CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Biomethane in California Common Carrier Pipelines: Assessing Heating Value and Maximum Siloxane Specifications

An Independent Review of Scientific and Technical Information

Today's Briefing:

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

1. **Welcome and Overview of Study Process**
   Dr. Sarah Brady, CCST Project Manager
   Professor Jim Sweeney, Stanford University, Steering Committee Chair

2. **Report Findings, Conclusions and Recommendations**
   Professor Adam Brandt, Lead Author, Stanford University
   Professor Jim Sweeney, Stanford University, Steering Committee Chair

3. **Closing Summary and Major Takeaways**
   Professor Adam Brandt, Lead Author, Stanford University

Questions

Study Request

SB 840 (2016) requested the California Council on Science and Technology (CCST) to complete a study analyzing the **minimum heating value** and **maximum siloxane specifications** for the delivery of biomethane to the public gas pipelines, and their impacts to:

- Cost
- Volume of biomethane sold
- Equipment operation
- Safety

California Council on Science and Technology (CCST) is …

- A nonpartisan, impartial, not-for-profit corporation established via Assembly Concurrent Resolution (ACR 162) in 1988 to provide objective advice from California's scientists and research institutions on policy issues involving science.

- Dedicated to providing impartial expertise that extends beyond the resources or perspective of any single institution.

- Governed by a Board of Directors and studies are funded by government agencies, foundations, and other private sponsors.

Sustaining Institutions & Lab Affiliates

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

University of California

California State Universities

California Community Colleges

Caltech

Stanford University

NASA Ames Research Center

Jet Propulsion Laboratory

Lawrence Berkeley National Laboratory

Lawrence Livermore National Laboratory

Sandia National Laboratories

SLAC National Accelerator Laboratory

National Renewable Energy Laboratory

CCST Study Process

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Recently, CCST has produced reports on hydraulic fracturing, water, energy, and STEM education in California.

CCST conducts a very rigorous process, which includes:

- Convening the most relevant experts to put together a robust and balanced team
- Addressing any potential conflict of interest issues
- And conducting an extensive and rigorous peer review

This process, modeled after the National Academy of Sciences, ensures the product is credible and responsive to the study charge.

Our goal is to provide credible, relevant, and useful science-based information to inform State decision making.

CCST Biomethane Steering Committee

CCST CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

- Provided oversight, scientific guidance and input for the project
- Developed consensus conclusions and recommendations

James L. Sweeney	Stanford	Chair
Adam Brandt*	Stanford	Lead Author
Charles Benson	etaPartners, LLC	Industrial use of biomethane
Fokion Egolfopolous	USC	Combustion and fuels research
Charles Kolstad	Stanford	Energy and environmental economics
Diane Saber	REEthink	Production, characterization of biomethane
Jessica Westbrook	Sandia National Labs	Systems analysis

*Ex Officio Non-voting Member

Study Authors

CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Authors analyzed and synthesized project-relevant data and wrote the report.

Adam R. Brandt, Assistant Professor, Stanford University

Gregory A. Von Wald, Graduate Student, Stanford University

Deepak Rajagopal, Assistant Professor, University of California, Los Angeles (UCLA)

Austin Stanion, Graduate Student, University of California, Los Angeles

The Basis of Our Assessment

- Peer-reviewed published literature.
- Analysis of available data from CPUC, CARB, CEC and other publicly available sources.
- Other relevant publications including reports and theses.
- The expertise of the steering committee, the scientific community, and the authors to identify issues.
- We state the qualifications of the information used in the report.

Study Purpose and Key Questions

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Conduct an independent scientific assessment of the minimum heating value and maximum siloxane specification for the delivery of biomethane to public gas pipelines.

Key Area 1: Regulation of minimum heating value specifications

Key Area 2: Regulations for maximum siloxane concentration

Key Area 3: Cost implications of upgrading biomethane

Key Area 4: Options for dilution of biomethane

Key Area 5: Alternatives to pipeline injection; regulation-induced market distortions

Overview of Recommendations

Recommendation 1: Keep the Wobbe Number minimum requirements as they are now.

Recommendation 2: Reexamine regulations on heating value (HV) minimum levels. Initiate a regulatory proceeding to examine the option of allowing biomethane satisfying current WN limits and all other requirements, but with a heating value as low as 970 BTU/scf.

Recommendation 3: Support a comprehensive research program to understand the operational, health, and safety consequences of various concentrations of siloxanes.

Recommendation 4: There is not enough evidence to recommend any changes to the maximum allowable siloxanes concentration at this time.

Recommendation 5: Consider the development of a reduced and simplified verification regime for sources that are very unlikely to have siloxanes, such as dairies or agricultural waste.

Recommendation 6: Monitor the ASTM International process to adopt and test a standard test method for siloxanes.

Recommendation 7: Use the learnings from the siloxane research and the ASTM process to revisit the siloxane maximum standards once more complete information becomes available.

Recommendation 8: State and Federal agencies should examine whether the substantial differences in incentives for various uses of biogas/biomethane are consistent with the State and Federal policy intentions.

Natural Gas and Biomethane: Similarities and Differences

- Raw biogas collected from landfills, wastewater treatment plants, or produced intentionally in dairy digesters can be processed and upgraded to become biomethane

- Biogas from wastewater and landfills is likely to contain silicon compounds, such as siloxanes

- Upgraded biomethane is a close substitute for natural gas

- Biomethane lacks higher molecular weight hydrocarbons (ethane, butane, etc.) that can be present in natural gas

Regulations Affecting Biomethane

Key regulations which affect pipeline addition of biomethane:

- Gas quality specifications
  - **Minimum heating value**
- Health protective constituents
- Pipeline integrity constituents
  - **Maximum siloxane concentration**

This study addresses the minimum heating value and maximum siloxane requirements.

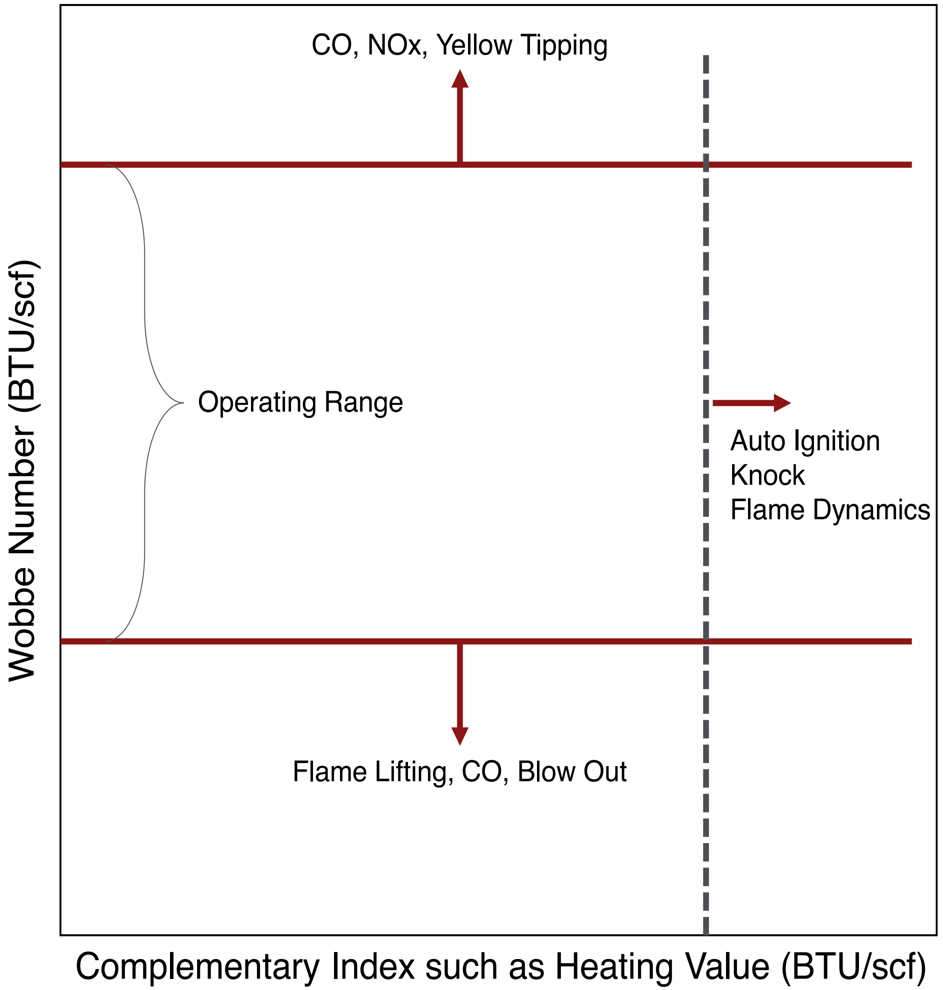
Summary Assessment of California Heating Value Specifications

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

- HV regulations are used to ensure safe combustion and reliable heat delivery – gas interchangeability metrics serve as a better indicator for these characteristics
- Current regulations require 990 BTU/scf (Rule 30, SoCalGas) or “consistent with standards for each receipt point” (Rule 21, PG&E)
- The minimum HV specification in California was 970 BTU/scf before 2006. It was increased to 990 BTU/scf in 2006 by regulatory decision to accommodate anticipated imports of liquefied natural gas (LNG), which typically has a higher HV than domestic gas supply.
- A minimum HV of 990 BTU/scf is highly constraining on allowable biomethane composition

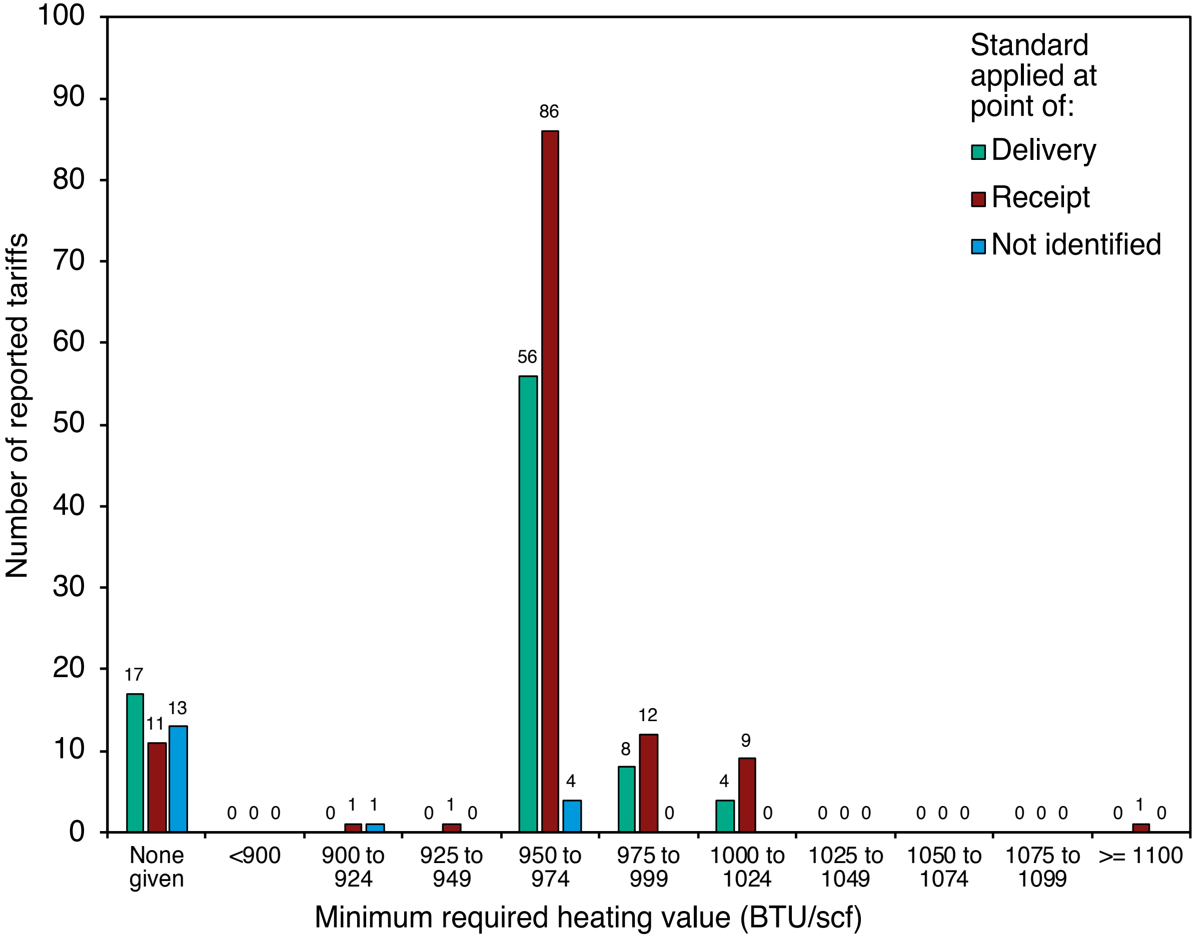
- **Shifting the minimum HV specification to values near 970 BTU/scf will allow more flexibility in gas supply for biomethane producers and should not affect safety or operations given industry guidelines**

Heating Value and Interchangeability



- Interchangeability is factor when switching between fuel gases of different composition
- Heating value is a component of interchangeability
- NGC+ working group recommends using Wobbe Number as the best indicator of interchangeability
- Wobbe Number measures the rate of energy delivered through a fixed orifice at a constant pressure
- At low Wobbe, flame lifting, incomplete combustion (CO) and blow out are concerns

Heating value specifications in other regions



AGA summary of HV specifications across North America

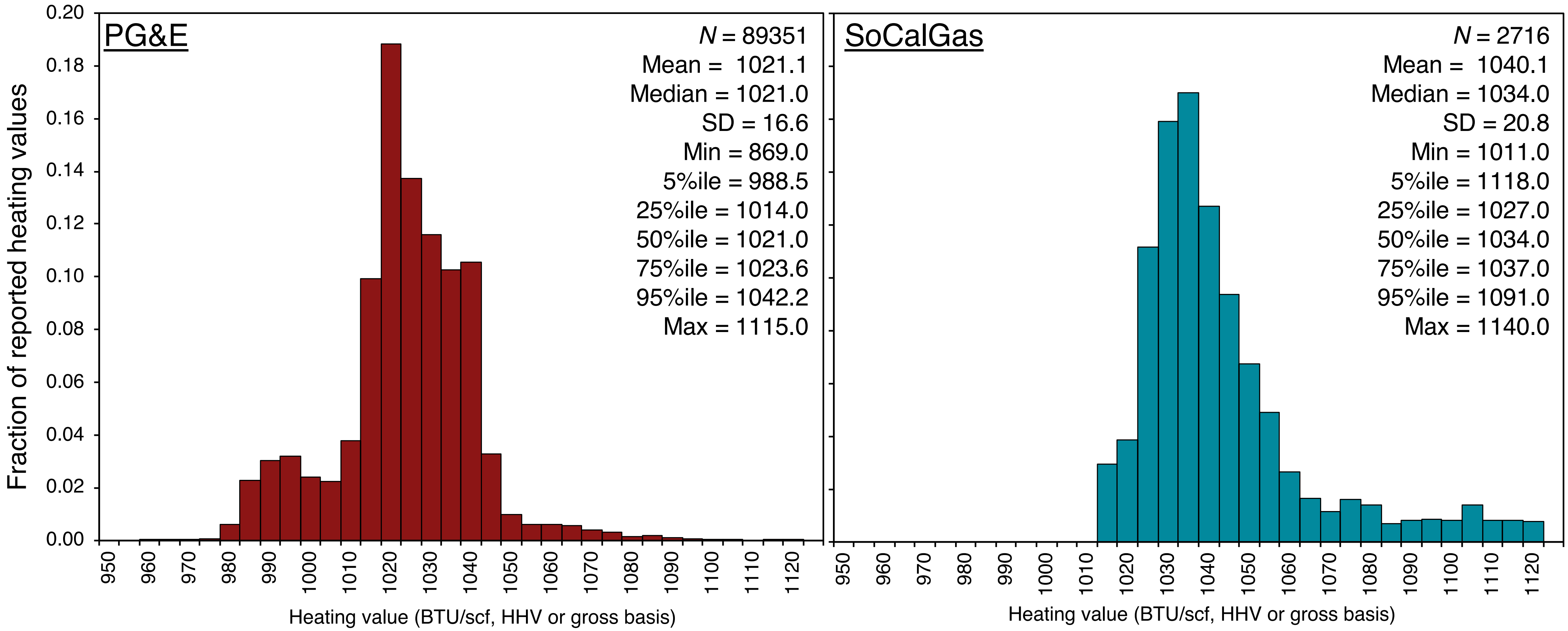
Most common value in 950-974 range

Rule 30 with 990 BTU/scf is among highest

No central database of delivered gas quality

Even if a region has minimum HV at 970 BTU/scf this does not mean that 970 BTU/scf is actually delivered

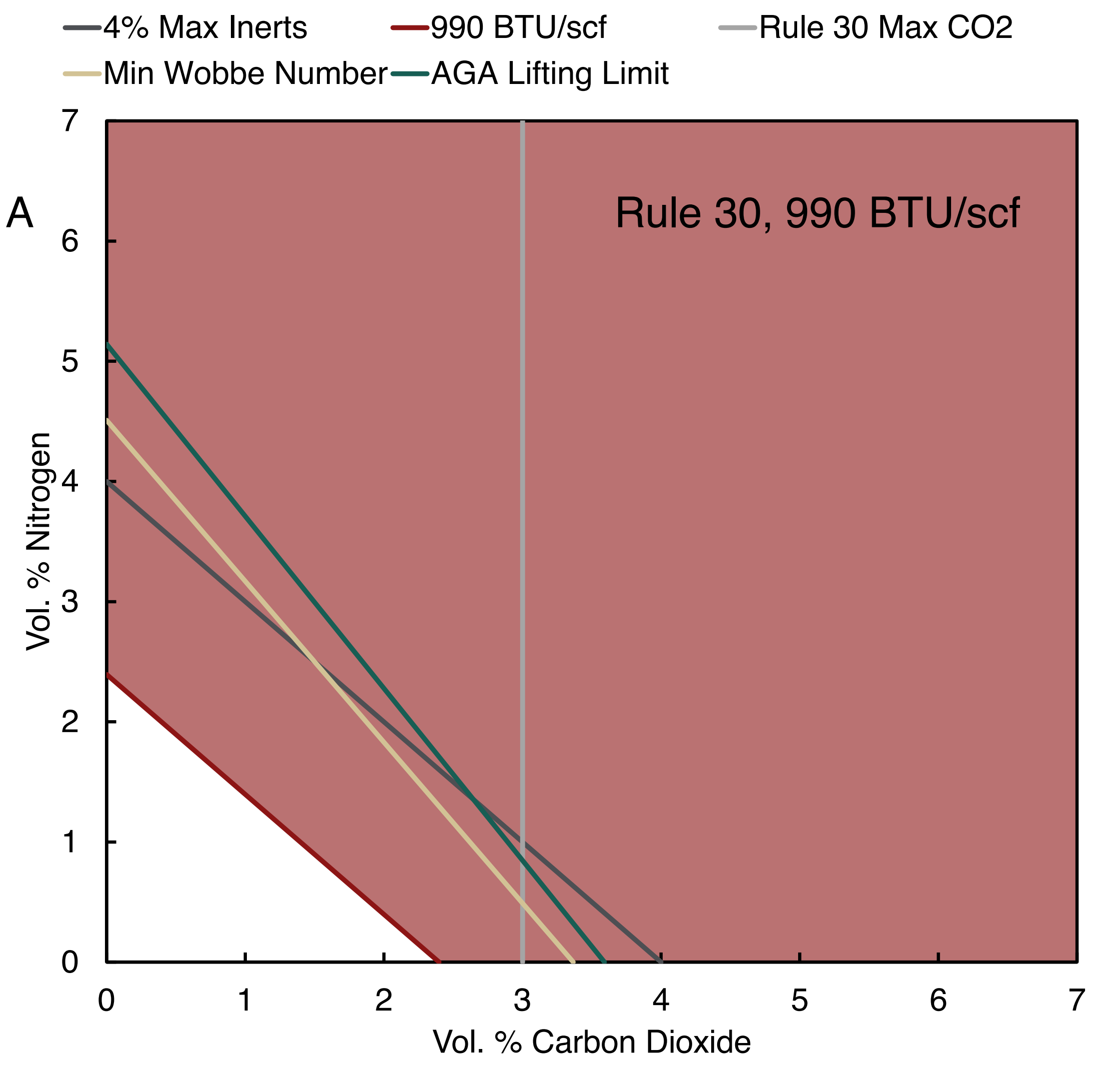
Historical heating value delivered



Historical delivered HV approx:

- 1021 BTU/scf in PGE territory
- 1034 BTU/scf in SoCalGas territory

Exploring Binding Constraints

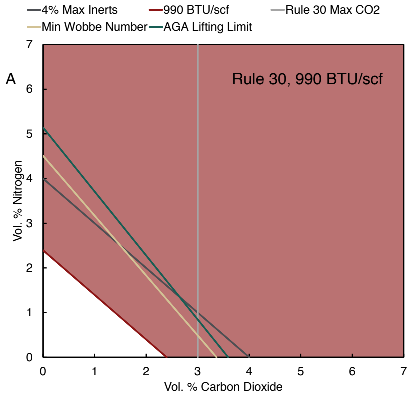


Model:

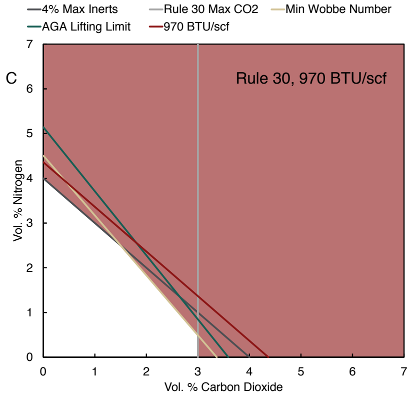
Biomethane as a mixture of CH_4, CO_2 and N_2

What fractions of CO_2 and N_2 are allowed given various specifications?

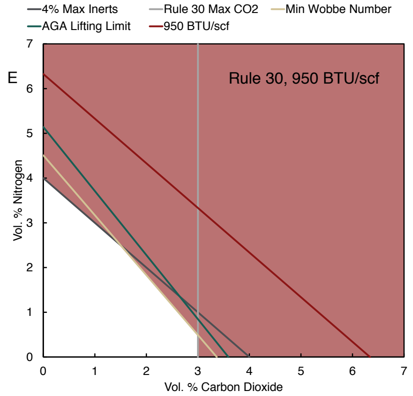
Quantitative assessment HVs: Rule 30 regions (SoCalGas)



990 BTU/scf



970 BTU/scf



950 BTU/scf

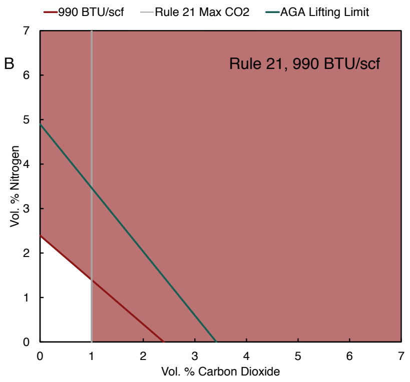
Changing minimum HV to level near 970 would allow greater operational area

More CO_2 and N_2 allowed in these mixtures reduces cost

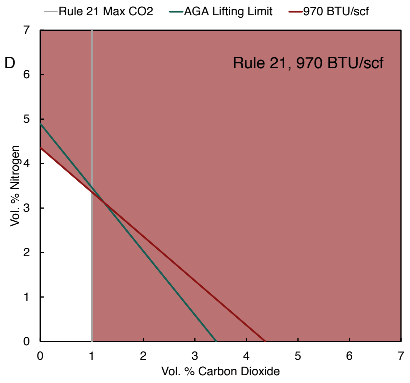
Can avoid AGA lifting limits and allow composition to be governed by minimum Wobbe Number and maximum inert gas limits

Changing minimum HV to a level near 950 BTU does not allow additional flexibility as compositions in that region will violate inerts or Wobbe limits

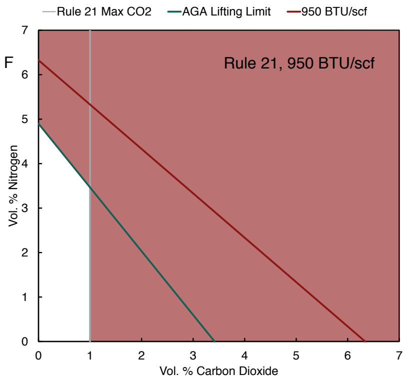
Quantitative assessment HVs: Rule 21 regions (PG&E)



990 BTU/scf



970 BTU/scf



950 BTU/scf

Changing minimum HV to level near 970 would allow greater operational area

More N_2 allowed in these mixtures

CO_2 limit of 1% max composition limits compositions more than Rule 30 regions

Changing minimum HV to a level near 950 BTU does not allow additional flexibility as compositions in that region will violate AGA lifting or CO_2

Conclusions on Heating Value

1. The scientific modeling by authors of this paper and the literature provide evidence that keeping the current minimum Wobbe Number (WN) and relaxing the heating value (HV) specification to a level near 970 is unlikely to impact safety or equipment reliability.

2. The admittedly incomplete available evidence suggests that relaxing the HV specification to a level near 950 could affect safety.

Recommendations on Heating Value

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Recommendation 1: Keep the Wobbe Number minimum requirements as they are now.

Recommendation 2: Reexamine regulations on heating value (HV) minimum levels. Initiate a regulatory proceeding to examine the option of allowing biomethane satisfying current WN limits and all other requirements, but with a heating value as low as 970 BTU/scf.

Summary Assessment of California Siloxane Specifications

- Scientific literature documents significant silica buildup and failure of combustion devices utilizing gas with siloxanes
- Current regulations require 0.1 mg Si/m^3
- Current specification is based on extrapolation from study of one or two appliances – not robustly supported by science
- Significant operational experience with siloxanes exists but lack of systematic study makes it less useful as evidence
- Poor agreement on measurement capabilities between different laboratories and parties
- Weak evidence for loosening specification, but if specification is maintained, financial risk due to measurement uncertainty will likely continue to bar development

Empirical evidence of impacts of siloxane

- SoCalGas sponsored work at USC
  - Tested a residential furnace at 8.6 mg Si/m^3; failure of flame sensor after 70 hrs informed recommendation for current CA specification of 0.1 mg Si/m^3
- GTI Phase II assessment
  - Tested residential oven and water heater at 8-14 mg Si/m^3; found no operational issues in water heater, failure in oven after simulating ~6.5 yrs
- DNV group in Netherlands
  - Tested residential boilers and water heaters at concentrations as low as 1.5 mg Si/m^3
  - Recommended a maximum silicon content of 0.23 mg Si/m^3 for National Grid UK

- Damage is appliance-specific
  - Clogging of narrow tubes or heat exchangers
  - Ionization probe failure or O_2 sensor failure
  - Deactivation of post-combustion catalyst
- Failure modes can be fail-safe or not
  - Flame sensor fails, appliance shuts off
  - Narrow-tubes in water heater clog, air-flow decreases, CO emissions gradually increase

Operational Experiences and Siloxane

CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

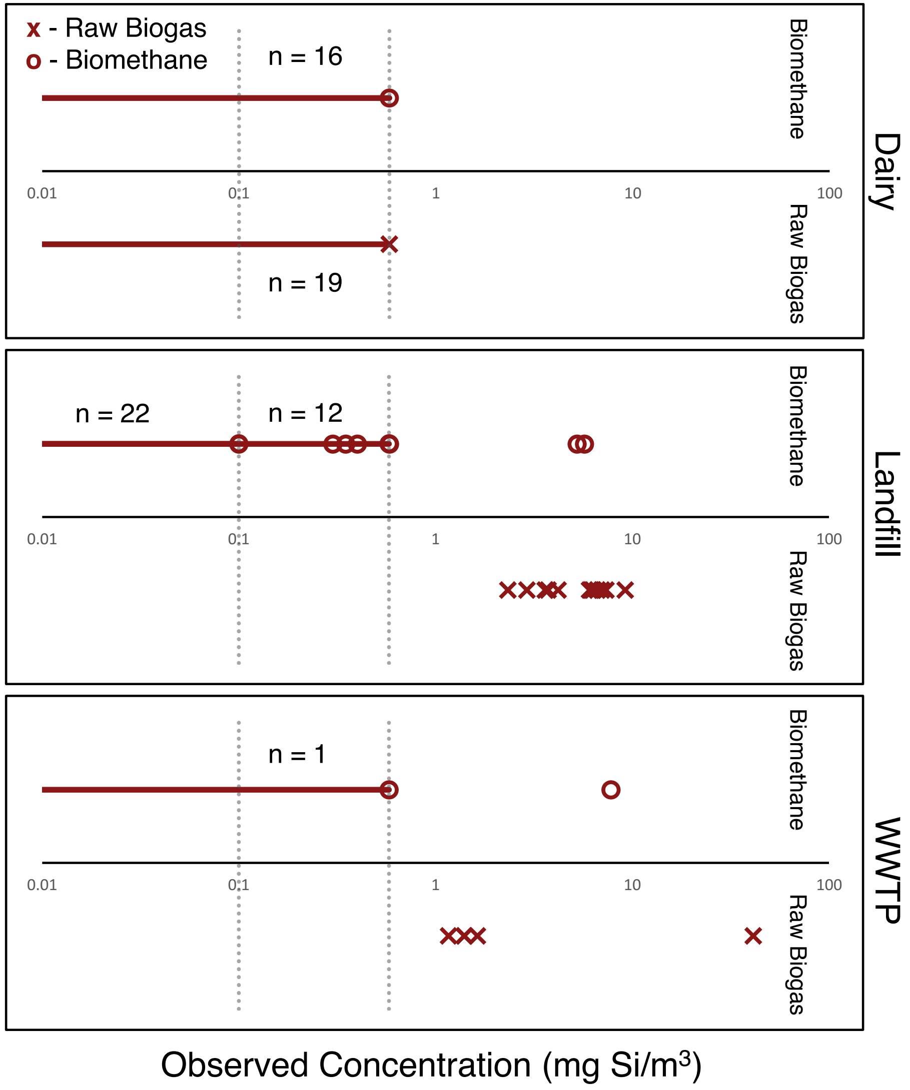
Source of biomethane	Number of projects	States where operational
Landfill, pipeline injected	41	-
CNG/LNG transportation fuel	31	AR, IL, KS, LA, MI, MS, NE, NY, OH, OK, PA, TN, TX, WA, WV
Electricity	3	GA, PA, TX
Heat/Electricity	2	TN, PA
Industrial	1	TX
Not specified/Other	4	KS, MI, MT, PA
Landfill, not pipeline injected	4	-
CNG/LNG transportation fuel	4	CA, IN, LA, MI
Landfill, injection status not listed	2	-
CNG/LNG transportation fuel	1	GA
Other	1	MI
WWTP, pipeline injected	5	-
CNG/LNG transportation fuel	3	CO, IA, KS
Electricity	1	CA
Heat/Electricity	1	OH
WWTP, not pipeline injected	1	-
CNG/LNG transportation fuel	1	CA
WWTP, injection status not listed	5	-
CNG/LNG transportation fuel	5	NE, OH, TX, WA, WI

Total landfill:
47 operational

Total WWTP:
11 operational

Source: Coalition for Renewable Natural Gas, Biomethane projects database

Siloxane removal



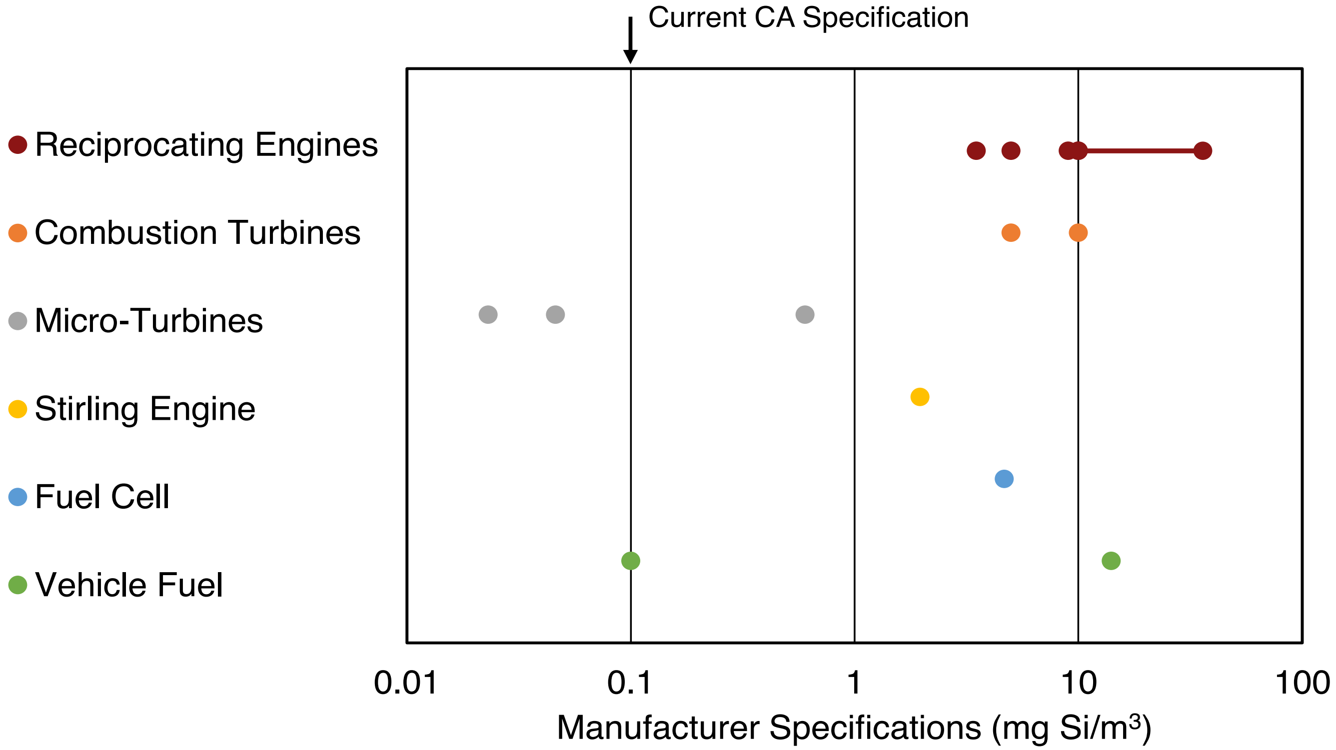
Key Points:

Dairy has no points above detection limit

GTI investigation of active landfill-derived biomethane pipeline addition projects:

- 22 of 27 samples tested below 0.1 mg Si/m^3; the remainder were below 0.4 mg Si/m^3
- Greater transparency on process by which Point Loma WWTP was approved such that other projects can follow
  - Significant concerns among producers about compliance and regulatory risk
  - SoCalGas approval depended on successful test and installation of siloxane polishing to meet 0.1 mg Si/m^3 standard
  - This pathway should be made more transparent to aid investment decisions

Manufacturer specifications



Key Points:

The CA siloxane specification is more stringent than most manufacturer imposed requirements.

Not all equipment has specifications established yet

Manufacturer specifications

End-Use Application	Manufacturer	Maximum siloxane conc. [mg Si/m³] (evaluated as D4 for biomethane at 990 BTU/scf)	Source
Reciprocating Engine	Various	10 – 36	[1]
	Caterpillar	3.5	[3]
	Jenbacher	10	[2]
	Waukesha	9	[6]
	Deutz	5	[2]
Combustion Turbine	Unknown (w/o Recup.)	10	[1]
	Unknown (w/ Recup.)	5	[1]
	Solar Turbines	5-10	[8]
Micro-turbine	Unknown	0.6	[1]
	Ingersoll-Rand Microturbines	0.046	[2]
	Capstone Microturbines	0.023	[2], [4]
Stirling Engine	STM Power	1.96	[5]
Fuel Cell	Fuel Cell Energy	4.66	[5]
Vehicle Fuel	Cummins	14	[1]
	Various (recommended)	0.1	[7]

[1] (Pierce, 2015)
[2] (Wheless & Pierce, 2004)
[3] ("Caterpillar G36000- G3300 Fuels," n.d.)
[4] ("Application guide, Landfill/Digester Gas Use with the Capstone MicroTurbine," 2004)
[5] (Lampe, 2006)
[6] ("Gaseous Fuel Specification for Waukesha Engines," 2014)
[7] (Kramer, Ferrera, Kühne, Moreira, & Magnusson, 2015)
[8] Personal communication

Potential Siloxane Health Impacts

- Silica (SiO_2) results from combustion of siloxane
  - Silica size distribution peaks at ~100 nm (25x smaller than $PM_{2.5}$)

- Unclear human health impacts of inhalation of amorphous silica nanoparticulate
  - Studies to date focus more on crystalline silica due to danger

- Exposure will depend on how much deposition on appliance surfaces occurs

Siloxane Measurement and Standards

CCST CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

- Biomethane advocates claim current siloxane specification is below reliable detection limits
  - Difficult to acquire project financing due to perceived risk of shut-in due to measurement error

- Utilities maintain that they have a lab that they trust and have verified that can measure well below 0.1 mg Si/m^3
  - In use to verify Point Loma

- Current ASTM International process underway to develop standard method for measurement of volatile silicon-containing compounds

Conclusions on Siloxanes

1. Current California siloxane specifications are based on very little data and involve large extrapolation from that data.
2. At present, no standardized measurement protocol exists for dependable measurement for the specification of 0.1 mg Si/m^3. Several testing laboratories claim detection limits of 0.1 mg Si/m^3 or lower. However, we have not been able to independently test these claims.
3. There is not enough information available now to determine whether 0.1 mg Si/m^3 is too stringent or not stringent enough to meet safety requirements.
4. Some sources are very unlikely to have siloxanes – e.g. dairies or agricultural waste. These sources could be held to a reduced and simplified verification regime to avoid unnecessarily encumbering sources that do not produce siloxanes.
5. Additional testing and experimentation is required in order to more rationally set a siloxane standard in the future.

Recommendations on Siloxanes

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Recommendation 3: Support a comprehensive research program to understand the operational, health, and safety consequences of various concentrations of siloxanes.

Recommendation 4: There is not enough evidence to recommend any changes to the maximum allowable siloxanes concentration at this time.

Recommendation 5: Consider the development of a reduced and simplified verification regime for sources that are very unlikely to have siloxanes, such as dairies or agricultural waste.

Recommendation 6: Monitor the ASTM International process to adopt and test a standard test method for siloxanes.

Recommendation 7: Use the learnings from the siloxane research and the ASTM International process to revisit the siloxane maximum standards once more complete information becomes available.

Summary Assessment of Regulatory Implications for Cost and Value

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

- The impact of the minimum HV specification on costs to produce biomethane depends on the composition of the raw biogas

- The siloxane specification increases costs to produce biomethane slightly
  - Perceived financial risk introduced by measurement uncertainty at the required level of siloxanes

- Substantial financial incentive exists to produce biomethane for transport, however uncertainty has greater impact than cost on volumes produced

Literature review: Cost of upgrading

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Technology	Study	Flowrate [Nm^3/h]	Upgrading Cost ($/MMBTU)
Water scrubbing	(Ong, Williams, & Kaffka, 2017)	130-160	4.69
	(Pierre et al., 2016)	230	4.14
	(Ullah Khan et al., 2017)	200-300	4.77
Chemical abs.	(Ong et al., 2017)	130-160	6.26
	(Pierre et al., 2016)	230	7.96
	(Ullah Khan et al., 2017)	200-300	8.28
PSA	(Ong et al., 2017)	130-160	9.12
	(Pierre et al., 2016)	230	5.41-8.91
	(Ullah Khan et al., 2017)	200-300	8.28
	(Angelidaki et al., 2018)	100	7.09
Membrane	(Ong et al., 2017)	130-160	4.43
	(Pierre et al., 2016)	230	7.00
	(Ullah Khan et al., 2017)	200-300	7.00

Water scrubbing: $4-$5 per MMBTU

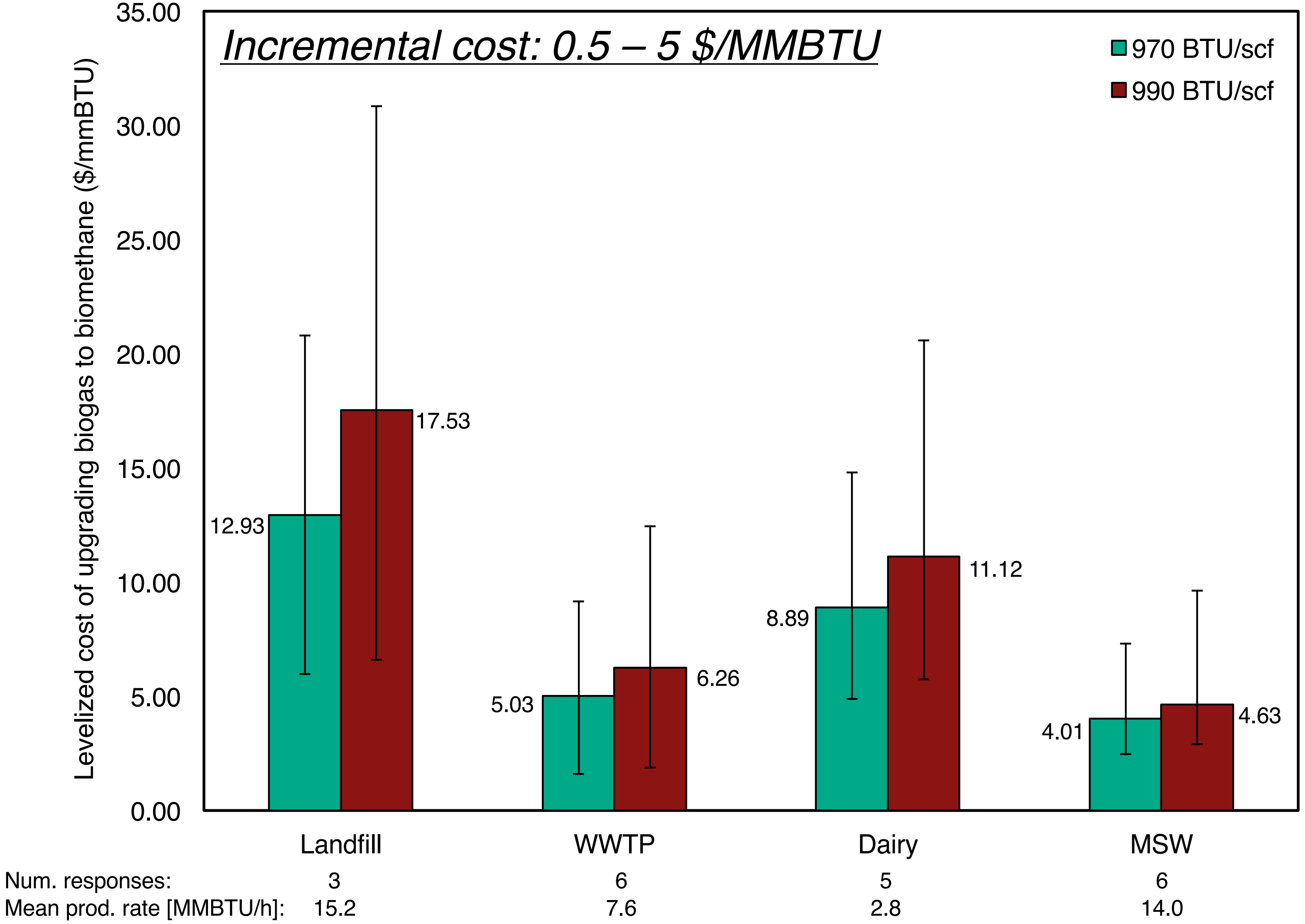
Chemical abs: $6-$9 per MMBTU

PSA: $5-$9 per MMBTU

Membrane: $4-$7 per MMBTU

Cost Implications of 970 vs. 990 BTU/scf

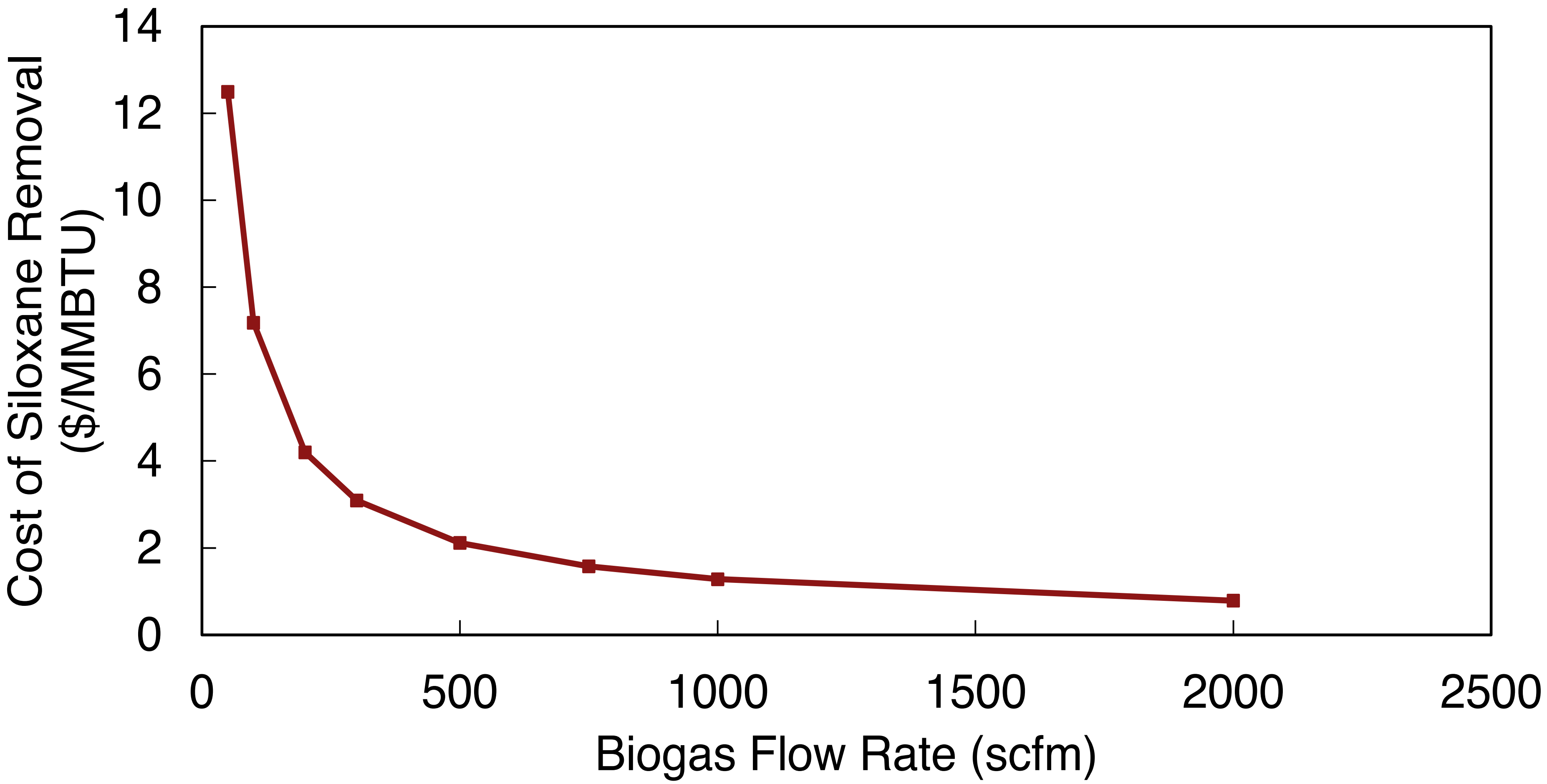
- No literature on cost of upgrading to 990 vs 970 BTU/scf
- We performed survey of biomethane upgrading equipment providers
- 28 companies contacted, 7 complete responses
- Constructed cost estimates for template projects



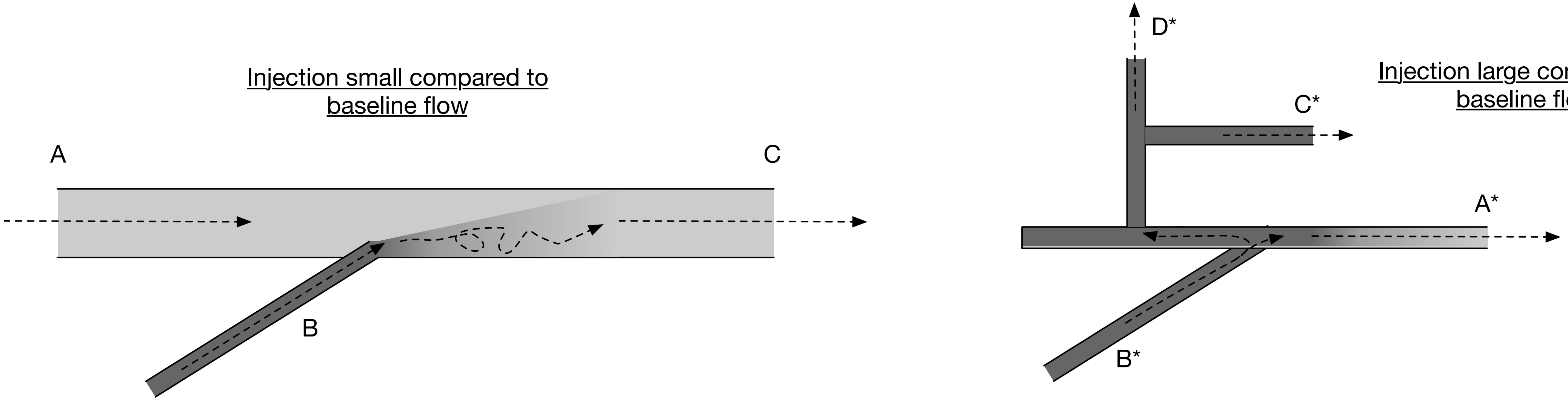
Cost Implications of Siloxane Removal

CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

- GTI (2014) performed survey of siloxane removal costs
- At Point Loma WWTP scale: $2 per MMBTU

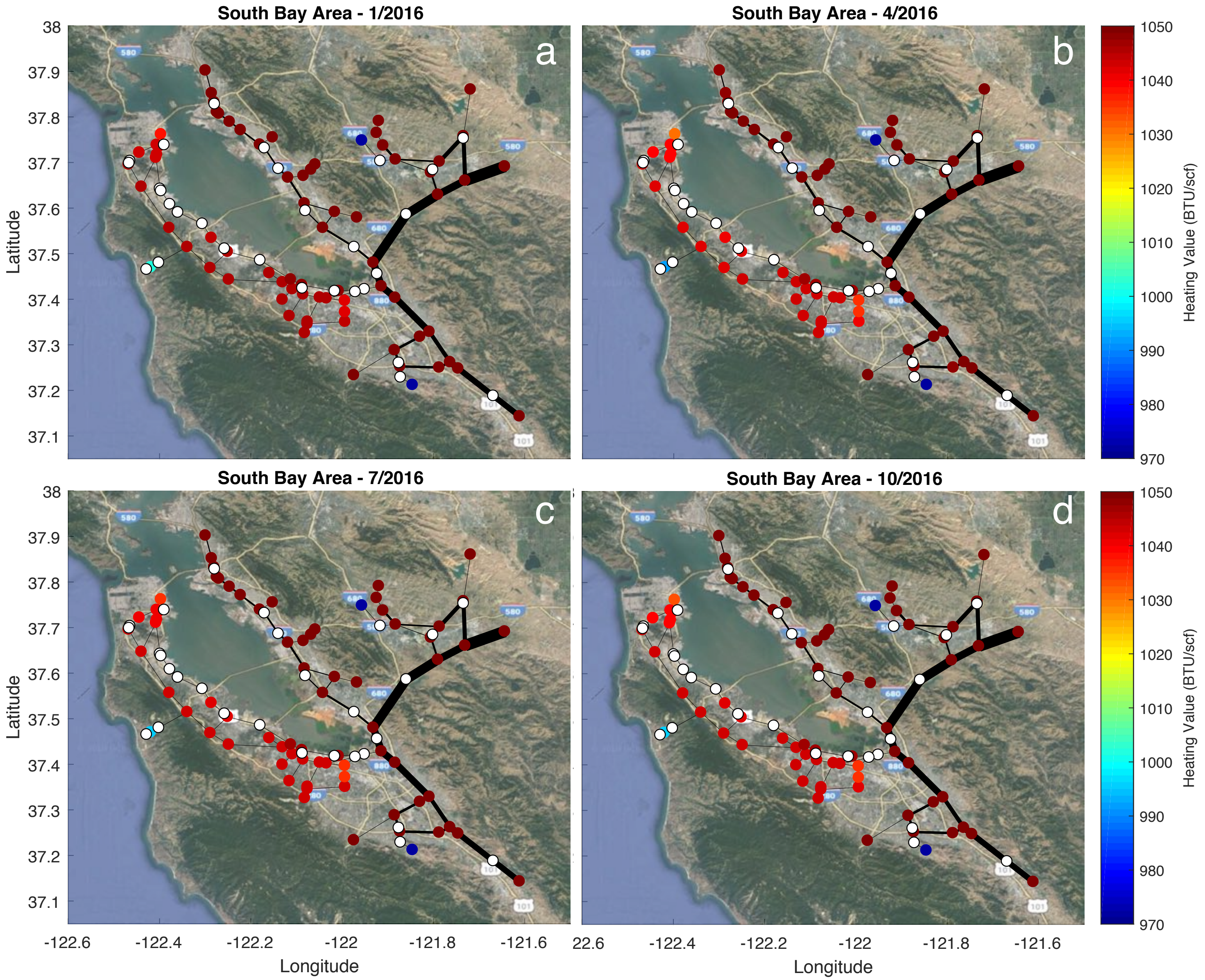


Options for dilution to meet specifications

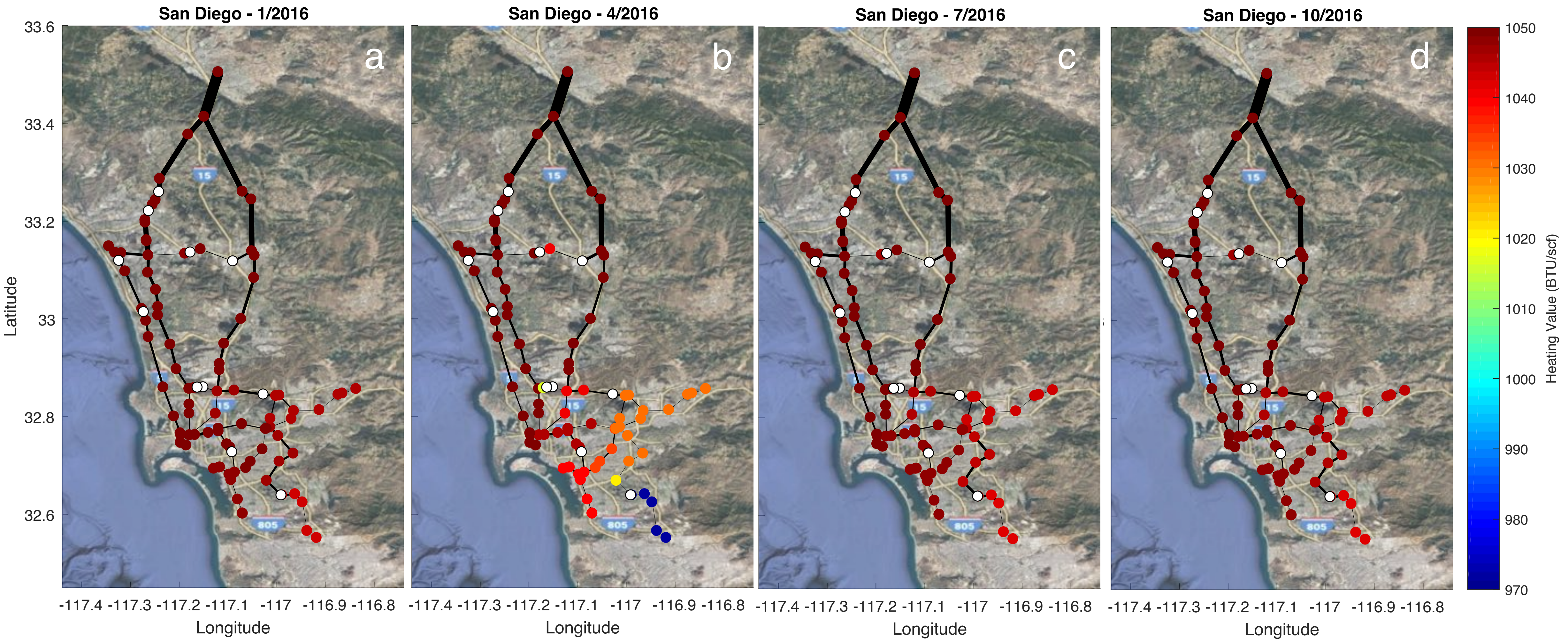


- If injection is small compared to flow, dilution will result in gas quality similar to FNG
- If injection is large, displacement of gas over larger region will occur
- In-pipe dilution not a general solution or replacement for injection standards

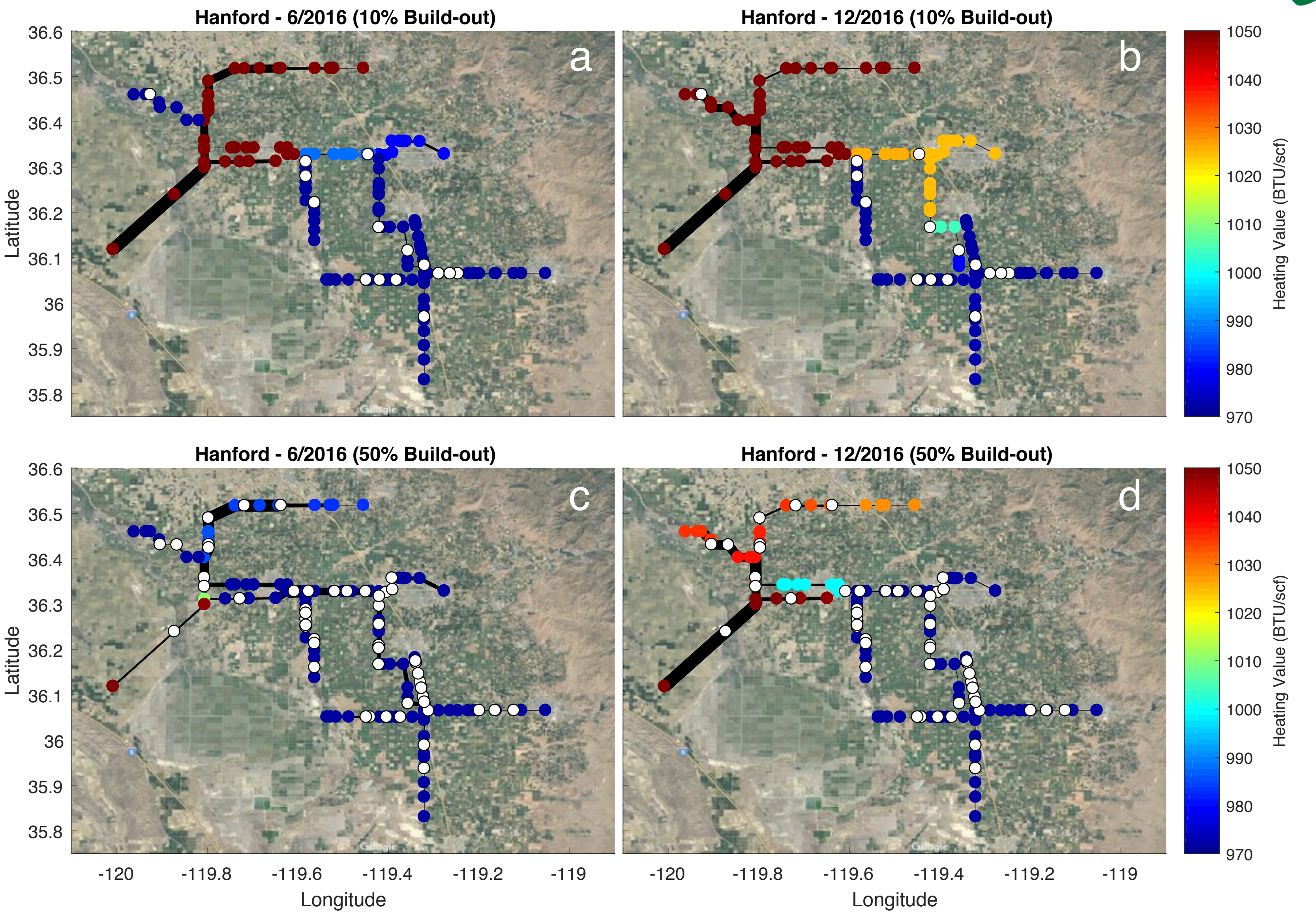
Regional modeling case studies



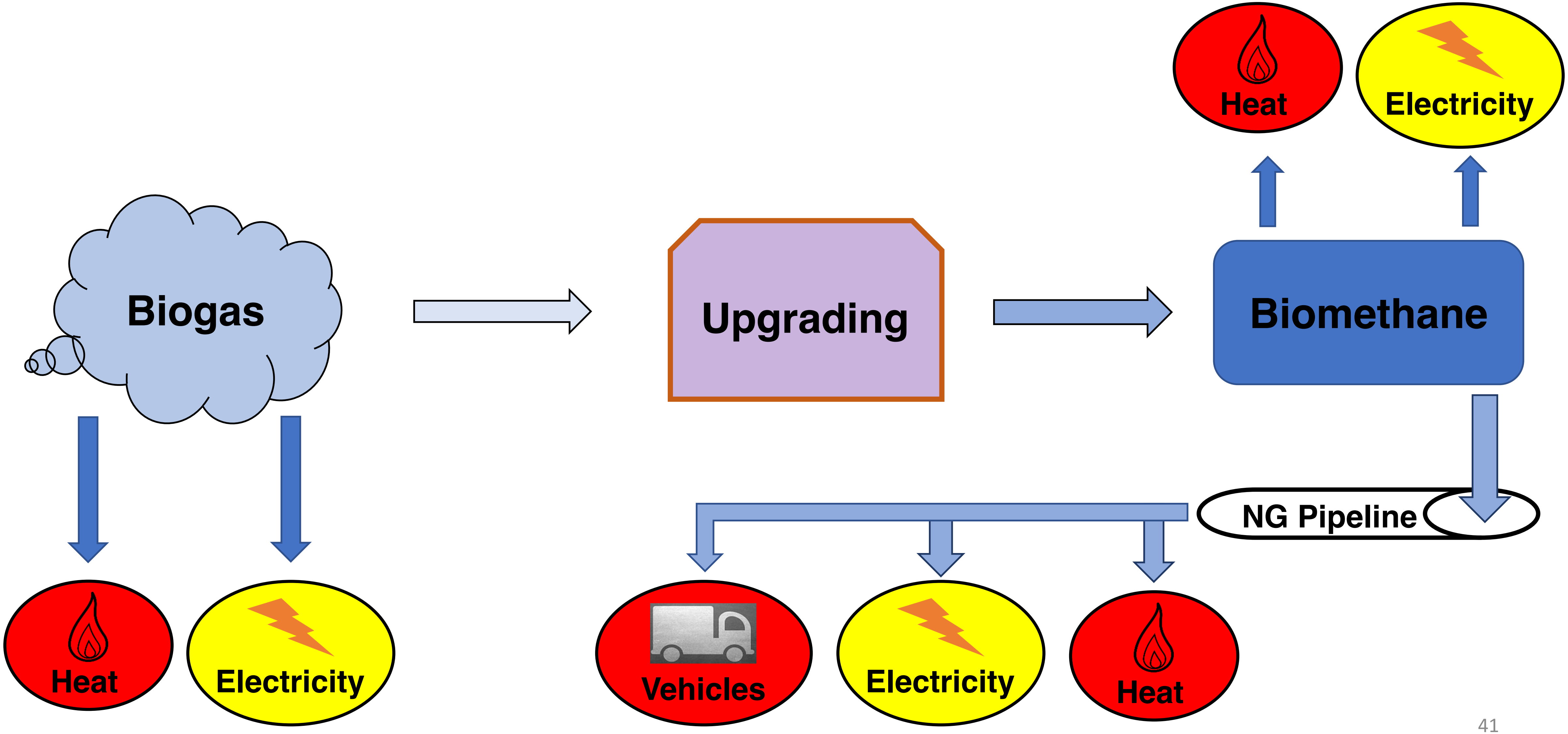
Regional Modeling Case Studies



Regional modeling case studies



Alternatives to Pipeline Transportation of Biomethane



Alternatives to Pipeline Transportation of Biomethane

- There are alternative ways to use biogas without incurring full costs of upgrading to biomethane.
- Some alternatives may be more economical than and environmentally-equivalent to upgrading biogas to biomethane and injecting into gas pipelines.
- These would substitute for equivalent BTU content of natural gas, just as would biomethane injected into a natural gas pipeline.
- However, State and Federal programs distort the market towards upgrading and pipeline injection rather than using for alternatives, including to generate electricity.

Alternatives to Pipeline Transportation of Biomethane: Greenhouse Gases

- Greenhouse gas impacts of biomethane injected into a pipeline and used for transportation are equivalent to greenhouse gas impacts of biogas to generate electricity. One MMBTU of biomethane or biogas offsets one MMBTU of natural gas.
  - Biomethane and natural gas are co-mingled in pipelines and are interchangeable.
  - Biogas to generate on-site electricity displaces the equivalent BTU of natural gas to generate electricity.

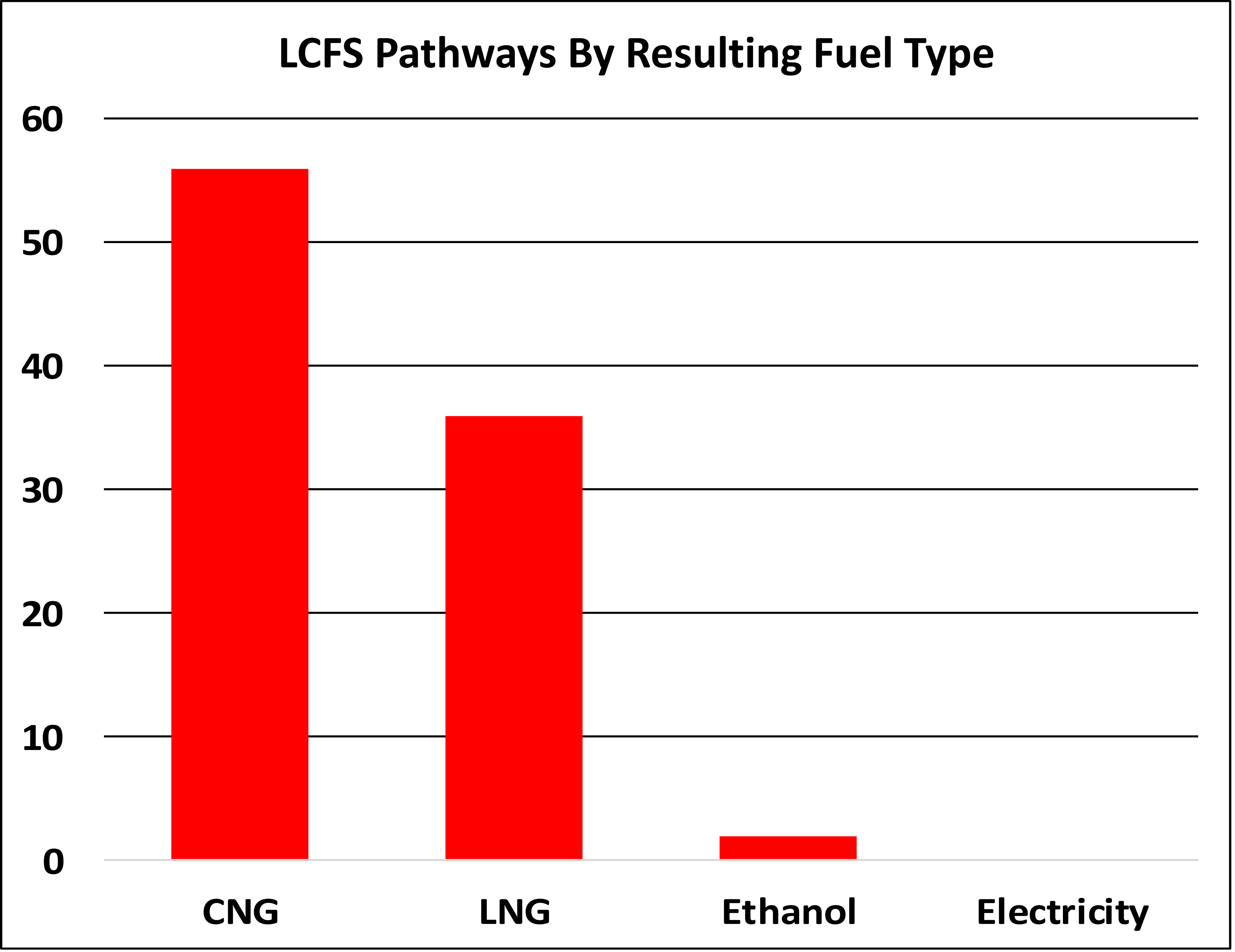
- For projects that avoid methane release, greenhouse gas impacts of biomethane used for transportation are equivalent to impacts of biogas for electricity generation.

Alternatives to Pipeline Transportation of Biomethane: Regulatory Incentives

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

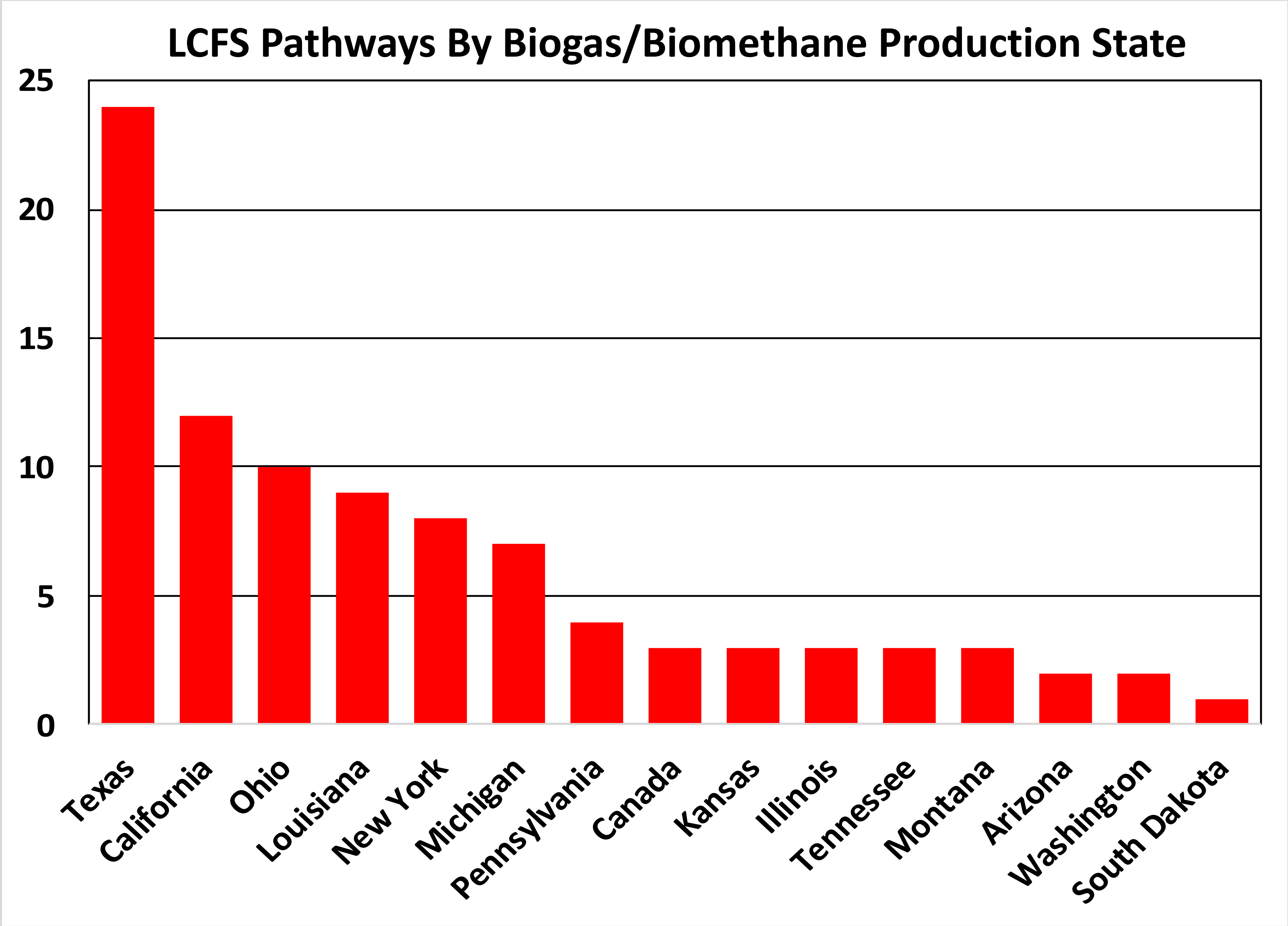
Biogas or Biomethane Use	Regulatory Incentive per MMBTU		
	State LCFS or Cap-and-Trade	Federal RFS	Total
Biogas upgraded to biomethane, transported in pipelines, used for transportation, certified pathway	\$6 - \$48	\$29	\$35 - \$77
Biogas or biomethane used for residential, commercial, industrial or electricity generation	\$1	\$0	\$1
Biomethane used to generate electricity, used for transportation: certified pathway	\$6 - \$48	\$15	\$21 - \$63

Citygate Market Price of Natural Gas: About \$3 per MMBTU



CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Source: CARB. https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm



CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Source: CARB. https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm

Conclusions and Recommendation on Alternatives to Pipeline Transportation

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

1. An important question for state of California is under what conditions biogas should be upgraded to biomethane and biomethane transported on common-carrier pipelines. An alternative is to use upgraded biogas (not meeting pipeline standards) or biomethane on-site, typically for generating electricity.

2. The differential treatment under Federal Renewable Fuel Standard program creates a substantial market distortion away from electricity generation and toward direct use of biomethane. In addition, if CARB regulations allow electricity to obtain only cap-and-trade credits rather than LCFS credits, that regulatory difference adds an additional substantial financial distortion away from electricity generation.

Recommendation 8: State and Federal agencies should examine whether the substantial differences in incentives for various uses of biogas/biomethane are consistent with the State and Federal policy intentions.

Concluding Remarks

1. Heating Value: Relaxing the current California HV standard of 990 BTU/scf to levels **near 970 BTU/scf should not pose operational, safety, or reliability hazards**
2. Siloxanes: The current California siloxane standard is not robustly supported, but **more research and data are needed** before science can support relaxing or tightening the standard. Recommendations given to allow investment in meantime. **Relaxed compliance process for dairies, food, and agricultural waste digesters.**
3. Current specifications affect volumes of biomethane available by affecting investment:
    1. Costs of meeting either standard are in the range of values of biomethane
    2. Compliance uncertainty (measurement) more important than simple $/MMBTU costs

Recommendations

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

Recommendation 1: Keep the Wobbe Number minimum requirements as they are now.

Recommendation 2: Reexamine regulations on heating value (HV) minimum levels. Initiate a regulatory proceeding to examine the option of allowing biomethane satisfying current WN limits and all other requirements, but with a heating value as low as 970 BTU/scf.

Recommendation 3: Support a comprehensive research program to understand the operational, health, and safety consequences of various concentrations of siloxanes.

Recommendation 4: There is not enough evidence to recommend any changes to the maximum allowable siloxanes concentration at this time.

Recommendation 5: Consider the development of a reduced and simplified verification regime for sources that are very unlikely to have siloxanes, such as dairies or agricultural waste.

Recommendation 6: Monitor the ASTM International process to adopt and test a standard test method for siloxanes.

Recommendation 7: Use the learnings from the siloxane research and the ASTM International process to revisit the siloxane maximum standards once more complete information becomes available.

Recommendation 8: State and Federal agencies should examine whether the substantial differences in incentives for various uses of biogas/biomethane are consistent with the State and Federal policy intentions.

Questions?