CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability

Gavin Newsom, Governor
October 2020 | CEC-500-2020-070

PREPARED BY:

Primary Author:
Vincent McDonell
Yan Zhao
Shiny Choudhury

UCI Combustion Laboratory
University of California, Irvine
949 824 5950 x11121
www.ucicl.uci.edu

Contract Number: PIR-16-017

PREPARED FOR:
California Energy Commission

Estella Shi
Project Manager

Virginia Lew
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The authors acknowledge David Morales, Leslie Hsiao and Max Venaas for their help on this project. Suggestions and technical support from technical advisory committee members are also appreciated.

Technical Advisory Committee members:

- Amin Akbari (Raypak), amin.akbari@raypak.com
- Marc Carreras (South Coast Air Quality Management District), msospedra@aqmd.gov
- Jeff Chase (Southern California Gas Company), jchase@socalgas.com
- Matt Gregori (Southern California Gas Company), mgregori@socalgas.com
- May Lew (Southern California Gas Company), mlew@semprautilities.com
- Rosalva Lopez (California Air Resources Board), rlopez@arb.ca.gov
- Dave Mehl (California Air Resources Board), dmehl@arb.ca.gov
- Steve Simons (Southern California Gas Company-Retired), ssimons@semprautilities.com
- Dana Waters (California Air Resources Board), dana.waters@arb.ca.gov

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Natural Gas-Related Transportation.

Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability is the final report for Contract Number PIR-16-017 conducted by University of California, Irvine. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This project examines how adding renewable biogas or renewable hydrogen to fossil-derived natural gas affects the performance of commercial and residential appliances. Displacing fossil natural gas with renewable gas decreases the net carbon emissions of these devices. Adding renewable biogas or hydrogen to the existing natural gas infrastructure can also help with near-term, low-cost carbon emissions reduction. The project included studies for nine typical combustion-based appliances with an unknown fuel mix: cooktop burner, oven burner, gas fireplace, low-oxides-of-nitrogen storage water heater, tankless water heater, space heater, pool heater, outdoor grill, and laundry dryer. The results showed that all devices can accept some level of biogas or hydrogen. Generally, adding renewable fuels tends to reduce emissions of oxides of nitrogen, carbon dioxide, and unburned hydrocarbons. Overall, the project results indicated that 5 percent to 10 percent (by volume) of hydrogen could be added without affecting general operation of these devices. The limiting behavior is flashback upon ignition or relight. Up to 10 percent biogas can be added but degraded cooking efficiency and flame stability so adding hydrogen is preferable from an operational and performance viewpoint. Adding 10 percent hydrogen to the existing natural gas infrastructure would remove 1.28 million tons of carbon dioxide emissions, equivalent to removing 278,000 gasoline vehicles from the road.

Keywords: residential appliances, fuel interchangeability, hydrogen enriched natural gas, biogas, pollutant emissions

Please use the following citation for this report:

McDonell, Vincent, Yan Zhao, and Shiny Choudhury (University of California Irvine, Combustion Laboratory). 2020. *Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability*. California Energy Commission. Publication Number: CEC-500-2020-070.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS i

PREFACE ii

ABSTRACT iii

EXECUTIVE SUMMARY 1

Introduction 1

Project Purpose 2

Project Approach 2

Project Results 3

Technology/Knowledge Transfer (Advancing the Research to Market) 3

Benefits to California 3

Future Research 6

CHAPTER 1: Introduction 7

Appliance Overview and Gas Use 7

Fuel Interchangeability 9

Project Objectives 14

CHAPTER 2: Project Approach 15

Burner Configuration Selection 15

Test Fuel Composition Selection 19

Fuel Classes 19

Gasified Biomass 23

Hydrogen 24

Recommendations 25

Experimental Methods 25

Instrumentation 25

Comments on Basis of Presented Emissions 27

CHAPTER 3: Project Results 29

Summary of Results 29

CHAPTER 4: Knowledge Transfer Activities 34

Journal Papers 34

Conferences 34

Stakeholder Presentations 36

CHAPTER 5: Conclusions/Recommendations 39
  Conclusions..39
  Recommendations..39
CHAPTER 6: Benefits to Ratepayers 40
LIST OF ABBREVIATIONS 42
REFERENCES 43
APPENDICES.. A-1

LIST OF FIGURES

Page
Figure ES-1: Breakdown of Natural Gas Used in California by Appliances 1
Figure 1: Market Saturation of Electric, Natural Gas, and Other Fuel Appliances 8
Figure 2: Statewide Natural Gas Energy Consumption 9
Figure 3: Heating Value and Wobbe Index Variation of Different Gas Mixtures 13
Figure 4: Investigated Residential Appliances...18
Figure 5: Block Diagram of the Gasification and Pyrolysis Processes 23
Figure 6: Experiment Setup Diagram..26

LIST OF TABLES

Page
Table ES-1: Performance Summary of Appliance Burners 4
Table ES-2: Greenhouse Gas Emission Reduction Estimation..5
Table 1: UC Irvine Natural Gas Species 10
Table 2: Natural Gas, Carbon Dioxide, and Hydrogen Property Comparison 10
Table 3: Unit Energy Consumption Score Criterion 15
Table 4: Natural Gas Consumption Score Criterion 16
Table 5: Future Expectation Score Criterion 16
Table 6: Ease of Burner Geometry Acquisition..16
Table 7: Benefit to California 17
Table 8: Burner Selection Matrix 18
Table 9: Potential Fuels of Interest: Dry, Clean Nominal Compositions (Volumetric Basis*) 19

Table 10: Classes of Renewably Derived Fuels and Ranges....................20

Table 11: Variation in California Natural Gas....................20

Table 12: Fuel Classes Recommended for Study....................25

Table 13: Calibration Gases....................27

Table 14: Performance Summary of Appliance Burners with Relative Trends....................30

Table 15: Performance Summary of Appliance Burners with Numeric Concentration Levels....................31

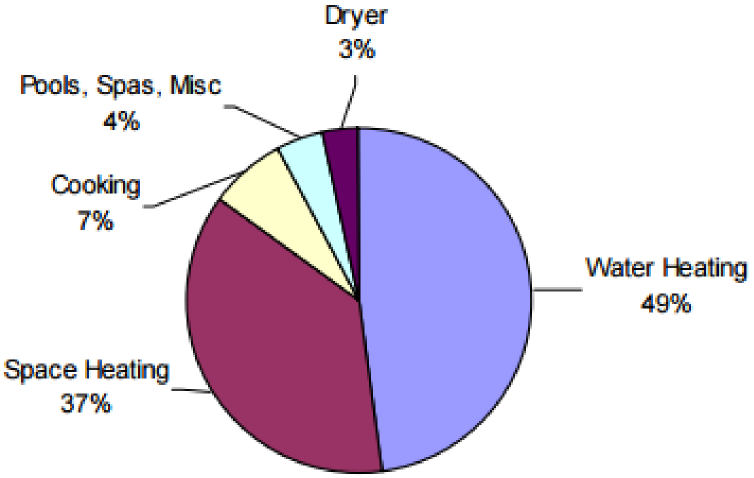
Table 16: Greenhouse Gas Emission Reduction Estimation....................40

EXECUTIVE SUMMARY

Introduction

In 2018, Californians consumed 2.1 million cubic feet of natural gas, about 21 percent of which was for residential use. As shown in Figure ES-1, almost half (49 percent) was for water heating, followed by space heating (37 percent). The high efficiency and abundance of natural gas makes it a particularly attractive source of energy to meet the state's stringent air quality and emissions requirements. However superior a fuel natural gas is to other fossil fuels, it remains a non-renewable resource and a significant source of greenhouse gas emissions. To meet California's aggressive goals, it is important to identify possible alternatives to natural gas.

Figure ES-1: Breakdown of Natural Gas Used in California by Appliances



Source: CEC-2009 California Residential Appliance Saturation Study

The *2011 Bioenergy Action Plan* indicated that biomass-derived fuels (biogas) could help California achieve waste reduction, increase adoption of renewable energy, and help meet climate change emissions reduction goals. However, using biogas(es) which are produced by waste in landfills, feedlots, and by anaerobic digestion processes at water treatment plants and dairies is problematic because of the impurities in those gases. To mix this renewable gas into the pipeline, the biogas must be purified to meet the pipeline natural gas standard. More recently, there is growing interest in injecting renewable hydrogen into the pipeline because this fuel is carbon-free, which helps reduce greenhouse gas (GHG) emissions. Multiple renewable sources can produce hydrogen including solar energy, biomass, wind power, and water electrolysis using electricity grid power. While interest in injecting renewable gases into existing natural gas infrastructure continues, little has been done to understand the air quality implications, proper fuel mixtures required for stable operational performance and safety, and modifications of equipment that may be required for efficient operation using these gases in residential appliances.

Of particular interest in the current project is how using biogas (renewable natural gas) or renewable hydrogen would affect the current stock of gas-using appliances, particularly those without control systems that can help the system accommodate variations in fuel composition.

Some examples of those appliances include water heaters, cook stoves, ovens, and clothes dryers. As California moves to using more renewable natural gas, it is important to understand how these end use devices are affected.

Project Purpose

The researchers addressed the need for data and analysis to understand how adding hydrogen, biogas, or both to natural gas affects residential appliances, and how much these renewable fuels can be added without negatively altering performance. Further, the project assessed how adding renewable fuels to natural gas affects criteria pollutant emissions. In the near-term, adding renewable fuels to the existing natural gas infrastructure represents a relatively low-cost option to reduce carbon dioxide (CO_2) emissions.

The goal of the project was to summarize the limits of added biogas or hydrogen to natural gas and the changes in criteria pollutants. These results will inform policy makers and provide data for assessing air quality impacts. In addition, appliance manufacturers can use the results when considering increasing the fuel flexibility of these devices to accommodate additional renewable fuel content.

Project Approach

While the project is largely simulation-based, it takes advantage of existing data sets on appliance performance developed by Lawrence Berkeley National Laboratory (LBNL) in which the emphasis was on addition of higher hydrocarbons. Work done by University of California Irvine demonstrated that the simulation method, anchored with experimental data on higher hydrocarbons, could be accurately applied to biogas and hydrogen/natural gas mixtures.

A key task was to establish appliance burner configurations and fuel composition ranges. To achieve this, information on typical operating features and geometries of dual-fuel cooktop burners, oven bottom burners, broiler burners, central forced air and wall furnaces, storage water heaters, and tankless water heaters was collected. In addition, the researchers developed a survey of existing commercial products, including appliances from abroad, where several companies are offering such products. A technical advisory committee was created, comprised of utilities, air pollution control districts, and appliance original equipment manufacturers. The technical advisory committee provided input used to establish the types of renewable gases that are of interest (such as dilute methane for biogas, added hydrogen for renewable hydrogen) along with their ranges. Their input was also used to guide selection of the actual burner configurations selected for study, with emphasis on total natural gas used, market share, and consideration for future use within California. Nine specific configurations and three fuel classes were used for this project.

To anchor simulation results, four appliance burners were used to validate the experiments: cooktop burner; low oxides of nitrogen (NO_X) storage water heater; space heater, and tankless water heater. A fuel mixing system was developed to accurately introduce precise levels of the renewable fuels into natural gas. Data obtained include stability limits (for example at what level of biogas or hydrogen addition does the appliance burner fail to operate reliably) and pollutant emissions (such as NO_X, carbon monoxide (CO), unburned hydrocarbons (UHC)). The influence of these added fuels on emissions of nitrous oxide (N_2O; commonly known as laughing gas) was also examined. The testing methods used followed American National

Standards Institute (ANSI) test procedures (if available) or those used by LBNL for their previous work on higher hydrocarbons. Environmental Protection Agency (EPA)-certified emissions measurement equipment was used for the measurements.

Project Results

Table ES-1 on the following page summarizes results from the study. The results are presented for both potential renewable gases considered for each of the nine burners analyzed. As a result, all of the key information is provided in a compact "performance matrix" manner. Table ES-1 focuses on (1) upper limit of addition for each renewable fuel and (2) the impact on emissions of NO_X, CO, and UHC compared to baseline natural gas. To aid in the visualization of the relative performance, if improvement is realized as the renewable fuel is added, the cell is shaded green. If the improvement degrades, the cell is shaded red. The burner performance matrix with more details are shown in Table 15 in the report.

The researchers concluded there is a lack of standard test procedures for different appliances. As a result, understanding how the results from the current project relate to overall performance specifications may be challenging. While these results followed previous appliance characterization programs, general performance comparisons should be made with some caution.

It was evident that emission regulation of these appliances, with few exceptions, are not widespread. Most focus on CO emissions, but there is little attention given to NO_X or other GHG emissions. The exception are water heaters, which have standard NO_X emission requirements for the United States.

The current limiting device for hydrogen addition is the low NO_x water heater at 10 percent addition by volume. Thus, if effort is carried out to provide a cost-effective retrofit approach for low NO_x water heaters, the results suggest the amount of hydrogen that could be added can be doubled to 20 percent (the next lowest limit).

Technology/Knowledge Transfer (Advancing the Research to Market)

The results for the cooktop burner, oven burner, and tankless water heater have already appeared in archival, peer-reviewed journal articles. Generally, the results indicate favorable benefits from adding hydrogen to natural gas to improve performance and reduce CO_2 emissions from these devices. This bodes well for blending hydrogen into the existing natural gas infrastructure as a near-term means for CO_2 reduction.

Benefits to California

Given the current natural gas use in California's market sector, estimates of the overall GHG reductions can be made (Table ES-2). A significant reduction in GHG emissions can be achieved if 10 percent hydrogen can be injected into the pipeline. With 10 percent hydrogen added, 1.63 million tons of carbon dioxide emissions would be removed, equivalent to removing 354,000 gasoline vehicles from the roads.

Table ES-1: Performance Summary of Appliance Burners

Appliance Burner		Natural gas + hydrogen	Natural gas + carbon dioxide (simulate biogas behavior)
Cooktop burner	Upper limit	20% (ignition); 55 (cooking); 75% (idle)	20% (ignition); 35% (cooking); 35% (idle)
	NO_X	-23.3% (0-50% H_2)	-51.4% (0–30% CO_2)
	CO	-14.0% (0-50% H_2)	+58.2% (0–30% CO_2)
	UHC	-74.2% (0-50% H_2)	+2128.4% (0–30% CO_2)
Oven burner	Upper limit	30%	15%
	NO_X	Variation within analyzer	-91.8% (0-10% CO_2)
	CO	-38.2% (0-25% H_2)	+113.8% (0-10% CO_2)
	UHC	+350.5% (0-25% H_2)	NA
Gas fireplace	Upper limit	100%	45%
	NO_X	+3966.4% (0-100% H_2)	-75.7% (0-40% CO_2)
	CO	-100% (0-100% H_2)	-99.9% (0-40% CO_2)
Low NO_X storage water heater	Upper limit	10%	15%
	NO_X	Variation within analyzer	-45.9% (0–10% CO_2)
	CO	+26.9% (0-5% H_2)	+334.4% (0–10% CO_2)
	UHC	-50.5% (0-5% H_2)	+159.3% (0–10% CO_2)
Tankless water heater (2 gal/min)	Upper limit	>20%	15%
	NO_X	-20.3% (0-20% H_2)	-44.8% (0–12% CO_2)
	CO	-9.7% (0-20% H_2)	+349.9% (0–12% CO_2)
	UHC	Variation within analyzer	+177.2% (0–12% CO_2)
Space heater	Upper limit	20% (ignition); 45% (operation)	10% (ignition); 30% (operation)
	NO_X	-4.2% (0-40% H_2)	-47.1% (0–25% CO_2)
	CO	-13.9% (0-40% H_2)	+897.8% (0–25% CO_2)
	UHC	Variation within analyzer	+193.9% (0–25% CO_2)
Pool heater	Upper limit	NA	20%
	NO_X	-95.6% (0–70% H_2)	-98.5% (0–15% CO_2)
	CO	+761.9% (0–70% H_2)	+2400% (0–15% CO_2)
Outdoor grill	Upper limit	> 40%	40%
	NO_X	+128.2% (0-40% H_2)	-~100% (0–35% CO_2)
	CO	-93.7% (0-40% H_2)	-77.5% (0–35% CO_2)
Laundry dryer	Upper limit	NA	15%
	NO_X	-61.9% (0-40% H_2)	-80.7% (0–10% CO_2)
	CO	-34.1% (0-40% H_2)	+118.1% (0–10% CO_2)

Source: UC Irvine

Table ES-2: Greenhouse Gas Emission Reduction Estimation

Appliance	**GHG emission under different H_2 percentages in the fuel**				**NG consumption percentage[1]**	**GHG reduction with 10% H_2 replacement**
	5% H_2	10% H_2	15% H_2	20% H_2		
Cooktop	-2.83%	-5.75%	-8.75%	-11.9%	Part of 7% shown in Figure ES-1	• 2017 California GHG emissions (converted to CO_2): 424 million tons.[3] • GHG reduction by replacing 10% pipeline natural gas with H_2: 1.63 million tons, which is 0.38% of the total California GHG emissions. • The GHG reduction from the residential sector is equivalent to around 354,000 gasoline vehicles removed from the road.[4]
Oven	-2.83%	-5.75%	-8.75%	-11.9%	Part of 7%	
Gas fireplace	-2.83%	-5.75%	-8.75%	-11.9%	Part of 37%	
Low NO_X storage water heater	-2.83%	-5.75%	-8.75%	-11.9%	Part of 49%	
Tankless water heater	-1.67%	-3.46%	-5.38%	-7.46%	Part of 49% (~15% in California)[2]	
Space heater	-2.83%	-5.75%	-8.75%	-11.9%	Part of 37%	
Pool heater	-1.67%	-3.46%	-5.38%	-7.46%	Part of 4%	
Outdoor grill	-2.83%	-5.75%	-8.75%	-11.9%	Part of 7%	
Laundry dryer	-2.83%	-5.75%	-8.75%	-11.9%	Part of 3%	

1. KEMA, Inc. 2010. 2009 California Residential Appliance Saturation Study. California Energy Commission. Publication number: CEC-200-2010-004-ES.

2. Diane M. Lamyotte. 2018. Tankless 2018: Annual Tankless Report. https://www.phcppros.com/articles/7609-tankless-2018-annual-tankless-report

3. California Air Resources Board. 2019. GHG Current California Emission Inventory Data. https://ww2.arb.ca.gov/ghg-inventory-data

4. Calculated based on "United States Environmental Protection Agency. 2018. Greenhouse Gas Emissions from a Typical Passenger Vehicle. https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle"

Source: UC Irvine

Future Research

It is noteworthy that a 2019 residential appliance saturation study (*2019 Residental Appliance Saturation Study* https://www.energy.ca.gov/data-reports/surveys/2019-residental-appliance-saturation-study) is currently in process. It would be helpful to update these results using the updated numbers.

Other steps that can follow on from this work include technology development that can increase the ability of these devices to tolerate additional renewable fuel content. A recommendation to this end is to establish support for development of appropriate appliances that can operate on as much as 100 percent hydrogen to help ensure the climate change goals for California can be met.

CHAPTER 1: Introduction

This chapter provides an overview of the current appliances that use most of the natural gas in California. The appliances used are presented along with details regarding their burner configurations. The chapter concludes with recommendations for (1) the burners/appliance types that should be incorporated into the project, and (2) those that should be studied experimentally to validate the simulation methods that will be applied.

Appliance Overview and Gas Use

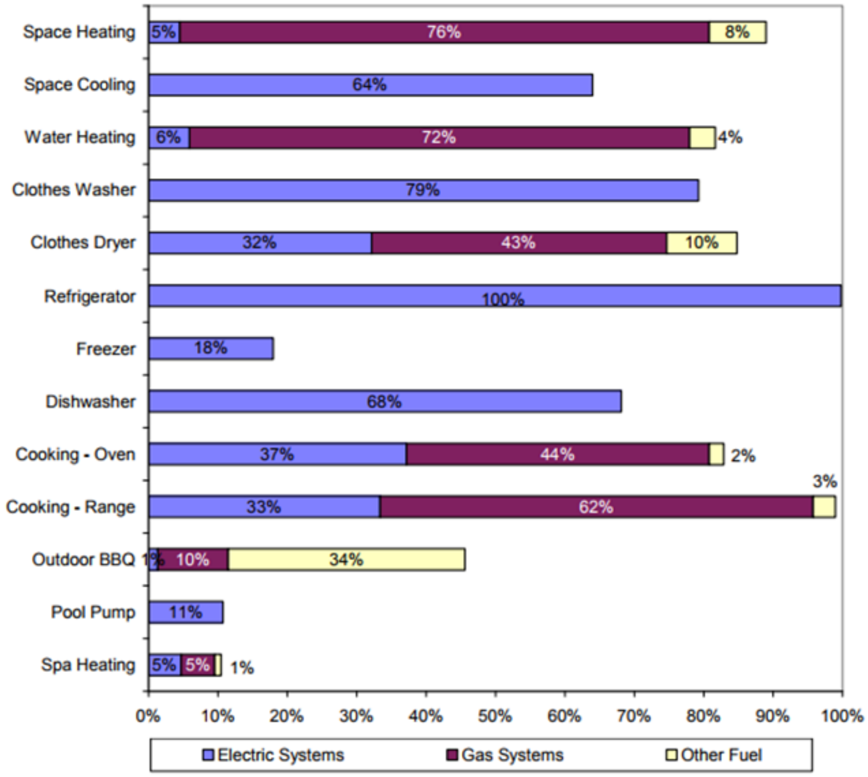
In 2017, the state of California consumed roughly 2.11 million cubic feet of natural gas [1], making it the nation's second biggest consumer of natural gas behind Texas. Currently, a significant portion (46.54 percent in 2018 [2]) of California's total in-state electricity production is generated by natural gas power plants. Indeed, natural gas constitutes a crucial component in California's total available energy resources. The high efficiency and abundance of natural gas makes it a particularly attractive source of energy in the context of the state's stringent air quality and emissions requirements.

However superior a fuel natural gas is to other fossil fuels, it is a significant source of greenhouse gas emissions in California and remains by nature a nonrenewable resource; and akin to the Earth's petroleum reserves, the world supply of natural gas will eventually be depleted at the current rate of consumption. To meet California's ambitious climate goals, it is important to consider sustainable alternatives to natural gas with low or zero GHG emissions. With the prevalence of infrastructure and equipment fueled by natural gas, it is worthwhile to consider sustainably-produced gaseous fuels which can directly replace natural gas in its current applications. Utilizing current natural gas pipelines to transport and distribute renewable gases needs less capital investment compared to laying new pipelines and avoids the existing infrastructure from becoming a stranded asset.

This study will investigate the compatibility of sustainable fuels with traditional residential appliances designed for use with natural gas. In this study, 12 burner types from natural gas home appliances are investigated, 9 of the 12 are studied using simulation methodology, and 4 of the 9 appliances are also tested experimentally. Of the 2.11 million cubic feet of natural gas consumed in California per year, around 20 percent [3] can be attributed to the residential sector. If alternative fuels to natural gas household appliances were found, more than 400,000 million cubic feet of natural gas could potentially be conserved annually. As such, the study will focus on household appliances with the greatest impact on the total natural gas consumption. Appliances were therefore chosen based on two criteria, household saturation and total contribution to natural gas consumption. Data from the 2010 California Residential Appliance Saturation Survey [4] depicted in the following two figures were referenced due to the fact that the 2017 update is currently underway. While the numbers may be dated, it is inferred that the result of the latest survey will not dramatically deviate from that of 2010.

First, in terms of popularity of natural gas appliances, it can be observed from Figure 1 that more than 80 percent of households in California own at least a space heater, a water heater, a laundry dryer, a cooking range and oven. In all the appliances listed, more than 40 percent are fueled by natural gas. These devices are a relatively high priority for study as they represent a significant number of individual devices.

Figure 1: Market Saturation of Electric, Natural Gas, and Other Fuel Appliances

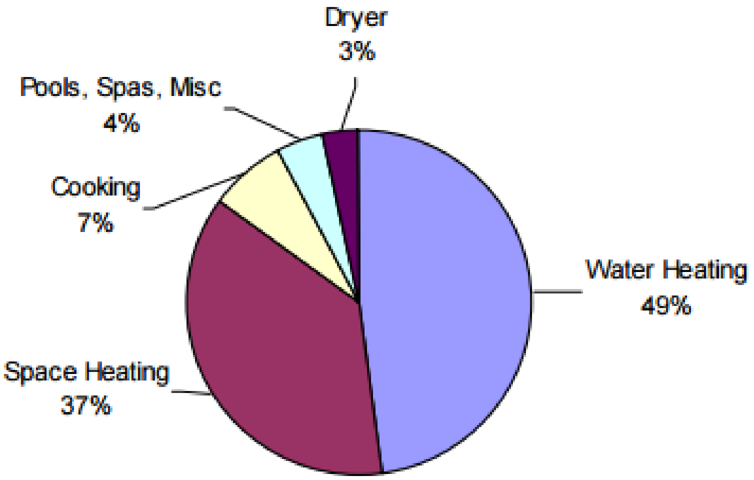


Source: CEC-2009 California Residential Appliance Saturation Study

Second, the relative contribution of major appliances to the aggregate residential natural gas consumption is considered. As depicted in Figure 2, the residential appliances with the greatest natural gas demand in the state are, by far, water and space heaters, at roughly 49 percent and 37 percent, respectively, followed by cooking appliances, such as stoves, at 7 percent, pool and spa heaters and miscellaneous at 4 percent, and dryers at 3 percent [4]. The relative use of these devices also warrants critical consideration for their inclusion in the study.

In both criteria, water and space heaters not only are highly saturated in households, but also contribute individually to more than 25 percent of total residential natural gas consumption. Therefore, multiple configurations of water and space heaters are considered with the aim of investigating alternative fuel compatibility with all popular burner configurations. In addition, the cooking range and oven were chosen for the same reasons of prevalence and consumption demand.

Figure 2: Statewide Natural Gas Energy Consumption



Source: CEC-2009 California Residential Appliance Saturation Study

Fuel Interchangeability

A concept critical to the current project is "fuel interchangeability". One may wonder why a given appliance cannot simply be fed with whatever fuel is of interest. In the marketplace, it is common to see "dual-fuel" appliances. In very recent times, this might be a reference to using either electricity or natural gas or a combination of both (two "fuel" sources). Traditionally, however, appliances marketed as "dual-fuel" refers to compatibility with Liquefied Petroleum Gas (LPG). This is important because natural gas and LPG are the common gaseous fuels used in residences. LPG tends to be used in regions where vast natural gas pipeline infrastructure does not exist, typically in more remote or sparsely populated regions. LPG has a higher "Wobbe Index"[1] than natural gas; therefore, the default natural gas orifice must be replaced with a narrower orifice designed specifically for LPG. This concept is equally applicable should hydrogen or biogas be considered as future fuels. When a blend of these fuels with natural gas is considered, the situation becomes a little more complex, but quite tractable from a theoretical viewpoint. In the current study, the fuels of interest include biogas (which is generally a mixture of carbon dioxide and methane) and hydrogen.

More details regarding interchangeability are provided for context of the current study. The species of the pipeline natural gas used in this study is shown in Table 1 [5]. The higher heating value is 1012.5 British thermal units (Btu) per standard cubic foot (scf), and low heating value is 912.6 Btu/scf measured at 21.1 °C, 1 atm. The analysis shows that methane percentage of the natural gas is 95.8 percent, which is higher than the United States average natural gas supply [5] [6].

---

[1] $Wobbe\ Index = \frac{HHV\ [\frac{BTU}{scf}]}{\sqrt{Specific\ Gravity}}$, a measure of the interchangeability of fuel gases and their relative ability to deliver energy.

Table 1: UC Irvine Natural Gas Species

Content	Molecular Formula	Mole Fraction
Methane	CH_4	95.8%
Ethane	C_2H_6	1.4%
Propane	C_3H_8	0.4%
Iso-butane	C_4H_{10}	0.05%
N-butane	C_4H_{10}	0.05%
Iso-pentane	C_5H_{12}	0.025%
N-pentane	C_5H_{12}	0.025%
C6	C_6H_{14}	0.017%
C7	C_7H_{16}	0.017%
C8	C_8H_{18}	0.016%
Carbon dioxide	CO_2	1.9%
Oxygen	O_2	0%
Nitrogen	N_2	0.3%

Source: University of California, Irvine

The major species in natural gas is methane, therefore, it is essential to be clear about the property differences between methane, biogas (represented by carbon dioxide), and hydrogen to better conduct fuel interchangeability study. The important property parameters, especially those related to combustion, are listed in Table 2. Most of the parameters are from reference [7] at room condition (25 °C, 1 atm), except where noted.

Table 2: Natural Gas, Carbon Dioxide, and Hydrogen Property Comparison

Property	Unit	Methane	Carbon Dioxide	Hydrogen
Density	kg/m^3	0.648	1.784	0.0813
Viscosity	10^{-5} Pas	1.11	1.50	0.89
Laminar Flame Speed	m/s	0.4	N/A	2.1
Low Flammability [8]	ϕ	0.53	N/A	0.1
	vol %	5	N/A	4
High Flammability [8]	ϕ	1.6	N/A	7.14
	vol %	15	N/A	75
Ignition Energy	10^{-5} J	33	N/A	2
Lower Heating Value [9]	MJ/m^3	34.0	0	10.2
	MJ/kg	49.9	0	120.1
Higher Heating Value [9]	MJ/m^3	37.8	0	12.5
	MJ/kg	55.5	0	142.1
Adiabatic Flame Temperature	K	2226	N/A	2318
Wobbe Index	MJ/m^3	51.9	0	48.5

Source: University of California, Irvine

As shown in Table 2, hydrogen has a relatively low density. This will allow it to disperse quickly rather than accumulating in the area close to any source of leakage. Hence, while the small molecular size of hydrogen may result in an inherent increased potential for leakage, the dispersion will decrease the possibility of an explosion. The laminar flame speed of hydrogen is five times that of methane, which poses a challenge for burner design to avoid flashback. The wide flammability range of hydrogen/air mixtures exacerbates this problem. Moreover, hydrogen is more reactive than methane, and the minimum ignition energy of hydrogen is 20 μJ, compared to 330 μJ for methane. This property of hydrogen makes it easier to ignite when present in the fuel mixture. Carbon dioxide, on the other hand, is essentially a diluent. For biogas to be blended with natural gas, from a combustion viewpoint, it is similar to simply adding carbon dioxide.

The heating values of methane, carbon dioxide, and hydrogen are also shown in Table 2. The difference between lower heating value (LHV) and higher heating value (HHV) is the latent heat of water in the combustion exhaust. In most combustion devices, LHV is realized as a result of not condensing the water. The latent heat can only be released under 100 °C, but if it can be captured and used, it will increase the overall efficiency of the device. But dealing with liquid water in the exhaust can also cause reliability issues. Most gas supply companies charge for HHV when selling their gases to consumers, although we are only going to use the LHV of the fuel. The heating value is a very important parameter to evaluate the ability of a fuel as an energy carrier. The hydrogen heating value on mass base is about 2.5 times the heating value of methane, which makes liquefied hydrogen a promising energy carrier. With the development of power-to-gas (P2G) technology, compressed hydrogen can be used as a very competitive energy storage method to serve the areas that the electricity grid cannot reach. Although the energy density of hydrogen is higher than that of methane on mass base, the volumetric heating value of methane is more than three times that of hydrogen. This implies that the same volume flowrate of the fuel will produce much less heat than originally needed, if we replace natural gas with hydrogen. However, in real combustion applications, this heating value difference does not cause much concern, because the Wobbe Index is the factor to evaluate the fuel interchangeability regarding heat release rate [10] [11]. If two different fuels have the same Wobbe Index, the heat output will be constant for a given inlet pressure.

$$Wobbe\ Index = \frac{High\ Heating\ Value}{\sqrt{Fuel\ Specific\ Gravity}} \qquad 1)$$

While the Wobbe Index is widely applied in combustion devices, the concept of using heating value over square root of fuel density as a fuel interchangeability parameter originated from work in the 1920s by the American Gas Association (AGA). The AGA conducted thousands of experiments to investigate on fuel interchangeability and finally came up with "C-Index" of change in performance of appliances, which is the predecessor of the widely used Wobbe Index today [12] . With a few assumptions, the Wobbe Index can be derived from the Bernoulli equation. By assuming the fuel flow within the pipeline and the combustion device is at steady state, and the flow is incompressible (constant fluid density), inviscid, also with negligible frictional losses. The Bernoulli equation is then reduced to Eq. 2.

$$p_1 + \frac{1}{2}\rho_f V_1^2 = p_2 + \frac{1}{2}\rho_f V_2^2 \qquad 2)$$

$$\dot{V}_f = A_2\sqrt{\frac{2\Delta p}{\rho_f(1-\left(\frac{A_2}{A_1}\right)^2)}} \qquad 3)$$

The subscript "1" stands for the household pipeline, "2" stands for the fuel orifice on the combustion device

As can be seen, the volume flow rate of the fuel is a function of the fuel density, fuel flow areas, and the pressure drop from the pipeline to the combustion device. For open-air flames, p_2 is essentially atmospheric pressure. However, due to the relatively small orifice area for the combustion device compared to the natural gas pipeline flow cross section, $(A_2/A_1)^2$ can usually be ignored in Eq. 3, which leads to Eq. 4.

$$\dot{V}_f = A_2\sqrt{\frac{2\Delta p}{\rho_f}} \qquad 4)$$

Then, the heat output of a combustion device can thus be presented as

$$\dot{q} = \dot{V}_f HHV = \sqrt{\frac{2\Delta p}{\rho_{air}}}\frac{HHV}{\sqrt{sg_f}} \qquad 5)$$

Based on the assumption of constant density and neglecting viscous effect, the heat output of the combustion device is only a function of the heating value over the square root of the fuel specific density.

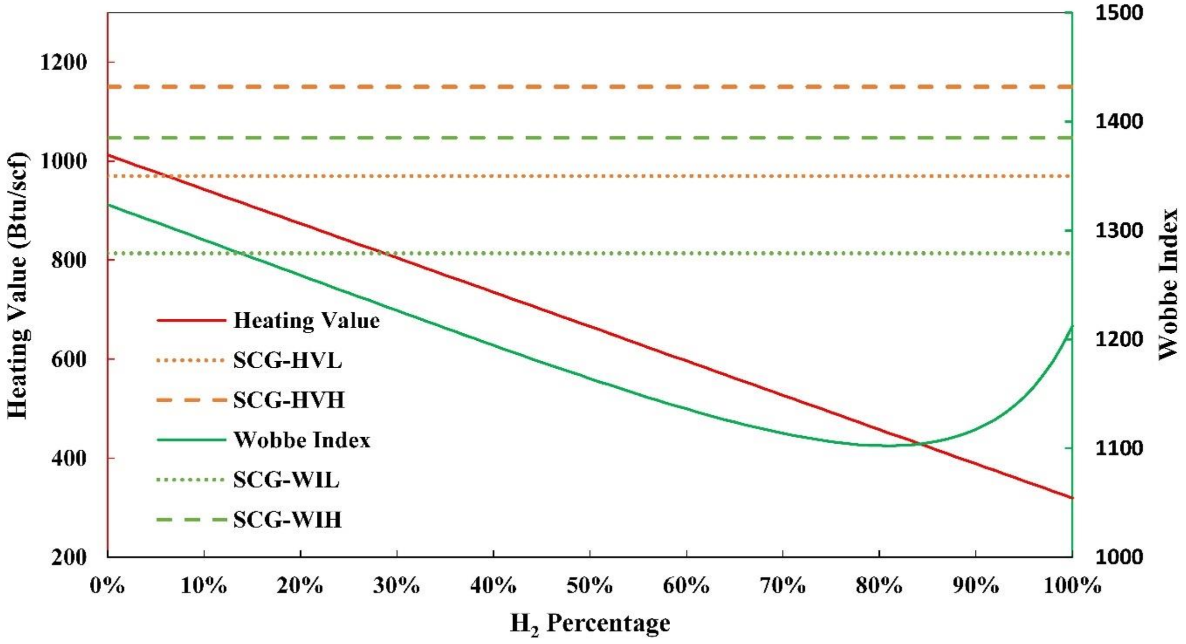
$$Wobbe\ Index = \frac{HHV}{\sqrt{sg_f}} \sim \dot{q} \qquad 6)$$

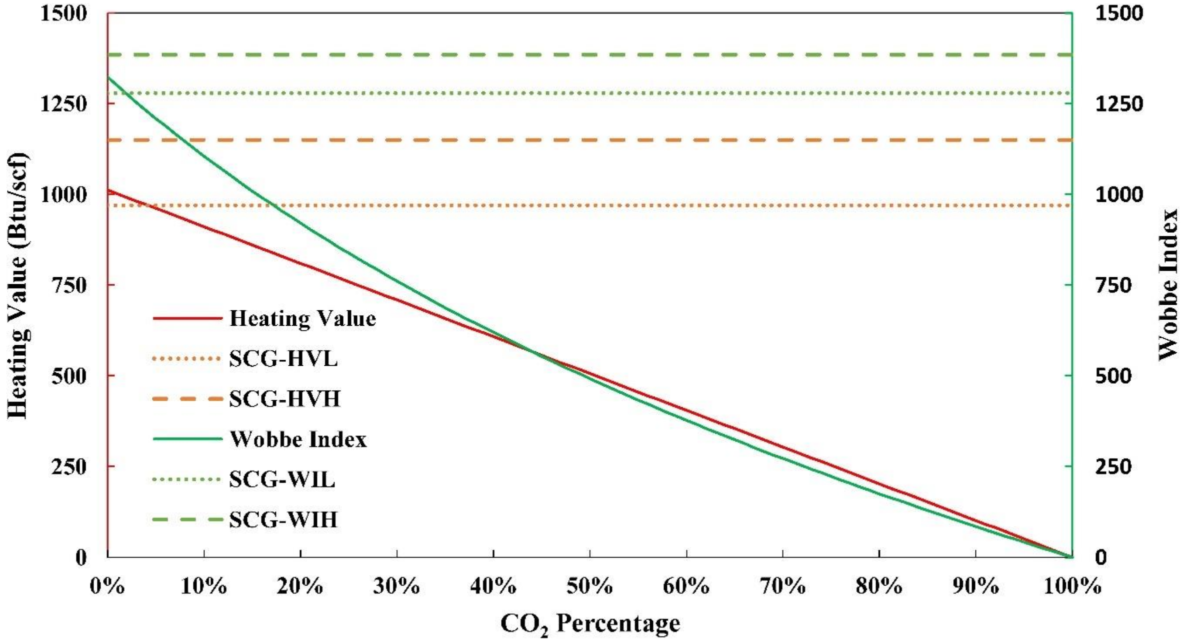
The Wobbe Index works well for predicting the heat output of different combustion devices in practice due to the validity of the assumptions. The gas flow velocity in the pipeline downstream of the home regulator is much slower than the sound velocity; therefore, the gas can be taken as incompressible. When the gas flows through the orifice of a control valve or combustion device, the gas pressure drop can accelerate the flow, which will result in friction loss. However, the gauge pressure in the pipeline in the home is only 2000 Pa, which is less than 2 percent of the atmosphere pressure, which is well below the 30 percent level at which point the friction loss can no longer be ignored [13].

As shown in Figure 3, although the heating values of hydrogen and methane are significantly different, they have similar Wobbe Indices. This leads to the observation that part of the pipeline natural gas can be replaced with hydrogen without influencing the heat output in current combustion devices.

The heating value and Wobbe Index as a function of mixture percentage is shown in Figure 3. The solid lines represent the fuel mixture property, and the dashed lines are the heating value and Wobbe Index regulations of the natural gas supplier for UCI Combustion Laboratory (UCICL). Every gas company has their own gas quality regulation; heating value and Wobbe Index are usually the most important factors.

Figure 3: Heating Value and Wobbe Index Variation of Different Gas Mixtures





Source: University of California, Irvine

Based on the heating value/Wobbe Index regulations, 2.2 percent/1.9 percent of the pipeline natural gas can be replaced by carbon dioxide. Considering the heating value regulation, 3.2 percent of pipeline natural gas can be replaced by hydrogen. However, 13.8 percent can be achieved if Wobbe Index is the only factor considered.

As can be seen in the hydrogen plot, the heating load shows a linear trend, but the Wobbe Index has an inflection point at around 81 percent hydrogen addition. Also, 100 percent hydrogen has identical Wobbe Index as 35 percent hydrogen/65 percent natural gas mixture. However, the fuel properties of these two fuel classes, for example, flammability, flame speed and flame temperature will be very different, and the combustion performance will differ significantly. This result shows that although Wobbe Index does a great job predicting the heating load, but it cannot be used as the only fuel interchangeability factor for combustion devices.

In this study, the fuel compositions go beyond the current regulations. Carbon dioxide and hydrogen are increased all the way from 0 percent to the failure of combustion to study the combustion performance of different fuel mixtures.

Project Objectives

This project summarized the limits of added biogas or hydrogen to natural gas along with the changes in performance of residential appliances. To reach this goal, these objectives were carried out:

1. Investigate and understand the working principles of residential appliances including 1) cooktop burner, 2) oven burner, 3) gas fireplace, 4) low NOX storage water heater, 5) tankless water heater, 6) central room furnace, 7) pool heater, 8) outdoor grill, 9) laundry dryer, 10) traditional storage water heater, 11) broiler, 12) ventless space heater
2. Based on the burner investigation results, four representative appliances are selected to conduct experiments: 1) cooktop burner, 2) central room furnace, 3) low NOX storage water heater, 4) tankless water heater.
3. Combustion performance of these appliances are tested: ignition time, flashback/blow-off limits, burner temperature, combustion noise, efficiency, emissions (NO, NO2, N2O, CO, UHC, NH3), etc.
4. Based on the experimental results, Chemical Reaction Network (CRN) models are generated to predict the emissions of nine representative: 1) cooktop burner, 2) oven burner, 3) gas fireplace, 4) low NOX storage water heater, 5) tankless water heater, 6) central room furnace, 7) pool heater, 8) outdoor grill, 9) laundry dryer.

These results can be used to inform policy makers and provide data with which air quality impacts can be assessed. In addition, appliance manufactures can consider the results relative to increasing the fuel flexibility of these devices in order to accommodate additional renewable fuel content.

CHAPTER 2:
Project Approach

This chapter provides an overview of the general approach taken in the project including selection of specific test devices and general features of the burner configurations.

Burner Configuration Selection

This section provides an overview of the current appliances that utilize the majority of natural gas in the state of California: 1) cooktop burner, 2) oven burner, 3) gas fireplace, 4) low NO_X storage water heater, 5) tankless water heater, 6) central room furnace, 7) pool heater, 8) outdoor grill, 9) laundry dryer, 10) traditional storage water heater, 11) broiler, 12) ventless space heater. The chapter concludes with recommendations for (1) the burners/appliance types that should be incorporated into the project, and (2) those that should be studied experimentally to validate the simulation methods that will be applied. Additional background and details regarding the operating principles of the burners found in these appliances can be found in Appendix J.

The 12 appliance burners are the most common burners in use and currently available on the market. To estimate the relative value of doing research on these 12 appliance burners, four criteria were adopted to prioritize these appliance burners. The four criteria are: unit energy consumption (UEC), current natural gas consumption, future expectation of natural gas consumption, and ease of burner geometry acquisition.

Unit Energy Consumption

UEC represents the amount of energy a single appliance is estimated to use in a single year. The saturation study provided UEC data from three companies: Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E) and Southern California Gas (SoCal Gas). The average UEC from three sources are calculated for each appliance, and the score system is shown in Table 3.

Table 3: Unit Energy Consumption Score Criterion

UEC	0-50 (therm)	50-100 (therm)	100-150 (therm)	>150 (therm)
Score	0	1	2	3

Source: University of California, Irvine

Current Natural Gas Consumption

UEC represents the energy consumption of a unit appliance. However, high UEC appliances are not necessarily the appliances that consume the most fuel in residential houses. A pool heater, for example, has high UEC, but only makes up a small percentage of the total natural gas consumption in residential homes according to the 2009 Residential Appliance Saturation Study [4] . Therefore, the natural gas consumption percentage (Table 4) in the 2009 Residential Appliance Saturation Study is used to score each appliance.

Table 4: Natural Gas Consumption Score Criterion

NG Consumption	0-5%	5%-10%	10%-30%	>30%
Score	0	1	2	3

Source: University of California, Irvine

Future Expectation of Natural Gas Consumption

The 2009 Residential Appliance Saturation Study provided the natural gas consumption from different end uses such as water heating, space heating, cooking, etc. However, different types of appliances are used within each type of end use. Water heating, for example, can be achieved using storage water heaters [14] or tankless water heaters [15]. But because of their high UEC and large space needs, storage water heaters have lower future market expectation compared to tankless water heaters. Consideration of pollutant emissions is another important aspect of future market expectation. For example, vented space heaters [16] have higher future market expectation than the ventless space heater, because the latter model discharges exhaust directly into the room which is harmful to human health. Future expectation of natural gas consumption for each appliance is scored using Table 5.

Table 5: Future Expectation Score Criterion

Expectation	Low	Medium Low	Medium High	High
Score	0	1	2	3

Source: University of California, Irvine

Ease of Burner Geometry Acquisition

Different appliances have different operating conditions and different burner configurations. For the simulation work, some details are needed regarding the geometry of the burner and the combustion “chamber.” Some appliance burners are more difficult to extract dimensions from than others. Hence, for this project “ease of burner geometry acquisition” is another scoring criterion (Table 6). For example, pool heaters usually have much higher heating loads than other appliances, and require a large amount of gas supply and cooling water when tested. Some appliance burners might be mounted inside of the appliances, making it difficult to obtain the precise burner geometry to conduct simulations required for the project. Additionally, most of ventless space heaters are forbidden in California due to high emissions in the exhaust, and so it is difficult to get them in California and there is little interest to study them.

Table 6: Ease of Burner Geometry Acquisition

Ease of Burner Geometry Acquisition	Very Hard	Hard	Easy	Very Easy
Score	0	1	2	3

Source: University of California, Irvine

Benefit to California

Since this project is mainly focused on appliances in California, each type of appliance is scored based on the situation in California using the criteria in Table 7. Due to the strict emission regulations in California, conventional water heaters share a smaller percentage on market compared to Low NO_X storage water heaters and tankless water heaters. Therefore, it will be more beneficial to study the last two water heaters. Regarding space heating, an increasing number of gas fireplaces are being replaced by central space heaters.

Table 7: Benefit to California

Benefit to California	Low	Medium Low	Medium High	High
Score	0	1	2	3

Source: University of California, Irvine

Selection

Based on the above four criteria, the 12 appliance burners are graded in the burner selection matrix shown in Table 8. According to the burner selection matrix, the ventless space heater has the lowest score and thus was not selected for study in this project. The broiler burner is excluded because of its high similarity to the oven burner. And, although the conventional storage water heater has a relatively high score, its market share is declining rapidly due to regulations on newly installed water heaters, and thus this appliance was not selected for study in this project.

Based on the scoring and input from the technical advisory committee, the nine appliances recommended for analysis in the current project (using computational fluid dynamics [CFD] methods) are:

- Cooktop burner
- Oven burner
- Gas fireplace
- Low NO_X storage water heater
- Tankless water heater
- Space heater
- Pool heater
- Outdoor grill
- Laundry dryer

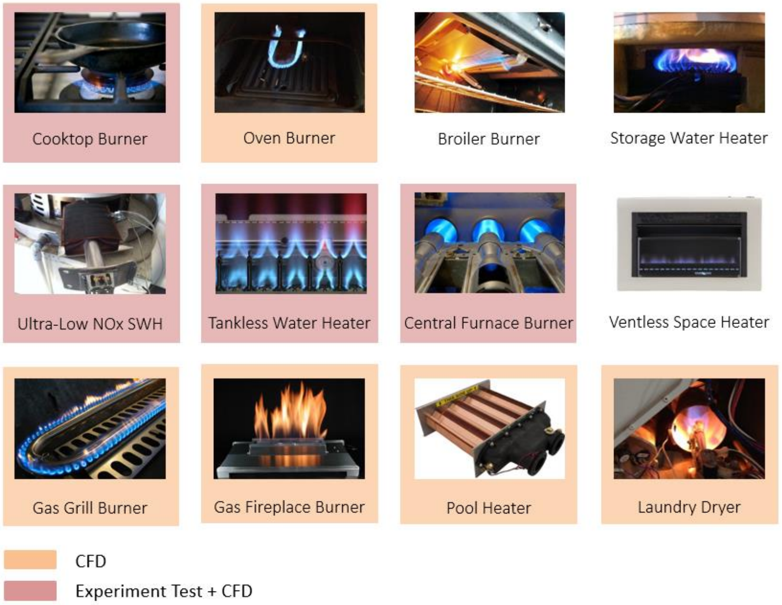
The appliances that have the highest scores are the three water heaters and the space heater. According to the burner geometry configuration results, some of these appliances possess similar burner geometries and working principles. To spread the scope of this research, instead of doing experiments on three water heaters and one space heater, 4 different appliances with different functions (Figure 4) were proposed for validation experiments: low NO_X storage water heater; tankless water heater; space heater; cooktop burner.

Table 8: Burner Selection Matrix

Appliance Burner	UEC	NG Consumption	Future Expectation	Geometry Acquisition	Benefit to California	Total Score
Cooktop Burner	0	1	1	3	3	8
Oven Burner	0	1	1	3	3	8
Broiler	0	1	1	3	3	8
Water Heater (Conventional Storage)	3	3	0	3	0	9
Water Heater (Low NO$_X$ Storage)	3	3	2	3	3	14
Water Heater (Tankless)	3	3	3	1	3	13
Space Heater	2	3	3	2	3	13
Ventless Space Heater	2	3	0	0	0	5
Pool Heater	3	0	0	3	3	9
Outdoor Grill	0	1	1	3	2	7
Laundry Dryer	0	0	1	3	3	7
Gas Fireplace	3	3	0	3	0	9

Source: University of California, Irvine

Figure 4: Investigated Residential Appliances



Source: University of California, Irvine

Test Fuel Composition Selection

Fuel Classes

Diversification of fuel choices for combustion systems can help mitigate cost fluctuations from supply and demand factors. Coupled with costs are impending regulatory pressures to consider renewable fuels and/or mitigate GHG emissions. Previous work by UCI developed the matrix of possible fuels (and representative ranges of composition) shown in Table 9.

As there is a current emphasis on renewable fuels in response to California's climate change goals, a number of the fuel classes can be eliminated. As noted, each fuel class would require some variation about the nominal composition, to reflect variation expected from the processes and feedstocks used. Note that the air-blown and O_2-blown sources with nitrogen dilution appear to overlap substantially when ranges are examined, and thus they can be treated as the same general class of fuel gas. Given the assessment presented herein, Table 10 presents the possible "fuel classes" and the ranges of composition variation for study. Table 10 adds a new class of fuel compared to those originally identified since it has garnered recent attention; hydrogen can provide a form of storage for excess renewable solar or wind energy, which can then be introduced into or stored in the natural gas pipeline. This approach has gained traction in Europe as a means to explore de-carbonizing fuels as discussed below.

Table 9: Potential Fuels of Interest: Dry, Clean Nominal Compositions (Volumetric Basis*)

Source	H_2	CO	CH_4	CO_2	N_2	C_{2+}	LHV (BTU/ft^3)	Wobbe Index
High H_2	100	0	0	0	0	0	265	1,006
Process and Refinery Gas	29	11	55	5	0	0	398	603
Gasified Coal/Petcoke (O_2-blown)	37	46	1	14	2	0	247	289
Gasified Biomass (air-blown)	17	17	5	13	48	0	142	152
Gasification w/N_2 Dilution	23	31	1	10	35	0	165	183
Landfill and Digester	0	0	~65	~25	~10	0	~650	650
Higher Hydrocarbon	0	0	75	0	0	25	~1,150+	1,385+

Source: University of California, Irvine

Table 10: Classes of Renewably Derived Fuels and Ranges

Source	H_2	CO	CH_4	CO_2	N_2	C_{2+}
Baseline: Natural Gas			80-100			0-20
High H_2	90-100	0	0-10	0	0	0
Gasified Biomass (air blown) and Gasification w/N_2 Dilution	15-25	15-35	0-5	5-15	30-50	0
Landfill and Digester	0	0	35-65	35-55	0-20	0
Power to Gas Scenario	0-20		80-100			

Source: University of California, Irvine

While this fuel space is broad, it is also evident that it could be viewed as consisting of (1) natural gas and it variants (for example with added hydrogen), (2) dilute natural gas fuels (e.g., digester gases), and (3) hydrogen-containing fuels (such as gasified biomass). The high reactivity of hydrogen often creates a situation where hydrogen dominates most of the behavior of these fuels.

Some background and additional details regarding baseline natural gas and renewable alternatives are provided in the following sections.

Natural Gas

Natural gas varies in composition throughout the United States due to sources and time of year. Table 11 shows the variation in natural gas composition within California. The composition within the state varies less than it does throughout the entire United States, though any new source entering the state (for example increased shale gas content), can result in additional variation.

Table 11: Variation in California Natural Gas

Species	Mean	Minimum	Maximum
Methane	93.5	91.3	96.9
Ethane	3.1	0.5	5.2
Propane	0.6	0.1	1.1
C_4+	0.3	0	0.7
Inerts (CO_2 + N_2)	2.6	1.4	4.2

Source: Liss et al. 1992

Renewable Methane-Based Fuels

Landfill Gas [17]

When a landfill is capped, landfill gas (LFG) is generated as organic portions of the municipal solid wastes (MSW) decompose. Traditionally, landfill gas is not controlled, and the expected period which landfill gas will be produced may range from 50 to 100 years. However, a usable landfill gas production rate lasts for only 10 to 15 years. A *bioreactor* is a controlled landfill in which water and other nutrient sources are added into the MSW to increase the landfill gas production rate.

Landfill gas is produced as a result of anaerobic ("in absence of air") decomposition of organic wastes. The organic portions of a landfill's MSW, including paper and paperboard, yard wastes, and food wastes, decompose through biochemical reactions where anaerobic conditions exist. The composition of the landfill gas varies with the characteristics of the waste, age of the landfill, weather conditions, and others. In general, landfill gas contains 50 percent methane (CH_4), 45 percent carbon dioxide (CO_2), and also other traces of gas such as nitrogen (N_2), oxygen (O_2), hydrogen sulfite (H_2S), and water vapor [18]. However, the gas composition varies with the nature of the organic material and also with time. Indeed variation in methane levels from 35 to 65 percent is common [18]. In addition, while the capping process seeks to eliminate air, leaks can lead to nitrogen and oxygen levels of up to 20 percent and 2.5 percent, respectively. The other issues associated with landfills are contaminants. Sulfur compounds can range from negligible to 1,700 parts per million (ppm), and other compounds like siloxanes can be significant. In recent years, attempts to convert landfill gas to energy have required varying degrees of care relative to gas cleanup, to prevent damage or coating of critical power generation device parts.

Landfill gas does represent an opportunity for upgrade and injection into existing natural gas pipelines. However, as pointed out by the California Energy Commission (CEC), the cost of appropriate cleanup and pressurization for pipeline injection may not be favorable from an economic or overall efficiency benefit viewpoint without additional market or policy forcing functions. However, California's Renewable Portfolio Standards and SB1505 (which mandates that hydrogen fuel for vehicles be a minimum of 33 percent renewable) are spurring California utilities and fuel providers to explore potential uses of landfill gas.

When landfill gas is vented, the GHG implications are serious, as methane is a much stronger greenhouse-effect forcing species than CO_2. However, conversion of the LFG to power generates CO_2 and also, potentially, criteria pollutants. While the benefits of generating power from this otherwise "wasted fuel" are apparent, regulatory pressures are requiring a significant reduction in criteria pollutant emissions. As a result, improvements in combustion technology using these gases are needed.

Wastewater Treatment [19]

As it does in landfills, organic matter in wastewater streams also contains potential fuel value. While in landfills, the methane generated is due to slow decay of matter; this process can be enhanced with use of "digestion" strategies. Essentially, these processes can accelerate the breakdown of organic material and generation of methane gases. Most common is the use of anaerobic digestion (AD), which is a biological process in which biodegradable organic matter is decomposed by bacteria into biogas, which consists of CH_4, CO_2, and other trace amounts of gases. That biogas can be used to generate heat and electricity. Other important factors, such as temperature, moisture and nutrient contents, and pH are also critical for AD's success. In terms of temperature, either mesophilic AD (30 °C–40 °C, or 86 °F–104 °F) or thermophilic AD (50 °C–60 °C, or 122 °F–140 °F) can be used. In general, AD at lower temperature is more common, but thermophilic temperature has the advantage of reducing reaction time, which corresponds to the reduction of digester volume. Moisture content greater than 85 percent is suitable for anaerobic digestion.

Types of anaerobic digesters include Covered Lagoon, Batch Digester, Plug-Flow Digester, Completely Stirred Tank Reactor (CSTR), Upflow Anaerobic Sludge Blanket (UASB), Anaerobic Sequencing Batch Reactor (ASBR), and others.

Due to the nature of the digestion processes, the composition of fuel gas from these systems varies far less than that of gas from landfills and tends to have overall higher methane content.

Anaerobic digester technology is well developed worldwide, with an estimated 5.3–6.3 gigawatts (GW) installed. Traditional, small, farm-based digesters have been used in China, India, and elsewhere for centuries. The number of digesters of this type and scale is estimated to exceed 6 million. European Union (EU) companies are world leaders in development of the AD technology. Currently, the EU has a total generating capacity of 307 MW from AD technology. The countries in the EU with the largest development figures are Germany (150 MW), Denmark (40 MW), Italy (30 MW), and Austria and Sweden (both 20 MW). Germany led the small on-farm digesters for odor control. Italy developed a series of farm AD systems. Larger, centralized anaerobic digestion plants, which use animal manure and industry waste in a single facility, are a newer development. These are most prevalent in Denmark, where there are 18 plants (worldwide there are 50 or so, all within Europe). Municipal solid waste digestion is the newest area for anaerobic digestion. The most recent is for source-separated feedstock, for which there are estimated to be more than 150 commercial-scale plants. These plants have a combined capacity in excess of 6 million tons per year, and the number of plants planned is increasing rapidly.

Obvious opportunities in California include sewage processing and agricultural waste streams, and these are discussed next.

Sewage Treatment [20]

California water systems treat 4 billion gallons of sewage per day while serving a population of about 40 million people in more than 13 million homes. Currently, there are approximately 900 publicly owned collection and treatment systems. Most of these treatment plants are small or moderate in size and treatment capacity; around 270 can treat over one million gallons per day (MGD). The largest individual treatment plants in California are in San Francisco and Los Angeles and can treat approximately 450 MGD. The average age of collection system pipes and manholes is approximately 40 years. Most of the existing systems and treatment plants appear to have adequate capacity and are prepared to meet the population needs for the next 10 to 20 years.

Other Applications

It is also possible to consider comingling of organic matter from waste streams (such as food waste from restaurants or personal residences) in anaerobic digesters. This could tremendously increase the feedstock available and thus maximize the production of alternative fuel. This same material could also be submitted to landfills, but the enhanced gas production by the digester provides a much shorter time frame for the production of waste to fuel.

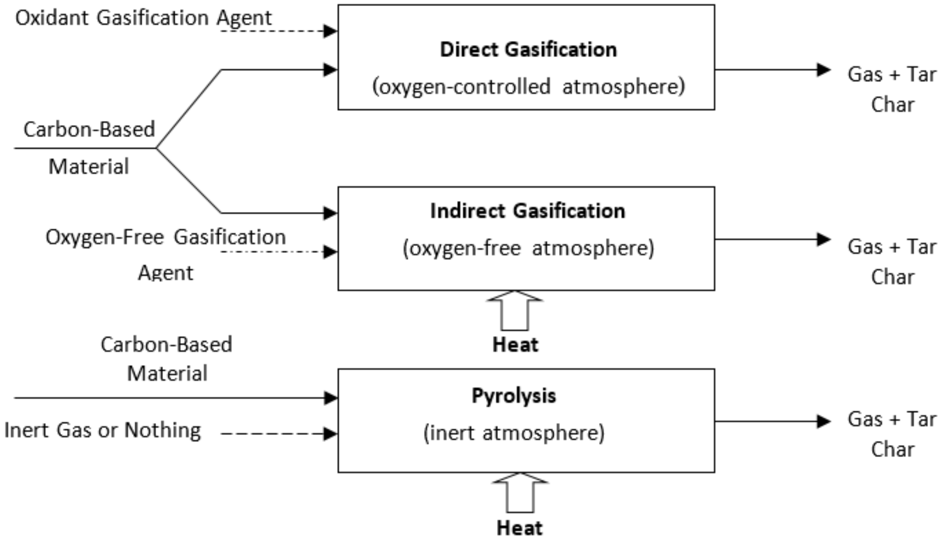
Cleanup and Pipeline Injection

While these renewable fuels can be used directly, if they are to be conveyed by the existing pipeline structure, they must be cleaned up and injected into the pipeline. In that case, these gases must achieve certain minimum specifications, which essentially renders them similar to existing pipeline natural gas. A question is the extent to which the current specifications regarding CO_2 content could be relaxed to incorporate more biogas with less refinement before injections.

Gasified Biomass

For California, the use of gasified biomass represents a significant opportunity as a renewable fuel source, which has the synergy of reducing landfill use while providing energy generation with a reduced carbon signature. It is noted that the landfill route for biomass disposal can ultimately lead to generation of a renewable fuel stream, but the time scale is much longer. In addition, some biomass waste can be digested to produce fuels. However, gasification may make more sense, depending on the feedstock available. Biomass is a renewable material that contains considerable amounts of H, C, and O, and can be converted into syngas with pyrolysis or gasification [21]. Like coal, biomass can have a wide range of compositional variation. The gasification and pyrolysis processes are detailed in Figure 5.

Figure 5: Block Diagram of the Gasification and Pyrolysis Processes



Source: Belgiorno et al. 2003.

In the process of *direct gasification,* the feedstock is partially oxidized using an oxidizing gasification agent, and the temperature is self-maintained through the reactions [22]. *Indirect gasification* involves the use of an oxygen-free gasification agent, and an external energy source is needed to maintain the reaction temperature. *Pyrolysis* is a specific type of indirect gasification in which the gasification agent is either an inert gas or is absent from the reaction altogether [23].

Pyrolysis involves heating the biomass or other feedstock to temperatures of 375°C–525°C (700°F–980°F) at pressures of 1–5 atm in the absence of air, and can be classified into the two categories of slow and fast pyrolysis. In slow pyrolysis, the biomass is heated at a slow rate, resulting in the production of char, vapor, and gas. Previous studies have shown that the actual product composition is dependent on the feedstock and temperature [24]. In fast pyrolysis, the feedstock is heated rapidly without air, resulting in gas-, liquid-, and solid-phase products. Gaseous products from fast pyrolysis include varying compositions of H_2, CH_4, CO, and CO_2.

$$Biomass + heat \rightarrow H_2 + CH_4 + CO + CO_2 + other\ products\ [21]$$

Methane can then be converted to more syngas and subsequent hydrogen with a reformation process and water gas shift (WGS) reaction.

Gasification is a thermo-chemical process in which a solid or liquid feedstock is converted into a combustible gas product with the use of a gasification agent. The gaseous product may contain H_2, CO, CO_2, CH_4, H_2O, small amounts of higher hydrocarbons, inert gases from the gasification agent, and contaminants [24]. The conversion of solid biomass occurs with the reaction shown in the following reaction.

$$Biomass + heat + steam \rightarrow H_2 + CO + CO_2 + CH_4 + hydrocarbons + char\ [21]$$

One of the major issues associated with biomass gasification occurs with the high nitrogen content of the syngas produced from air gasification. To eliminate this problem, pure oxygen gasification can be used, but the cost of producing the pure oxygen is estimated at around 20 percent of the total cost for a gasification plant [22]. Other issues with biomass gasification include dealing with any tar and ash formation in the product [21].

Cleanup and Pipeline Injection

While these renewable fuels can be used directly, if they are to be conveyed by the existing pipeline structure, they must be cleaned up and injected into the pipeline. In that case, these gases must achieve certain minimum specifications which essentially renders them similar to existing pipeline natural gas. Because the primary fuel components are hydrogen and carbon monoxide, it is unclear if the current specifications really apply. One question to ask is to what extent the current specifications could be relaxed to incorporate more renewable gases.

Hydrogen

Hydrogen can be created renewably from hydrolysis of water if the electricity used is generated by solar photovoltaics or wind. In particular, if these resources are used during times of excess generation to create hydrogen, instead of curtailed, hydrogen can be viewed as an energy storage medium. If it can be stored and conveyed in the natural gas pipelines, then it has potential to result in cleaner operation without compromising on efficiency. Subsequent methanation of the stored hydrogen is also an option. Adding H_2 to existing natural gas pipelines seems like a lucrative option toward cleaner operation, but the question remains regarding how much hydrogen in the natural gas pipelines falls within the safe operation zone. Existing research on the problem suggests a blend of 10-20 percent of H_2 into the pipelines is the threshold amount for safe operations in industrial burners, after that flash back and other concerns are associated with existing infrastructure [25][26].

Hydrogen is shown to have synergies with other low carbon alternatives, and can enable a more cost-effective transition to a cleaner energy system. While industry users have already started marketing hydrogen for fuel cell systems including fuel cell electric vehicles and micro-combined heat and power devices, the use of hydrogen at grid scale [27] and residential application requires the challenges of clean hydrogen production, bulk storage and distribution to be resolved.

It is reasonable to think that, even though a range from 5 percent to 30 percent of hydrogen in methane has been considered, the limit of 20 percent considered for combustion engines in order to avoid the risk of detonation will be the maximum limit to be used in existing distribution networks. For these engines, new technologies such as Mild Combustion can offer further solutions to improve the yield of engines fueled with hydro-methane. By using the Wobbe Index definition, the flow from the fuel orifices of the appliances can easily be calculated. Due to the similarity in Wobbe Index between natural gas and hydrogen, the heating load does not vary much when hydrogen is used instead of natural gas as long as the appliances can tolerate the hydrogen percentage [28]. Ultimately, more research with collaborative support from government, industry, and academia is still needed to realize hydrogen's potential across all economic sectors.

Recommendations

There are multiple generation sources for both biogas and hydrogen. The technology to purify biogas into a high methane concentrated fuel and the similarity between natural gas and hydrogen enables the adoption of biogas and hydrogen in current natural gas facilities. Based on the summary of possible future low to zero carbon fuels, biogas and renewable hydrogen are competitive gases to replace pipeline fossil-derived natural gas in the future.

The following three fuel classes and ranges are proposed for study as shown in Table 12.

Table 12: Fuel Classes Recommended for Study

Scenario	H_2	CO	CH_4	CO_2	N_2	C_{2+}
Baseline: Natural Gas			90-100			0-10 (ethane)
Landfill and Digester	0	0	45-100	55-0		0
Power to Gas Scenario / Hythane® / High H_2	0-100		100-0			

Source: University of California, Irvine

Experimental Methods

Instrumentation

In this Section, a brief overview of the experimental methods used is presented. How the fuels were mixed and the diagnostics used are discussed. Details regarding the specific burners are included in the subsequent appendices.

Fuel Blending

In this study, natural gas and hydrogen are mixed through a mixing station and regulated down to 2000 Pa (8 inches of water), which is at the same pressure level specified for the devices under test and the same as they would receive from standard pipeline natural gas. When testing for biogas, a mixture of natural gas and carbon dioxide is used to simulate behaviors. Various sized critical flow orifices are used in the mixing station with the gases of interest to create mixtures desired at the flow rates required by the particular device under test. The percentage of hydrogen or carbon dioxide in the fuel mixture is increased gradually from 0 percent to any upper limit established by operability issues (general flashback in the case of hydrogen and blow off in the case of carbon dioxide).

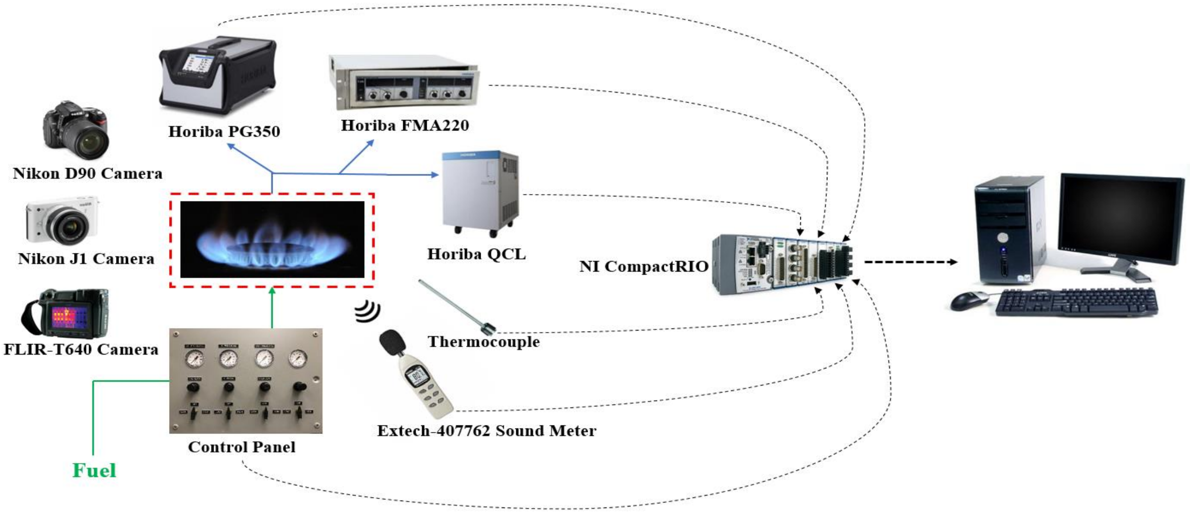
Diagnostics

Flame images are recorded by a Nikon D90 digital 35 mm camera. Ignition behavior is recorded by a Nikon J1, operated at up to 1400 frames per second in slow motion recording mode. A FLIR-T640 IR camera is used to record and determine the burner surface temperature. The combustion sound and temperature are recorded by Extech-407762 sound level meter and thermocouples, respectively. Horiba QCL, PG350, FMA220 are used to measure the emissions including NO, NO_2, N_2O, CO, UHC, NH_3. The output signals of these devices are sent to National Instrument CompactRIO, and then processed on the computer by LabView. The experiment tool diagram is shown in Figure 6.

The details of the emission analyzers are shown as following:

- Flame Ionization Magneto-Pneumatic Analyzer 220 (FMA220): UHC measurement range: 100 ppm. Accuracy: ±1 percent of the maximum range setting. Zero and span drift: ±1 percent of the maximum range setting.
- Horiba Quantum-Cascade Laser Analyzer 1400 (QCL1400): NO: 0-100 ppm, NO_2: 0-50 ppm, N_2O: 0-100 ppm. NH_3: 0-50 ppm. Zero drift: ±1 percent of the maximum range setting. Span drift: ±2 percent of the maximum range setting.
- Horiba Portable Gas Analyzer 350 (PG350): NO: 0-250 ppm, NO_X: 0-250 ppm; CO: 0-500 ppm; CO_2: 0-10 vol percent; O_2: 0-25 vol percent. Zero drift: ±1 percent of the maximum range setting. Drift: ±1 percent of the maximum range setting.

Figure 6: Experiment Setup Diagram



Source: University of California, Irvine

The span gases for emission analyzers are shown in Table 13.

Table 13: Calibration Gases

Species	Concentration
Nitrogen Dioxide (NO_2)	40ppm (40.31ppm)
Nitric Oxide (NO)	40ppm (40.56ppm)
Nitrous Oxide (N_2O)	80ppm (86.34ppm)
Ammonia (NH_3)	40ppm (42.3ppm)
Carbon Monoxide (CO)	300ppm (302.5ppm)
Methane (CH_4)	2% (2.042%)
Carbon Dioxide (CO_2)	4% (4.018%)
Oxygen (O_2)	14% (14.01%)

Source: University of California, Irvine

Comments on Basis of Presented Emissions

Fuel mixtures are generated by the mixing station. The station uses sonic orifices to regulate the flow of each gas. The sonic orifice allows the upstream pressure alone to dictate the flow, hence pressure transducers are used with a calibration curve to set the individual gas flow rates. Once mixed, the gases are regulated down to 8 inches of water before being supplied to appliances. In this manner, the appliance has no knowledge of the fuel composition which mimics the case if varying amounts of these gases are introduced into the pipeline.

The heating load of an appliance is usually governed by the fuel valve/orifice size, which is related to Wobbe Index. Hence for added CO_2, the total heat input allowed by the valve/orifice arrangement would decrease in proportion to the amount of CO_2. Because hydrogen has similar Wobbe Index as natural gas, adding hydrogen does not alter the heat output significantly, though it is reduced slightly. Basically, the procedure is intended to mimic the situation in which an appliance is specified for natural gas (e.g., 38, 000 BTU/hr for storage water heater, 9,100 BTU/hr for cooktop burner) and then the fuel composition changes without any alteration to the appliance fuel system itself. Of course, as with many devices, the fuel regulating orifice could be changed (such as a natural gas stove can be changed to a propane stove by changing the orifice diameter in accordance to the relative Wobbe Index of each fuel).

Most residential appliances employ open-air flames, which usually result in dilution in the exhaust samples for emission measurement. Therefore, emissions need to be corrected under the same reference before comparison.

Oxygen correction of emissions is widely adopted in gas turbine industry [29]. Lean premixed combustion technology has been widely adopted in gas turbine industry, which will result in extra air in the exhaust. Therefore, emissions are usually corrected under a certain level of oxygen. Different oxygen references are used depending on specific situations, 3 percent, 6 percent, 15 percent are most common references in industry. The equation of absolute emission concentration corrected at 3 percent oxygen is shown as following.

$$[Emi]_{3\%\,O_2,ppm} = [Emi]_{meas\,,ppm} \frac{20.9 - 3}{20.9 - [O_2]_{meas\,,\%}}$$

Carbon dioxide correction is usually adopted in light industry, and commercial and residential combustion devices using diffusion or partially premixed combustion technology [30]. The carbon dioxide concentration reference of 12 percent is most widely used, which is the carbon dioxide concentration (on a dry base) in the exhaust of methane combustion in air at stoichiometric condition. This correction method is also called air-free method.

$$[Emi]_{12\%\,CO_2,ppm} = [Emi]_{meas\,,ppm} \frac{12}{[CO_2]_{meas\,,\%} - [CO_2]_{air\,,\%}}$$

Calorific correction is usually adopted in relatively low heating load burners in commercial or residential applications. It describes how much emission is generated per unit energy consumption [31]. HHV and LHV can both be used in this correction, but the emission concentration using HHV is relatively lower than using LHV. In the present work, LHV is adopted as it reflects the actual heating value extracted from the fuel for the cookstove. The correction equation is given below.

$$[Emi]_{\frac{ng}{J}} = \frac{0.1 * [Emi]_{meas\,,ppm}}{[CO_2]_{meas\,,\%} - [CO_2]_{air\,,\%}} \frac{mol\ CO_2}{MJ\ Fuel} M_{Emi,\frac{g}{mol}}$$

CHAPTER 3:
Project Results

This study investigates the influence of biogas/natural gas and hydrogen/natural gas mixtures on the performance of appliances based on both experiments and simulations. The details of the results obtained for each appliance are shown in the Appendix A-I and the reader is referred to these Appendices to get in depth understanding of how each device performs. The focus of the current study is on 1) determining upper limits of biogas or hydrogen addition and 2) establishing trends for pollutant emissions. Other observations regarding stability, sound levels, various temperatures, etc. have also been documented in the Appendices.

Regarding biogas, generally speaking, CO_2 addition in the natural gas tends to increase the risk of flame blow-off. CO and UHCs emissions from appliances are usually higher when appliances operate on fuels with high CO_2 concentration. The results show that less than 5 percent CO_2 could be added into natural gas without significantly influencing the appliance performance.

Regarding hydrogen, adding H_2 increases the reactivity of the fuel. At low percentage of H_2 addition into natural gas, the emission performance of most appliances is optimized. However, high percentage of H_2 increases the flashback risk of appliances.

Summary of Results

The overall results of this project are summarized in the form of tables that indicate relative performance compared to pure natural gas. The details of the results for each of the nine burners studied are provided in appendices in case additional information is desired.

Table 14: Performance Summary of Appliance Burners with Relative Trends

Appliance Burner		Natural gas + hydrogen	Natural gas + carbon dioxide
Cooktop burner	Upper limit	20% (ignition); 55% (cooking); 75% (idle)	20% (ignition); 35% (cooking); 35% (idle)
	NO_X	-23.3% (0-50% H_2)	-51.4% (0–30% CO_2)
	CO	-14.0% (0-50% H_2)	+58.2% (0–30% CO_2)
	UHC	-74.2% (0-50% H_2)	+2128.4% (0–30% CO_2)
Oven burner	Upper limit	30%	15%
	NO_X	Variation within analyzer accuracy	-91.8% (0-10% CO_2)
	CO	-38.2% (0-25% H_2)	+113.8% (0-10% CO_2)
	UHC	+350.5% (0-25% H_2)	NA
Gas fireplace	Upper limit	100%	45%
	NO_X	+3966.4% (0-100% H_2)	-75.7% (0-40% CO_2)
	CO	-100% (0-100% H_2)	-99.9% (0-40% CO_2)
Low NO_X storage water heater	Upper limit	10%	15%
	NO_X	Variation within analyzer accuracy	-45.9% (0–10% CO_2)
	CO	+26.9% (0-5% H_2)	+334.4% (0–10% CO_2)
	UHC	-50.5% (0-5% H_2)	+159.3% (0–10% CO_2)
Tankless water heater (2 gal/min)	Upper limit	>20%	15%
	NO_X	-20.3% (0-20% H_2)	-44.8% (0–12% CO_2)
	CO	-9.7% (0-20% H_2)	+349.9% (0–12% CO_2)
	UHC	Variation within analyzer accuracy	+177.2% (0–12% CO_2)
Space heater	Upper limit	20% (ignition); 45% (operation)	10% (ignition); 30% (operation)
	NO_X	-4.2% (0-40% H_2)	-47.1% (0–25% CO_2)
	CO	-13.9% (0-40% H_2)	+897.8% (0–25% CO_2)
	UHC	Variation within analyzer accuracy	+193.9% (0–25% CO_2)
Pool heater	Upper limit	NA	20%
	NO_X	-95.6% (0–70% H_2)	-98.5% (0–15% CO_2)
	CO	+761.9% (0–70% H_2)	+2400% (0–15% CO_2)
Outdoor grill	Upper limit	> 40%	40%
	NO_X	+128.2% (0-40% H_2)	-~100% (0–35% CO_2)
	CO	-93.7% (0-40% H_2)	-77.5% (0–35% CO_2)
Laundry dryer	Upper limit	NA	15%
	NO_X	-61.9% (0-40% H_2)	-80.7% (0–10% CO_2)
	CO	-34.1% (0-40% H_2)	+118.1% (0–10% CO_2)

Source: University of California, Irvine

Table 15: Performance Summary of Appliance Burners with Numeric Concentration Levels

Appliance Burner		Natural gas + hydrogen	Natural gas + carbon dioxide
Cooktop burner	Upper limit	20% (ignition); 55% (cooking); 75% (idle)	20% (ignition); 35% (cooking); 35% (idle)
	NO_X	Decreases from 109.9 ppm @3% O_2 (53.9 ng/J) to 84.3 ppm @3% O_2 (44.4 ng/J) at 50% H_2.	Decreases from 109.9 ppm @3% O_2 (53.9 ng/J) to 53.4 ppm @3% O_2 (26.5 ng/J) at 30% CO_2.
	CO	Decreases from 191.2 ppm @3% O_2 (57.9 ng/J) to 164.5 ppm @3% O_2 (52.9 ng/J) at 50% H_2.	Increases from 191.2 ppm @3% O_2 (57.9 ng/J) to 302.4 ppm @3% O_2 (96.8 ng/J) at 30% CO_2.
	UHC	Decreases from 42.3 ppm @3% O_2 (7.1 ng/J) to 10.9 ppm @3% O_2 (1.9 ng/J) at 50% H_2.	Increases from 42.3 ppm @3% O_2 (7.1 ng/J) to 942.6 ppm @3% O_2 (158.4 ng/J) at 30% CO_2.
Oven burner	Upper limit	30%	15%
	NO_X	Varies from 91.9 ppm @3% O_2 (51.3 ng/J) to 93.2 ppm @3% O_2 (50.8 ng/J) at 25% H_2.	Decreases from 88.3 ppm @3% O_2 (61.7 ng/J) to 7.2 ppm @3% O_2 (5.1 ng/J) at 10% CO_2.
	CO	Decreases from 124.9 ppm @3% O_2 (42.2 ng/J) to 77.2 ppm @3% O_2 (25.6 ng/J) at 25% H_2.	Increases from 124.3 ppm @3% O_2 (52.9 ng/J) to 265.8 ppm @3% O_2 (114.0 ng/J) at 10% CO_2.
	UHC	Increases from 9.7 ppm @3% O_2 (1.8 ng/J) to 43.7 ppm @3% O_2 (8.3 ng/J) at 25% H_2.	NA
Gas fireplace	Upper limit	100%	45%
	NO_X	Increases from 57.5 ppm @3% O_2 (43.6 ng/J) to 2338.2 ppm @3% O_2 at 100% H_2.	Decreases from 57.5 ppm @3% O_2 (43.6 ng/J) to 14.0 ppm @3% O_2 (10.1 ng/J) at 40% CO_2.
	CO	Decreases from 11389.1 ppm @3% O_2 (5253.3 ng/J) to 0 ppm @3% O_2 (0 ng/J) at 100% H_2.	Decreases from 11389.1 ppm @3% O_2 (5253.3 ng/J) to 13.6 ppm @3% O_2 (6 ng/J) at 40% CO_2.
Low NO_X storage water heater	Upper limit	10%	15%
	NO_X	Decreases from 10.9 ppm @3% O_2 (7.8 ng/J) to 9.5 ppm @3% O_2 (6.9 ng/J) at 5% H_2.	Decreases from 10.9 ppm @3% O_2 (7.8 ng/J) to 5.9 ppm @3% O_2 (4.2 ng/J) at 10% CO_2.
	CO	Increases from 27.9 ppm @3% O_2 (11.8 ng/J) to 35.4 ppm @3% O_2 (15.3 ng/J) at 5% H_2.	Increases from 27.3 ppm @3% O_2 (11.9 ng/J) to 118.6 ppm @3% O_2 (52.2 ng/J) at 10% CO_2.
	UHC	Decreases from 41.8 ppm @3% O_2 (12.1 ng/J) to 20.7 ppm @3% O_2 (5.2 ng/J) at 5% H_2.	Increases from 41.8 ppm @3% O_2 (12.1 ng/J) to 108.4 ppm @3% O_2 (27 ng/J) at 10% CO_2.

Appliance Burner		Natural gas + hydrogen	Natural gas + carbon dioxide
Tankless water heater (2 gal/min)	Upper limit	>20%	15%
	NO_X	Decreases from 37.5 ppm @3% O_2 (22.0 ng/J) to 29.9 ppm @3% O_2 (17.4 ng/J) at 20% H_2.	Decreases from 37.5 ppm @3% O_2 (22 ng/J) to 20.7 ppm @3% O_2 (12.6 ng/J) at 12% CO_2.
	CO	Decreases from 107.6 ppm @3% O_2 (38.3 ng/J) to 97.2 ppm @3% O_2 (34.4 ng/J) at 20% H_2.	Increases from 107.6 ppm @3% O_2 (38.3 ng/J) to 484.1 ppm @3% O_2 (177.9 ng/J) at 12% CO_2.
	UHC	Varies from 28.9 ppm @3% O_2 (5.7 ng/J) to 31.4 ppm @3% O_2 (6.1 ng/J) at 20% H_2.	Increases from 28.9 ppm @3% O_2 (5.7 ng/J) to 80.1 ppm @3% O_2 (16.1 ng/J) at 12% CO_2.
Space heater	Upper limit	20% (ignition); 45% (operation)	10% (ignition); 30% (operation)
	NO_X	Decreases from 100.9 ppm @3% O_2 (56.1 ng/J) to 96.7 ppm @3% O_2 (53.6 ng/J) at 40% H_2.	Decreases from 100.9 ppm @3% O_2 (56.1 ng/J) to 53.4 ppm @3% O_2 (30.8 ng/J) at 25% CO_2.
	CO	Decreases from 18 ppm @3% O_2 (6.1 ng/J) to 15.5 ppm @3% O_2 (5.2 ng/J) at 40% H_2.	Increases from 18 ppm @3% O_2 (6.1 ng/J) to 179.6 ppm @3% O_2 (63.2 ng/J) at 25% CO_2.
	UHC	Increases from 4.9 ppm @3% O_2 (0.9 ng/J) to 5.4 ppm @3% O_2 (1.2 ng/J) at 40% H_2.	Increases from 4.9 ppm @3% O_2 (0.9 ng/J) to 14.4 ppm @3% O_2 (2.9 ng/J) at 25% CO_2.
Pool heater	Upper limit	NA	20%
	NO_X	Decreases from 6.8 ppm @3% O_2 (1.8 ng/J) to 0.3 ppm @3% O_2 (0.3 ng/J) at 70% H_2.	Decreases from 6.8 ppm @3% O_2 (1.8 ng/J) to 0.1 ppm @3% O_2 (0.1 ng/J) at 15% CO_2.
	CO	Increases from 9.7 ppm @3% O_2 (4.8 ng/J) to 83.6 ppm @3% O_2 (76.0 ng/J) at 70% H_2.	Increases from 9.7 ppm @3% O_2 (4.8 ng/J) to 242.5 ppm @3% O_2 (145.2 ng/J) at 15% CO_2.
Outdoor grill	Upper limit	> 40%	40%
	NO_X	Increases from 318.3 ppm @3% O_2 (237.4 ng/J) to 726.4 ppm @3% O_2 (502.8 ng/J) at 40% H_2.	Decreases from 318.3 ppm @3% O_2 (237.4 ng/J) to ~0 ppm @3% O_2 (~0 ng/J) at 40% CO_2.
	CO	Decreases from 6517.5 ppm @3% O_2 (2959.4 ng/J) to 409.2 ppm @3% O_2 (172.4 ng/J) at 40% H_2.	Decreases from 6517.5 ppm @3% O_2 (2959.4 ng/J) to 1466.5 ppm @3% O_2 (606.7 ng/J) at 40% CO_2.
Laundry dryer	Upper limit	NA	15%
	NO_X	Decreases from 19.7 ppm @3% O_2 (13.9 ng/J) to 7.5 ppm @3% O_2 (5.7 ng/J) at 40% H_2.	Decreases from 19.7 ppm @3% O_2 (13.9 ng/J) to 3.8 ppm @3% O_2 (2.7 ng/J) at 10% CO_2.

Appliance Burner		Natural gas + hydrogen	Natural gas + carbon dioxide
	CO	Decreases from 83.3 ppm @3% O_2 (35.7 ng/J) to 54.9 ppm @3% O_2 (23.1 ng/J) at 40% H_2.	Increases from 83.3 ppm @3% O_2 (35.7 ng/J) to 181.7 ppm @3% O_2 (78.4 ng/J) at 10% CO_2.

Source: University of California, Irvine

CHAPTER 4: Knowledge Transfer Activities

This chapter summarizes the knowledge transfer activities that were conducted to disseminate information from this project. The primary means of knowledge transfer is through archival journal publications. Conference papers and presentations are available via links from our UCICL website (http://www.ucicl.uci.edu/).

Journal Papers

These publications are already available online, under review, or to be submitted for publication.

- Influence of Hydrogen Addition to Pipeline Natural Gas on the Combustion Performance of a Cooktop Burner (2019). International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2019.03.100
- Investigation of Visible Light Emission from Hydrogen-air Research Flames (2019). International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2019.06.105
- Experimental Assessment of the Combustion Performance of an Oven Burner Operated on Pipeline Natural Gas Mixed with Hydrogen (2019). International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2019.08.011
- Combustion Performance of Low-NO_X and Conventional Storage Water Heaters Operated on Natural Gas/Hydrogen Mixtures (2019). International Journal of Hydrogen Energy. https://www.sciencedirect.com/science/article/abs/pii/S0360319919342247
- Assessment of the Combustion Performance of a Room Furnace Operating on Pipeline Natural Gas Mixed with Simulated Biogas or Hydrogen (2020). International Journal of Hydrogen Energy. https://www.sciencedirect.com/science/article/abs/pii/S0360319920306340

Conferences

Several conferences/seminars were attended in the name of this project. Either papers or posters were presented during the conferences/seminars. The audience of the presentations include students, researchers, professors, policy makers or people from industry. Communications were established during the conferences and future cooperation opportunities are being further established through further connection after the conferences/seminars.

1. AirUCI Research Workshop: 9/24/2018-9/26/2018, Lake Arrowhead, CA.
    a. Description: This activity was held by UCI Chemistry Department. Presented on water heater and cooktop burner experimental results. Interact with people working on atmospheric environment.
    b. Attendance: 32 people presented in the workshop.
    c. Communication: 4 people requested experimental data. Connection between UCI Combustion Lab and UCI Chemistry Department was established.

2. 14th International Mechanical Energy Congress and Exposition: 11/9/2018-11/15/2018, Pittsburgh, PA.
    a. Description: This is a large annual Mechanical Engineering Conference. The paper was included as part of a "Combustion Mini-Symposium" that was organized as part of the overall conference. A paper on the cooktop top burner combustion performance operating on simulated biogas was presented.
    b. Attendance: More than 3000 general attendees were present at the overall conference. Approximately 30 people attended the actual presentation.
    c. Communication: Established connection with AO Smith for further communications. The Gas Technology Institute requested information as did John Zink.
    d. Paper: A paper is published for worldwide readers: Influence of Renewable Gas Addition to Natural Gas on the Combustion Performance of Cooktop Burners (2018). Paper IMECE 2018-87932, Presented at 14th IMECE Congress and Expo, Pittsburgh, November, https://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=2722161
3. 11th US National Combustion Meeting: 3/24/2019-3/27/2019, Pasadena, CA.
    a. Description: This is a combustion conference held every two years. Two papers on storage water heaters and an oven burner were submitted to this conference. Presentations were given in Pasadena.
    b. Attendance: Hundreds of professors/engineers/students from all over the world attend this conference.
    c. Communication: Around 20 people attended the presentation and a couple of questions were asked regarding the experimental results and the forecast of future regulations.
    d. Papers: Combustion Performance of Storage Water Heaters Operated on Mixtures of Natural and Renewable Gas (2019). Paper 2J11—Presented at the 11th US National Combustion Meeting, Pasadena, CA, March; Experimental Assessment of the Combustion Performance of an Oven Burner Operated on Pipeline Natural Gas Mixed with Hydrogen (2019). Paper 2J13—Presented at the 11th US National Combustion Meeting, Pasadena, CA, March.
4. University of California Global Climate Leadership Council (GCLC) Meeting, 5/23/2019, Irvine, CA.
    a. Description: Poster presented on experimental results of how residential appliance operate on renewable gases.
    b. Attendance: Around 20 professors/scientists and policy makers from UC universities and related agencies attended.
    c. Communication: Talked to almost every attendee and introduced the experimental results and forecast on utilizing hydrogen in residential buildings.
    d. Poster: Reducing CO_2 emissions by Replacing Natural Gas with Renewable Gas in Residential Buildings.

5. 10th Princeton Combustion Summer School, 6/23/2019-6/28/2019, Princeton, NJ.
    a. Description: This is an international combustion summer school organized by Princeton University every year. Poster presented highlighted the project work.
    b. Attendance: More than 150 combustion researchers attended from around the world.
    c. Communication: Around 10 people asked for details about this project or experimental results. Some followed up with PI relative to possible collaboration and/or graduate studies.
    d. Poster: Influence of Renewable Gases on Combustion Behavior of Cooking and Air Heating Appliances.
6. 15th International Mechanical Energy Congress and Exposition: 11/8/2019-11/14/2019, Salt Lake City, UT.
    a. Description: This is a combustion conference held every two years. Two papers on storage water heaters and an oven burner were submitted to this conference. Presentations were given in Pasadena.
    b. Paper: Influence of Blending Hydrogen and Biogas into Natural Gas on the Combustion Performance of a Tankless Water Heater (2019). Paper IMECE 2019-10792, ASME 2019 International Mechanical Engineering Congress and Exhibition, Salt Lake City, Nov 2019. https://asmedigitalcollection.asme.org/IMECE/proceedings/IMECE2019/59452/V008T09A018/1073360
7. International Colloquium on Environmentally Preferred Advanced Generation: 9/14/2020-9/16/2020, Online.
    a. Description: This activity was held by UCI Advanced Power and Energy Program. Presented on water heater and cooktop burner experimental results. Interact with people from academia, industry and government agencies.
    b. Attendance: more than 100 people.
    c. Communication: 4 people asked questions during the presentation and report was requested by email after the conference.

Stakeholder Presentations

Due to technical advisory meetings and outreach activities, a number of stakeholder meetings were arranged to provide results from the project. The stakeholders include gas suppliers, infrastructure construction companies, appliance manufactures, policy makers, etc. The results or benefits of this project were introduced to the stakeholders in the meetings.

1. Meeting with SoCal Gas Advanced Engineering Center: 6/20/2018, Downey, CA.
    a. Description: Introduced the preliminary results of appliance combustion performance operating on natural gas/hydrogen mixtures.
    b. Attendance: 10 people attended including personnel from the Advanced Engineering Center and SoCalGas headquarters.

    c. Communication: Significant interest was expressed in the results shared. To the point where discussion regarding additional support for expanding/continuing the work was initiated.
2. Workshop with Fortis BC and SoCal Gas: 7/25/2018, Irvine, CA.
    a. Description: Presented on the historical pipeline gas, gas interchangeability background and cooktop burner experiment results.
    b. Attendance: Around 15 technical and administrative representatives from Fortis BC and SoCal Gas attended the meeting.
    c. Communication: Answered around 5 questions regarding the historical pipeline gas and renewable gas utilization expectations. They were especially interested in the pipeline gas involvement and technical concerns in renewable hydrogen injection into current natural gas infrastructure.
3. Program Reviews with UCI COSMOS Summer Camp: 8/1/2018, Irvine, CA.
    a. Description: Introduced the background of this project to high school students. Presented some experimental results.
    b. Attendance: Around 30 high school students and tutors attended the tour.
    c. Communication: Around 10 questions from the audience were answered. Students were interested in utilizing renewable hydrogen to alleviate global warming.
4. AEE SoCal Annual Conference: 9/19/2018, Downey, CA.
    a. Description: Interacted with researchers, engineers, policy makes from industry and government. Introduced the background of this project.
    b. Attendance: Around 100 people from industry, government agencies and universities attended.
    c. Communication: Talked to around 15 representatives from industry and government agencies and communicated ideas regarding technical challenges of renewable gas utilization in current natural gas infrastructure.
5. Meeting with SoCal Gas: 2/15/2019, Irvine, CA.
    a. Description: Presented the experimental results of appliance operating on natural gas/hydrogen mixtures.
    b. Attendance: 10 people attended including managers associated with clean transportation and technology development,
    c. Communication: Funding for related efforts were discussed and interest in timing about public release of the information from the project was indicated, in particular archival journal papers.
6. International Colloquium on Environmentally Preferred Advanced Generation (ICEPAG); March 2019, Irvine, CA.
    a. Description: This is an annual conference hosted by the Advanced Power and Energy Program at UC Irvine. The conference is located at UC Irvine and no cost to register for APEP personnel.

   b. Attendance: There were more than 100 people from industry and academia attended this conference.
   c. Communication: Interacted with around 10 people from the conference and exchanged ideas regarding renewable energy utilization in the future.

7. Sustain SoCal 10th Annual Conference & Expo: Energy Infrastructure: Innovating Toward Sustainability: 4/11/2019, Irvine, CA.
   a. Description: Interact with researchers, engineers, policy makes from industry and government. Introduced the background of this project.
   b. Attendance: Around 100 people attended the conference.
   c. Communication: Interacted with around 10 representatives on the topic of renewable energy sources. People have doubts regarding the advantage of utilizing renewable gas in residential buildings over utilizing renewable electricity from solar.
8. Meeting with AO Smith: 4/18/2019, Irvine, CA.
   a. Description: Presented the experimental results of appliance operating on natural gas/hydrogen mixtures.
   b. Attendance: Vince McDonell, Yan Zhao and the representative from AO Smith.
   c. Communication: This was a one on one meeting. Several technical questions were answered regarding combustion experiments on water heaters. The details of fuel mixing station is requested by AO Smith.
9. Meeting with Raypak: 4/19/2019, Irvine, CA.
   a. Description: Presented the experimental results of appliance operating on natural gas/hydrogen mixtures. Gave a lab tour.
   b. Attendance: Vince McDonell, Shiny Choudhury, Yan Zhao and two representatives from Raypak.
   c. Communication: After presenting the experimental results, a lab tour was given to the representatives from Raypak. They expressed interest in reading the detailed experiment reports. They have also expressed interest in collaborating with us on future research associated with low emission appliance development.

CHAPTER 5: Conclusions andRecommendations

With the increasing need to reduce GHG emissions and adopt a sustainability-oriented mindset when considering combustion systems, the injection of renewable gases into the pipeline natural gas is of great interest. However, questions arise regarding the upper limit of how much renewable gas can be injected into the pipeline and its influence on residential appliances' operation, flexibility, and emissions.

Conclusions

The results of this project provide insight relative to the injection of renewable gas into pipeline natural gas from the perspective of the end user. Based on the results from this study, some general conclusions are summarized:

- A high percentage of CO_2 in natural gas causes ignition failure or flame blow-off. For example, 10 percent CO_2 addition in natural gas causes ignition failure of the space heater burner.
- Adding CO_2 to natural gas tends to increase CO and UHC emissions but decrease NO_X emissions of appliances.
- A high percentage of H_2 in natural gas causes ignition failure or flame flashback. For example, more than 10 percent H_2 addition in natural gas causes ignition failure of the low NO_X storage water heater. The amount of H2 that can be added varies among the appliance types as summarized in the Executive Summary.
- Adding H_2 to natural gas does not influence the emission performance of these appliances, especially when the H_2 percentage is under 10% by volume. Generally, NOx and CO emissions tend to be reduced as H_2 is added to natural gas.

Recommendations

Based on the results from this project, several recommendations are given to help California achieve its goals of reducing GHG emissions and optimizing the overall performance of the residential sector:

- Due to the current appliances' low tolerance level for CO_2, the CO_2 in the biogas should be eliminated or decreased to a very low level before it is injected into the pipeline natural gas.
- Due to the smaller quenching distance of H_2, the flame ports size could be downsized to incorporate higher percentage of H_2 in the fuel.
- The Venturi burner geometry could be furtherly optimized to optimize the primary air/fuel ratio in the burner.

CHAPTER 6:
Benefits to Ratepayers

California aims to reduce GHG emissions to 1990 levels by 2020 and 80 percent below 1990 levels by 2050. This study predicts the feasibility of reducing GHG emissions from the residential sector. Table 16 summarizes the results relative to CO_2 reduction potential with current upper limits identified in the present study.

Table 16: Greenhouse Gas Emission Reduction Estimation

Appliance	GHG emission under different H_2 percentages in the fuel				NG consumption percentage[1]	GHG reduction with 10% H_2 replacement
	5% H_2	10% H_2	15% H_2	20% H_2		
Cooktop	-2.83%	-5.75%	-8.75%	-11.9%	Part of 7% shown in Figure ES-1	• 2017 California GHG emissions (converted to CO_2): 424 million tons.[3] • GHG reduction by replacing 10% pipeline natural gas with H_2: 1.63 million tons, which is 0.38% of the total California GHG emissions. • The GHG reduction from the residential sector is equivalent to around 354,000 gasoline vehicles removed from the road.[4]
Oven	-2.83%	-5.75%	-8.75%	-11.9%	Part of 7%	
Gas fireplace	-2.83%	-5.75%	-8.75%	-11.9%	Part of 37%	
Low NO_X storage water heater	-2.83%	-5.75%	-8.75%	-11.9%	Part of 49%	
Tankless water heater	-1.67%	-3.46%	-5.38%	-7.46%	Part of 49% (~15% in California) [2]	
Space heater	-2.83%	-5.75%	-8.75%	-11.9%	Part of 37%	
Pool heater	-1.67%	-3.46%	-5.38%	-7.46%	Part of 4%	
Outdoor grill	-2.83%	-5.75%	-8.75%	-11.9%	Part of 7%	
Laundry dryer	-2.83%	-5.75%	-8.75%	-11.9%	Part of 3%	

1. KEMA, Inc. 2010. 2009 California Residential Appliance Saturation Study. California Energy Commission. Publication number: CEC-200-2010-004-ES.

2. Diane M. Lamyotte. 2018. Tankless 2018: Annual Tankless Report. https://www.phcppros.com/articles/7609-tankless-2018-annual-tankless-report

3. California Air Resources Board. 2019. GHG Current California Emission Inventory Data. https://ww2.arb.ca.gov/ghg-inventory-data

4. Calculated based on "United States Environmental Protection Agency. 2018. Greenhouse Gas Emissions from a Typical Passenger Vehicle. https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle"

Source: University of California, Irvine

Based on the results, a significant reduction in GHG emissions can be achieved if 10 percent hydrogen can be injected into the pipeline. With 10 percent hydrogen added, 1.28 million tons of carbon dioxide emissions would be removed, equivalent to removing 278,000 gasoline vehicles from the roads.

More than 80 percent of residential appliances in California use natural gas. To replace these appliances with electric versions will require a huge capital investment from ratepayers, with large impact on people from disadvantaged communities. By reducing the carbon intensity of natural gas, significant reduction in CO_2 can be attained while taking advantage of the significant infrastructure in place for transporting and distributing gaseous fuels. Abandoning this infrastructure is a major stranded asset issue for the utilities and ratepayers. Furthermore, with understanding gained from this research, the path to increasing the amount of renewable gas that can be used in these appliances is clear. Hence, a relatively cost-effective means of gaining further CO_2 emission reduction can be achieved with retrofits to existing appliances or modifications or both to newly installed ones, thus reducing the financial impact to California's ratepayers when compared with replacing all existing appliances using natural gas.

LIST OF ABBREVIATIONS

Term	Definition
CFD	Computational fluid dynamics
CO	Carbon monoxide
GHG	Greenhouse gas
LPG	Liquefied petroleum gas
N_2O	Nitrous oxide
NG	Natural gas
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_X	Oxides of nitrogen
P2G	Power to gas
UEC	Unit energy consumption
UHC	Unburned hydrocarbon
WI	Wobbe Index

REFERENCES

[1] U.S. Energy Information Administration. 2019. Natural Gas Consumption by End Use. U.S. Energy Information Administration.

[2] Nyberg, Michael. 2019. QFER CEC-1304 Power Plant Owner Reporting Database. California Energy Commission.

[3] U.S. Energy Information Administration. 2019. California Natural Gas Consumption by End Use. U.S. Energy Information Administration.

[4] KEMA, Inc. 2010. 2009 California Residential Appliance Saturation Study. California Energy Commission.

[5] Zhao, Yan; Choudhury, Shiny; McDonell, Vincent. 2018. Influence of Renewable Gas Addition to Natural Gas on the Combustion Performance of Cooktop Burners. ASME 2018 International Mechanical Engineering Congress and Exposition.

[6] Rao, Ashok. 2015. Sustainable energy conversion for electricity and coproducts: principles, technologies, and equipment. John Wiley & Sons.

[7] Turns, Stephen. 1996. An Introduction to Combustion. New York: McGraw-Hill.

[8] Glassman, Irvin; Yetter, Richard; Glumac, Nick. 2014. Combustion. Academic press.

[9] Baukal Jr, Charles. 2003. Industrial burners handbook. CrC press.

[10] Zhao, Yan; McDonell, Vincent; Samuelsen, Scott. 2019. Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. International Journal of Hydrogen Energy.

[11] Zhao, Yan; McDonell, Vincent; Samuelsen, Scott. 2019. Experimental assessment of the combustion performance of an oven burner operated on pipeline natural gas mixed with hydrogen. International Journal of Hydrogen Energy.

[12] Weaver, Elmer. 1951. Formulas and graphs for representing the interchangeability of fuel gases. Journal of Research of the National Bureau of Standards.

[13] Munson, Bruce Roy; et al. 2013. Fluid mechanics. Singapore: Wiley.

[14] Choudhury, S., McDonell, V.G. and Samuelsen, S., 2020. Combustion performance of low-NOx and conventional storage water heaters operated on hydrogen enriched natural gas. International Journal of Hydrogen Energy.

[15] Zhao, Y., Morales, D. and McDonell, V., 2019, November. Influence of Blending Hydrogen and Biogas Into Natural Gas on the Combustion Performance of a Tankless Water Heater. ASME 2019 International Mechanical Engineering Congress and Exposition.

[16] Zhao, Y., McDonell, V. and Samuelsen, S., 2020. Assessment of the combustion performance of a room furnace operating on pipeline natural gas mixed with simulated biogas or hydrogen. International Journal of Hydrogen Energy.

[17] Energy Research and Development Division. 2019. http://www.energy.ca.gov/biomass/landfill_gas.html. California Energy Commission.

[18] Tillman, David; Harding, Stanley. 2004. Fuels of opportunity: characteristics and uses in combustion systems. Elsevier.

[19] Energy Research and Development Division. 2019. https://ww2.energy.ca.gov/biomass/anaerobic.html. California Energy Commission.

[20] American Society of Civil Engineers. Report Card for California's Infrastructure. Region 9 of the American Society of Civil Engineers. 2019.

[21] Ni, Meng; et al. 2006. An overview of hydrogen production from biomass. Fuel processing technology.

[22] Belgiorno, V., et al. 2003. Energy from gasification of solid wastes. Waste management.

[23] Hauserman, W. B.; et al. 1997. Biomass gasifiers for fuel cells systems. La Chimica e l'industria.

[24] Maschio, Lucchesi; G. Stoppato. 1994. Production of syngas from biomass. Bioresource Technology.

[25] Leicher, Jörg; et al. 2017. Power-to-gas and the consequences: impact of higher hydrogen concentrations in natural gas on industrial combustion processes. Energy Procedia.

[26] Zhao, Yan; N. Soto Leytan, Kliah; McDonell, Vincent; Samuelsen, Scott. 2019. Investigation of visible light emission from hydrogen-air research flames. International Journal of Hydrogen Energy.

[27] Brandon, N. P; Z. Kurban. 2017. Clean energy and the hydrogen economy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.

[28] De Santoli, Livio; Romano Paiolo; Gianluigi Lo Basso. 2017. An overview on safety issues related to hydrogen and methane blend applications in domestic and industrial use. Energy Procedia

[29] Lefebvre, Arthur; Dilip, Ballal. 2010. Gas turbine combustion: alternative fuels and emissions. CRC press.

[30] Jahnke, James. 2000. Continuous emission monitoring. John Wiley & Sons.

[31] Singer, Brett; et al. 2009. Natural gas variability in California: Environmental impacts and device performance experimental evaluation of pollutant emissions from residential appliances. No. LBNL-2897E. Lawrence Berkeley National Lab (LBNL).

APPENDICES

The following appendices are available under separate cover upon request (Publication Number CEC-500-2020-070-APA-J) by contacting Yu Hou at Yu.Hou@energy.ca.gov.

- Appendix A: Cooktop Burner
- Appendix B: Oven Burner
- Appendix C: Gas Fireplace
- Appendix D: Low-NO_x Storage Water Heater
- Appendix E: Tankless Water Heater
- Appendix F: Room Furnace
- Appendix G: Pool Heater
- Appendix H: Grill Burner
- Appendix I: Laundry Dryer
- Appendix J: Burner Configuration