Targeting reductions in digestate-handling emissions provides the greatest environmental improvements, though it is noted that detection and mitigation strategies would require additional expense and regulation.

Impact of biogas-upgrading technologies

Upgrading biogas to biomethane can cause significant emissions. The literature provides scant data on specific upgrading technologies, though available evidence shows that membrane filters and chemical absorption leads to lower emissions than pressure swing adsorption (PSA) and water and chemical scrubbers (see Figures 4A and 4B). Therefore, initial indications are that chemical absorption technology is the best available technology for upgrading to reduce CH_4 emissions, which is the line with previously reported values.[46,47] PSA and water scrubber utilization should be avoided, though more measurements should be conducted.

Total supply chain emission estimates versus whole-site mobile measurements

Alongside the on-site (aggregation of component-based emission) Monte Carlo approach described above, whole-site (off-site) measurements are a useful benchmark. In the literature, CH_4 emissions from 792 whole-site measurements varied between 0.1 and 483 g $CO_{2\text{-eq.}}/MJ_{HHV}$, with an average of 51.7 and a median of 24.6 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (see Figure 5A). This is a larger range with lower median and higher estimate of upper limit than our Monte Carlo simulation of on-site measurements. While the mean of the Monte Carlo runs (51.4–52.7 g $CO_{2\text{-eq.}}/MJ_{HHV}$) and whole-site measurements (51.7 g $CO_{2\text{-eq.}}/MJ_{HHV}$) are comparable, the median of the Monte Carlo runs (40.0–42.3 g $CO_{2\text{-eq.}}/MJ_{HHV}$) are greater than the whole-site measurements (24.6 g $CO_{2\text{-eq.}}/MJ_{HHV}$) due to the heavy-tailed distribution of the Monte Carlo runs. Before running the Monte Carlo simulation, the emissions probability density function of each stage is identified to establish a good fit. The heavy-tailed distribution is due to the presence of super-emitters in each supply chain stage in the Monte Carlo runs, while whole-site emissions data did not exhibit this heavy tail.[48] However, super-emitters are certainly observed in the whole-site measurements and the maximum emission is greater than in the Monte Carlo runs, but these are insufficient in quantity and magnitude to raise the median above the mean. This discrepancy between the distribution of whole-site measurements and that observed in the Monte Carlo approach (i.e., from aggregation of measurements from each stage) is

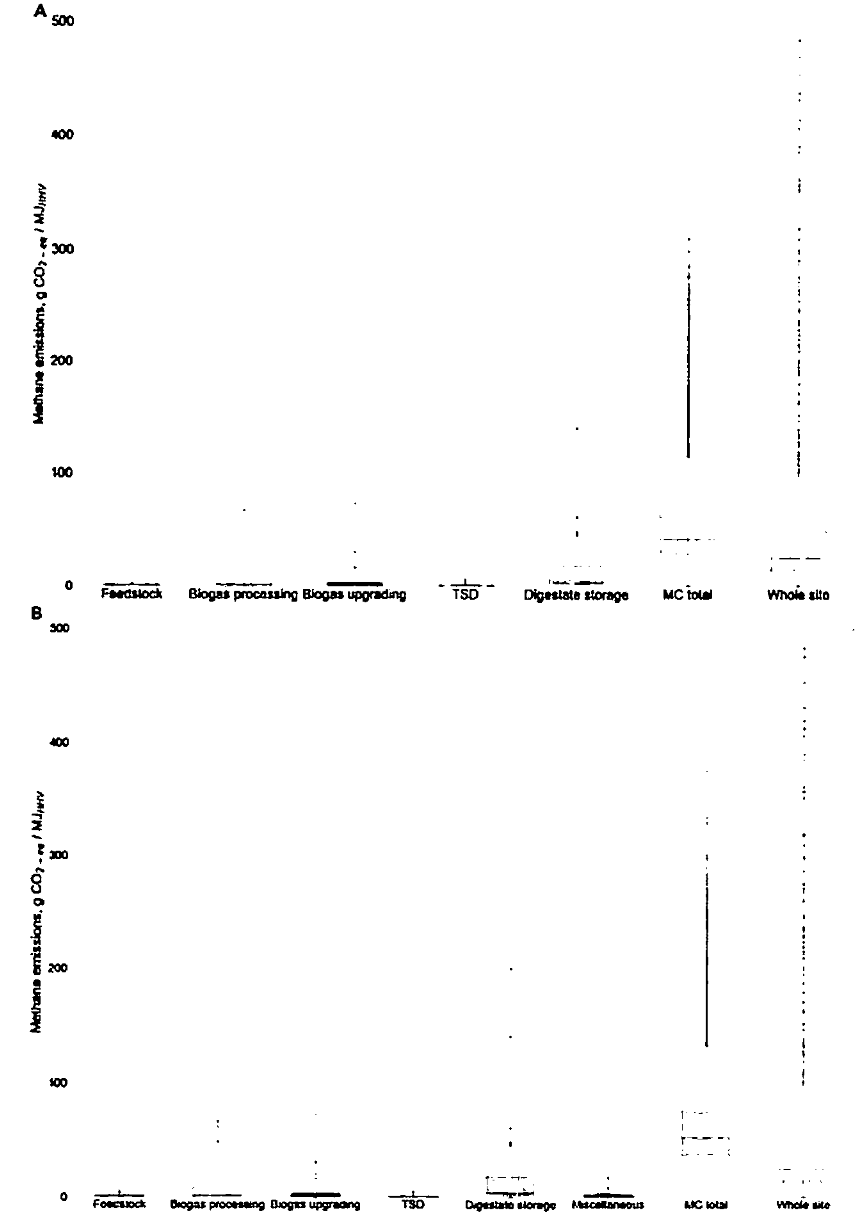

Figure 5. Each stage of emissions with the whole-site measurements and MC runs

(A) Literature emissions range for feedstock (n = 49), biogas processing (n = 100), biogas upgrading (n = 35), TSD (n = 44), and digestate storage (n = 119) stages with whole-site measurements (n = 792) and 10,000 Monte Carlo runs (MC total) with respect to g CO_{2-eq}/MJ_{HHV}.

(B) Miscellaneous sources (n = 19) were added as an additional stage emission and MC total was reassessed to compare with whole-site emissions (off-site measurements).

Individual estimates are shown as circles in the same color at each stage of the supply chain, with median and 25[th] and 75[th] percentile boxes. Sample size for each stage and whole-site emissions are depicted. The median of the MC run is substantially higher than the medians of the five stages added together because (1) the medians of the derived KDE functions for each supply chain stage are substantially higher than those of the raw data and, (2) in any case, it is not expected that the sum of medians from each supply chain stage necessarily approximates the median of the sum of stages (see the experimental procedures for details).

worthy of further research in the future. A number of factors are known to affect measurements, including meteorological conditions during the survey, duration of measurements, uncertainties in emissions rate calculation models, the presence of super-emitters, and process conditions of facilities.[18] It is also likely to be influenced by miscellaneous sources (see Figure 5B),[19] such as biofilters used for odor reduction, stored solids causing fermentation, emissions from service opening,[19] or leakages located on top of units,[49] which are not quantified by the on-site measurement studies. We combined the miscellaneous sources reported in a few studies[19,23,50,51] and estimated their impacts on total emissions using a Monte Carlo simulation (see Figure S2) after identifying the associated KDE (see the experimental procedures), which impacts the data distribution. Figure 5B demonstrated that miscellaneous sources could increase total supply chain emissions by 22%. However, it is noted that, because only four studies reported emissions from biofilters and solid separators, more detailed monitoring surveys are required to better understand the impact of miscellaneous emission sources on supply chain emissions. The high leakage rate reported in off-site measurements could also be due to process disturbances or extensive venting and flaring caused by insufficient infrastructure, which results in an intermittent and highly unpredictable emissions pattern that can overestimate or underestimate significant CH_4 sources.[38] The divergence between on-site and off-site measurements is most likely due to abnormal operating conditions resulting in high CH_4 emissions primarily from the production segment,[31] which is consistent with that of oil and natural-gas supply chains.[39] We agree with Zavala-Araiza et al.[52] and Rutherford et al.[31] that increasing on-site, component-level emission data through continuous emission monitoring and effective characterization of emission sources can reduce the uncertainty and divergence between on-site and off-site measurements.

DISCUSSION

Overall, this study showed that the broad features of the biomethane supply chain led to emission profiles similar to those of oil and natural gas, although digestate handling, biogas production, and upgrading are key differentiators. The synthesis of

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available data here showed that this leads to lower direct CH_4 emissions than the oil and natural-gas supply chain but much higher CH_4 loss rates than the oil and natural-gas supply chain. This conclusion is pertinent in the context of global efforts to mitigate CH_4 emissions, which to date largely focuses on natural-gas supply chains. It is also pertinent to broaden efforts to mitigate climate change, where CH_4 emissions are increasingly recognized as a key climate forcer. Given the strong potential role of biomethane in Paris Agreement compliant energy futures, best available technology must be applied to detect and reduce supply chain emissions, policy and regulation[53] must consider these emissions more systematically, and a better understanding of the counterfactual life cycle emissions for waste and by-product biomethane feedstocks must be developed. It should be noted that, even if feedstocks are not used to generate biomethane, they may still emit CH_4; in fact, some studies have suggested that treating manure for biomethane production could be a mitigation strategy.[54] We believe that this large amount of CH_4 emissions from the biomethane supply chain, on the other hand, can be avoided by taking appropriate emission identification, detection, measurement, and quantification measurements. It is critical to emphasize that, if biomethane is widely used in the future to achieve decarbonization goals, biomethane supply chain emissions should be avoided in order to achieve net zero goals.

Reflecting on these results with respect to the EU Renewable Directive (RED) 2009/28/EC,[55] it is clear that cutting emissions from digestate handling and gas engines could underpin more sustainable biomethane production. According to an EU report[56] on the sustainability of solid and gaseous biomass used for electricity, heating, and cooling, the GHG threshold for biomethane production is 34.8 g $CO_{2\text{-eq}}$./MJ_{HHV},[56] excluding digestate emissions. In contrast, CH_4 emissions from the biomethane supply chain are estimated in this study to range from 2.5 to 343 g $CO_{2\text{-eq}}$./MJ_{HHV} and 0.8 to 182 g $CO_{2\text{-eq}}$./MJ_{HHV} (18.3–19.5 g $CO_{2\text{-eq}}$./MJ_{HHV} for the median and 64–74 g $CO_{2\text{-eq}}$./MJ_{HHV} for the 95th percentile) when digestate emissions are excluded (see Figure S3). In view of CO_2 and N_2O (GWP_{100} = 273 ± 130)[10] emissions from biomethane production, total GHG emissions from the biomethane supply chain are likely to exceed this threshold limit unless urgent actions are taken. Given the different lifetimes and GWPs of CO_2, CH_4, and N_2O, future research can focus on integrating emissions across different timescales in order to further expand the impact of the biomethane supply chains on global warming and climate change. Clearly, under these operating conditions and in light of the wide diversity of biogas production pathways, biomethane production may lose its advantages as a clean-energy technology and may jeopardize Paris Agreement targets if used extensively. This study would serve as a guideline for the emission ranges associated with each stage while also recommending appropriate measures for each stage to cut emissions and make progress toward Paris Agreement goals. Therefore, emission-minimizing technologies and techniques and more specific regulations on emissions and leak detection and repair are essential to significantly reduce supply chain emissions. We are also aware of the counterfactual case for what level of CH_4 emissions would occur if the feedstock had not been converted into biomethane. Future studies should focus on counterfactual analyses to assess the GHG credits under various counterfactual scenarios.

Our biomethane supply chain emissions model presented in this study represents the most common technologies used in the industry, but it has some limitations regarding data availability and resolution. Firstly, input data were taken only from measurement surveys, and the sample size is not large enough to determine a probability distribution model for each supply chain. As such, the KDE function was used rather than goodness of fit since the data could not be fitted to certain distribution functions, due to the lack of data and heavy-tailed distribution. Furthermore, much of the literature data were excluded, owing to the use of default emission factors, especially in modeling studies. Secondly, some studies could not be included because they did not report biogas or biomethane production rates despite reporting CH_4 emissions.

The most detailed measurement surveys have been conducted in various regions of Europe and mainly at agricultural plants, so this study substantially reflects European agriculture. Further possible research directions associated with this work include adapting the emissions profiles of theoretical supply chain routes, for example, using life-cycle-assessment tools. Future research should target data collection from various biomethane supply chain routes in other countries to reduce uncertainty in the data and improve size and representativeness of the samples, which can help to identify the most sustainable biomethane production routes. This accumulated database can be used to improve equipment, processes design, and operations that would mitigate CH_4 emissions.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Semra Bakkaloglu (s.bakkaloglu@imperial.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

All original datasets used in this work were made available as part of the publications referenced and described in the text. The Python code used for the Kernel density estimation (KDE) function and Monte Carlo simulation with the data have been deposited at Zenodo Data: https://doi.org/10.5281/zenodo.6550794.

Methodological approach

This study aims to estimate CH_4 emissions from the biomethane supply chain and characterize the emissions sources in the various stages of the supply chain (described in Figure S1). The screening criteria for mobile CH_4 emissions measurements required on-site or off-site direct measurements be reported by the study authors, rather than drawing on experimental, lab-scale, and theoretical studies.

The existing literature reports emission rates in different units, and some studies provide insufficient information to allow for unit conversion. In this study, CH_4 emission estimates were converted into percentage of total production (volume of CH_4 emitted/volume of produced gas) and grams of CO_2 equivalent per megajoule of energy based on higher heating value (HHV). These were chosen to allow for comparisons with the oil and natural-gas supply chain without inferring downstream services. The source emissions were divided by the total expected volume of biomethane that would be generated for energy utilization.

Assumptions were applied to convert published emission rates into metric units. It was assumed that the GWP_{100} of CH_4 is 27.2,[10] with an HHV of

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38.1 MJ/m^3 or 55.5 MJ/kg. The average volume percentages of CH_4 in biogas and biomethane were taken as 65% and 95%, respectively, unless otherwise stated in a study. We assumed the CH_4 content is 55% in biogas for manure feedstock. We neglect uncertainty of measurements and GWP_{100} (±11), although measurement uncertainty exists whenever an emissions rate is quantified. Similar to Brandt et al.,[28] we evaluate all emissions at their reported levels and investigate the impact of emissions distribution. GHG emissions other than CH_4, such as CO_2, N_2O, and NH_3, were not included because they are out of the scope of this study. Moreover, CH_4 emissions based on GWP_{20} (80.8) were provided in the Figure S4. The three stages of this study are:

1. Building the emissions inventory
2. Assessing the supply chain emissions model
3. Applying Monte Carlo simulations to produce total emissions ranges.

Emissions inventory

Following systematic reviews of the existing evidence base, 51 papers reporting mobile CH_4 emissions measurements were examined, including academic papers as well as governmental and industry reports (see the supplemental experimental procedures). We utilized the data from mobile CH_4 measurements using on-site leak detection and ground-based remote sensing methods (off site). CH_4 emissions from landfill were excluded because there is a lack of data on the amount of biogas and biomethane generated from landfill-gas-collection system, which is mainly calculated using landfill-modeling tools, and CH_4 emissions depend on CH_4 oxidation rate as well as top soil cover material rather than infrastructure emissions.[57] In addition, we only considered the emissions from wastewater treatment plants with anaerobic digesters. The details of the chosen biomethane supply chain route employed in this study are described in detail in the Figure S1.

Emission inventory data availability is highly variable, owing to variations in the applied methodologies, differing plant design and operation, and insufficient data for each supply chain. Most emissions data were for Europe. Datasets for each emissions source were divided into subcategories, where there was discernible variation between feedstock materials (see Table S1). The stages in the biomethane supply chain are (1) collecting and storing organic materials (feedstock); (2) converting them to biogas under anaerobic conditions (AD); (3) upgrading biogas to biomethane (upgrading); (4) transportation, gas storage, and distribution of generated gas (TSD); and (5) digestate storage.

Feedstock storage

Any biodegradable material, such as agricultural residues, maize, crops, sewage sludges, or food and drink waste, utilized in anaerobic digestion is called feedstock. The yield of biogas from a specific feedstock can vary based on the dry-matter content, residence time in the digester, and feedstock purity.[58] Feedstock transported from a third party to the production facility is stored in the facility and pre-treated before being sent to the biogas-production stage. This stage covers four major components: runoff ponds, screw conveyor, mixing tank (homogenization tank), and substrate storage. Substrate storage tanks and biomass-receiving units, such as feedstock piles, runoff ponds, screw conveyors, and mixing (homogenization) tanks, are the main sources of emissions, although few studies have investigated emissions from this stage.[15,17,19,22,46,49,59–61] Feeding system emissions are included in substrate storage emissions (see Table S1). These emissions are mainly fugitives, predominantly from open storage tanks and feeding units.

Biogas production

The physically treated material is pasteurized and delivered to an anaerobic digester to generate biogas. The CH_4 concentration in the biogas depends on the type of digestate feedstock, type of anaerobic digester, and conditions in the digester, such as mesophilic and thermophilic. The biogas production stage consists of a buffer (hygienization) tank and a reactor (anaerobic digester). Previously reported CH_4 emissions from hygienization tanks, anaerobic digesters, and post-digesters are included in this stage (see Table S1).[15–17,19,41,49,50,59,62–76] These emissions are fugitives and venting.

Biomethane production: Biogas upgrading process

The biogas can be upgraded into biomethane by removing impurities. Depending on the biogas quality and the end use, different upgrading technologies can be used. Currently, water scrubbing is the most common commercial technology, followed by chemical scrubbers, membrane, PSA, organic physical scrubber, and cryogenic separation.[77] CH_4 emissions from various upgrading processes, such as carbon filters, chemical and water scrubbers, and membrane technologies, were reported in previous studies[17,19,46,47,49,50,71,78–81] and have been included in the upgrading processes stage (see Table S1). These are fugitives and vent from PSA exhausts and aeration and ventilation ducts.

Transmission, storage, and distribution

Biogas can be utilized to generate heat, electricity, or both. Biomethane can be injected into a gas grid or used as a renewable transport fuel in vehicles. Previous studies reported exhaust CH_4 from cogeneration, electricity production, heat utilization, combined heat and power units, gas engine slip, flare, and gas holder.[17,19,23,41,50,62,67,71,82–85] Emissions from pipeline, flare, compressors, and pressure-relief valves (PRVs) are considered in the transmission, storage, and distribution stage (see Table S1) in order to compare with natural-gas supply chain. End-use emissions mainly coming from incomplete combustion from combined heat and power (CHP), as well as fugitive leaks and vents from energy production units, were not included into emissions from this stage.

Digestate storage

Digestate can be used as is or can be further processed through different methods to be used as fertilizer. The PAS 110 for digestate quality specification is designed to ensure that digestate is no longer classified as waste and is safe and reliable to use as a fertilizer, soil improver, or conditioner, and it recommends that all types of digestate be covered.[45] Although some facilities follow the PAS 110 scheme, none of the published papers address whether the digestate complies with the standard. The solids-liquids separators, such as centrifuge and screw-press separators, membrane filters, biofilters, aerobic treatment, and composting, are widely used to process digestate.[86] The processing and storage of liquid and solid digestate can also cause emissions, depending on the temperature, wind, atmospheric pressure, plant process parameters, and storage tank filling level.[19] Emissions data by digestate types (e.g., solid or liquid) and storage properties (closed or open tanks) were collected from previous studies (see Table S1).[15–17,19,23,24,43,44,49,50,59,62,67,71–73,85,87–92] The emissions are mostly fugitives and venting from open PRVs. The emissions associated with digestate use, such as fertilizer application and post-composting, were excluded from the supply chain because digestate is not always used in the operation area and their emissions are only reported in a few studies.

Miscellaneous emissions

An additional emission stage has been added to account for a variety of sources that are not necessarily present in every biomethane supply chain. The CH_4 emissions from biofilters for odor reduction, compost filters, and separators have been reported in a few studies[18,73,50,51] and are included as miscellaneous emissions.

Whole-site mobile measurements

Whole-site mobile measurements were included for comparisons to the modeled of total emissions from each supply chain.[17,19–23,46,49–51,61–65,71,73,75,88,93] Various emission-measurement techniques were used to quantify emissions and their sources in the whole supply chain, which caused a large variation in emissions.

Supply chain emission models

It is important to determine the probability density function (PDF) of emissions in each stage before running the Monte Carlo simulation.[48] The PDF establishes a good fit of the emissions for each stage, including an uncertainty assessment. Because the emissions in each stage exhibit unique characteristics, particularly with respect to various super-emitters, their data and probability distributions differ (see Table S2 for the characteristics of PDFs). Due to the heavy-tailed distribution (Figure S3) and lack in the sample size, the nonparametric PDF ,which is the KDE, were generated to investigate the PDFs of the emissions from each stage using Python. KDE typically provides more accurate estimates of data distributions than parametric approaches.[94–96] The bandwidth of KDE for each stage was determined automatically in Python's SciPy library using Scott's Rule,[97] which is dependent on the number of data points.[77] The total sample size is 347 and 399 for g $CO_{2\text{-eq}}$/MJ_{HHV} and production normalized data, respectively.

Monte Carlo simulation

The total supply chain emissions were estimated using Monte Carlo simulations,[98] which has been widely applied to estimate CH_4 emissions[25,30] with uncertainty assessment. Each supply chain's PDF, obtained from the KDE, was defined in the simulation to sample from each stage, followed by summing up each stage. Rather than separating the data by feedstock type, we divided it by stage of the supply chain, as shown in Figure S1. The total CH_4 emissions were assessed 10,000 times with random draws from the distributions for each stage. The 10,000 estimates were then used to assess the cumulative CH_4 distribution across the supply chain models by the Python code.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.05.012.

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AUTHOR CONTRIBUTIONS

Conceptualization, S.B. and A.H.; methodology, S.B., J.C., and A.H.; software, S.B.; validation, S.B. and J.C.; formal analysis, S.B. and J.C.; investigation, S.B., J.C., and A.H.; writing – original draft, S.B.; writing – review & editing, J.C. and A.H.; funding acquisition, A.H.; resources, S.B. and A.H.; supervision, A.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Roanoke Gas Company
Case No. PUR-2022-00125
Environmental Respondent
Third Set

ii. Please describe and quantify the anticipated greenhouse gas emissions of the replacement materials.

Response:

The emissions associated with both production and transport of these medias was included in the inventory under Scope 3 emissions. The RWPCP currently has iron hydroxide vessels, so the greenhouse gas emissions for that media show up in both scenarios. An additional emission of 25.4 metric tons CO2e/year is included in the RNG scenario for granular activated carbon associated with the siloxane vessels.

iii. Please confirm whether repair of the digesters is included in the inventory.

Response:

Emissions from construction of this project (including repair of the digesters) are not included in the inventory.

(c) Please reference specifically Assumption 4 under the heading "General," which states, "5% downtime for operation of RNG system."

i. Please restate in different words and explain this statement more fully.

Response:

The greenhouse gas inventory assumes that during 95% of the year, 100% of the biogas is routed through the biogas upgrading system, converted to renewable natural gas, and injected into the natural gas pipeline. During 5% of the year, 100% of the biogas is flared in the existing waste gas flare. This 5% downtime is assumed for equipment maintenance.

ii. Also reference Note 6 on in Table 3, on page 6 of Exhibit 1 of the Direct Testimony of Becky J. Luna in Volume 3 of the Application. Note 6 states, "Biogas is assumed to be flared in the existing waste gas burner during the remaining 5 percent of the year to allow for equipment maintenance." Please confirm whether Assumption 4 and Note 6 both refer to the same assumed 5% downtime period per year for maintenance.

Response:

Yes, these are referring to the same assumed 5% downtime period per year for maintenance.

Roanoke Gas Company
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iii. Please indicate whether the Company has reviewed data from other water treatment plants and whether that data supports Assumption 4.

Response:

Yes, based on our conversations with wastewater treatment facilities operating RNG systems, and in our discussion with equipment manufacturers, an assumption of 95% uptime is valid.

iv. Please confirm whether the biogas generated during the downtime of the RNG facility will be flared and, if not, explain what will happen to the gas generated during this time.

Response:

Biogas generated during the downtime of the RNG facility will be flared.

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