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Air Quality and Greenhouse Gases Impacts Associated with Zero and Near-Zero Heavy-Duty Vehicles in California

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Air Quality and Greenhouse Gases Impacts Associated with Zero and Near-Zero Heavy-Duty Vehicles in California

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Alejandra Cervantes

Thesis Committee:
Professor G. Scott Samuelsen, Chair
Professor Jack Brouwer
Professor Donald Dabdub

2017

DEDICATION

To my family, Jose, Martha, Andrea, Alma, Jose and Isis.

This document showcases the work I have done,

but doesn’t show the support, love, and lessons each of you have given me

as well as the sacrifices you have done for me.

TABLE OF CONTENTS

Page

LIST OF FIGURES v

LIST OF EQUATIONS vii

LIST OF TABLES viii

NOMENCLATURE ix

ACKNOWLEDGMENTS x

ABSTRACT OF THE THESIS xi

1. Introduction 1

 1.1 Goal 2

 1.2 Objectives 2

2. Background 4

 2.1 Transportation Emissions Contribution Overview 6

 2.2 Biopower Generation Overview 9

 2.3 Summary 12

3. Approach 15

 3.1 Task 1 15

 3.2 Task 2 15

 3.3 Task 3 16

 3.4 Task 4 16

 3.5 Task 5 16

4. California Biogas Resources and Potential Pathways 18

 4.1 Landfill Gas Inventory 18

 4.2 Anaerobic Digester Gas Inventory 25

 4.3 Biogas Power Generation and Transportation Fuel Pathways 30

 4.4 Summary 40

5. Biogas Power Generation and Transportation Fuel Production Cost 42

 5.1 Biopower Economic Module Methodology 42

 5.2 Economic Results for Pathways Considered 47

 5.3 Summary 51

6. Emissions and Air Quality Effects of Biogas Pathways 52

6.1 Greenhouse Gases 56
6.2 Air Quality Effects 58
6.3 Summary 67
7. Alternative Fuel Application of Transportation Greenhouse Gas Emissions 69
7.1 Development of Low-NO_x Engine Transition Scenario 70
7.2 Renewable Natural Gas Feedstock Mixes 74
7.3 Greenhouse Gas Emissions 77
7.4 Criteria Pollutant Emissions 80
7.5 Air Quality Results 81
7.6 Summary 87
8. Summary and Conclusions 89
8.1 Summary 89
8.2 Conclusions 91
9. Bibliography 94
APPENDIX A: Biogas Inventory 99
APPENDIX B: Economic Model 117

LIST OF FIGURES

Figure 1: California GHG emissions broken down by sector. [9] 5
Figure 2: Emission contribution for on-road vehicles in 2015.[12] 7
Figure 3: California in-state generation capacity for 2015.[28] 11
Figure 4: California Landfill locations with Biomethane Production 24
Figure 5: Wastewater Treatment Plant locations in California with Biomethane Production...29
Figure 6: Economic model flowchart for the scenarios considered. 46
Figure 7: Utilization Scenario 1 – 3 MW Combined Cycle WWTPs. 48
Figure 8: Economic Model results for Power Generation Utilization Scenarios at Landfills with no Co-Firing and Biogas Cost. 50
Figure 9: Economic Model Results for Pipeline Injection and Hydrogen Utilization Scenarios at WWTPs with Co-Firing and Biogas Cost. 50
Figure 10: PM Emissions of Onsite Power Production Scenarios. 54
Figure 11: NO_x Emissions of Onsite Power Production...54
Figure 12: SO_x Emissions of Onsite Power Production...55
Figure 13: CO Emissions of Onsite Power Production...55
Figure 14: VOC Emissions of Onsite Power Production. 55
Figure 15: GHG Emissions for Additional Onsite Power Generation at Landfills...............57
Figure 16: GHG Emissions from Additional Onsite Power Generation at WWTP. 58
Figure 17: Air Quality Impacts of Biogas Scenario 2: (a) Impact on Peak Ozone in Summer,(b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter. 61
Figure 18: Air Quality Impacts of Biogas Scenario 4: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter. 62
Figure 19: Air Quality Impacts of Biogas Scenario 6: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the winter. 63

Figure 20: Air Quality Impacts of Biogas Scenario 7: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter. 64
Figure 21: Air Quality Impacts of Biogas Scenario 8: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter. 65
Figure 22: Air Quality Impacts of Biogas Scenario 14: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) impact on 24-hour Average PM2.5 in the Winter. 66
Figure 23: Framework for the Vision 2.1 Model.[50] 71
Figure 24: Daily vehicle population transition of MDV and HDV from the year 2010 to 2035. 72
Figure 25: Well-to-wheels GHG emissions for the Baseline, SIP Case and case including the transition to low-NO_x CNG engine. 79
Figure 26: Total HDV and MDV emissions in 2035 for the baseline, SIP and 1A case in tons per day. 81
Figure 27: Ambient max 8-hr average ozone in the Base Case for (a) Summer and (b) Winter. 82
Figure 28: Ambient 24-hr average PM2.5 for the Base Case for (a) Summer and (b) Winter. 83
Figure 29: Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average PM2.5 for Case 1A relative to the baseline case. 84
Figure 30: Predicted difference in winter episode 24-hr average PM2.5 for Case 1A relative to the Baseline Case. 85
Figure 31: (a) Ambient max 8-hr average ozone in the SIP Case for Summer and (b) the difference in maximum 8-hr ozone between the SIP and Base Case. 86
Figure 32: Ambient 24-hr PM2.5 in the SIP Case for (a) Summer and (b) Winter in the SIP Case. 87

LIST OF EQUATIONS

Equation 1: Average waste in place for currently opened landfills up until 2012. 22

Equation 2: Average waste in place for landfills closed before 2012. 22

Equation 3: Methane volume calculation for WWTP. 27

Equation 4: Mass of cell tissue produced per day in anaerobic digerter. 27

LIST OF TABLES

Table 1: Database sources referenced for building California landfill gas inventory and information contained within each database. [45]–[47] 19
Table 2: EPA LMOP Database Information Summary.[47] 21
Table 3: WWTP Recorded under CBC and CIWQS Database 25
Table 4: Summary of CIWQS Database Influent Flow per Day. 26
Table 5: Potential biogas pathways considered for the use of biogas derived from landfills and wastewater treatment plants. 31
Table 6: Pathways for biogas utilization from landfills and wastewater treatment plants. 32
Table 7: Summary of Power, Heat, and Transportation Fuel Generation from Biogas. 39
Table 8: Emission Factors for Technologies Used in Scenarios.[54] 52
Table 9: Emissions from On-site Hydrogen Production.[55] 53
Table 10: Percentage of Annual Miles Driven by Alternative Fuel. 53
Table 11: Daily availability of RNG estimated to be available for HDV and MDV fuel. 75
Table 12: Carbon intensities for currently available low carbon fuels in California. Adapted from [57], [58]. 76
Table 13: RNG fuel feedstock mixes considered for scenarios. 77
Table 14: Daily demand for scenarios in megajoules (MJ). 78
Table 15: Percentage of natural gas demand met when considering LFG, ADG from WWTP, and conventional feedstock for the production of natural gas for cases considered. 79
Table 16: Percentage of natural gas demand met when considering LFG, ADG from WWTP, ADG from dairy farms, ADG from MSW, and conventional feedstock for the production of natural gas for cases considered. 79

NOMENCLATURE

ADG	Anaerobic digester gas
AQ	Air Quality
ARB	Air Resources Board
CNG	Compressed Natural Gas
EMFAC	Emission Factor Model
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases
GWh	Gigawatt-hours
GW	Gigawatt
H_2	Hydrogen
HDV	Heavy-Duty Vehicles
HiGRID	Holistic Grid Resource Integration and Deployment
LDV	Light-Duty Vehicles
LFG	Landfill Gas
MDV	Medium-Duty Vehicles
NOx	Nitrogen Oxides
PM	Particulate Matter
ppb	Parts per billion
PV	Photovoltaic
RNG	Renewable Natural Gas
SIP	State Implementation Plan
SMR	Steam Methane Reformation
SMOKE	Sparse Matrix Operator Kernel Emissions Modeling System
Mg/m3	Micrograms per meter cubed
MSW	Municipal Solid Waste
WWTP	Wastewater Treatment Plant

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ABSTRACT OF THE THESIS

Air Quality and Greenhouse Gases Impacts Associated with Zero and Near-Zero Heavy-Duty Vehicles in California

By

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Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2017

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California's transportation and power generation sectors emit more than 50 percent of the state's greenhouse gas (GHG) emissions. The state GHG emission mitigation goals include reducing GHG emissions to 1990 levels by 2020. Additionally, to improve air quality throughout the state, aggressive criteria pollutant emission standards have been established for both sectors. Transitioning from fossil fuels to renewable fuels is one strategy to meet these environmental goals. Landfills and wastewater treatment plants are a source for the production of alternative fuels like renewable natural gas (RNG) and hydrogen (H_2) which could then be used in either sector. To evaluate this strategy, the impact on GHG and criteria pollutant emissions, and on air quality resulting from the production and use of RNG in zero or near-zero emission medium-duty vehicles (MDV) and heavy-duty vehicles (HDV) are analyzed. The research reveals that (1) RNG produced from biogas is the most cost effective strategy to utilize the limited resource of biogas available in California even though H_2 is the most attractive fuel, (2) the transportation sector is the more effective sector for the use of

RNG fuel, (3) MDV and HDV outfitted with commercially available near-zero emission CNG engines with RNG results in substantial reductions in both GHG and criteria pollutant emissions, and significantly improves air quality than the use of H_2 in LDV, and (4) the reductions in GHG and criteria pollutant emissions and improvements in air quality exceed those achieved with the MDV and HDV populations envisioned by the State Implementation Plan (SIP).

1. Introduction

Over the past few decades, the air quality within the California state has been a major focus of study due to the large number of communities suffering from health effects triggered by poor air quality. Atmospheric chemistry, California geography, emissions from stationary and mobile sources contribute to the air quality within California. A substantial reduction of criteria air pollutants has occurred through the advancement of clean technology, increases in efficiency, and implementation of alternative fuels.[1]

Additionally, California has adopted other environmental goals which include the reduction of greenhouse gas emission (GHG) goals to mitigate climate change. [2] The state's energy portfolio over the years has increased the amount of renewable energy like solar and wind to reduce its dependence in fossil fuel and thereby lower greenhouse gas emissions. Bio-resources are another renewable energy source which California has also adopted.[3] These resources include forest and agricultural biomass, landfill gas, and anaerobic digester gas produced at wastewater treatment plants.[4] A particularly attractive bio-resource product is renewable natural gas (RNG).

The transportation sector in California is also a major source of GHG and criteria pollutant emissions. In 2015, 37 percent of the GHG emissions from California came from the transportation sector.[5] While at the same time, contributing 81.2 percent of NO_x and 16.7 percent of $PM_{2.5}$ emissions for the state.[6] While the implementation of zero emission and near-zero pollutant emission technologies is playing a key role in the reduction of criteria pollutants and improvement of air quality in California, the implementation is currently in different stages for the various types of vehicles.[7] For example, light-duty vehicles (LDV) with zero emissions are commercially available while for medium-duty vehicles (MDV) and heavy-duty vehicles (HDV), the technology is still being developed and demonstrated.[8], [9] Available near-zero emission engines for the MDV and HDV sectors can bridge the gap between current technology and zero pollutant emission technology for the future. Also, using zero emission and near-zero emission engines with renewable sources can reduce GHG emissions as well.[10]

This work examines the potential amount of available renewable natural gas (RNG) found within California from waste resources, analyzes the different pathways in which it can be utilized to its full potential while considering the environmental and economic effects, and evaluates the environmental impacts of RNG in the transportation sector..

1.1 Goal

The goal of the research is to delineate the GHG and criteria emissions and air quality impacts associated with the implementation of renewable natural gas for medium-duty and heavy-duty vehicles in California.

1.2 Objectives

The following objectives must be achieved to meet this goal:

1. Build a library of California landfills and wastewater treatment plants, which includes the available biomethane at each location, current technology installed, and geographical location of sources.
2. Evaluate power generation and transportation fuel production pathways from the use of available biomethane as renewable natural gas.
3. Spatially and temporally resolve pollutant emissions related to power generation and transportation fuel production pathways, and assess air quality impacts.

4. Analyze power generation and transportation fuel production cost for the pathways selected.
5. Identify and evaluate the air quality and greenhouse gas impacts from the implementation of RNG and zero emission and near-zero emission technology in the medium-duty and heavy-duty transportation sectors.

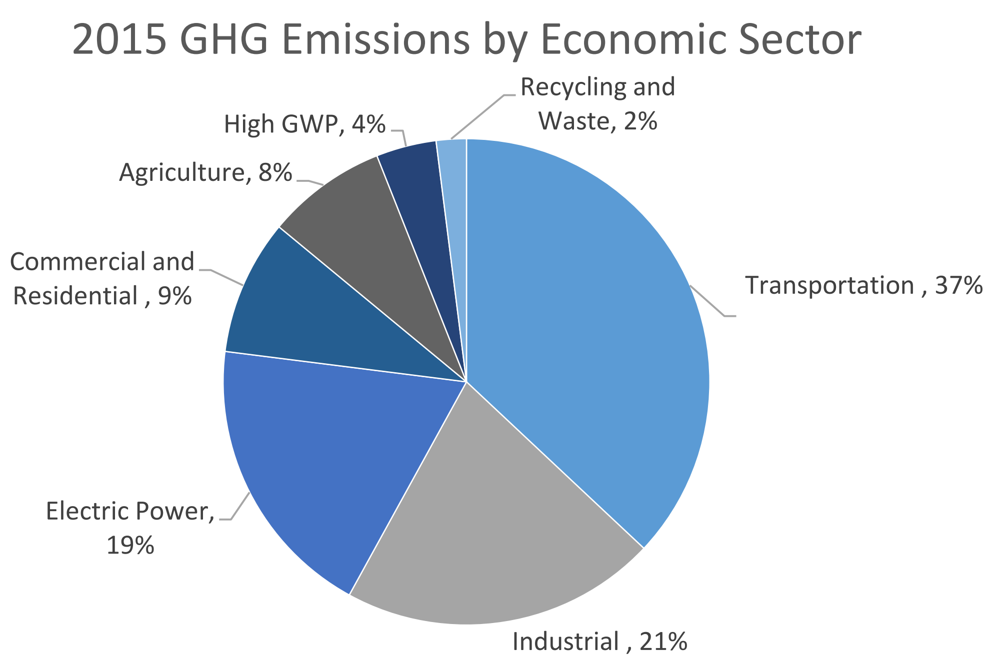
2. Background

In the past decades, California has focused on the improvement of air quality and reduction of greenhouse gas (GHG) emissions. The exponential growth of GHG emissions over the last decades has impacted climate change. Worldwide, attention has been directed to the reduction of GHG emissions in order to mitigate climate change. Within the United States, California has established state legislation AB 32, which "requires California to reduce its GHG emissions to 1990 levels by 2020" from all sectors.[11] Additionally, over the past decades, California has also focused on improving air quality within the state. Data show over 90 percent of Californians breath in unhealthy levels of pollutants throughout the state. Breathing in unhealthy levels of pollutants can cause various health issues from trouble breathing to emergency hospitalizations. Other health issues related to continuous exposure to degraded air quality include impaired lung development in children, increased morbidity, increased asthma hospitalization, decreased cardiovascular health, and increased asthma within children and elder age groups. [12]–[16]

Under the Federal Clean Air Act of 1970, technology has been developed to reduce criteria pollutant emissions to meet state and national ambient air quality standards (NAAQS). With the advancement in technology and emissions controls, air quality has improved throughout the country. However, when looking at California, regions within the state continue to be in violation of the NAAQS for $PM_{2.5}$ and ozone.[1] In order to achieve the NAAQS and improve air quality throughout the state, the California Air Resources Board continuously monitors pollutant emissions and revises emissions regulations in all sectors.

The main sectors contributing to degrade air quality and high levels of GHG emissions are the power generation and transportation sectors. The transportation sector is a major contributor of GHG and criteria pollutants within the United States.[7][8] In 2015, 37 percent of the GHG emissions from California came from the transportation sector; the following highest contributor of GHG emissions came from the industrial sector at 21 percent.[5] Figure 1 shows the contribution of GHG emissions broken down by different economic sectors. When evaluating criteria pollutant emissions from the transportation sector, the transportation sector contributes on different percentages for each different air pollutant. Transportation criteria pollutant emissions account for 48.6, 53.4, 5.1, and 10.3 percent of the total NO_x, CO, SO_x, and $PM_{2.5}$ emissions in California, respectively. [6]

Figure 1: California GHG emissions broken down by sector. [5]



2.1 Transportation Emissions Contribution Overview

California's transportation sector includes various types of vehicles, examples of which include light-duty vehicles, medium-duty vehicles, heavy-duty vehicles, rail, planes, and ships. In order to reduce GHG and criteria pollutant emissions from the transportation sector, California has implemented regulations focused on transitioning part of light-duty gasoline vehicles to zero-emission vehicles, which includes technologies like fuel cell electric vehicles and electric vehicles.[19] However, the HDV sector is fueled by diesel and needs to be addressed as well.

While HDV constitute a small percentage of the vehicle population, they produce a large percentage of the GHG and criteria pollutant emissions from the transportation sector.[7] For example, MDV and HDV are a small percentage of the vehicle population for 2015 (5.5 million vehicles), but contribute to more than 75 percent of NO_x emissions and 45 percent of $PM_{2.5}$ emissions as shown in Figure 2. Additionally, the pollutant emissions associated with these vehicles are concentrated in heavily populated areas and have a major effect on air pollution and public health. Most HDV in California are involved in the freight system which transports goods either within California or across state boundaries to the rest of the country. As population increases with each year in California and the United States, the transportation of goods is predicted to increase as well, which means emissions associated with the freight system will increase without a transition to lower emitting technologies. For California to meet its environmental goals, attention is being directed to the freight transportation system due to its vast potential in reducing GHG, NO_x, and $PM_{2.5}$. Currently, vehicles from this category produce close to 43 percent of GHGs emissions, 55 percent of NO_x emissions, and 70 percent Diesel $PM_{2.5}$ emissions in California.[7]

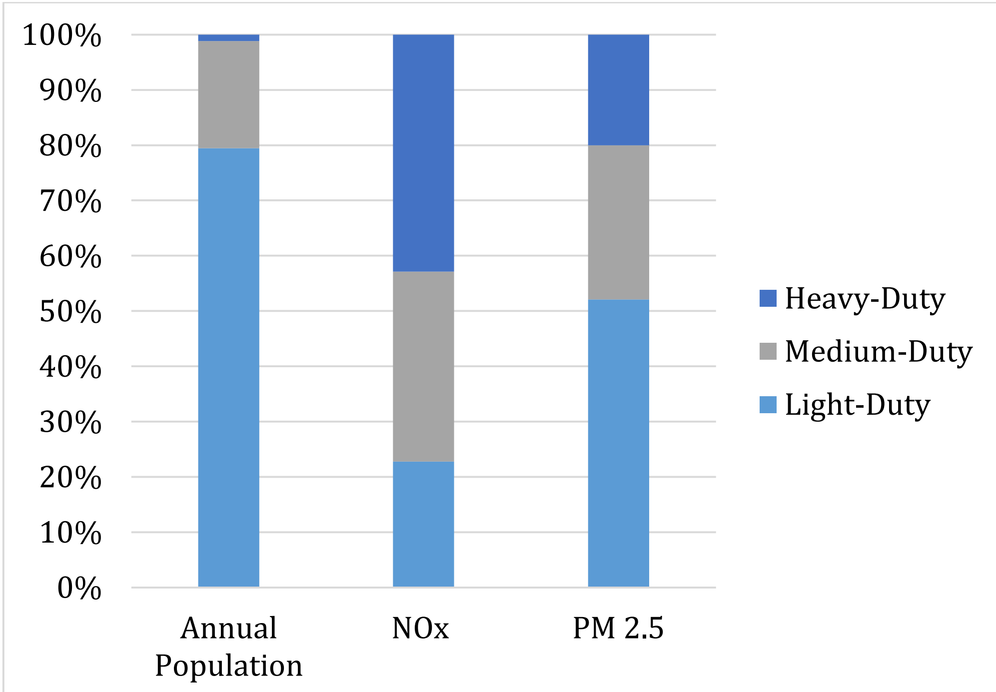


Figure 2: Emission contribution for on-road vehicles in 2015.[20]

To decrease GHGs and criteria pollutants, freight vehicle manufacturers and agencies have invested in research and demonstrated both alternative fuels and technologies that will aid in the replacement of conventional technologies in HDV used within the freight system. Currently, the heavy-duty sector consists mostly of diesel fueled compression ignition engines.[21] Studies show that the exposure to diesel engine emissions is associated with respiratory problems, hospital admissions, mortality, and other health related issues.[22] Additionally, the high emissions of NO_x from these vehicles reacts with the atmosphere and causes an increase in ozone (O_3). Exposure to raised levels of ozone causes respiratory issues, worsening of asthma issues, and lung tissue inflammation. [23], [24]

To reduce the GHG and criteria pollutant emissions from diesel engines found in heavy-duty engines, attention has been directed to the development and advancement of battery electric trucks, hybrid engines, hydrogen fuel cell trucks, and natural gas trucks due to their potential in reducing or eliminating tail-pipe emissions.[23],[25] Having HDV run on an alternative fuel over various vehicle categories will support the state goal to improve air quality and reduce the emission of carbon. At this time, natural gas vehicles show promising results as an alternative fuel which can be expanded into different categories in the transportation sector.

Previously mentioned zero emission technologies are at different stages of development and demonstration for HDV. While the deployment of fuel cell electric and battery electric trucks are expected to be available for HDV in the next decades, compressed natural gas (CNG) engines and hybrid technologies are currently available and engaged in demonstrations.[8]–[10], [26] These vehicles can immediately reduce harmful $PM_{2.5}$ and NO_x emissions from diesel heavy duty vehicles and can help bridge the transition between current vehicle technologies and future zero emission vehicles. Presently, current infrastructure of natural gas fueling stations can support the application of natural gas engines for long-haul; however, the technology developed and currently available for CNG engines can only be applied to vehicles serving short range trips.[27]

Even though natural gas is a fossil fuel, it is still considered a viable alternative fuel due to its lower carbon footprint and lower criteria pollutant emissions, and a variety of MDV and HDV fleets (e.g., transit districts, waste management companies, delivery vehicles, utility vehicles, and long-haul Class A trucks) have replaced diesel vehicles and fleets with natural gas vehicles. Studies show reductions in $PM_{2.5}$, NO_x, and GHG emissions from transitioning into CNG engines.[10],[28] Using RNG derived from bio-resources like landfill gas and anaerobic digester gas rather than conventional natural gas from fossil fuels, can further reduce GHG emissions for vehicles. Fleet agencies throughout the world are transitioning to fueling their natural gas vehicles with (RNG rather than conventional natural gas. The transition to RNG is seamless due to the similar composition RNG achieves after a clean-up process.[29] Additionally, fleet agencies are able to capture GHG reduction since the production of RNG from biogas has a lower carbon footprint and lower net GHG emissions than the production of conventional CNG. [30]

CNG has mostly been applied to short distance MDV and HDV since CNG has a lower energy content and mileage than diesel. To apply CNG vehicles in a long-haul setting with the current engine sizes, additional fuel capacity on the vehicle is required. Today, this is commercially viable and in the early stages of deployment. Waste resources can serve as a feedstock in the production of RNG and provide the necessary demand to expand the natural gas infrastructure for MDV and HDV.

2.2 Biopower Generation Overview

Biogas is produced through anaerobic digestion in landfills and wastewater treatment plants. The organic waste and bacterial population present in the absence of oxygen convert to biogas, which its composition includes mostly methane (CH_4) and carbon dioxide (CO_2).[31] Over the years, biogas usage has come increasingly popular. Facilities use biogas to fuel various power generation technologies like microturbines, gas turbines, and fuel cells and produce electricity and heat on-site. Other facilities collect and sell the biogas to generate revenue.[32] The biogas produced from landfills and wastewater treatment plants can also be refined into biomethane, which is a form of RNG that meets natural gas pipeline standards and can be introduced into the natural gas system.

Using RNG from waste streams to produce power and support the current California grid allows for lower GHG emissions from the California power sector and the reduction of its carbon footprint. Due to its higher warming potential, methane emissions have a greater impact on climate change that the emission of carbon dioxide. Therefore, unused methane produced from landfills and anaerobic digesters in wastewater treatment plants is flared to reduce GHG intensity from the site. Collecting and using the methane from these waste streams to generate power can reduce emissions from waste resources while at the same time reduce emissions from the power generation sector by avoiding emissions related to fuel procurement.[29]

California currently produces power from biogas collected from landfills, wastewater treatment plants and municipal solid waste. In 2015, California produced 196,195 GWh of electricity in the state and had a total of 78,742 GW of capacity installed.[3], [33] Figure 3 shows the generation capacity divided by the different fuel types in California. Most of California's power generated in the state comes from combined cycle plants fueled by natural gas. Natural gas has been the main fuel used to generate power in California for the last couple of decades. With the decrease in cost and the advancement of solar technology, California has seen an increase in solar photovoltaic (PV) capacity installation. Between 2014 and 2015, an additional 1,303 MW of solar PV was installed throughout California. In contrast, the power capacity between 2014 and 2015 fueled by biomass sources were decreased by 9 MW. The decrease in capacity from biomass can be affiliated to the low production of biogas in locations not being able to support the installed technology or biomass facilities being retired.

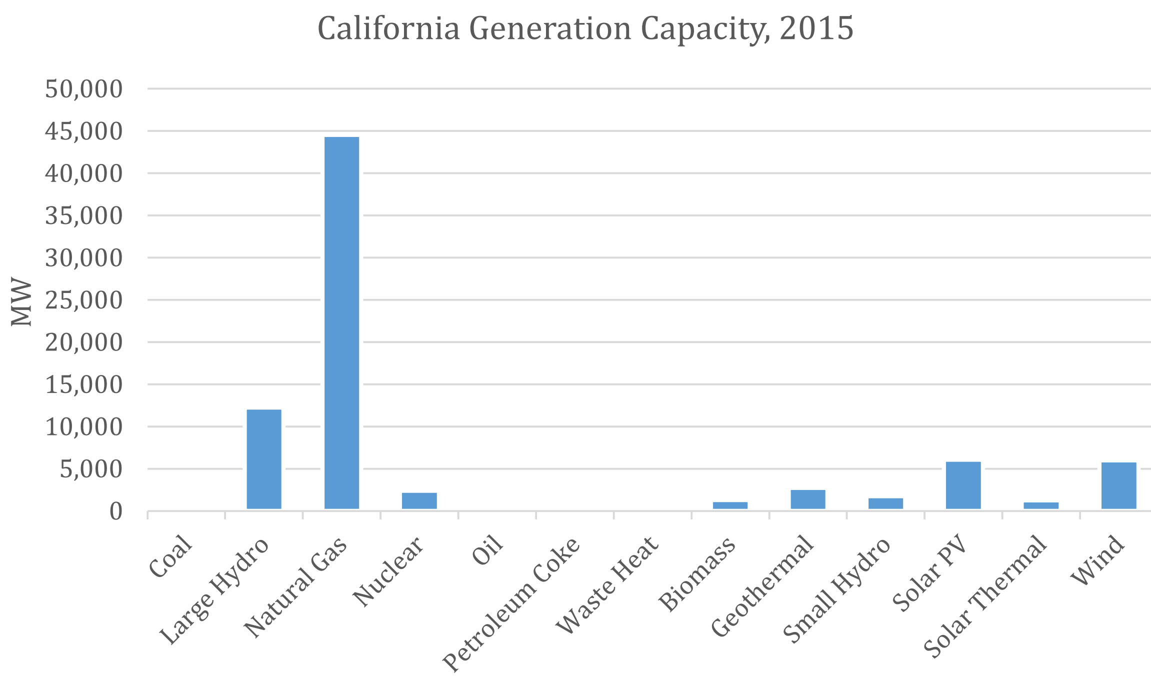


Figure 3: California in-state generation capacity for 2015.[3]

From the total generation capacity installed in California in 2015, 390 MW represent power systems which are fueled by biogas collected from waste sources and represent only 0.5 percent of the capacity installed.[34] However, these 55 locations reported include only locations in which the facility produces greater than .1 MW. Over 300 wastewater treatment plants and landfills in California are producing biogas and have the potential for a project. Collecting the biogas produced at these locations and utilizing it can increase California's renewable energy portfolio and help balance other intermittent renewable sources like solar and wind. [35]

Fuel cells, reciprocating engines, gas turbines, microturbines and other technologies have the flexibility to utilize biogas as the main fuel. Studies show successful application of power system and utilization of biogas. The way in which these systems pretreat the biogas before using it in the system vary from mixing the biogas with natural gas or hydrogen fuel to increase heating value, to using the biogas directly at an increased temperature.[36]–[40] Since the production of biogas stems from waste sources, the emissions related to recovery are highly reduced compared to emissions from mining for fossil natural gas. Installed projects show a reduction in GHG emission factors for the electricity produced. When fuel cells are used as the power generator, both GHG and criteria pollutants are reduced.[41], [42]

Even though the biogas is produced as a byproduct, the installation of power generation systems and the associated maintenance do have a related cost. The cost of the electricity produced is dependent upon the technology installed, the capacity of the system, the available biogas, the need of pre-treatment for the biogas, and the need of any after treatment for technologies. When considering the installation of a power generation system at landfills and wastewater treatment plants, the related costs, environmental impacts, and fuel availability at locations need to be considered.

2.3 Summary

The California transportation and power generation sectors contribute a large percentage of the total emissions of GHG and criteria pollutants in California. California has established various environmental goals which focus on the reduction of GHG and criteria pollutant emission by (1) increasing renewable power generation in the state, (2) reducing the use of fossil fuels, and (3) improving urban air quality. Biomass resources currently are used to generate power and will be further developed to support the electric grid in California. Biomass resources include the production of biogas from waste sources like landfills and anaerobic digesters in wastewater treatment plants. The biogas generated at these sources can be used to produce RNG and substitute for natural gas recovered from fossil sources. RNG can aid in the reduction of GHG emissions in both the transportation and power generation sectors since natural gas is a common fuel that can be used or is currently used in both sectors.

In the next years, the MDV and HDV sectors in California aim to transition the current diesel engines in vehicles to zero or near-zero emission technology. Currently available low-NO_x CNG engines for MDV and HDV will provide immediate reduction in criteria pollutants and improvements in air quality. In 2016, the introduction of a low-NO_x CNG engine became the first alternative fuel engine which can be applied to MDV and HDV categories. Cummins Westport's 8.9 liter (L) SI CNG engine has been certified by the U.S. EPA and the ARB to a 0.02 gram per brake horsepower-hour (g/bhp-hr) optional NO_X standard and is commercially available starting 2017.[26]In addition, when fueling these engines with RNG, additional GHG reductions can be captured. This near-zero emission technology, together with RNG, will provide a transition from current conventional diesel vehicles to zero emission vehicles while still providing significant improvements in emission reductions.

The power sector in California continuously explores ways to reduce GHG emissions while still providing the necessary capacity for the state. While increasing renewable power generation through solar and wind produces a reduction in GHG emissions, wind and solar sources are intermittent and California will not be able to meet power demand without a clean, firm (24/7, load-following) power generation strategy. Using biogas from landfills and wastewater treatment power plants as a substitute for natural gas reduces GHG emissions and provides power without intermittency. Additionally, criteria pollutant emissions from power generation can also be achieved due to the different power generation technologies and after-treatment technologies available commercially.

The work presented in this thesis addresses the current and projected biogas generation from landfills and wastewater treatment plants, the cost related to generating power or transportation fuel using biogas, and the environmental impacts related to using biogas in the transportation and power generation sectors. Since biogas resources are limited, it is important to assess and establish the best utilization of biogas resources to meet California environmental goals.

3. Approach

3.1 Task 1

Build a database of California landfills and wastewater treatment plants including available biomethane, current technology installed, and location of sources.

Renewable natural gas feedstock can be derived from various waste streams producing biomethane. Biomethane production at the source depends on the operation of each landfill and wastewater treatment plant. This task focuses on developing a database (biomethane production, the biomethane utilized, and the available biomethane at each location) while taking into consideration any currently installed technology at the locations utilizing the biomethane. The database includes the potential.

3.2 Task 2

Evaluate power generation and transportation fuel production pathways from the use of available biomethane as renewable natural gas.

After treating and cleaning the biomethane, recovered from landfills and wastewater treatment plants, the fuel can be utilized as renewable natural gas. RNG serves as a substitute for natural gas and can be utilized in power generation or as transportation fuel. This task identifies various pathways in which the RNG can be utilized. The power generation pathways include using RNG in microturbines, combined cycles, gas turbines, fuel cells, and reciprocating engines. The transportation fuel pathways consider using the renewable natural gas to produce hydrogen and compressed natural gas.

3.3 Task 3

Spatially and temporally resolve pollutant emissions related to power generation and transportation fuel production pathways and assess air quality impacts within California.

Using the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system in conjunction with emission changes from power generation and transportation fuel production pathways, the emission profiles are introduced into an air quality model which considers the atmospheric chemistry and transport. Using the air quality model and considering a business as usual case, we can examine the effect on ozone (O_3) and $PM_{2.5}$ concentrations from the emission changes of the pathways considered.

3.4 Task 4

Analyze power generation and transportation fuel production costs for the pathways.

The renewable natural gas recovered from landfill and wastewater treatment plants biomethane is limited. Determining the pathway with the greatest benefit includes analyzing the related costs along with the environmental impacts. This task focuses upon the cost of electricity related to each of the power generation technologies considered as well as the cost related to the transportation fuel production. Examining the costs related to each pathway allows consideration of the feasibility of its implementation.

3.5 Task 5

Identify and evaluate the air quality and greenhouse gas impacts from the implementation of near-zero emission technology within the medium-duty and heavy-duty transportation sector.

Using results from previous tasks, the effects of the implementation of advanced technologies within the heavy-duty sector can be evaluated. The results will allow one to assess the effects on air quality and greenhouse gas emissions as the development of a sustainable heavy-duty transportation sector moves forward.

4. California Biogas Resources and Potential Pathways

Biogas generated at landfills and waste water treatment plants (WWTP) contains a blend of methane and carbon dioxide that can be used to produce power. Currently, 20 percent of the landfills and 12.5 percent of WWTP in California power waste-to-energy projects through biogas. For the landfills and WWTP that currently do not have a waste-to-energy capability, the unused biogas (which is today collected and discarded either through flaring or another process) can be processed and used to produce renewable natural gas and used in power generation or as a transportation fuel.

California has a high number of landfills and WWTP distributed throughout the state. To assess the different pathways these resources can be utilized, an inventory of the various locations of these facilities in California and the associated biogas production was created using databases from the Landfill Methane Outreach Program, the California Biomass Collaborative, the California Water Boards' California Integrated Water Quality System Project, and other agencies. The inventory includes annual amounts of biogas produced from landfills and WWTP, currently installed projects at locations, available unused biogas for future projects, and locations of sites.

4.1 Landfill Gas Inventory

Municipal Solid Waste (MSW) generation increased from 88.1 million tons annually in 1960 to 250.4 million tons annually in 2010 in the United States. The waste generation per capita has increased from 2.68 pounds per person per day in 1960 to 4.40 pounds per person per day in 2010. The amount of MSW deposited in landfills has oscillated around 120 million tons annually from 1975 to present due to the combination of different recycling, combustion with energy recovery, and composting projects that have been implemented.

Current regulations in California aim to divert waste into landfills by recycling beverage containers and manage nonhazardous waste.[43], [44] Overall, these projects have increased steadily over the decades and reduced the tons of waste discarded into landfills.[45] However, the waste placed in landfills continues to produce biogas which needs to be collected and discarded to reduce GHG emissions.

The Environmental Protection Agency (EPA) Landfill Methane Outreach Program (LMOP) creates partnerships between state agencies, energy consumers and producers, the landfill gas industry, and communities to promote waste to energy projects for landfills throughout the United States. The LMOP mission is "to reduce methane emissions by lowering barriers and promoting the development of cost-effective and environmentally beneficial landfill gas (LFG) energy projects" [46]. Through this program, a database has been created that includes all the current and planned landfills in the United States. The database also includes projects occurring in landfills from power generation to transportation fuel production.

The existing LMOP databases were examined to develop a biogas inventory for the landfills found in the state of California. The LMOP database was cross-examined with databases from the CalRecycle Solid Waste Information System, and the California Biomass Collaborative Facilities database.

Table 1: Database sources referenced for building California landfill gas inventory and information contained within each database. [47]–[49]

Database Source	Information Within Source
EPA LMOP	• 314 municipal solid waste landfills • 1.35 billon tons of waste in place.
CalRecycle Solid Waste Information System (SWIS)	• 240 permitted solid waste landfills • Upper bound of 1.6 billon tons in place (actual tonnage unknown because of data gaps).

California Biomass Collaborative Facilities Database (CBC)	• 370 solid waste landfills • 1.4 billion tons in place.

Out of the three databases examined, the EPA LMOP database was selected as the main source for the inventory based upon the following criteria:

- Comprehensive data on current landfill gas-to-energy projects, project type, MW capacity, start date, shutdown date (if applicable), and emissions reductions.
- Landfills are classified by project status, including operational, construction, closure date, candidate, and potential.
- As compared to the other databases, the LMOP database has the least amount of missing data on waste in place, landfill opening year, and landfill closure year and landfill owner.

Table 2 summarizes the number of landfills categorized by project status found in the LMOP database. Landfills are categorized based whether there is a project related to the biogas produced at that landfill. A landfill that currently has an operational biogas project falls under the operational category even if there are additional projects in construction or has previously shutdown. Approximately 230 landfill locations do not have a project associated with them. These locations are expected to become a major interest and source of biogas to produce renewable natural gas since it is assumed that the currently extracted biogas is being flared. As shown in Table 2, currently 70 landfill projects are either installed or in construction in California producing about 380 megawatts (MW) of power nearly continuously. The power produced through these facilities generates electricity at a lower carbon footprint than a power system being fueled by conventional natural gas. However, the air pollutant emissions factors associated with the power generated at each facility varies due to the different technologies used.

Table 2: EPA LMOP Database Information Summary.[49]

	Number of Landfills	Waste in Place (tons)	Current MW Capacity	Description
Total Operational	65	910,793,188	298	Landfill has an operational project
Total Construction	5	31,976,218	53	Landfill has a project in construction
Total Shutdown	14	108,540,854	81	Landfill has a project that has been shutdown
Total Candidate	32	160,166,741	0	Landfill accepting waste or has been closed for ≤ 5 years. Landfill has at least 1,000,000 tons of waste in place and does not have an operational or under-construction project.
Total Potential	198	143,861,864	0	Landfill does not meet any of the above criteria
Total Number of Landfills	314	1,355,338,865	432	

Calculating the amount of biogas produced at each landfill location depends on various elements. Variables affecting biogas production at a landfill are annual waste in place, landfill closure date, landfill opening date, and the amount of organic material being received. The annual biogas production for each landfill was calculated using the EPA Landfill Gas Emissions Model (LandGEM) tool. LandGEM uses the annual waste set in place at a landfill, calculates the annual amount of biogas produced, and takes into account factors such as waste composition and the decrease in methane percentage over time as the waste anaerobically digests.[50] Based upon the annual waste in place, landfill opening year and landfill closing year, LandGEM calculates the amount of biogas and biomethane produced in megagrams per year (Mg/year) at each landfill. Based on the information found in the LMOP database, the annual waste in place for a landfill was determined by dividing the reported total amount of waste in place (tons) by the number of years the landfill has been open, as shown below:

Equation 1: Average waste in place for currently opened landfills up until 2012.

$$\boldsymbol{MSW\ per\ year} = \frac{\boldsymbol{'Waste\ in\ Place'}}{\mathbf{2012} - \boldsymbol{'YearLandfill\ Opened'}}$$

MSW per year:	Average waste in place at landfill
Waste in Place:	Total waste in place at landfill
Year Landfill Opened:	Year landfill opened and started receiving waste

The data were collected up to year 2012 in order to evaluate an average of waste in place for the landfill. For those landfills closed prior to 2012, average waste in place was calculated using the formula below:

Equation 2: Average waste in place for landfills closed before 2012.

$$\boldsymbol{MSW\ per\ year} = \frac{\boldsymbol{'Waste\ in\ Place'}}{\boldsymbol{'Landfill\ Closure'} - \boldsymbol{'YearLandfill\ Opened'}}$$

MSW per year:	Average waste in place at landfill
Waste in Place:	Total waste in place at landfill
Year Landfill Opened:	Year landfill opened and started receiving waste
Landfill Closure:	Year landfill closed and stopped receiving waste

Figure 4 shows a map of California landfill locations with their respective average methane produced per year. The map shows higher concentrations of biomethane production on those landfills which are located close to large populated areas since there is more waste placed in these locations. Locations producing larger amounts of methane are ideal candidates for either power generation or transportation fuel pathways since they are near higher population density areas. Either pathway can help local governments and agencies to meet their fuel demand for transportation or power generation due to their higher demand in these locations.

California produced 2,410,000 Mg in 2013 from landfills based upon the data from the LMOP database and LandGEM outputs. However, when considering the biomethane utilized in existing projects at landfills, the available total potential biogas that can be utilized to produce RNG. Appendix A includes the landfill gas inventory created from the LMOP database. The inventory comprises of tables in excel with biomethane generation, coordinates of its location, technology installed, and biomethane utilized for each landfill. According to the LMOP database, in California 352 MW of power is being generated from current projects in landfills. Taking into account an efficiency of 35 percent for currently installed projects and the heating value of biogas, the overall available biomethane potential for California derived from landfills is estimated at 1,479,738 MG per year. Therefore, 60 percent of the biomethane produced in California is available for the production of RNG. The RNG can then be used as a substitute for conventional natural gas in power generation and transportation fuel production processes to further reduce GHG emissions in the California energy mix.

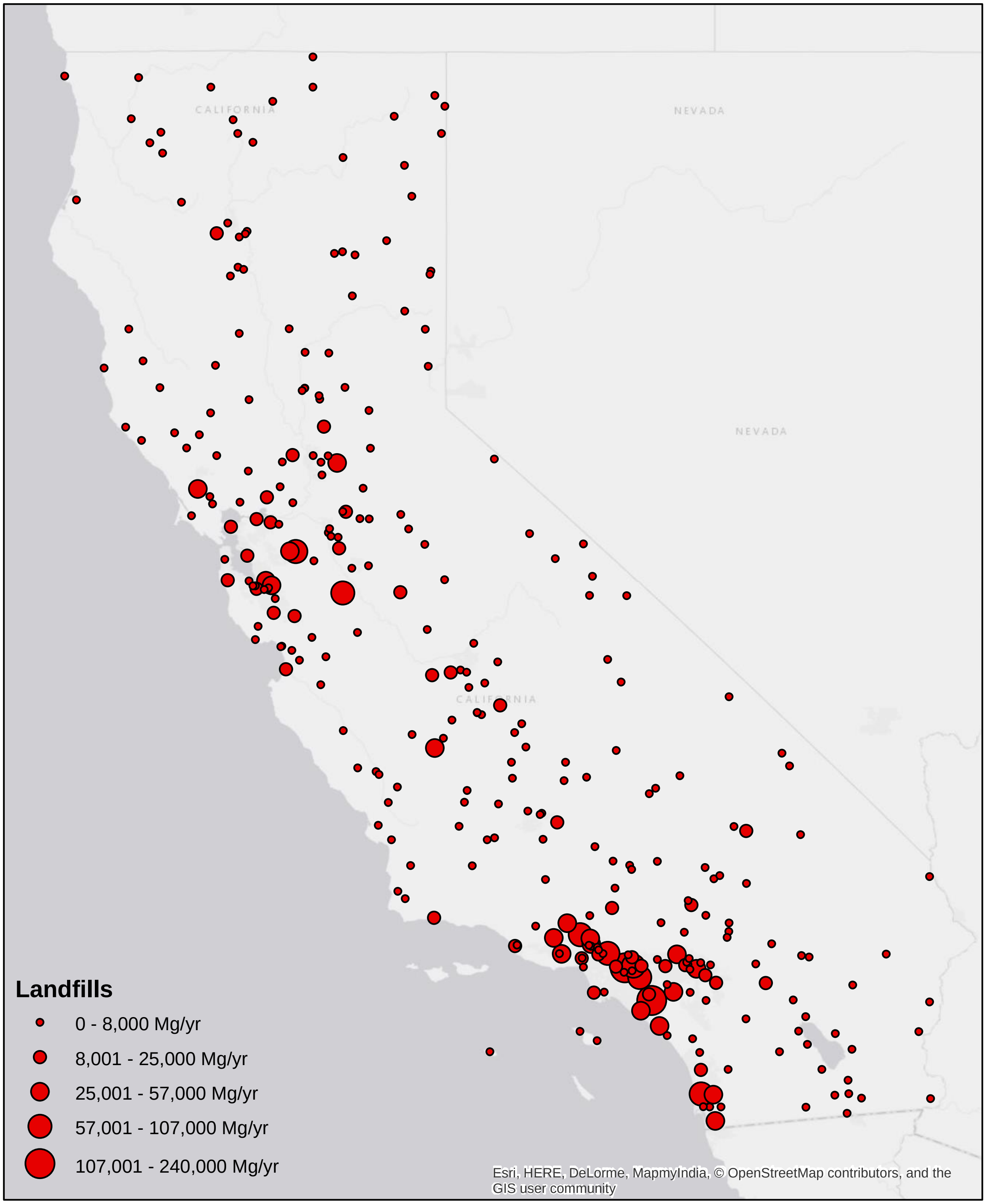


Figure 4: California Landfill locations with Biomethane Production

4.2 Anaerobic Digester Gas Inventory

In parallel, WWTP databases were reviewed to quantify wastewater flow and determine the biogas produced. During the process of wastewater treatment, the sludge typically exiting from the clarification tanks in the primary and secondary cleanup process is transported to anaerobic digesters. In the anaerobic digesters, the sludge which is an array of microorganisms, break down solids in the absence of oxygen and produce biogas, which includes methane and carbon dioxide.[51]

Building an inventory of biogas produced within WWTP required known information in which each WWTP operates. The two main databases consulted for the production of biogas from WWTP were the California Biomass Collaborative Facilities Database (CBC) and the California Water Board – California Integrated Water Quality System (CIWQS). These two databases each include the flow of the WWTP listed along with their locations. Table 3 summarizes the data extracted from the databases.

Table 3: WWTP Recorded under CBC and CIWQS Database

CBC Database		CA Integrated Water Quality System	
WWTP with Anaerobic Digesters	140	All WWTP	303
Aggregate Flow (MGD)	2,500	Aggregate Flow (MGD)	3,700
MW capacity	85		

The CBC database includes WWTPs with anaerobic digesters as well as information on gross MW capacity, net MW capacity, cogeneration operations, project status, influent flow, average dry weather flow, power generation technology, and plant location. Upon request to the California Water Board headquarters, a detailed version of the CIWQS data was delivered that includes monthly flow data for all wastewater released in California from 2010 to 2013. Additionally, the three-year timeframe of the data accounts for intra-annual seasonality and inter-annual variability. However, the data acquired from the CIWQS do not include information on any current use of the biogas generated from the anaerobic digesters. Using the data acquired, the average million gallons per day (MGD) of influent flow for each wastewater treatment plant was calculated. The CIWQS database average flow rates were selected to calculate biomethane potential since the database includes data on both WWTPs with and without anaerobic digesters whereas the data from the CBC only include those locations with installed projects. Table 4 presents further information derived from the CIWQS database which reveals that the majority of wastewater flow comes from power plants and only 25% of wastewater flow travels to wastewater treatment plants. For the development of the WWTP biogas inventory, focus was given to the 303 wastewater treatment plants from the CIWQS database due to their ability and readiness to use the sludge from the wastewater treatment process and deliver it to anaerobic digesters to produce biogas.

Table 4: Summary of CIWQS Database Influent Flow per Day.

	Number of plants	**Total MGD**
CIWQS	352	15634
CIWQS WWTP only	303	3771
CIWQS WWTP > 1 MGD	205	3741
CIWQS > 5MGD	119	3542
CBC	140	2552
1MGD < WWTP < 5MGD	86	199

Potential biomethane production calculated for the inventory is based upon the method outlined in Metcalf and Eddy's "Wastewater Engineering: Treatment and Resource Recovery."[49] This method was selected based on available information. Equation 3 and Equation 4 shown below were used to calculate biomethane production.

Equation 3: Methane volume calculation for WWTP.

$$\boldsymbol{V_{CH_4}} = (\mathbf{0.35})\left[(\boldsymbol{S_o} - \boldsymbol{S})(\boldsymbol{Q})\left(10^{-3}\frac{g}{kg}\right)\right] - \mathbf{1.42}\,\boldsymbol{P_x}$$

V_{CH_4}:	Volume of methane produced at standard conditions, 0C and 1 atm
0.35:	Theoretical conversion factor for the amount of methane produced, m^3, from conversion of 1 kg of bCOD at 0C (conversion factor at 35C = 0.40)
Q:	Flowrate m^3/day
S_o	bCOD in influent mg/L
S:	bCOD in effluent mg/L
P_x:	Net mass of cell tissue produced per day

Equation 4: Mass of cell tissue produced per day in anaerobic digester.

$$\boldsymbol{P_x} = \frac{\left[\boldsymbol{YQ}(\boldsymbol{S_o} - \boldsymbol{S})\mathbf{10^{-3}}\frac{g}{kg}\right]}{[1 + k_d(SRT)]}$$

P_x:	Net mass of cell tissue produced per day
Y:	Yield coefficient
Q:	Flowrate m^3/day
S_o	bCOD in influent mg/L
S:	bCOD in effluent mg/L
k_d:	Endogenous coefficient
SRT:	Solid retention time

Appendix A includes the inputs and assumptions used in the equations listed above for the calculation of biogas in each of the WWTP. The calculated volume of biomethane produced per day was converted to megagrams (Mg) of biomethane per year and used for scenario development. In total, the 303 WWTP in the CIWQS database produces 313, 300 Mg of biomethane per year, which is 12.5 percent of the annual biomethane production potential of California landfills. Figure 5 shows the locations of WWTP in California considered in the analysis with the associated potential biomethane production. However, as in Figure 4, the amount of biomethane shown does not include the usage of biogas currently utilized in projects at the facilities. To account for the biogas being used in current projects within the wastewater treatment plant, the database of the CBC was used to calculate the biogas used in addition to querying annual wastewater treatment plant reports. The biomethane gas available for the projects is 247, 957 Mg of biomethane per year, which is 80 percent of the biomethane produced. The inventory compiled comprises of tables in excel with biomethane generation, coordinates of its location, technology installed, and biomethane utilized for each WWTP. Appendix A lists the location of wastewater treatment plants used in the analysis along with the potential biomethane produced and power currently generated at locations. The wastewater treatment plant biomethane in conjunction with the available biomethane produced from landfills becomes the basis of the feedstock available for power generation and transportation fuel production pathways.

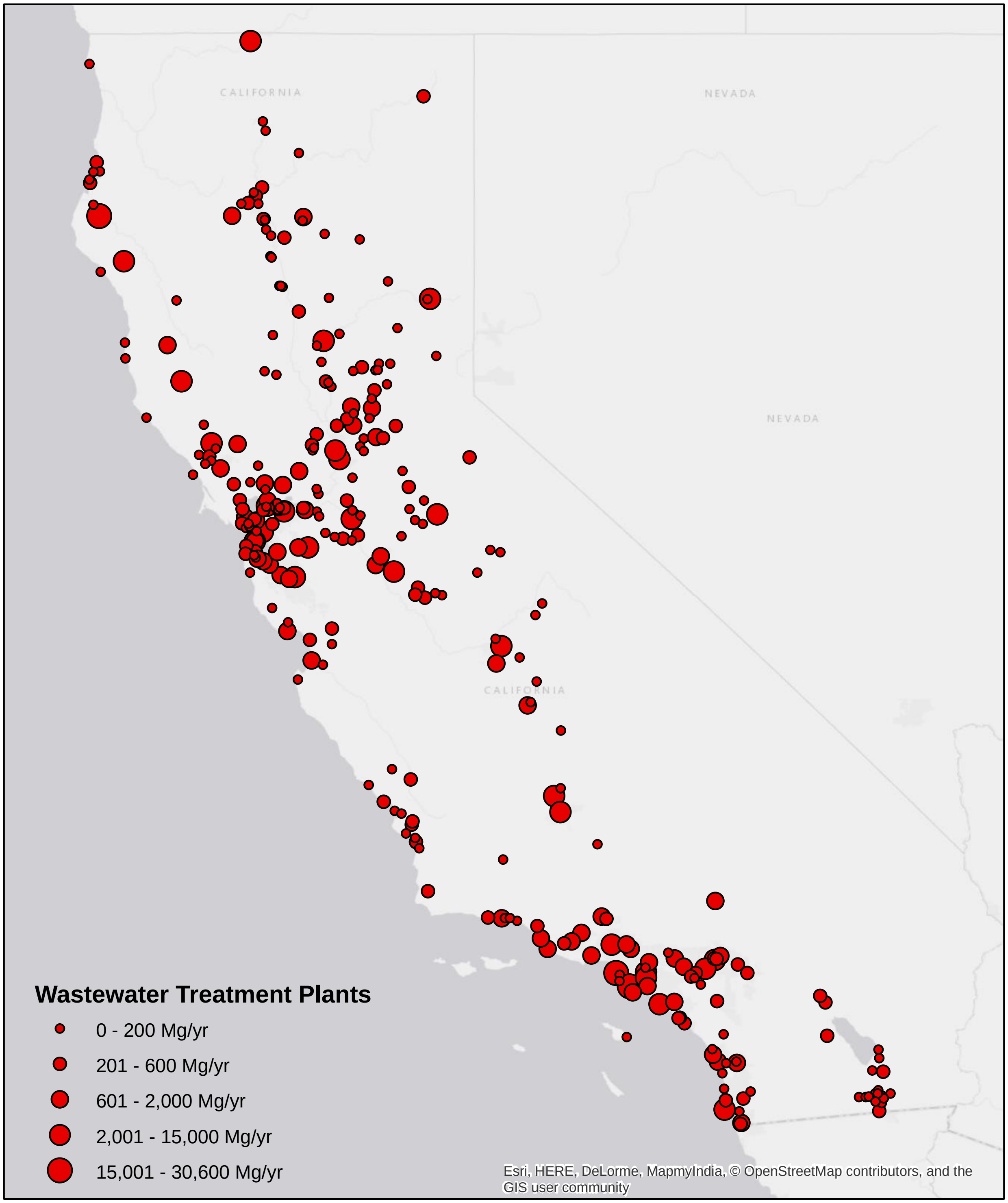


Figure 5: Wastewater Treatment Plant locations in California with Biomethane Production.

4.3 Biogas Power Generation and Transportation Fuel Pathways

Current projects across California landfills and wastewater treatment plants utilize biogas to produce electricity, supply heat, or produce transportation fuel. Some examples of these projects include the generation of power from the Sanitation District of Los Angeles County through steam turbines and reciprocating engines and the production of 13,000 gallons of liquefied natural gas (LNG) per day from the landfill gas captured from the Altamont Landfill in Livermore.[52], [53] As mentioned previously, technologies used to generate power with natural gas can also be used with renewable natural gas derived from biogas. These technologies include fuel cells, microturbines, and combined gas turbine steam turbine cycles. However, the biogas has to be processed and cleaned as required by the technology in order to generate power and not damage the equipment considered.

Most often biogas projects utilize a reciprocating engine either by itself or in a combined heat and power system due to its fuel flexibility. However, the use of a reciprocating engine requires additional emission reduction technologies to be able to meet emission standards. Fuel cells can also be used with biogas to generate power while at the same time meeting emission standards of distributed generation. The Eastern Municipal Water District (EMWD) currently powers a 900 kW fuel cell at the Moreno Valley Water Reclamation Facility with the produced biogas. The power generated from the fuel cell provides 40 percent of the facility's energy requirements.[54] These technologies along with other power generation technologies suitable for biogas use were considered when forming utilization scenarios to analyze the best technical and economically feasible scenarios to maximize environmental benefits and power generation. The different pathways in which biogas can be utilized and considered in the current analysis are presented in Table 5.

Table 5: Potential biogas pathways considered for the use of biogas derived from landfills and wastewater treatment plants.

Electricity	• On-site reciprocating combustion • On-site gas turbine combustion • On-site fuel cell • On-site tri-generation
Heat	• On-site direct-fired boiler • On-site combined heat and power system • On-site tri-generation
Transportation	• On-site CNG production • On-site tri-generation • Pipeline injection for central CNG, LNG, or SMR

The scenarios considered in this study are listed in Table 6 and described below. Each scenario adopts a pathway from Table 5 and establishes an application with the associated additional power, heat, and transportation production based on the available biogas. The heat recovery efficiency for the WWTP locations is defined as the total heat recovered divided by the total fuel energy input. The scenarios described include both currently available and existent pathways and technologies for biogas usage like reciprocating engines and injection to the natural gas pipeline; as well as pathways and technologies which have been demonstrated and considered for future installation like a tri-generation technology system and hydrogen production through SMR.

- ***Scenario 1: On-site combined cycle combustion***

This scenario models the use of the available biogas to fuel an on-site combined gas turbine steam turbine cycle system at landfills and wastewater treatment plants. A combined cycle is only considered when sufficient biogas is available to support a system of at least 3 MW capacity. Combined cycle systems are among the most efficient systems since they use the combination of a gas turbine and a steam turbine to generate power. The combined cycle electrical efficiency is assumed to be 50 percent for all of these systems. The biogas from the landfill and wastewater treatment plant needs to be processed before entering the combined cycle system in order to reduce emissions and extend the equipment lifetime. However, additional equipment may need to be installed to be able to meet emissions standards.

Table 6: Pathways for biogas utilization from landfills and wastewater treatment plants.

Scenario	Description
1	On-site combined cycle combustion
2	On-site reciprocating engine
3	On-site reciprocating engine combined heat and power system or on-site combined cycle system if available biogas would support 3 MW of combined cycle capacity
4	On-site microturbine combined heat and power system or on-site combined cycle system if available biogas would support 3 MW of combined cycle capacity
5	On-site fuel cell combined heat and power system
6	On-site fuel cell combined heat and power system or on-site combined cycle system if available biogas would support 3 MW of combined cycle capacity
7	On-site fuel cell tri-generation system (power, heat, and hydrogen production)
8	On-site Compressed Natural Gas (CNG) production
9	Pipeline injection of biomethane (Sized for 1 million scfd of available biomethane)
10	Pipeline injection for central CNG production
11	Pipeline injection for combined cycle electricity generation
12	On-site hydrogen production using steam methane reformation (SMR)
13	On-site microturbine

- ***Scenario 2: On-site reciprocating engine***

This scenario models the use of the available biogas to fuel a reciprocating engine on-site at landfills and wastewater treatment plants. The installation of a reciprocating engine is considered when sufficient biogas is available to support a 1 MW engine. Installing a combined heat and power (CHP) system with the reciprocating engine can increase the efficiency of the overall system. The installation of a CHP system is considered only at wastewater treatment plants because landfills do not have a direct use for the exhaust heat produced. The electrical efficiency of the reciprocating engine is assumed to be 32 percent and the heat recovery efficiency of the CHP system is 35 percent. Reciprocating engines typically have high criteria pollutant emissions and need additional emission reducing equipment in order to meet emission standards. Nonetheless, these types of systems are the most popular installations for biogas projects because of their fuel flexibility and low cost in the size class needed.

- ***Scenario 3: On-site reciprocating engine combined heat/Combined Cycle***

  This scenario models the use of available biogas to fuel either a reciprocating engine or a combined cycle system on-site at landfills and wastewater treatment plants. The combination of these technologies would allow for power generation at higher efficiencies for locations with a higher amount of biogas and can support a 3 MW system. For locations that produce a lower amount of biogas, but can still support a reciprocating engine but not a combined cycle, a 1 MW reciprocating engine is considered. The efficiencies for each system are the same as the ones considered in scenario 1 and 2. A CHP system with the reciprocating engine is considered only at wastewater treatment plants where a reciprocating engine is installed.

- ***Scenario 4: On-site microturbine combined heat and power/Combined Cycle***

  This scenario models the use of available biogas to fuel either a microturbine or a combined cycle on-site at landfills and wastewater treatment plants. The combined cycle would be installed where enough biogas is produced to support a 3 MW combined cycle system. Such a combined cycle system will have an electrical efficiency of 50 percent. For locations where a combined cycle cannot be supported, a 130 kW microturbine with an efficiency of 29 percent is considered instead. For wastewater treatment locations a CHP system coupled with a microturbine at a heat-recovery efficiency of 26 percent is considered only at wastewater treatment plants.[55]

- ***Scenario 5: On-site fuel cell combined heat and power system***

  This scenario models the use of a fuel cell on-site at landfills and wastewater treatment plants to generate power. Solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) types allow biogas to be used as the primary fuel due to their fuel flexibility and operating temperatures. The high operating temperatures allow the exhaust heat to be used for fuel reforming and operations. This scenario looks at the application of a 1.4 MW fuel cell performing at a 44 percent electrical efficiency. As in the previous scenarios, the fuel cell is coupled with a CHP system at a heat-recovery efficiency of 24 percent when the location is a wastewater treatment plant, while at landfills only the fuel cell is installed.[55]

- ***Scenario 6: On-site fuel cell combined heat and power system/Combined Cycle***

This scenario models using the available biogas to fuel either a fuel cell or a combined cycle on-site at landfills and wastewater treatment plants. The combined cycle will be installed at locations generating enough biogas to support a 3 MW combined cycle system with an electrical efficiency of 50 percent. For locations where not enough biogas is produced to support the combined cycle a 1.4 MW fuel cell with an electrical efficiency of 44 percent is considered. A CHP system coupled with a fuel cell is installed at wastewater treatment plants.[55]

- ***Scenario 7: On-site fuel cell tri-generation system***

This scenario models using the biogas to generate power and transportation fuel. The installation is only considered when there is sufficient biogas available to support the capacity of the 1.4 MW fuel cell. For landfill locations the fuel cell generates power at an electrical efficiency of 44 percent and hydrogen fuel on-site at a generation efficiency of 20 percent. At a wastewater treatment plant location, a fuel cell generates power, heat, and hydrogen fuel. The electricity, heat recovery, and hydrogen generation efficiencies are 41, 24, and 20 percent, respectively. Each efficiency is defined as the energy product (e.g., power, heat, and hydrogen fuel) divided by the total input of the fuel. [55]

- ***Scenario 8: On-site Compressed Natural Gas (CNG) production***

This scenario models using the biogas from landfills and wastewater treatment plants to produce compressed natural gas (CNG) on-site. The biogas is cleaned and upgraded to CNG at the landfill or wastewater treatment plant. Analysis takes into consideration the losses related to the upgrading and compression process while producing CNG at a smaller scale. The compression on-site is assumed to have an 80 percent efficiency while at the same time considering an energy penalty of 5.25 percent for on-site CNG production.

- ***Scenario 9: Pipeline injection of biomethane***

  This scenario models using the biogas from landfills and wastewater treatment plants and upgrading it to pipeline standards for use mostly in residential areas. The scenario analysis takes into consideration the transportation and upgrading losses of producing renewable natural gas.

- ***Scenario 10: Pipeline injection for central CNG production***

  This scenario models using the biogas from landfills and wastewater treatment plants to produce CNG at centralized plants. The scenario consists of cleaning and upgrading the biogas to pipeline quality and injecting it to the California natural gas pipeline to have an end-use of producing CNG at centralized plants. Before injecting the renewable natural gas into the pipeline, the biogas is cleaned and upgraded to meet pipeline quality standards. The analysis considers the losses of methane from the production and transportation of the renewable natural gas to the centralized plants as well as the higher efficiency of CNG production at centralized plants. The production of CNG is assumed to have an 80 percent efficiency while at the same time considering an energy penalty of 5.25 percent for the compression and clean-up of biomethane and a 1.5 percent loss due to distribution losses.

- ***Scenario 11: Pipeline injection for combined cycle electricity generation***

  This scenario models using the biogas from landfills and wastewater treatment to produce electricity at a central plant. The scenario considers cleaning and upgrading the biogas to meet pipeline standards and injecting the renewable natural gas to the natural gas pipeline. The end-use of the injected renewable natural gas is producing electricity at a centralized natural gas power plant. The analysis factors the losses related to the upgrading and the transportation of the renewable natural gas to the natural gas pipeline. The production of bopmethane for pipeline injection is assumed to have an 80 percent efficiency while at the same time considering an energy penalty of 5.25 percent for the compression and clean-up of the biomethane CNG and a 1.5 percent loss due to distribution losses. The electricity production from a natural gas plant performs more efficiently than if it were produced at a smaller scale.

- ***Scenario 12: On-site hydrogen production using steam methane reformation***

  This scenario models using the biogas from landfills and wastewater treatment plants to produce hydrogen fuel on-site for vehicles. The hydrogen is produced through steam methane reformation. The process includes the cleaning and processing of the methane to produce hydrogen fuel. The scenario assumes the hydrogen production occurs at the landfills and wastewater treatment locations. The hydrogen produced would support a fueling station for hydrogen fuel cell vehicles.

- ***Scenario 13: On-site microturbine***

  This scenario models using the biogas from landfills and wastewater treatment plants to generate power through a microturbine. A 130 kW microturbine with an electrical efficiency of 29 percent generates power at landfills. A CHP system with a heat recovery efficiency of 26 percent is installed with a microturbine at wastewater treatment plant locations. The microturbine installation is considered only when there is enough biogas to support a 130 kW microturbine.

As noted from the scenario descriptions above, any heat exhaust from the power generation is not being captured at landfills. Landfills typically do not have a use for process heat and exhaust heat from the technology installed is, as a result, vented to the atmosphere rather than collected and used in another process. Some projects exist where heat produced at landfills from power generation supply heat to adjoining locations. However, all the scenarios studied assume heat to be a by-product for landfill locations. In the case of WWTP, the heat produced can be used within the plant; therefore, heat generation is considered in the WWTP analyses.

Each utilization scenario looks at the methane amount recovered from the biogas as the starting point. The amount of power, heat, and transportation fuel produced is based upon the annual methane available from the landfills and wastewater treatment plants. Related efficiency factors, conversion losses, and leakages are included in the analysis to determine the amount of power, heat and transportation fuel generated. The pathway scenarios are designed to provide insights into the biopower capacity available from biogas produced in landfills and WWTP. Table 7 summarizes the results of the power, heat and transportation fuel generation results for each scenario.

Table 7: Summary of Power, Heat, and Transportation Fuel Generation from Biogas.

Scenario	Landfills			Wastewater Treatment Plants			
	Additional MW capacity	CNG (Mg)	H2 (Mg)	Additional MW capacity	Heat (MW) capacity	CNG (Mg)	H2 (Mg)
1	815			69			
2	590			69	76		
3	883			101	27		
4	917			132	45		
5	621			85	46		
6	875			104	16		
7	687		*105024*	78	34		*16348*
8		*932300*				*189685*	
9	923			184			
10		*918317*				*186839*	
11	923			171			
12			*606428*				*85253*
13	575			90	44		

Scenarios 9 and 11, which consider the production of RNG, produce the greatest amount of power. Each of these two scenarios generate over 1,000 MW of power. These two scenarios consider the available biogas from the sites to be processed and conditioned to meet natural gas pipeline standards. The conditioned gas is assumed to be injected into the natural gas pipeline and to be used in a mixture with conventional natural gas in power plants. Since efficiencies are greater in large power plants compared to distributed generation sites there is a higher power generation.

Comparing scenarios where power is generated on-site, Scenario 4 produces the greatest amount of power. In this scenario a total of 1049 MW of power are produced; landfill locations generate 917 MW and WWTP location generate 132 MW of power and 45 MW of heat capacity. This scenario considers the available biogas for the installation of either a combine cycle or microturbine. Combined cycle systems are installed in sites where 3 MW combined cycle systems can be supported by the available biogas and lower producing biogas locations microturbines are installed.

As for the production of transportation fuel, producing compressed natural gas (CNG) on-site rather than producing at a central plant is found to be more efficient. When producing CNG on-site 932,300 Mg of CNG are produced; whereas, when transporting the biogas to a centralized location the total CNG produced in 918,317 Mg of CNG. The decrease in losses when generating on-site allows for a greater yield in distributed CNG. Additionally, utilizing the biogas to produce CNG rather hydrogen fuel generates more transportation fuel on a per mas basis. However, the emissions from CNG fuel production and vehicle utilization has greater impacts then if hydrogen fuel where produced utilized in vehicles. CNG vehicles generate tailpipe emissions where hydrogen fuel cell vehicles have none. However, there are emissions related to the production of hydrogen through steam methane reformation that need to be considered.

4.4 Summary

Biogas produced from landfills and WWTP can be utilized to generate power or transportation fuel. The high methane content of biogas allows for it to be able to produce power from technologies such as reciprocating engines, fuel cells, microturbines, gas turbines, and combined cycles. The composition of biogas also allows for transportation fuel to be produced such as CNG, LNG, and hydrogen. The scenario pathways considered identified both the potential power generation and transportation fuel production using landfills and WWTP. When considering on-site power generation, the installation of either a combined cycle plant or a microturbine generated the most amount of power. However, due to the higher efficiencies in larger power plants, injecting RNG into the natural gas system generated over 85 MW more power than in distributed generation cases.

When considering the transportation fuel production pathways, the production of CNG results in a higher yield (1.6x) when compared to the production of hydrogen since the production of CNG is more efficient than hydrogen (due to lower losses associated with the production of CNG from a biogas resource). However, the FCEV is more efficient (exceeding 2x) in converting H2 into propulsive power than CNG vehicles with the concomitant attribute of zero emissions during operation.. Transportation fuel production and power generation pathways need to also consider GHG and criteria pollutant emissions, and related health effects associated with each path as well as the economic feasibility.

5. Biogas Power Generation and Transportation Fuel Production Cost

5.1 Biopower Economic Module Methodology

The Biopower Economic Module calculates the levelized cost of energy ("LCOE") for each WWTP and LFG facility in California for each of the utilization scenarios shown in Table 6. The module is an extension of the Holistic Grid Resource Integration and Deployment (HiGRID) tool which accounts for the increase in biopower in California.[56] The module takes into account the cost of equipment, applicable current incentives, depreciation of the technology, any applicable taxes from the use of technology for each scenario and gives the average LCOE for each site. The LCOE calculated presents the cost for the production of electricity per energy generated or the fuel produced. However, the model does not account for the different methane content generated at each landfill or WWTP location or additional unique equipment needed for further processing the biomethane. The starting point for each LCOE calculation is the annual amount of available biomethane remaining at each facility after existing equipment at that facility has been fully utilized. For each facility and utilization scenario, the heat rate of the primary equipment determines the amount of megawatts (MW) of capacity the equipment could support based upon the available biomethane. The total MW of supportable capacity determines the number of full-load units of the primary equipment and the fractional capacity supported by one marginal unit. The LCOE of a full-load unit is calculated based on the default cost and operating values for the primary equipment. These default values used to calculate the LCOE of a full-load unit are contained in a main matrix, the "G Matrix", of the module and may be changed by the user either directly within the matrix or by over-writing them within the Biopower Module code.

Appendix B shows the default values within the main matrix for each piece of equipment included in the HiGRID Biopower Module.

The fractional capacity supportable by the one marginal unit establishes the capacity factor of the marginal unit used to calculate the LCOE for the marginal unit. If the fractional capacity is less than the threshold percent as specified by the user, no marginal unit is installed. The default threshold percent is 50 percent, but this can be changed within the Biopower Module code. If a facility's available biomethane is not enough to support even one piece of equipment at a 50 percent load factor, no equipment will be installed at that facility for the utilization scenario. In the case when considering that all of the biomethane is used at each WWTP and LFG facility, co-firing of natural gas needs to be considered. Within the model an on-off toggle is available to enable co-firing with natural gas. Natural gas makes up the balance of the fuel required to make the capacity factor of the marginal unit equal to the default capacity factor of a full-load unit. The module includes heat recovery units for WWTPs for combined heat and power configurations while LFG facilities do not. In order to calculate the weighted average LCOE for each scenario, the number of full-load units is multiplied by the LCOE of each full-load unit and added to the LCOE of the marginal unit. Afterwards, the resultant total LCOE "cost" is divided by the lifetime production of all units and all equipment.

Biogas Cleanup Costs

The default variable operating and maintenance (VOM) costs in the main matrix for each piece of equipment increases to reflect different levels of biogas cleanup required for each piece of equipment. The Biopower Module includes two levels of biogas cleanup. The first level cleans the biogas for use in engines, and the second level is for upgrading the biogas to pipeline quality for use in CNG, LNG, and SMR production and for pipeline injection. The costs associated with the two levels of biogas cleanup are as follows:

- The cost of biogas cleanup for use in engines is specified by the user. The biogas cleanup costs are set at $1.764/MMBtu (HHV) for WWTPs and at $1.56/MMBtu (HHV) for LFG facilities in the current analyses.

- The cost of upgrading biogas to pipeline quality is based upon a multiple of the cost of biogas cleanup. The multiplier is set at 1.33 for WWTPs and at 1.25 for LFG facilities.

- The cost of biogas cleanup for use in fuel cells is assumed to be 1.33 times greater than the cost of biogas cleanup for use in engines. This multiplier is specified by the user and reflects the fact that the electrochemical process used by the molten carbonate fuel cell or the solid oxide fuel cell is more sensitive to contaminants than a combustion engine.

Selective Catalytic Reduction Costs

To meet California air quality regulations, it is often necessary to add selective catalytic reduction (SCR) equipment to combustion engines. The Biopower Module adds $75/kW in capacity costs and $3.80/MWh in VOM costs for reciprocating engines, microturbines, gas turbines, and combined cycle equipment to reflect the costs of the required SCR equipment and its impact on operating costs.

Calculation of Utilization Scenario LCOE Values

All LCOE calculations are performed using a discounted cash flow model that calculates the LCOE based on a lifetime analysis of the portfolio of equipment associated with each biogas supply chain or utilization scenario. The default cost, financial, and operating parameters associated with each piece of equipment in the portfolio include energy penalties and losses associated with operating each piece of equipment.

The LCOE for each full-load unit of equipment is calculated using the cost, financial, and operating parameters associated with that piece of equipment. These LCOE values are common to all utilization scenarios that include full-load units of that equipment. The LCOE for each marginal unit of that same equipment is calculated based on parameters specific to each facility and each utilization scenario. Standard conversion factors are used to convert all units to equivalent megawatts ("MW") and megawatt-hours ("MWh") prior to the LCOE calculations being performed.

There is no analysis of the upstream costs associated with the production of the available biomethane at each facility since the biogas would already be required to be collected and processed (e.g., flared). Figure 6 illustrates how the characteristics for the full-load units and the marginal unit of each piece of equipment included in each utilization scenario flow through the model to calculate the weighted average LCOE for each utilization scenario.

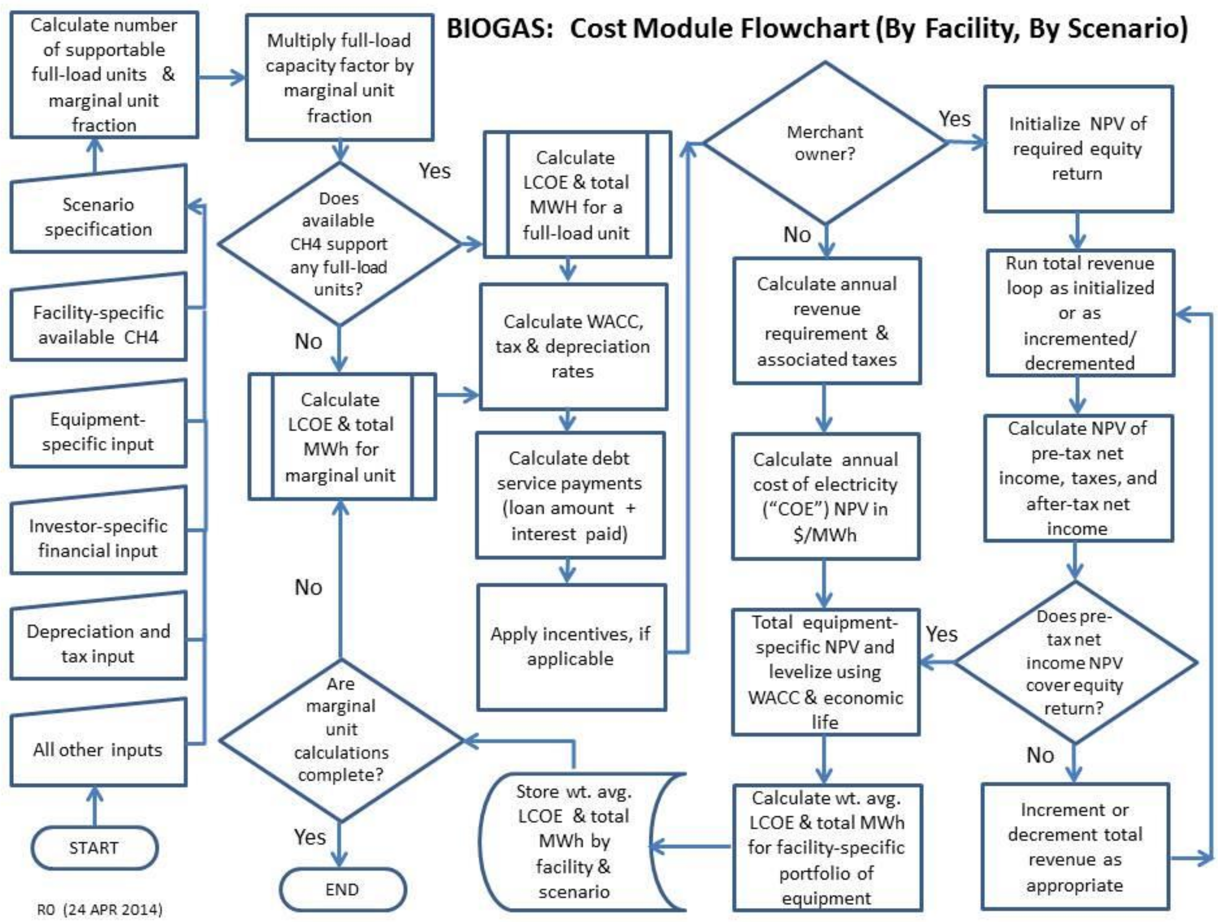


Figure 6: Economic model flowchart for the scenarios considered.[57]

Output of Results

The Biopower Module output consists of a series of matrices that contain facility-by-facility results for each utilization scenario. This output can be used to inform other parts of the biogas project (e.g., air quality modeling) by identifying the incremental LCOE cost associated with choosing one utilization scenario over another for any given WWTP or LFG facility. Additionally, the LCOE associated with each scenario looks at the average LCOE.

The Biopower Module produces the following results for each facility for each utilization scenario:

- Identification of the primary equipment
- Number of full-load units
- Lifetime units of fuel used by each full-load unit
- Lifetime units of production of each full-load unit
- LCOE of each full-load unit
- Capacity factor of the marginal unit
- Lifetime units of fuel used by the marginal unit
- Lifetime units of production of the marginal unit
- LCOE of the marginal unit
- Total lifetime units of production for all units
- Total lifetime MMBtu of fuel used by all units
- Weighted average LCOE for all units (i.e., full-load units plus the marginal unit). The weighted average LCOEs are reported (in $/MWh) for each facility and each utilization scenario
- Total capital expenditure required for all units installed in millions

5.2 Economic Results for Pathways Considered

The economic model was run for all of the utilization scenarios using both anaerobic digester gas from WWTP and landfill gas. The model simulated the economics at each landfill or WWTP in the state and the cost related to the installation of new equipment at each site. An example of the full results for each WWTP is shown in Figure 7 for Scenario 1. In general, the LCOE increases as the potential biogas availability decreases. This is the result of a decrease in the capacity factor of the marginal unit, which can also be observed in Figure 7. The left panel shows the total WWTP facilities, which are a total of 304, with their respective LCOE. The facilities are numbered so that facility 1 has the largest amount of available biogas and facility 304 has the smallest or amount of available biogas. Therefore, for facilities which do not have sufficient biogas to support the technology, no LCOE appears since LCOE is not considered in the analysis. In Figure 7, the data correspond to the facilities numbered 30 or higher. The right panel shows a zoomed in version of the left panel which focuses on the locations where enough biogas is available to support a 3 MW combined cycle. The right panel displays that as the amount of full load units installed increases the LCOE for the facility decreases.

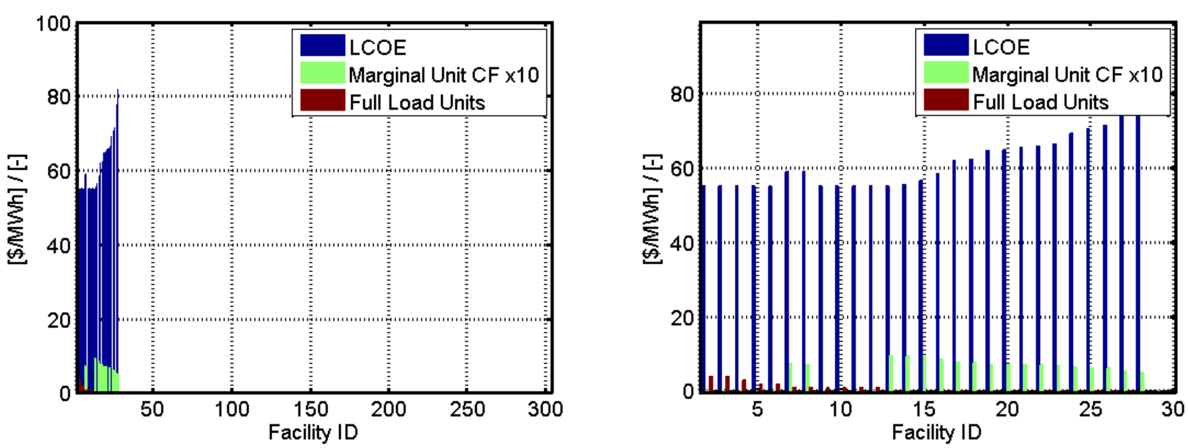


Figure 7: Utilization Scenario 1 – 3 MW Combined Cycle WWTPs.

Figure 8 shows the overall LCOE for all the power generation utilization scenarios for the WWTP and landfills when considering different aspects related to the costs and the mixture of biogas co-firing with natural gas. For the no co-firing and no attribution of cost to the biogas scenario (Scenario 3) in which smaller WWTP install 1 MW reciprocating engines and large WWTP install 3 MW combined cycles, the 49.93 $/MWh LCOE is the lowest. This results from combining the low installed cost combined cycles that are too large for many WWTP with the reciprocating engines that allow utilization of more biogas at the smaller WWTP. It is interesting to note that including CHP or hydrogen co-production decreases the LCOE of a facility. The increase of utilization per biogas available allows for the cost reduction since more energy is utilized for the same amount of equipment as shown by comparing the 1.4 MW FC case with the 1.4MW FC Tri-generation case. Figure 9 shows the results for the pipeline injection and production of vehicle fuel scenarios at WWTP and landfills when considering different aspects related to the costs and the mixture of biogas co-firing with natural gas. In the case with no co-firing and no attributed biogas cost, the most cost-effective scenario for biogas utilization at WWTPs and landfills is to produce CNG fuel on-site.

When looking at Figure 8 and focusing on the landfill results, the case with no co-firing and no attribution of cost to the biogas results in a LCOE for Scenarios 1, 3, and 4 that are very close. The cost difference is only a couple of cents. The scenario considering the installation of reciprocating engines at landfill site have the lowest LCOE at 55 $/MWh. Scenario 3, which considers either a CC or a reciprocating engine, has the second lowest LCOE of $55.45/kWh. Scenario 4, which is similar to Scenario 3 but considers a microturbine instead of a reciprocating engine, has a LCOE of $55.89/kWh.

When considering the ability of co-firing natural gas with the biogas at landfills and WWTP, the addition of co-firing increases the cost of the system; nonetheless, the scenarios with the lowest LCOE remain the same as if there was no co-firing. This can be seen in Figure 8 and Figure 9.

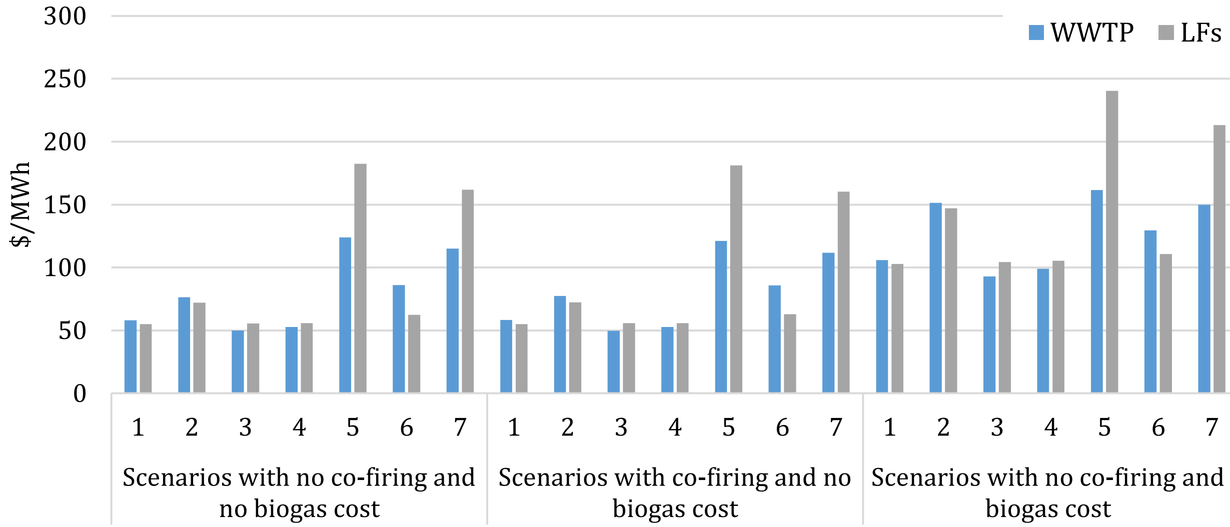


Figure 8: Economic Model results for Power Generation Utilization Scenarios at Landfills with no Co-Firing and Biogas Cost.

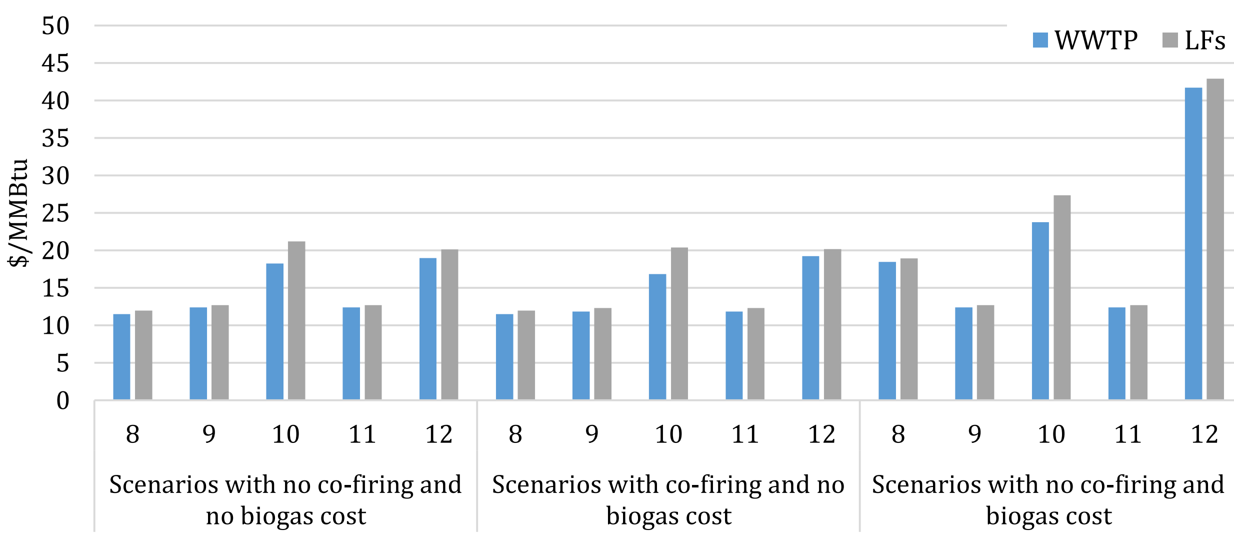


Figure 9: Economic Model Results for Pipeline Injection and Hydrogen Utilization Scenarios at WWTPs with Co-Firing and Biogas Cost.

When attributing a cost to the biogas itself, the cost for biogas in the model is considered to be the same as the cost of natural gas. Figure 8 and Figure 9 show that LCOEs are now much higher than the previous two sets of results (no co-firing, co-firing). The scenarios showing the lowest LCOE in both landfills and WWTP are those which include the installation of a combined cycle plant either by itself or in combination with another technology. As for production of transportation fuel or RNGs, both scenarios have the lowest LCOE for the production and injection into the pipeline for use as RNG.

5.3 Summary

When considering the costs related to the production of power or transportation fuel from biogas, the cost of producing fuel is considerably less expensive. Equipment costs for power generation technologies are higher than the equipment needed to produce RNG. Also, a high yield of power is not available to make the installation and maintenance costs of equipment sufficient to bring down electricity cost. The equipment needed to generate fuel or renewable natural gas costs less and yields a higher production making it more economical to install and receive a return on investment. The production of RNG as a substitute for CNG for use as transportation fuel is the most cost-effective pathway when utilizing biogas from the sources considered.

6. Emissions and Air Quality Effects of Biogas Pathways

Primary criteria pollutant emissions released into the atmosphere and the effects they cause on air quality need to be considered when planning for new power plant installations. Criteria pollutant emissions produced from power generation technology are dependent upon various factors like fuel composition, the technology used for the energy conversion, and the efficiency of the technology. The fuel considered in this analysis is biogas and it is assumed that the composition of the biogas resembles that of the conventional natural gas mix (i.e., the biogas has been processed to yield a low concentration of carbon dioxide and high concentration of methane). Emissions were calculated through the use of emissions factors established by the EPA technology characterization catalog and emission factors for air pollutants under AP-42. [55] Table 8 shows the emission factors applied to the estimated energy production based on the available gas at landfills and WWTP. These emission factors are used for the scenarios that are producing power on-site and are applied to each location to determine the emissions at locations.

Table 8: Emission Factors for Technologies Used in Scenarios.[55]

	Emissions Factors [lb/MWh]				
Technology	**PM**	**NOx**	**SOx**	**CO**	**VOC**
Reciprocating Engine	0.000263	0.070	0.002	0.200	0.100
Microturbine	0.005780	0.060	0.003	0.060	0.020
Fuel Cell	0.000020	0.010	0.000	0.020	0.020
Combined cycle	0.035000	0.083	0.013	0.102	0.049
Gas Turbine	0.078000	0.477	0.153	1.500	0.044
Direct-Fired Boiler	0.025400	0.334	0.002	0.281	0.018

For the transportation fuel cases, on-site criteria pollutant emissions to produce transportation fuels are assumed to be low and have low to no effect on air quality with the exception of hydrogen production through steam methane reformation. Emissions per kilogram of hydrogen produced on-site are shown in Table 9.

Table 9: Emissions from On-site Hydrogen Production.[58]

	PM	NO_x	SO_x	CO	VOC
Steam Methane Reformation	.022 g/kg H_2	.8979 g/kg H_2	0 g/kg H_2	.0798 g/kg H_2	0 g/kg H_2

When considering the use of biogas to produce transportation fuel, tailpipe emissions need to be considered since they will cause an effect on air quality when increasing the vehicle miles traveled of alternative fuel vehicles. Emissions in these scenarios are accounted for by considering the vehicle miles traveled by CNG or hydrogen vehicles replacing light duty gasoline vehicles. Emissions related to transportation are reduced assuming a certain percentage of the miles traveled are powered by renewable fuels. Table 10 shows the percentage of miles driven based upon the amount of alternative fuel recovered from biogas. The percentage change shows the change in miles driven from light duty gas vehicles to those powered by either hydrogen or CNG.

Table 10: Percentage of Annual Miles Driven by Alternative Fuel.

Utilization Scenario	Description	Landfills	WWTP	Total
7	Trigeneration	3.12 %	0.486 %	3.606 %
8	CNG Production	6.07 %	1.24 %	7.31 %
10	Pipeline Injection for Central CNG Production	5.98 %	1.22 %	7.2 %
12	Hydrogen by SMR	18 %	2.53 %	20.53 %

Figure 10 through Figure 14 show the emissions related to producing power on the landfills and wastewater treatment sites. From the figures it can be seen that the scenarios producing the least amount of criteria pollutant emissions are those where only fuel cells are installed to produce power. Comparing scenarios where either a combined cycle or another technology is installed to the scenarios where only that technology is installed shows that combined cycle plants produce higher emissions. However, combined cycle plants work at higher efficiencies than the rest of the technologies considered and are able to produce more power. The emissions presented in these figures are spatially resolved and inputted into the air quality model to analyze their effects throughout California.

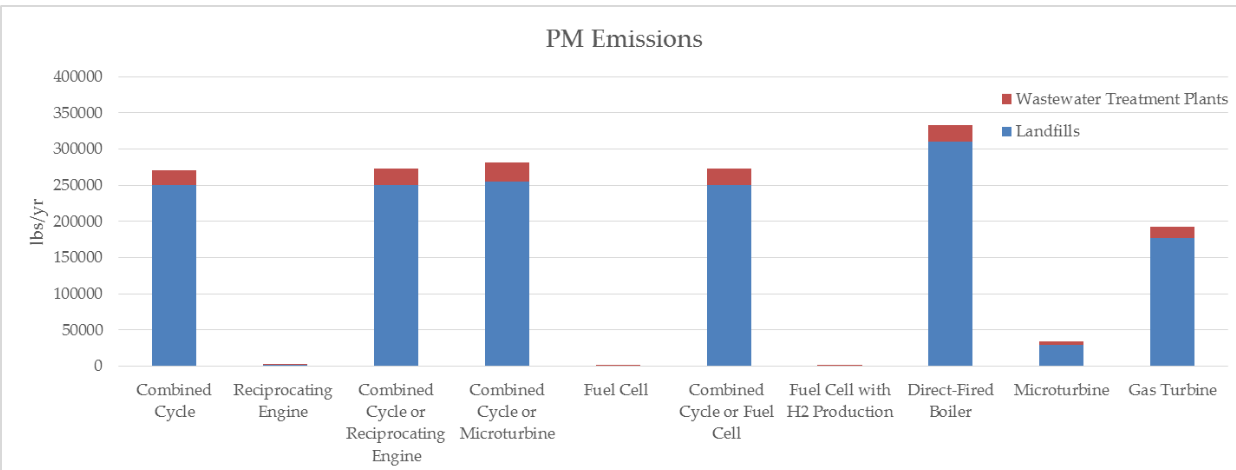


Figure 10: PM Emissions of On-site Power Production Scenarios.

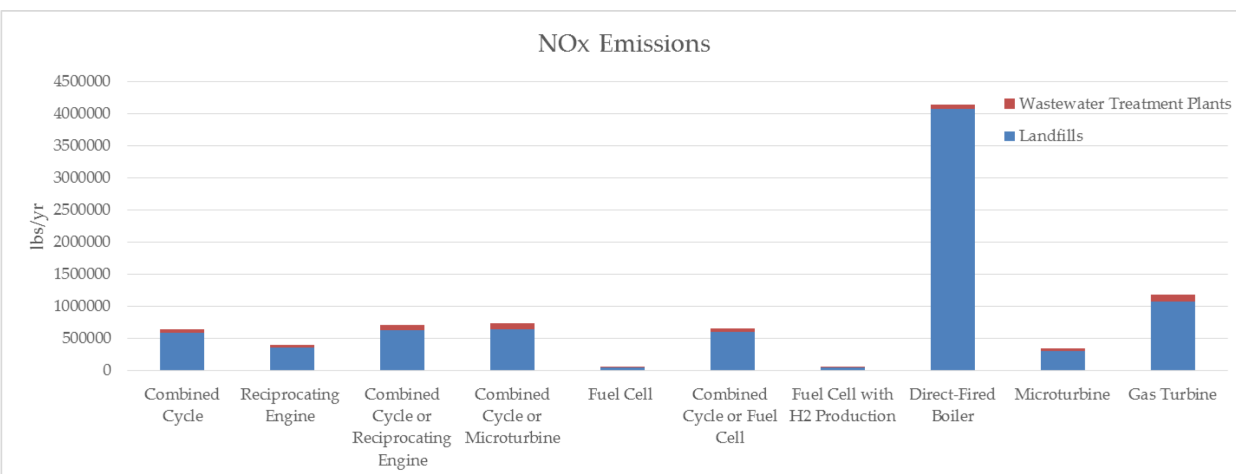


Figure 11: NO_x Emissions of On-site Power Production.

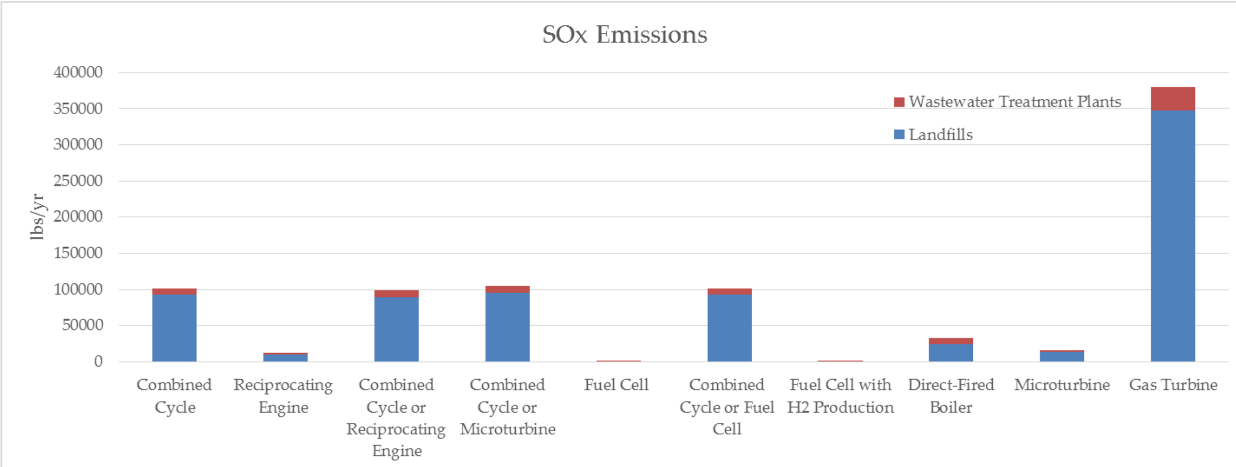


Figure 12: SO_x Emissions of On-site Power Production.

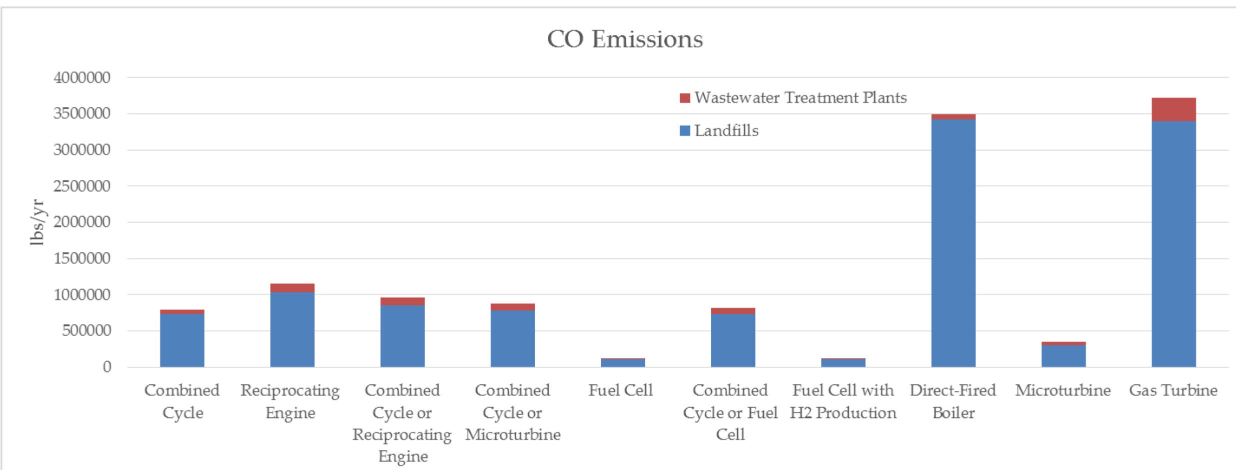


Figure 13: CO Emissions of On-site Power Production.

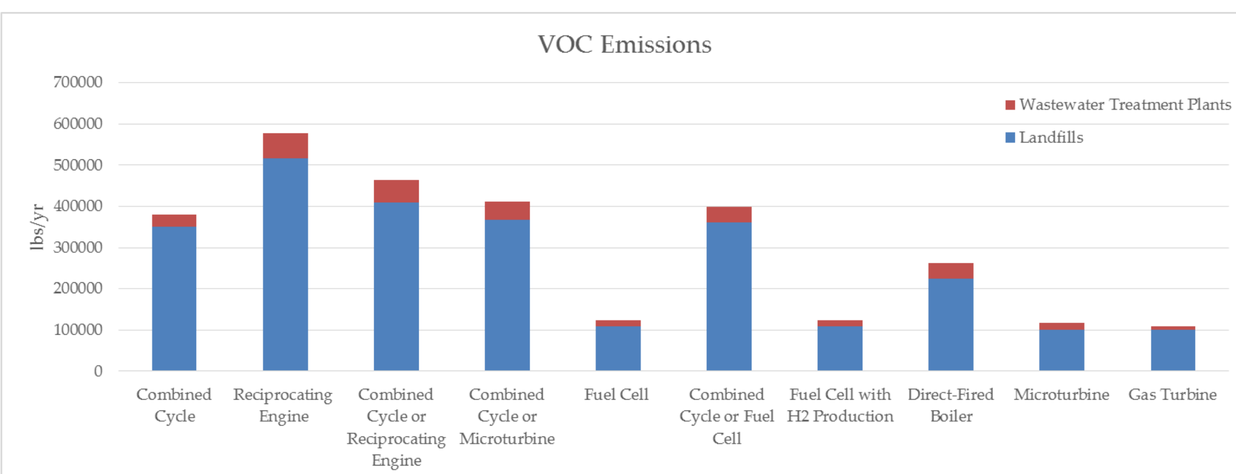


Figure 14: VOC Emissions of On-site Power Production.

6.1 Greenhouse Gases

Methane is the second most abundant greenhouse gas (GHG) in the atmosphere and persists in the atmosphere for about 20 years. While methane resides in the atmosphere for a shorter amount of time than carbon dioxide; methane traps radiation from the atmosphere more efficiently and has greater global warming potential than carbon dioxide. In order to reduce greenhouse gas emissions, landfills and WWTP endeavor to collect the methane produced and either flare it or use it for waste-to-energy projects.

Over the course of time, the CO_2 and methane from biological waste in landfills and WWTP is naturally released into the atmosphere. Harvesting methane produced from waste sites and using it to generate power or transportation fuel can offset the GHG emissions from energy fossil fueled plants or transportation fuels derived from fossil fuels. Producing CNG and LNG from anaerobic digester gas has lower well-to-wheel greenhouse gas emissions than transportation fuel derived from fossil reserves [30].

The GHG emissions related to on-site power generation consist on the combustion of the collected methane. Since neither additional collection nor transportation of the methane produced at landfills and WWTP are required, no additional GHG emission is produced from the collection of biogas. The emissions considered are those related to the production of power from the additional equipment installed at landfill and WWTP. Figure 15 and Figure 16 show the emissions of GHG in megagrams of CO_2 equivalent (Mg CO2eq) from the additional power generation at landfills and WWTP, respectively. The positive emissions shown in gold in Figure 15 and Figure 16 are related to the generated emissions on-site, while the negative emissions shown in blue are the savings from the power produced that would be displaced by the California power mix. Using the current GHG emission factor from the Emissions & Generation Resource Integrated Database (eGRID) and the amount of electricity produced per scenario gives the emission saving from the biopower produced. For California, eGRID shows that 613 lb CO2 eq/ MWh (eGRID 2015). The GHG emissions are related to the amount of power generated, so scenarios generating more power also exhibit more GHG emissions. For both landfills and WWTP, power generation from the installation of gas turbines produces the lowest amount of GHG emissions on-site.

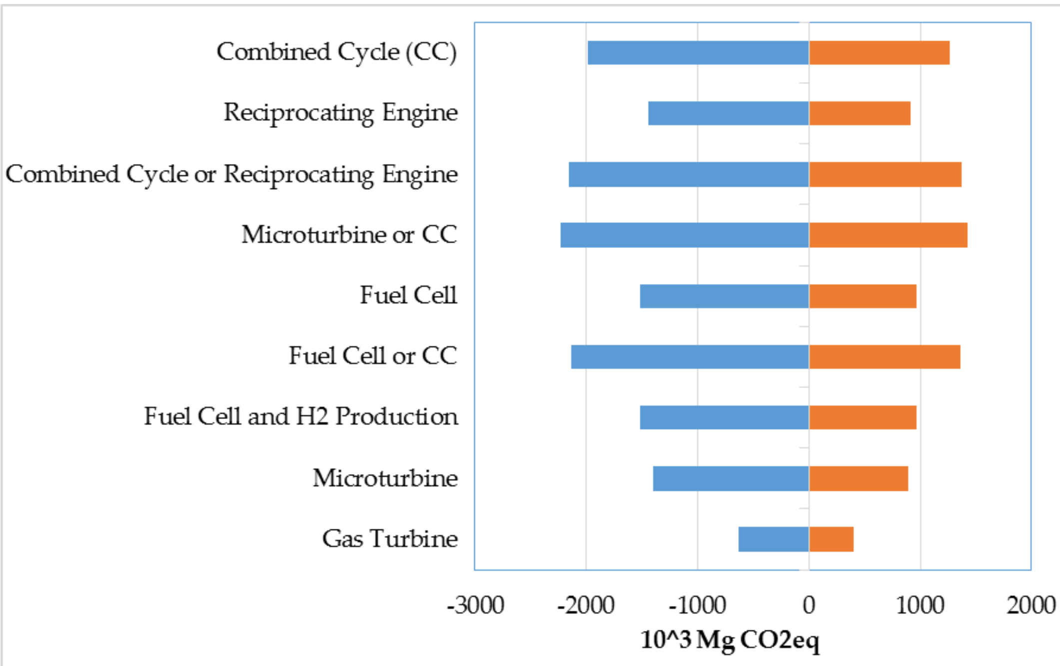


Figure 15: GHG Emissions for Additional On-site Power Generation at Landfills.

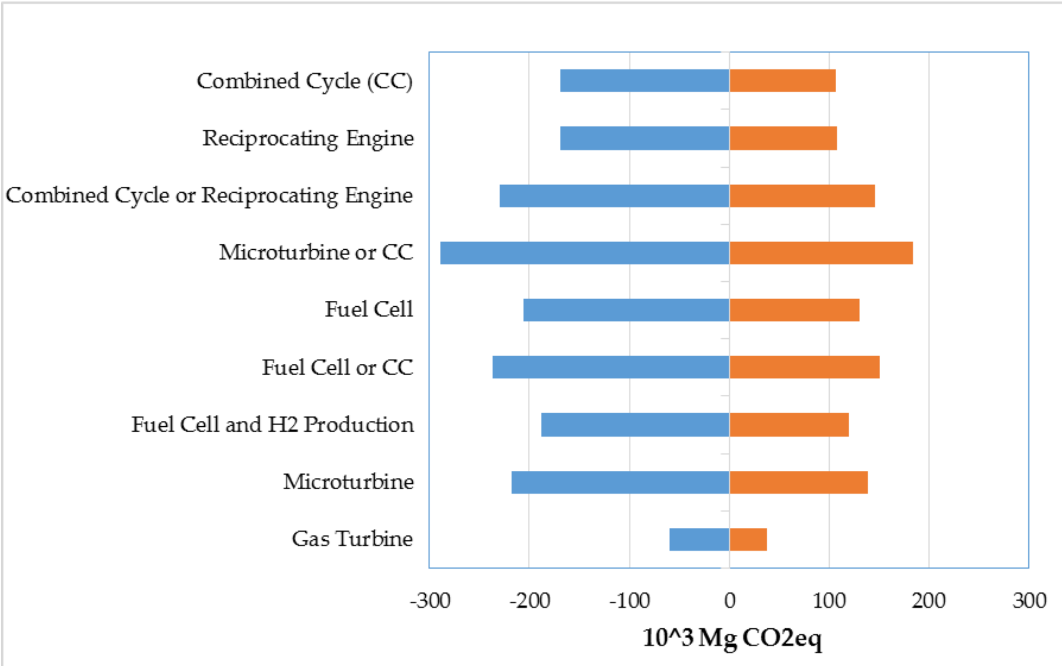


Figure 16: GHG Emissions from Additional On-site Power Generation at WWTP.

6.2 Air Quality Effects

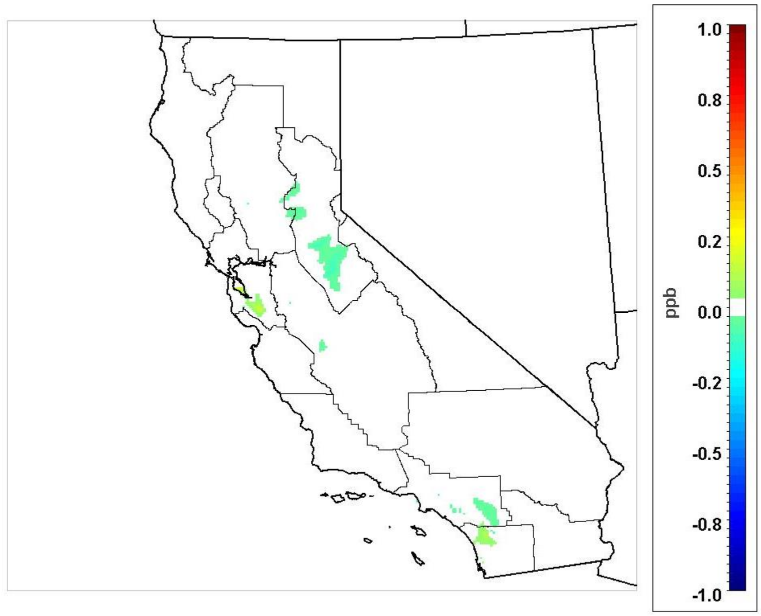
Scenario emissions from the previous section were spatially and temporally allocated using Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System and inputted into an air quality model to study the effect of increasing biopower in California. The approach is to adopt 2020 as the base case and then evaluate the change in air quality as a result of fueling the MDV and HDV populations and power generators with biogas for different scenarios. The model provides concentration changes in ozone and particulate matter with a diameter of 2.5 microns or less (PM 2.5) for each scenario. The additional power generated from biogas resources is a very small percentage in comparison to both the total power generation within California and the amount of biomass power generated. Scenarios modeled from power generation are those that would cause the greatest effect in air quality and are most likely to be implemented at landfill and WWTP locations. These scenarios include the installation of reciprocating engines, combined cycles or microturbines, and fuel cells. The transportation fuel scenarios include the production of CNG, LNG, and hydrogen for light duty vehicles. The air quality simulation results are presented in the following figures:

- Figure 17: Scenario 2 (reciprocating engines on-site)
- Figure 18: Scenario 4 (combined cycle or microturbine on-site)
- Figure 19: Scenario 6 (fuel cell or combined cycle on-site)
- Figure 20: Scenario 7 (generating power and hydrogen fuel using a fuel cell on-site)
- Figure 21: Scenario 8 (production of CNG on-site)
- Figure 22: Scenario 12 (production of hydrogen through SMR on-site)

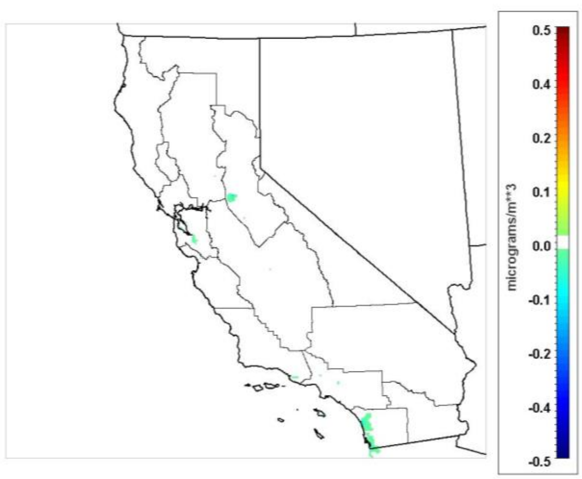
Each scenario shows the impact on peak ozone in the summer as well as the 24-hr average $PM_{2.5}$ in the summer and winter. As mentioned above, $PM_{2.5}$ impacts are more sensitive in the winter season than in summer and accordingly $PM_{2.5}$ scenarios are worse in the winter, but still at very low concentrations compared to the baseline case. For ozone, the maximum concentration changes is less than .5 ppb while for $PM_{2.5}$ the maximum concentration change is .5 $\mu g/m^3$ or less.

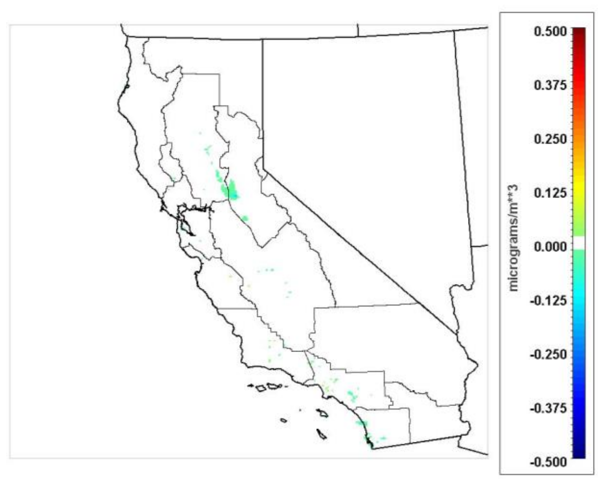
Figure 17 through Figure 22 show that the effect of using biogas to generate power and produce transportation fuel has a small impact on air quality throughout the state. In some cases, the scenario modeled shows an impact so small that it is negligible. Biogas produced at landfills and WWTP is directly related to the capacity of each location. Locations which produce a large amount of biogas already have a project utilizing the biogas. Therefore, due to the low amount of available biogas the power generation and transportation fuel production and air quality impacts are much smaller than other power generation or fuel production plants found within the state. Also, landfill and WWTP locations are distributed throughout the state so emissions from these technologies are controlled and dispersed.

The air quality results from Scenario 4, which produced the greatest amount of emissions, show an increase of about 0.2 ppb of ozone in the San Francisco Air Basin and the San Diego County Air Basin while other air basins show a small decrease. Similar responses can be seen in the air quality results from the other scenarios modeled. These areas have larger population densities than the rest of the state and generate more waste. The increase in waste allows for more biogas to be produced and consequently more emissions from power or transportation fuel generated in these areas. However, generating power and hydrogen using a fuel cell (Figure 20), ozone decreases over a large area of the basins considered with the exception of a slight increase in the San Francisco Air Basin and the San Diego County Air Basin. Power generated from fuel cell systems is the cleanest power generation technology considered in the analysis.



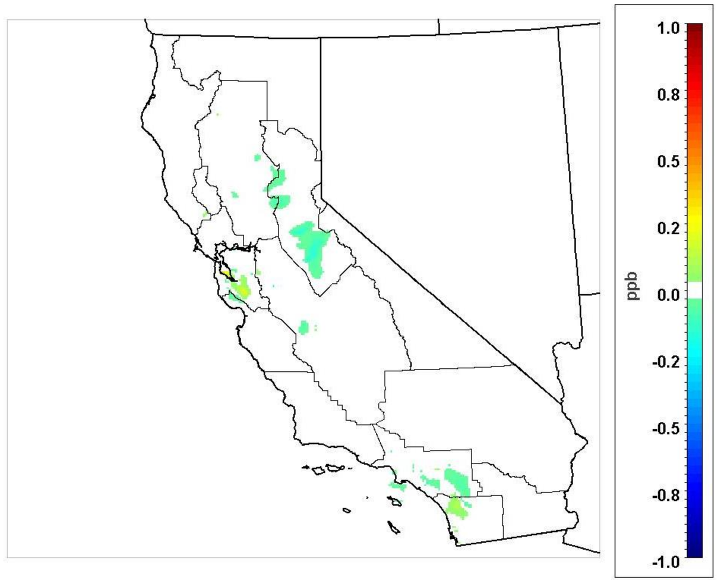
(a)



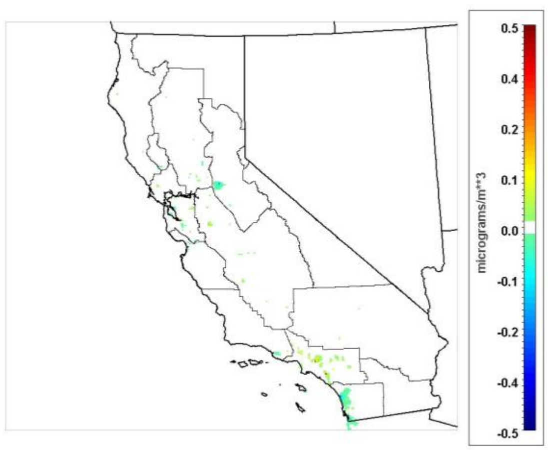


(b) (c)

Figure 17: Air Quality Impacts of Biogas Scenario 2: (a) Impact on Peak Ozone in Summer,(b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter.



(a)



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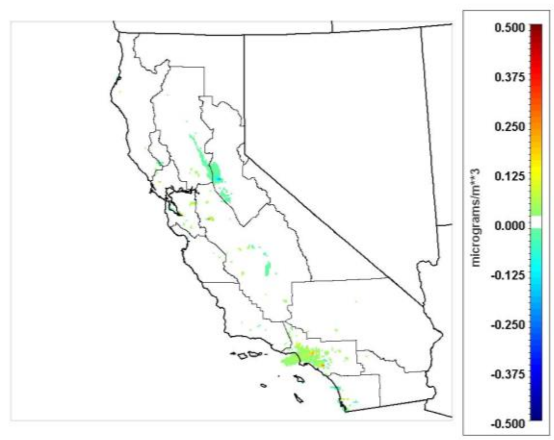
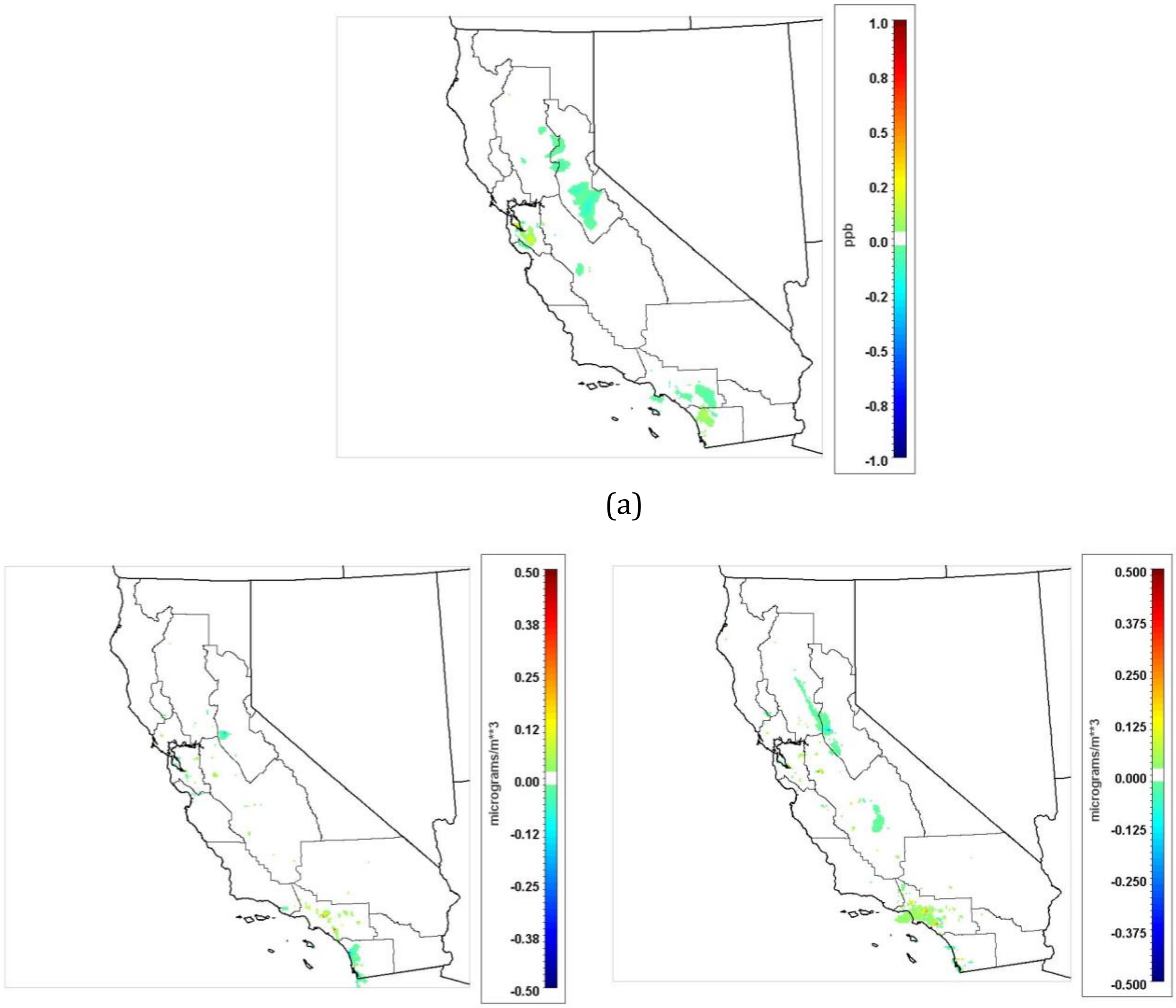


(c)

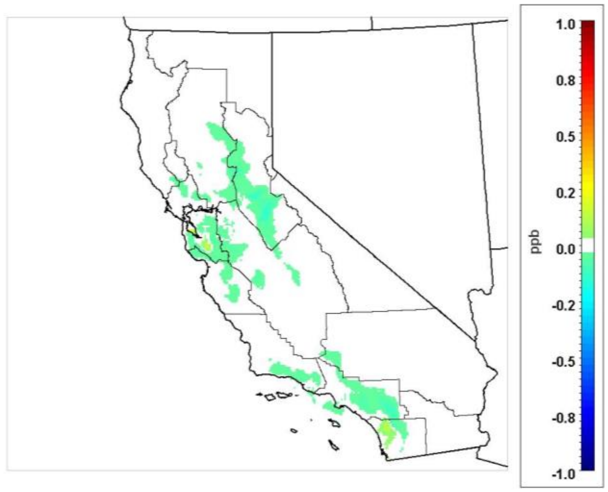
Figure 18: Air Quality Impacts of Biogas Scenario 4: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter.



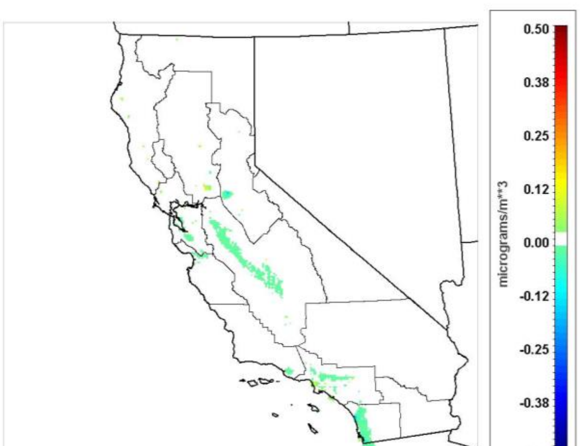
(a)

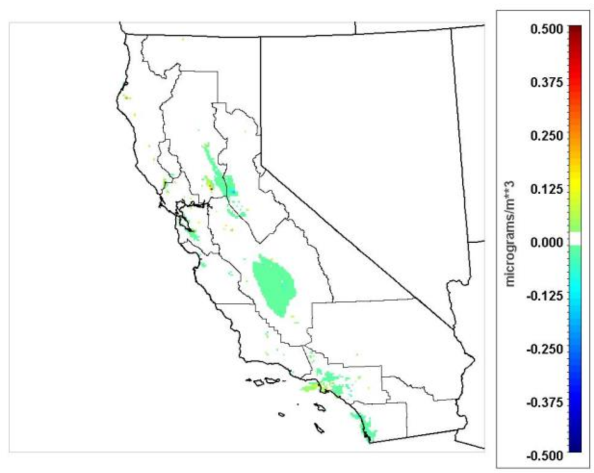
(b) (c)

Figure 19: Air Quality Impacts of Biogas Scenario 6: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the winter.



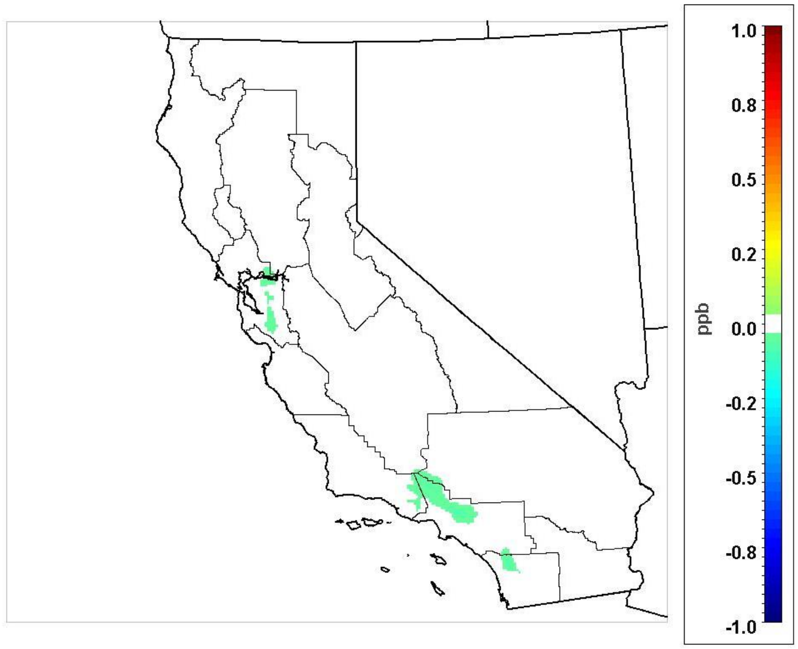
(a)



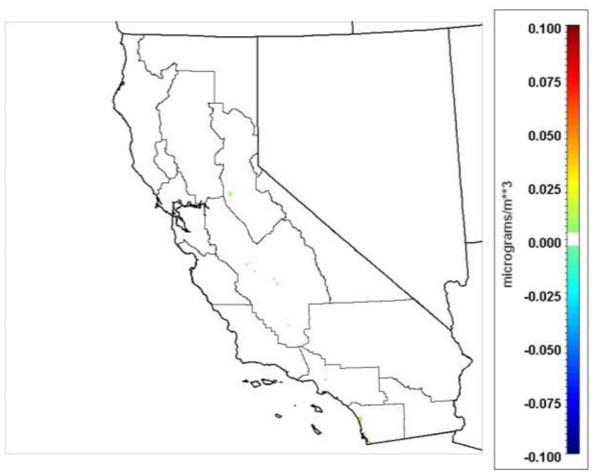


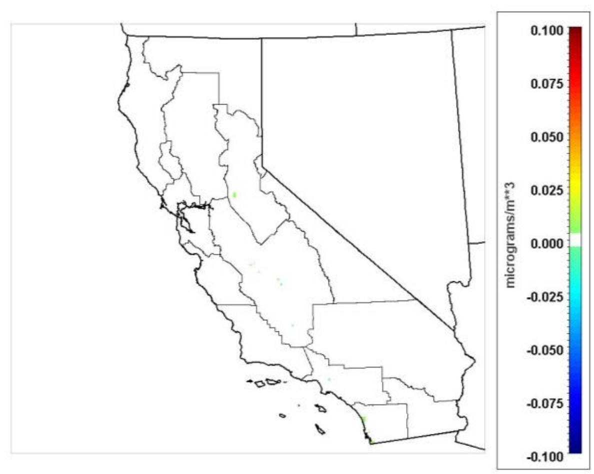
(b) (c)

Figure 20: Air Quality Impacts of Biogas Scenario 7: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter.



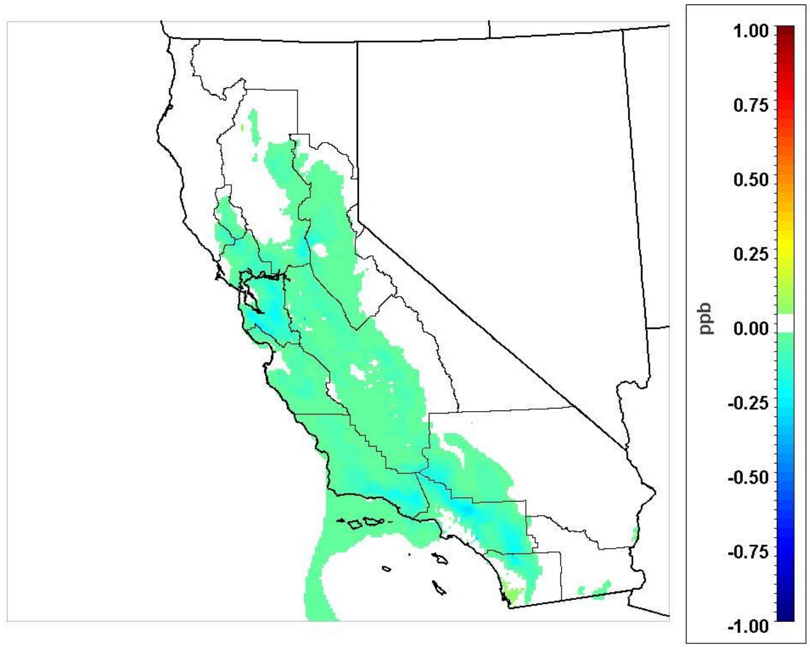
(a)



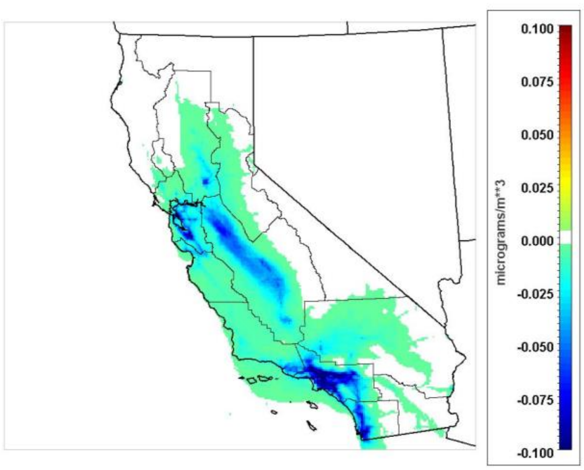


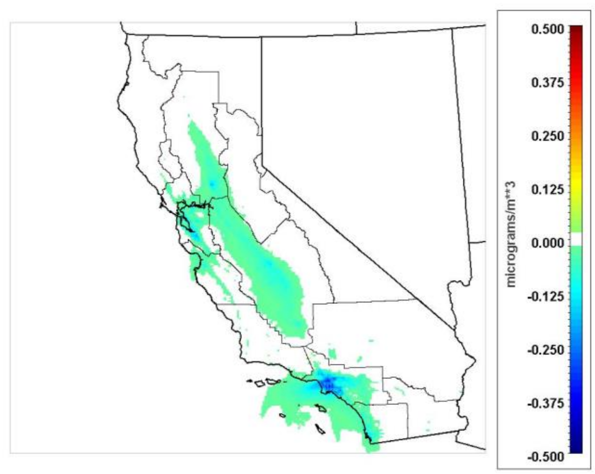
(b) (c)

Figure 21: Air Quality Impacts of Biogas Scenario 8: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) Impact on 24-hour Average PM2.5 in the Winter.



(a)





(b) **(c)**

Figure 22: Air Quality Impacts of Biogas Scenario 14: (a) Impact on Peak Ozone in Summer, (b) Impact on 24-hour Average PM2.5 in the Summer, (c) impact on 24-hour Average PM2.5 in the Winter.

Similar to the change in ozone concentration, Scenario 4 (Figure 18) shows the greatest increase in $PM_{2.5}$. Scenario 7 (Figure 20) shows the greatest overall effect on air quality when considering power generation pathways. Using a fuel cell to produce power while at the same time generating hydrogen for transportation shows a decrease in $PM_{2.5}$ over a large area in the basins and a small change of less than 0.25 micrograms per meter cubed in the basins. When using biogas to produce transportation fuel, positive impacts in the air quality result for both the production of CNG and H_2. Utilizing biogas to produce CNG, the air quality model revealed no significant change. Emissions from CNG LDV do not differ to those from gasoline LDV; hence, no significant air quality impact when changing fuel. The greatest difference in the 24-hour average difference was less than 0.025 micrograms per cubic meter throughout the scenario modeled. The greatest impact throughout the state observed was the use of biogas to produce H_2 fuel for FCEV. When substituting gasoline LDV with FCEV, tailpipe emissions are avoided and produces the overall reduction in both ozone and $PM_{2.5}$ observed in Figure 22. As a result, the use of biogas to produce hydrogen for vehicles shows a greater improvement in air quality compared to biogas for CNG production.

6.3 Summary

Overall air quality results show that using biogas for either power or transportation fuel causes only a small difference in the air quality and, in some cases, improves air quality. Additionally, air quality results show that using biogas as a transportation fuel, specifically hydrogen, is more beneficial for air quality than using biogas to produce power. When taking into consideration (1) the different pathways associated with biogas, (2) the economics, (3) the emissions and air quality effects, and (4) the potential for each pathway:

- Using biogas to produce RNG for use as a CNG vehicle fuel is the most viable option.
- Using biogas to produce hydrogen for use in either a fuel cell to generate power or in a FCEV to reduce transportation emissions reduces both GHG and improves air quality. However, the costs related to both hydrogen pathways are currently high compared to other pathways analyzed.

Overall, the use of RNG within the transportation sector can displace fossil fuels and produce a reduction in GHG emissions and general improvement in air quality for selected pathways.

7. Alternative Fuel Application of Transportation Greenhouse Gas Emissions

For California to meet its environmental and air quality goals, a reduction in emissions from medium-duty vehicles (MDV) and heavy-duty vehicles (HDV) is required. These vehicles form a small percentage of the population of on-road vehicles in California, but generate over 75 percent of NO_x emissions and 45 percent of $PM_{2.5}$ emissions. Every year technology is being developed and enhanced to achieve lower emissions while still meeting travel and goods movement demands; however, a small population of zero emission and near-zero emission vehicles are readily available for commercial use. In 2016, the introduction of a low-NO_x CNG engine became the first alternative fuel engine which can be applied to MDV and HDV categories. Cummins Westport's 8.9 liter (L) SI CNG engine has been certified by the U.S. EPA and the ARB to a 0.02 gram per brake horsepower-hour (g/bhp-hr) optional NO_X standard and is commercially available starting 2017. [26] Within the next couple of years, Cummins Westport expects to release large sized low-NO_x CNG engines which can be used in a variety of medium-duty and heavy-duty vehicle categories. Low-NO_x CNG engines can help bridge the gap between the current technology and zero emission technology used in the MDV and HDV categories.

Additionally, the use of these engines with RNG recovered from landfills and wastewater treatment plants can not only reduce criteria pollutants and improve air quality, but also reduce GHG emissions from the transportation sector. To examine the possible effects of the implementation of a low-NO_x CNG engine has in GHG and air quality, a scenario set in the year 2035 was considered wherein the all MDV and HDV are converted to operate from the current 2010 regulation to the low-NO_x CNG engine.

7.1 Development of Low-NO_x Engine Transition Scenario

The Vision Scenario Planning Model is a tool developed by the California Air Resources Board to conduct multi-pollutant assessments for the transportation sector system-wide in California. [59] Vision version 2.1 is utilized here to produce the scenario of advanced CNG deployment in California in 2035. A schematic of the model framework is provided in Figure 7. Vision accounts for vehicle sales, activity, technologies, fuels, and efficiencies to estimate energy demand and emissions (both vehicle and upstream) for various transportation outcomes. The Vision model incorporates the retirement of a fraction of vehicles, the purchase rate at which vehicles are introduced for various categories, and the emissions factors related to each category and other inputs in order to create an emission inventory for a specific calendar year. These features allow for scenario development to study the introduction of novel technologies and fuels, current and future regulations, etc., in terms of energy and emissions. Vision Model 2.1 is comprised of 6 different modules, with 5 pertaining to specific transportation sectors and a module dedicated to energy.[59] For the development of this scenario, the Heavy Duty Vehicle Module including trucks with over 8,500 pounds gross vehicle weight rating is used to develop a database of the emissions for difference scenarios introducing advanced CNG engines into the MDV and HDV population for the year 2035. The HDV module uses EMFAC 2014 data as a baseline with the option for users to modify range of parameters that effect emissions including MDV and HDV population, VMT, efficiency, and emission factors. Scenarios incorporating advanced technology introduction can then be modeled to evaluate impacts on emissions, fuel, and energy demand. The advanced technologies which are incorporated in the HDV module for trucks include gasoline, diesel, battery electric, natural gas, and hydrogen fuel cell powered vehicles.

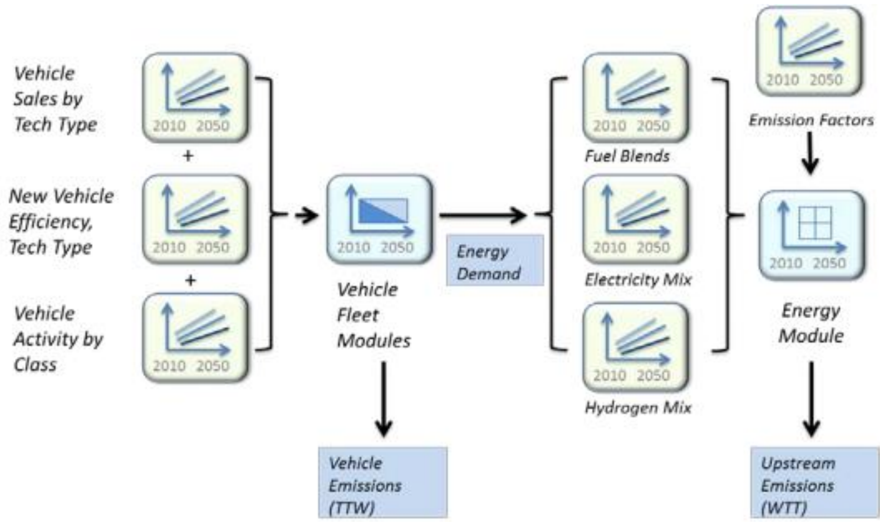


Figure 23: Framework for the Vision 2.1 Model.[59]

The scenario developed was derived from a business as usual case in which the only regulation in place for MDV and HDV is the current 2010 regulation. A description of the base case along with the scenario considered is described below:

- **Base Case:** Considers no implementation of emission reduction programs to current vehicles using a business-as-usual approach. The Base Case represents a "frozen" technology case with changes occurring only in total demand for VMT, etc. Comparison with the Base Case allows for insight into the role that advanced CNG can play in improving AQ in coming decades from current levels.
- **1A:** With the Base Case as a starting point, vehicles in all categories, both MDV and HDV, completely transition to advanced CNG engines. Case 1A provides an upper bound for the impacts of advanced CNG engines in California.

The case is meant to see the possible emissions reduction when only considering the adoption of low-NO_x CNG engines and not zero-emission technologies like hydrogen fuel cell vehicles or electric vehicles. Figure 24 shows the transition from current technology to the low-NO_x CNG engine for the scenario. From the can be seen that the earliest introduction of low-NO_x CNG engines begin in 2016 and by the year 2031 all vehicles in MDV and HDV categories have transitioned to the new engine.

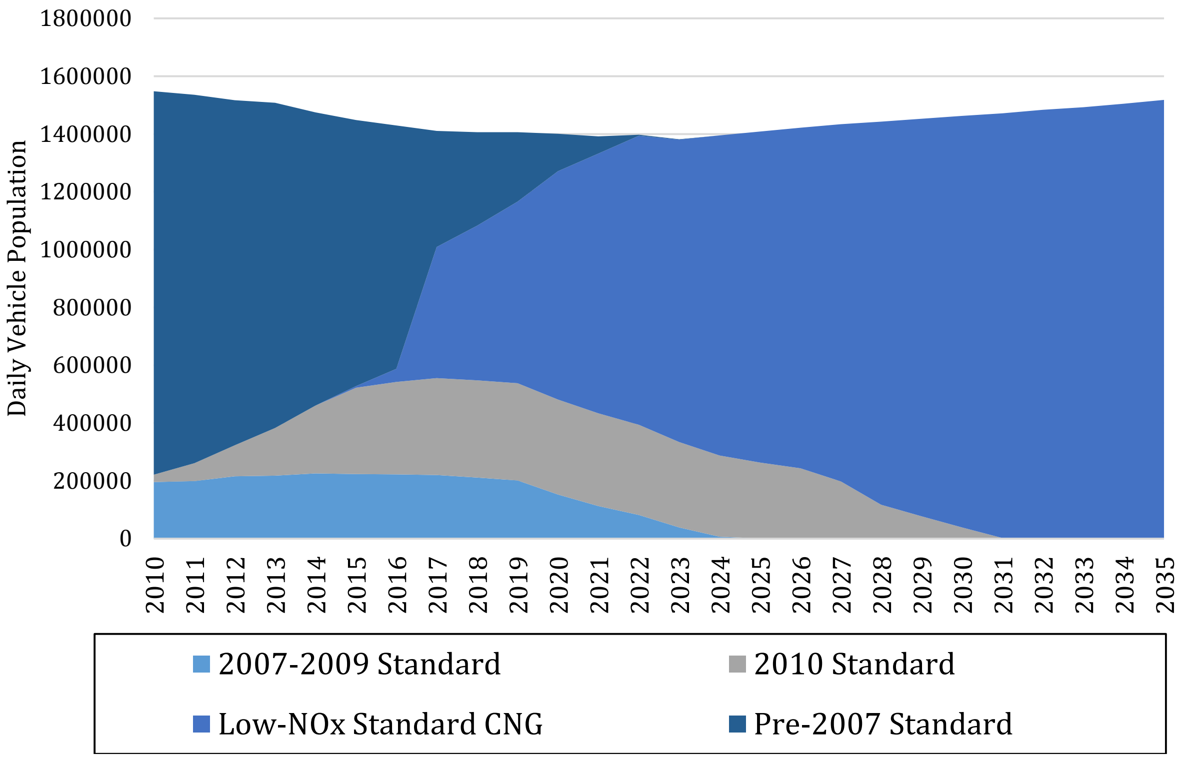


Figure 24: Daily vehicle population transition of MDV and HDV from the year 2010 to 2035.

California developed the State Implementation Plan (SIP) which lays out specific goals within each sector in order to meet its environmental goals. Creating a case which includes the controls and regulations specified in the SIP will allow to the additional reduction which can be achieved through the implementation of a low-NO_x engine in MDVs and HDVs. The goals included in the SIP that affect the heavy-duty sector and reflect the case included in the Vision HDV Module are listed below:

- **GHG Phase 2 Regulation:** Reductions in CO_2 and fuel consumption phase in from 2018 to 2027 with 5 to 25 percent efficiency improvements depending on vocation beyond currently adopted GHG Phase I and ARB's Tractor-Trailer Regulation

- **Federal Low-NO_x Engine Standards:** Combining the Low-NO_x Engine Standards and Lower In-Use Emission Performance level measures, a flat 90 percent reduction in NO_x emissions from the current 2010 standard for all exhaust processes throughout the life of the vehicle. Assumed 100% of model year 2024 and newer trucks will be impacted by the measure. The engine standard is assumed to affect both diesel and natural gas engines. The engine fuel per category is based upon technology availability, vocation and infrastructure. Long-haul trucks are dominated by low-NO_x diesel while local delivery trucks are assumed to have higher penetration of natural gas low-NOx.

- **California Only Low-NO_x Engine Standards:** Similar to Federal Low-NOx Engine Standards but impacts only new vehicles purchased in California. Includes simplified purchase fractions and derived survival rates to simulate the overall impact of California Only Low-NO_x Standard.

- **Zero Emission Vehicles for Last Mile Delivery Trucks:** Assumes local Class 3 to 7 vehicle categories in EMFAC2014 which are most like to transition to ZEV. The scenario assumes 2.5 percent of new vehicle sales starting 2020 to be battery or fuel cell technologies and increasing to 10 percent by 2025, which remaining flat thereafter.

Comparing case 1A with a business as usual and the SIP case will be able to see the greatest possible reduction from the implementation of near-zero emission vehicles. The SIP scenario includes a small amount of zero emission vehicles, but still includes the use of diesel and gasoline vehicles. Comparing the transition of all MDV and HDV from conventional engines to a low-NO_x CNG engine will possibly produce further reductions in air pollutants and GHG emissions compared to the SIP case.

7.2 Renewable Natural Gas Feedstock Mixes

Natural gas demand will increase with when considering the transition of all MDVs and HDVs to a low-NO_x CNG engine. To achieve GHG emission reductions in addition to reducing air pollutant emissions, renewable natural gas from landfills and wastewater treatment plants will play an important role. Table 11 lists the projected available renewable natural gas recovered from landfills and wastewater treatment plants in California for year 2035. Table 11 also lists the potential RNG derived from additional waste sources in California taken from a report published by Jaffe, A.M. et al. [60]. The report considers additional production of RNG within California coming from anaerobic digesters in dairy farms and through the collection and digestion of municipal solid waste (MSW). Considering these additional renewable feedstock will allow us to increase RNG available to meet the demand for the scenario and reduce the amount of conventional natural gas in the feedstock mix.

Table 11: Daily availability of RNG estimated to be available for HDV and MDV fuel.

	Biogas Inventory	Reference 2[60]
Fuel	[MJ/day]	[MJ/day]
WWTP RNG	27,140,931	5,274,147
LFG RNG	78,350,936	97,571,729
MSW AD RNG	--	21,096,590
Dairy AD RNG	--	26,370,737

To estimate the impact on GHG emissions from using RNG pathways to provide CNG for MDV and HDV fueling, fuel consumption was determined by Vision for the scenario. Using the estimated available fuel volumes per day listed in Table 11 and carbon intensity values for each fuel, upstream emissions are quantified (i.e., well-to-tank) for the fuel consumed. Combining the upstream emissions with tail pipe emissions (i.e., tank-to-wheel) of CO_2 and CH_4 reported by Vision, the total well-to-tank emissions for the transition of engine technology can be calculated.

The carbon intensity of RNG is highly dependent on the feedstock. All carbon intensities considered are listed in Table 12 and are derived from fuels which are produced by California sources and listed under the California Air Resources Board Low Carbon Fuel Standard.[61] When comparing the carbon intensities for each feedstock, the use of RNG derived from anaerobic digestion of dairy manure achieves the most significant benefit with a well-to-wheel (WTW) value of -276.2 g CO2e per MJ. Assuming the tank-to-wheel (TTW) emissions would be the same as those in Table 12, the well-to-tank (WTT) emissions are -333.54 grams of CO_2e per MJ, representing the lowest carbon intensity for the production of RNG. RNG produced from anaerobic digestion of MSW also achieves an overall negative value of -22.9 CO2e per MJ. RNG from WWTP sources results is assumed to have a value of 19.3

CO2e per MJ. Landfill RNG has the highest carbon intensity of considered RNG sources at 46.4 g CO2e per MJ, but still results in a reduction from conventional natural gas of 42%.

Table 12: Carbon intensities for currently available low carbon fuels in California. Adapted from [60], [61]**.**

	Well-to-Tank [g of CO_2e per MJ]	**Tank-to-Wheel [g of CO_2e per MJ]**	**Well-to-Wheel [g of CO_2e per MJ]**
Conventional CNG	22.2	57.3	79.5
Conventional Diesel	27.9	74.9	102.8
Landfill Gas RNG	-11.3	57.3	46.4
Anaerobic Digester Gas from WWTP RNG	-37.9	57.3	19.3
Anaerobic Digester Gas from Dairy RNG	-333.5	57.3	-276.2
Anaerobic Digester Gas from MSW* RNG	-80.2	57.3	-22.9
CA Mix Electricity	105.2	0	105.2
H_2 Produced in CA	47.7	0	47.7

*Municipal Solid Waste

For the scenarios evaluated, the TTW emissions are taken from the Vision model output in order to better capture the different vehicle categories evaluated. The TTW emission factor listed in Table 12 only accounts for a single type of heavy-duty vehicle with a fuel economy of 4.8 MJ per mile.[62] The Vision model calculates the tons per day of emissions of CO_2 and CH_4 for each scenario specific to each MDV and HDV technology type. Taking the global warming potential to be 25 for CH_4 and 1 for CO_2 for a 100-yr period, the daily greenhouse gas emissions can be calculated in tons of CO_2e. [63]

When considering the accessibility of the renewable feedstock, RNG from WWTP and landfills is more easily available than RNG from other sources and represents the bulk of currently available RNG. Contrastingly, RNG from MSW and dairies requires additional technical advancement prior to widespread utilization, e.g., the construction of digesters and established infrastructure. However, they will still be considered in the feedstock mixes due to their high potential of reducing GHG emissions. The feedstock mixes considered for meeting the natural gas demand of the scenario are listed in Table 13.

Table 13: RNG fuel feedstock mixes considered for scenarios.

Natural Gas Feedstock Mixes	Feedstock Mix Description
All Conventional	All diesel, gasoline, and natural gas fuels are derived from conventional fossil fuel feedstock
Use of LFG+ADG+Conv	Natural gas fuel demand is first met by RNG derived from LFG and ADG from WWTP, in that order. Afterwards, any other natural gas demand is met by fuels derived from conventional fossil fuel feedstock
Use of LFG+ADG+Dairy+ MSW+Conv	Natural gas fuel demand is first met by RNG derived from LFG, ADG from WWTP, ADG from Dairy, and ADG from MSW, in that order. Afterwards, any other natural gas demand is met by fuels derived from conventional fossil fuel feedstock

7.3 Greenhouse Gas Emissions

The amount of GHG emissions will be greatly affected by the carbon intensity of the fuel utilized. In the three cases considered, the fuel demand from the baseline case is led by the use of diesel. The SIP case has a mixture of different types of fuel, but a large percentage of it is still diesel. The third case considers the transition to a CNG engine so its demand includes only CNG. Table 14 shows the daily energy demand for the scenarios considered. For the baseline scenario, the total daily demand is 1,648,947,555 MJ and considers the use of diesel, gasoline, and natural gas. In this scenario, diesel account for 91.6 percent of the fuel demand where natural gas accounts for only 1.5 percent. In addition to the fuels considered in the baseline, the SIP case also hydrogen and electric vehicles implemented in MDV and

HDV categories. The total energy demand for the SIP case is 1,346,748,922 MJ. Diesel demand for this case remains high at 82.8 percent of the daily demand while natural gas demand remains low at 9.2 percent. The increase in natural gas demand can be accounted for by the transition of diesel vehicles into natural gas. Scenario 1A which includes a large transition to a low-NO_x engine has a daily demand of 1,273,063,974 MJ. Where 99.7 percent is natural gas demand and 0.3 percent is diesel. The scenario considers a small number of diesel engines due to the slow retirement rate.

Table 14: Daily demand for scenarios in megajoules (MJ).

Case	Diesel	Natural Gas	Gasoline	Electricity	H_2
Baseline	1,509,974,798	24,030,380	114,942,376	-	-
SIP	1,115,452,118	123,246,467	98,195,819	8,869,066	985,452
1A	3,245,586	1,269,818,388	-	-	-

Taking into consideration the daily demand listed in Table 14, the carbon intensities listed previously for each fuel, and TTW outputs from the VISION model we can calculate the GHG emissions for each scenario when considering the different feedstock mixes in Table 13. Figure 25 shows the metric tons of CO_2e per day WTW emissions for the scenarios and different feedstock mixes considered. The figure shows that the feedstock mixture including the dairy and MSW sources produces the least amount of emissions for each scenario. Overall in each of the scenarios considered the incorporation of any renewable fuel reduces the amount of GHG emissions. Table 15 and Table 16 show the different feedstock mixes and the percentage each renewable source meets of the natural gas demand for the scenario. When examining case 1A, the percentage contribution of the RNG to the total natural gas is less than 15 percent in either case, but the small contribution is still able to reduce GHG emissions from 141,000 mt CO2e per day to 137,000 mt CO2e per day when only considering LFG and ADG from WWTP and 126,000 mt CO2e per day when considering the other feedstock mix.

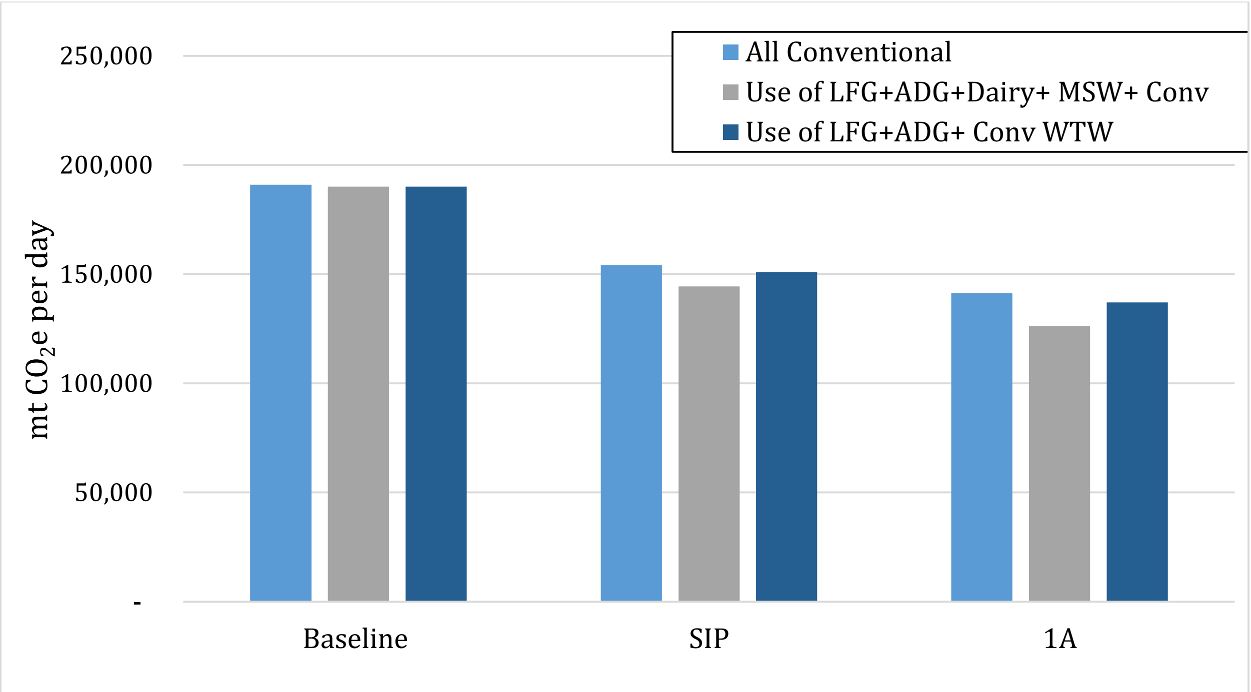


Figure 25: Well-to-wheels GHG emissions for the Baseline, SIP Case and case including the transition to low-NO_x CNG engine.

Table 15: Percentage of natural gas demand met when considering LFG, ADG from WWTP, and conventional feedstock for the production of natural gas for cases considered.

Case	Conventional	Landfill Gas	ADG from WWTP
Baseline	0 %	100 %	0 %
SIP	14 %	63 %	22%
1A	91 %	6 %	2 %

Table 16: Percentage of natural gas demand met when considering LFG, ADG from WWTP, ADG from dairy farms, ADG from MSW, and conventional feedstock for the production of natural gas for cases considered.

Cases	Conventional	LFG	ADG	Dairy	MSW
Baseline	0 %	100 %	0 %	0 %	0 %
SIP	0 %	79.17 %	4.28 %	16.55 %	0 %
1A	88.16 %	7.68 %	0.42 %	2.08 %	1.66 %

7.4 Criteria Pollutant Emissions

The main criteria pollutant reduced in the new CNG model by Cummins Wesport is NO_x.[26] The low-NO_x CNG engine provides a 90 percent reduction in NO_x compared to the current emission standard of the 2010 engine regulation. Figure 26 shows the NO_x, ROG, and $PM_{2.5}$ emissions for the cases considered. The NO_x emission from the baseline scenario totaled 157 tons per day. For the SIP case total NO_x emissions were 71 tons per day while case 1A has a total of 13 tons per day. There was a 91 percent reduction in NO_x emissions from the baseline to case 1A which correlates with the expected NO_x emission reductions. Comparing case 1A with the SIP case, an 81 percent reduction in NO_x emissions is observed. The SIP case already considers part of the vehicle population to be comprised of low-NO_x engine technology whether the fuel be diesel, natural gas, or gasoline. However, the SIP case still considers some of its population to be comprised of older regulations or non near-zero emission technology.

When considering the other criteria pollutants, a reduction in both ROG and $PM_{2.5}$ results in both the SIP case and 1A case. The reduction in these criteria pollutants in the SIP case stem from the advanced lower emitting technology and the introduction of ZEV in class 6 vehicles. The reduction in case 1A comes from the lower emissions related to the introduction of the low-NO_x engine. However, when comparing current engines to the low-NO_x CNG engine, no notable reduction occurs with these criteria pollutants. Further investigation and more data concerning the new engine performance are needed to accurately predict the reduction in ROG and $PM_{2.5}$.

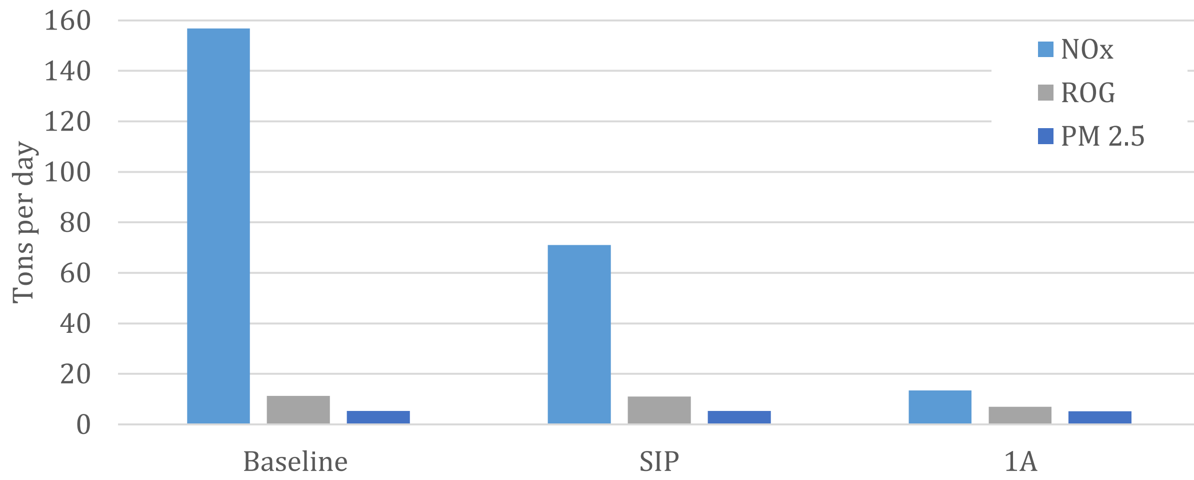


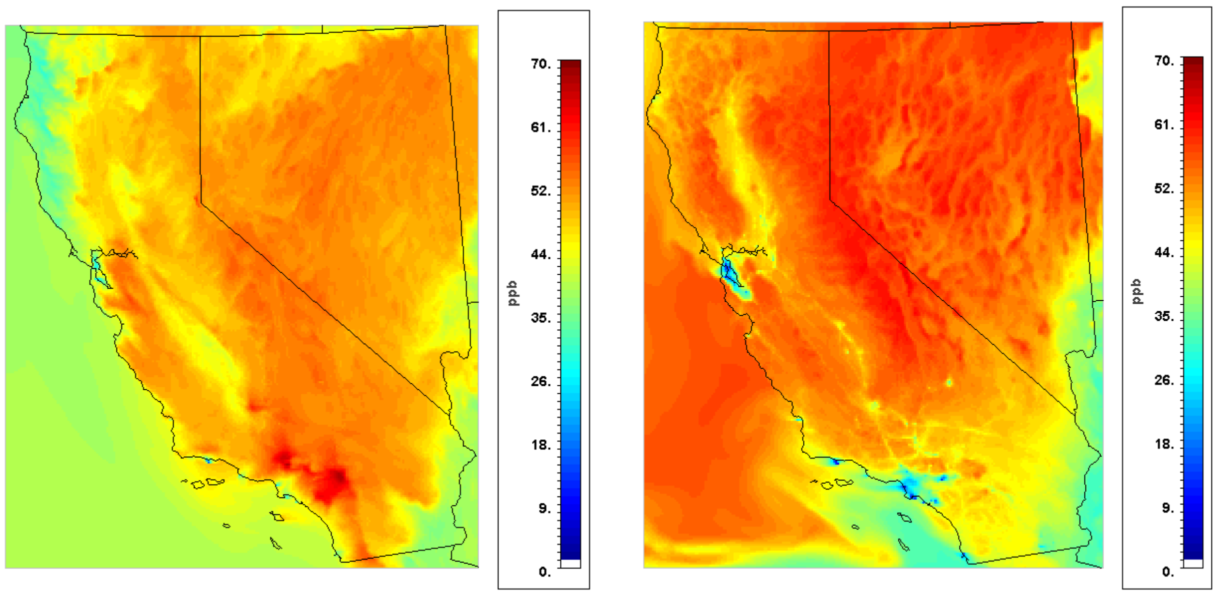
Figure 26: Total HDV and MDV emissions in 2035 for the baseline, SIP and 1A case in tons per day.

7.5 Air Quality Results

Air quality results are predicted by CMAQ and reveal the change in atmospheric pollutant concentrations from the change in emissions depicted in the baseline case, SIP case and 1A case. Differences in ground-level ozone are reported as maximum 8-hour average while the 24-hour average ground-level is used for $PM_{2.5}$. For each case, results are provided as difference plots for ozone and $PM_{2.5}$ in summer, and $PM_{2.5}$ in winter.

Baseline Case

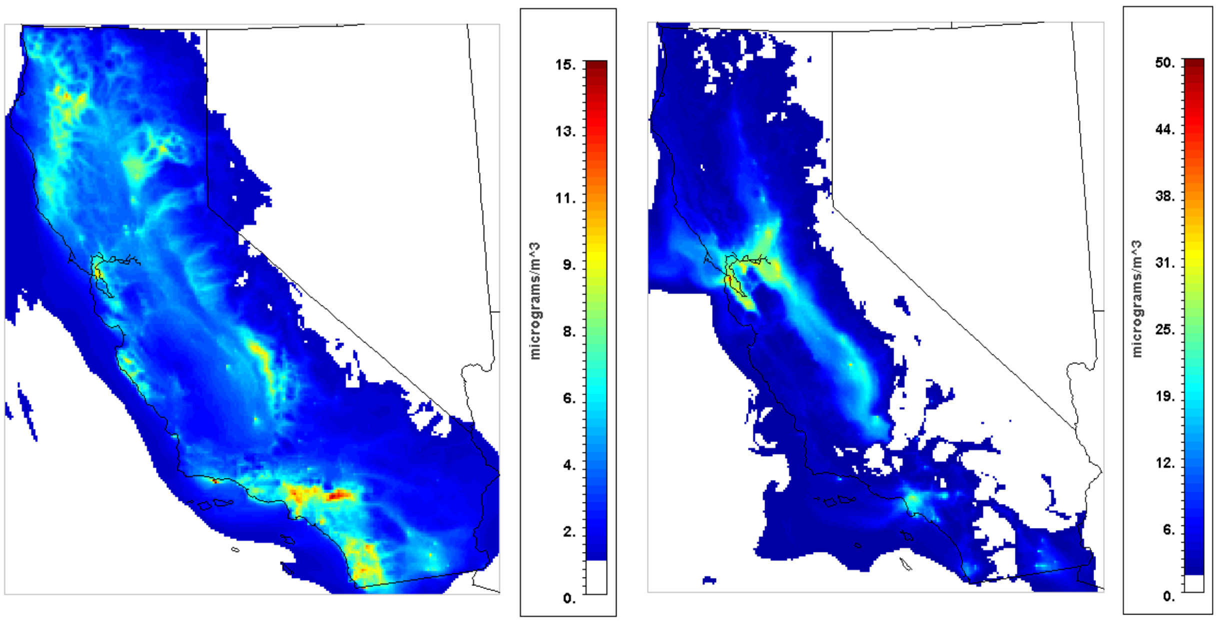
Ground-level concentrations of ozone reach 68 ppb in maximum 8-hour average (shown in Figure 27a) and 78 ppb in maximum 1-hour average in the baseline case. Peak levels of ozone occur in major urban areas including the southern California, the San Francisco Bay Area, the Central Valley, and the Greater Sacramento area. Ground-level concentrations of ozone in the Winter Baseline Case peak at 63 ppb maximum 8-hour average (shown in Figure 27b) and 63 ppb maximum 1-hour average. Ozone concentrations in winter follow a reverse trend that in summer, i.e., urban areas have the lowest concentrations while concentrations peak in rural areas.



(a) (b)

Figure 27: Ambient max 8-hr average ozone in the Base Case for (a) Summer and (b) Winter.

Figure 28 shows the predicted 24-hr average PM2.5 for the summer (Figure 28a) and winter (Figure 28b) cases in 2035. For the summer episode, concentrations reach 17.8 μg/m^3 with peak impacts located in areas of the South Coast Air Basin in southern California. Additional areas experiencing high levels include San Diego County, areas in the Central Valley, the Sacramento Valley, and the San Francisco Bay Area. Concentrations are significantly higher in the winter episode at 46.07 μg/m^3, but impacts differ spatially from the summer results. The San Francisco Bay Area and different areas of the Central Valley experience the highest concentrations in the winter rather than regions in the South Coast Air Basin. Results highlight the seasonal variation of $PM_{2.5}$. Within the Central Valley the peak levels of $PM_{2.5}$ occur in winter months, although concentrations remain above NAAQS and remain of concern in summer and fall.[64] Contrastingly, the highest levels within the SoCAB are reached in summer months. Thus, impacts of alternative MDV and HDV technology-driven emissions changes differ depending upon region and season and must be considered spatially and seasonally for thorough assessment.



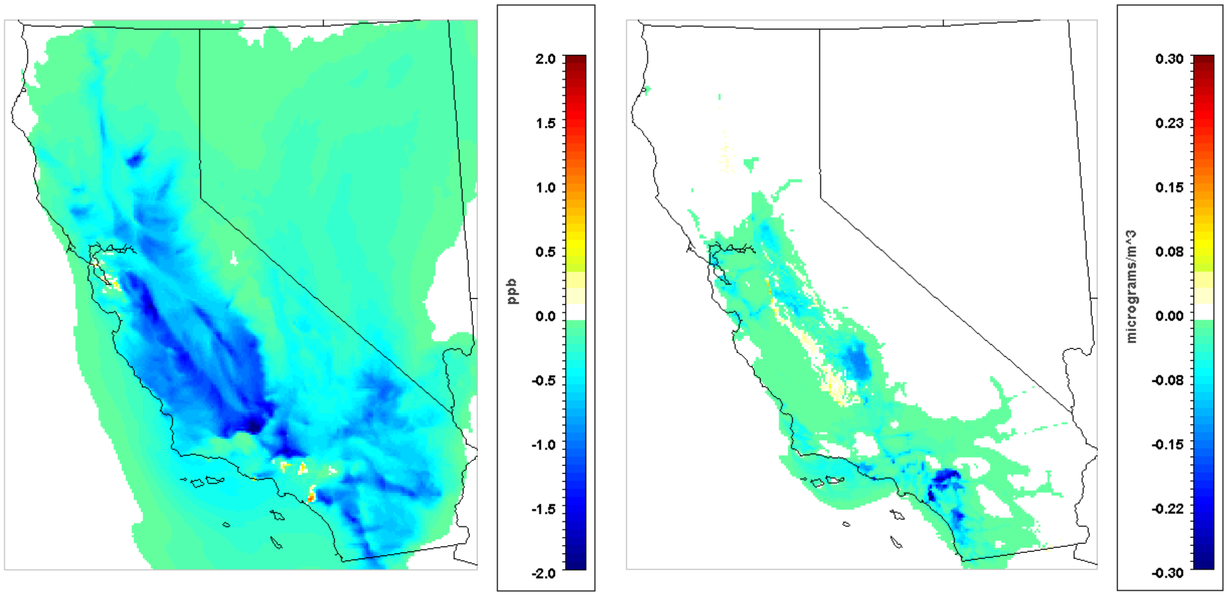
(a) (b)

Figure 28: Ambient 24-hr average PM2.5 for the Base Case for (a) Summer and (b) Winter.

Case 1B

Figure 29 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the Base and 1A Case for the summer episode. Reductions in ozone reach -2.77 ppb in 8-hr average. The areas which experience the highest reduction in ozone are those in southern California, San Francisco Bay Area, and Central Valley which have highest levels of ozone in the baseline scenario, as seen in Figure 27. Reductions in $PM_{2.5}$ reach -0.60 ug/m^3 in 24-hr average. The greatest reduction of $PM_{2.5}$ can be noted in the southern

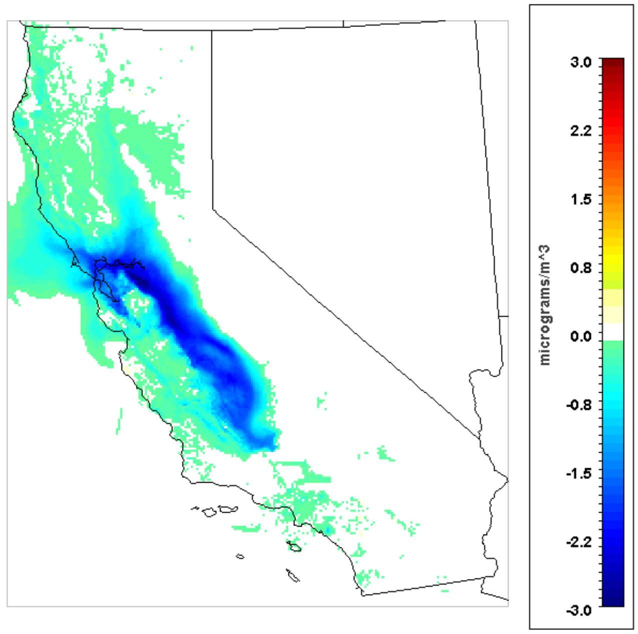
California region. However, there are also reductions in the San Francisco Bay Area and the Central Valley.



(a) **(b)**

Figure 29: Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average PM2.5 for Case 1A relative to the baseline case.

Figure 30 displays the predicted difference in 24-hr $PM_{2.5}$ between the Base and 1A Case for the winter episode. Improvements in ground-level $PM_{2.5}$ are significant with reductions reaching -3.41 ug/m^3 in 24-hr average. The highest improvements can be seen in the San Francisco Bay Area and the Central Valley. As for the rest of the state, there are small improvements found in southern California and areas north of the San Francisco Bay Area. In the eastern part of the state, no reduction or increase in the $PM_{2.5}$ concentration are revealed.

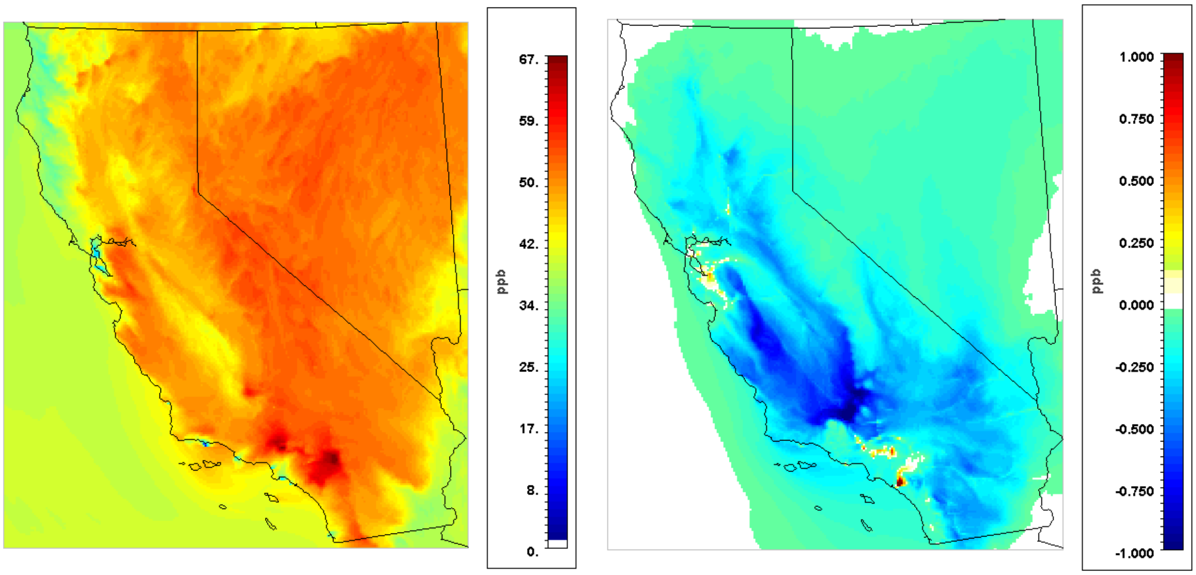


(a)

Figure 30: Predicted difference in winter episode 24-hr average PM2.5 for Case 1A relative to the Baseline Case.

SIP Case

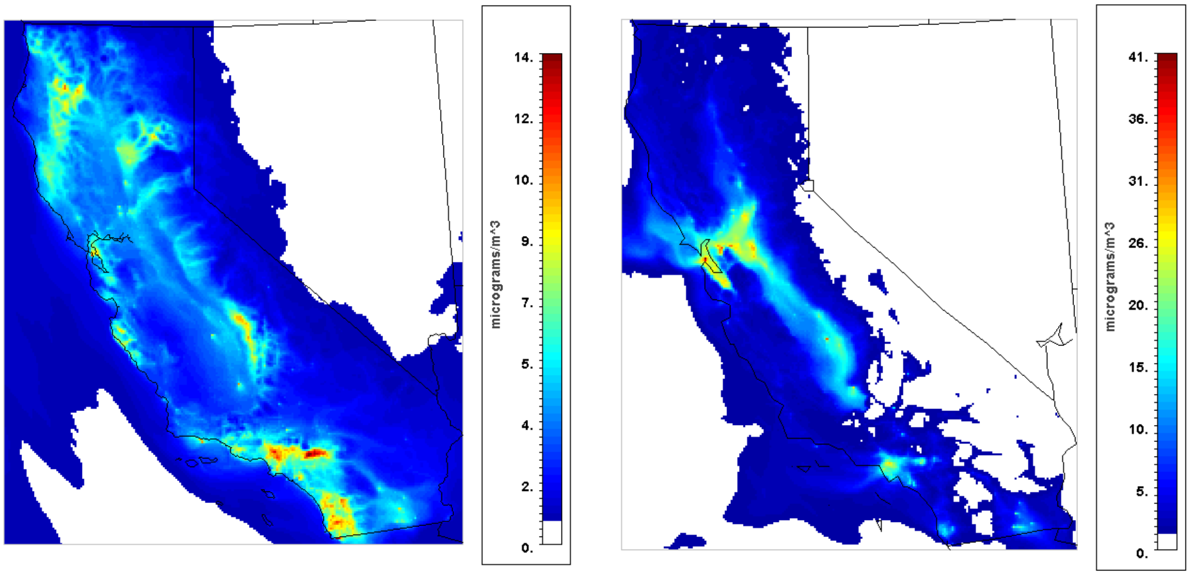
In the SIP Case, simulated ground-level concentrations of summer ozone reach 78 ppb and 67 ppb in maximum 1-hr and 8-hr average (shown in Figure 31a). Peak levels are comparable spatially to those predicted for the Baseline Case. Figure 31b shows the difference plot in 8-hr ozone between the SIP Case and Baseline Case. Reductions in ozone attributable to reductions in NO_x of 85 tpd from the cleaner mix of HDV and MDV in the SIP Case and reach approximately 1.24 ppb. As shown in Figure 31b, the area benefitting from the reductions in criteria pollutants from the SIP Case is the Central area of the state. The San Francisco Bay Area and southern California experience an increase in ozone concentration of 1 ppb.



(a) **(b)**

Figure 31: (a) Ambient max 8-hr average ozone in the SIP Case for Summer and (b) the difference in maximum 8-hr ozone between the SIP and Base Case.

Figure 32 shows the predicted 24-hr average $PM_{2.5}$ for the summer (Figure 32a) and winter (Figure 32b) cases in 2035. For the summer episode, concentrations reach 14.47 μg/m^3 with peak impacts located in areas of the South Coast Air Basin. Additional areas experiencing high levels mirror the Baseline Case. Similar to the Base Case, $PM_{2.5}$ concentrations are higher in the winter episode, reaching 41.69 μg/m^3, and are highest in the S.F. Bay Area, Central Valley, and South Coast Air Basin. With similarity to the ozone results for the SIP Case, concentrations of $PM_{2.5}$ are lower than those for the Base Case due to the assumed cleaner technology mix used in the cases considered.



(a) **(b)**

Figure 32: Ambient 24-hr PM2.5 in the SIP Case for (a) Summer and (b) Winter in the SIP Case.

7.6 Summary

The transportation sector, as one of the main contributors of GHG emissions and criteria air pollutants, is considering a transition to cleaner more efficient technologies. Currently, the MDV and HDV operating in California are large contributors of emissions. Original equipment manufacturers are working together with agencies to develop and deploy zero emission and near-zero emission technologies which could be applied in MDV and HDV. As a primary example, Cummins Westport Innovations has developed a low-NO_x CNG engine which emits 90 percent less than the current emission standard for trucks.[26] Transitioning the current fleets to operate with this low-NO_x CNG engine, including the incorporation of RNG as a transportation fuel, can aid California in meeting its environmental goals. This section addressed GHG and criteria pollutant emissions, and air quality effects from the transition of all MDV and HDV to low-NO_x CNG emissions, and compared the results to a baseline scenario and a SIP scenario.

Biogas generated in California from landfills and anaerobic digesters in wastewater treatment plants can be processed to create RNG. As shown in this section, even using a small percentage of RNG to meet the daily natural gas demand for vehicles produces a reduction in GHG emissions. The greatest reduction in GHG emissions is a complete transition to a low-NO_x engine while using a feedstock mix which includes landfill gas, WWTP anaerobic digester gas, anaerobic digester gas from dairy farms, MSW anaerobic digester gas, and conventional natural gas. However, the most readily available RNG is biogas produced from landfills and WWTP.

When comparing criteria pollutant emissions and air quality impacts of the three scenarios, the transition to a low-NO_x CNG engine, case 1A, produces the greatest benefits. The further reductions in NO_x, ROG, and $PM_{2.5}$ obtained from case 1A in comparison to the SIP case, which covers current state goals, aid in the improvement of air quality in those areas which are highly populated and produces higher concentrations of ozone and $PM_{2.5}$ in the baseline case.

The SIP case included the adoption of low NO_x engines and, from the air quality modeling, air quality is improved. However, to also meet GHG reduction goals, diesel engines must be transformed to CNG engines.

8. Summary and Conclusions

8.1 Summary

Depending upon the application and the pathway for the generation and utilization of the fuel, biogas produced from landfills and wastewater treatment plants can be utilized to generate power or transportation fuels, reduce GHG and criteria pollutant emissions, and improve air quality. The high methane content of biogas allows power to be produced from reciprocating engines, fuel cells, microturbines, gas turbines, and combined cycles. The composition of biogas also allows for transportation fuels to be produced such as CNG, LNG, and hydrogen.

In the present study, a biogas inventory was created to establish the available biogas and biomethane from landfills and WWTP in California. In addition, the study examined various biomethane utilization pathways for a number of scenarios. The scenarios that included either a combine cycle or microturbine for power generation showed the highest potential in power production. When examining the potential transportation fuel production, the generation of renewable compressed natural gas (RNG) on-site from biogas was the most viable pathway for transportation fuel production.

The cost for producing vehicle fuels are lower than for the generation of power. The equipment and maintenance cost related to the power generation is considerably higher than the equipment and maintenance cost for producing transportation fuels. Producing RNG from biogas proves to be the most cost effective utilization of biogas for vehicle fuels. However, the air quality modeling of the biogas scenarios show how the production of hydrogen fuel from biogas results in the largest overall reduction of ozone and $PM_{2.5}$ concentrations.

Using biogas over conventional natural gas results in an immediate reduction in GHG emissions. Transportation fuels derived from renewables have overall less GHG emission than fuels derived from fossil fuels.[30] However, GHG emissions from the tailpipe are not removed since the vehicle performance does not change if it is fueled by RNG or conventional CNG. The production of hydrogen from biogas allows for the greatest reduction in GHG since fuel cell vehicles operating on hydrogen have no GHG from their tailpipe emissions. However, producing hydrogen through steam methane reformation from biogas emits carbon dioxide.

Taking into consideration biogas availability, cost, emissions and air quality effects, biogas resources are best utilized in the production of RNG for vehicles. GHG emission reductions and air quality improvements are higher if the RNG produced is used in the medium- and heavy-duty vehicles with currently available near-zero emission engines.

When examining a case where all MDV and HDV transition to a low-NO_x CNG engine fueled by fuel feedstock mixes including RNG in the year 2025, a substantial reduction in GHG emissions and improvements in air quality result. Even with a small percentage of the natural gas demand for transportation is met by RNG, GHG emissions decrease. Current goals focused on California's State Implementation Plan include the introduction of zero emission vehicles and near-zero emission vehicles in MDV and HDV classes. However, when considering only a low-NO_x CNG engine used in MDV and HDV, air quality improvements exceed the SIP case. Using biogas from landfills and wastewater treatment plants to produce RNG and fuel low-NO_x CNG engines in MDV and HDV is an important pathway for California to meet its environmental goals.

8.2 Conclusions

- **Biogas is best utilized for vehicle fuel production rather than for the generation of power**

  Biogas can be used to generate power or vehicle fuels. When used as a fuel for vehicles, the losses associated with producing RNG are less than those to generate power. RNG can be seamlessly used as CNG within vehicles. The costs associated with producing RNG are also substantially less than the costs to generate power. Additionally, when coupled with the appropriate technologies, vehicle fuel from biomethane can reduce criteria air pollutants and improve air quality along with reducing GHG emissions.

- **Producing RNG from biomethane is the most cost-effective option whereas the production of H_2 is the most environmentally-sensitive option**

  Both RNG and H_2 produced from biomethane have positive environmental impacts. Using these alternative fuels result in a reduction in GHG from the transportation sector. The production of H_2 from biomethane results in 60 percent more gallons of gasoline equivalent than RNG. However, the cost of RNG production is 40 percent less, which does not include the fuel station construction. Even though the use of H_2 is more attractive, currently the most viable vehicle fuel that can be produced from biomethane is RNG and as seen in Figure 29. When using RNG in MDV and HDV, greater improvements in air quality are captured that even surpass that of H_2 FCV in LDV.

- **Using a low-NO_x CNG engine with RNG in MDV and HDV advances environmental goals**

  The use of RNG in LDV results in little to no air quality improvements, as seen in Figure 21. When considering the transition of all MDV and HDV to a low-NO_x CNG engine and fueling with RNG rather than conventional natural gas, the reduction in GHG and criteria pollutant emissions are significant as shown in Figure 29. The reduction exceeds projected GHG and criteria pollutant reductions in the State Implementation Plan which considers only diesel and gasoline engines for MDV and HDV. Additionally, the air quality improvements are more extensive with the installation of low-NO_x CNG engines throughout the MDV and HDV population than in the SIP case as seen in Figure 29 through Figure 31.

- **When considering biogas for generating power on-site, fuel cell technology is the most advantageous technology**

  Distributed generators have strict emission limits of criteria pollutants which makes it difficult to install common power generation technology like reciprocating engines or gas turbines. Fuel cell installations produce power with virtually zero criteria pollutant emission. A fuel cell installation at a WWTP can provide e electricity needed to operate the plant while providing heat to support the anaerobic digester on site and, if appropriately configured, produce H_2 fuel for FCEVs. Also, fuel cells have the flexibility to scale down to better fit the biogas availability while still generating power more efficiently than reciprocating engines. Figure 20 shows how the installation of a fuel cell systems result in either zero or a decrease in ozone and $PM_{2.5}$

concentrations; whereas the installation of combustion technologies resulted in a zero or increase in ozone and $PM_{2.5}$ concentrations (Figure 17 through Figure 19.)

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APPENDIX A: Biogas Inventory

LandGEM first order rate decomposition equation

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \left(\frac{M_i}{10} \right) e^{-kt_{ij}}$$

LandGEM inputs:

Q_{CH4} = annual methane generation in the year of the calculation *(m^3/year)*

M_i = mass of waste accepted in the i^{th} year (*Mg*)

i = 1-year time increment

t_{ij} = age of the j^{th} section of waste mass M_i accepted in the i^{th} year (*decimal years*, e.g., 3.2 years)

n = (year of the calculation) - (initial year of waste acceptance)

j = 0.1-year time increment

k = methane generation rate (*$year^{-1}$*)

L_o = potential methane generation capacity (m^3/*Mg*)

Model Parameters from User Inputs:

k = 0.050 *$year^{-1}$*

L_o = 170 *m^3/Mg*

WWTP Methane Calculation Methods[1]

$$V_{CH_4} = (0.35)\left[(S_o - S)(Q)\left(10^{-3}\frac{g}{kg}\right)\right] - 1.42\,P_x$$

V_{CH4}	Volume of methane produced at standard conditions, 0C and 1 atm	
0.35	Theoretical conversion factor for the amount of methane produced, m^3, from conversion of 1 kg of bCOD at 0C (conversion factor at 35C = 0.40)	
Q	Flowrate m^3/day	
S_o	bCOD in influent mg/L	300/.65
S	bCOD in effluent mg/L	20
P_x	Net mass of cell tissue produced per day	

$$P_x = \frac{\left[YQ(S_o - S)10^{-3}\frac{g}{kg}\right]}{[1 + k_d(SRT)]}$$

Y = yield coefficient	0.5
kd = endogenous coefficient	0.6
SRT = solid retention time	

[1] Same equations shown in Section 4.2

California Landfill Inventory

ID No.	Landfill Name	Current MW Capacity	Unused Mg CH_4/year
1	Puente Hills LF	57.80	109195.95
2	Frank R. Bowerman SLF	0.00	88884.31
3	Fink Road LF	0.00	62903.26
4	Sunshine Canyon Landfill	0.00	60180.83
5	West Miramar SLF	9.90	54956.16
6	Altamont SLF	8.90	41537.13
7	BKK Landfill-Phases I & II	10.90	37009.03
8	Scholl Canyon SLF	8.00	35562.05
9	Bradley Landfill	6.75	33384.98
10	Tri-Cities Landfill	0.00	29015.97
11	Avenal LF	0.00	28481.32
12	Chiquita Canyon SLF	6.00	27911.01
13	El Sobrante SLF	4.05	27417.27
14	Olinda Alpha SLF	35.60	26956.68
15	Vasco Road SLF	0.00	24116.11
16	Otay LF	8.20	22630.46
17	San Timoteo Sanitary Landfill	0.00	22547.44
18	Mid-Valley Sanitary LF	2.52	21014.64
19	Simi Valley LF	2.70	20573.61
20	Kiefer LF	15.00	20467.42
21	American Avenue Disposal Site	0.00	20346.62
22	Sycamore SLF	1.50	19912.03
23	Victorville Sanitary Landfill	0.00	19521.57
24	Central Disposal Site (Sonoma) - Phases I, II, & III	7.50	19367.85
25	Calabasas SLF	13.80	19004.46
26	Lamb Canyon Disposal Site	0.00	18268.02
27	Bakersfield Metropolitan SLF (BENA)	1.60	17353.67
28	Chateau Fresno LF	0.00	16557.35
29	Prima Deshecha SLF	5.50	16092.37
30	Newby Island SLF Phases I, II, & III	6.50	15684.84
31	Santiago Canyon SLF	2.00	15501.42
32	Operating Industries, Inc. LF (OII)	0.40	14745.22
33	West Contra Costa LF	2.00	14375.76
34	San Marcos LF	1.70	13470.06
35	Kirby Canyon Recycling & Disposal Facility	0.00	12338.84
36	Lopez Canyon SLF	6.00	11668.08
37	Fort Irwin Sanitary Landfill	0.00	11039.64
38	Austin Road Landfill	0.80	10453.02
39	North County Recycling Center and Sanitary LF	0.00	10432.89
40	Tajiguas SLF	3.10	10355.94
41	Milliken SLF	2.20	10318.90
42	Antelope Valley Public LF	0.00	9969.18
43	Highway 59 Disposal Site	0.00	9899.50
44	Yolo County Central LF	1.75	9812.09
45	Edom Hill Disposal Site	0.00	8360.57
46	Azusa Land Reclamation Company, Inc.	0.00	8181.54
47	Acme LF	2.20	8164.03
48	West Central LF	0.00	7731.39
49	Guadalupe Sanitary Landfill	2.68	7220.31

50	Davis Street LF	0.00	7078.36
51	Penrose LF	0.00	6547.54
52	Shafter-Wasco SLF	0.00	6292.26
53	Colton Sanitary Landfill	1.20	6118.62
54	Arvin SLF	0.00	5954.94
55	Badlands Disposal Site	1.10	5893.19
56	Ridgecrest-Inyokern SLF	0.00	5880.83
57	Monterey Peninsula SLF	4.60	5773.55
58	Shoreline LF at Mountain View	3.00	5458.19
59	Toyon Canyon LF	3.00	5432.64
60	Toland Road SLF	0.07	5346.59
61	Lancaster Landfill	0.00	5184.53
62	Bailard LF	1.70	4979.18
63	Keller Canyon LF	3.80	4926.61
64	Visalia Disposal Site	1.50	4852.49
65	China Grade SLF	0.00	4798.63
66	Double Butte Disposal Site	0.00	4740.15
67	Foothill Sanitary Landfill, Inc.	0.00	4491.28
68	Western Regional LF	2.40	4356.07
69	Spadra LF	8.50	4297.15
70	Geer Road SLF	0.00	4249.90
71	Cold Canyon LF Solid Waste Disposal Site	0.00	4116.24
72	Sacramento City LF	0.00	3982.54
73	Coachella Sanitary Landfill	0.00	3918.56
74	Landers Sanitary Landfill	0.00	3863.24
75	Palo Alto LF	0.00	3810.81
76	Barstow Sanitary Landfill	0.00	3609.91
77	Woodville Disposal Site	0.60	3472.32
78	Tehachapi SLF	0.00	3451.41
79	Bonzi SLF	0.00	3396.35
80	L & D Landfill Company	0.00	3270.12
81	Burbank LF Site No. 3	0.55	3198.92
82	American Canyon SLF	1.00	3196.89
83	Taft SLF	0.00	2938.35
84	Santa Cruz City SLF	1.60	2919.59
85	Mead Valley Disposal Site	0.00	2913.86
86	Harney Lane SLF	0.00	2883.07
87	Teapot Dome Disposal Site	0.00	2833.88
88	Highgrove SLF	0.00	2814.72
89	Sheldon-Arleta LF	0.00	2776.51
90	Red Bluff Landfill	0.00	2748.81
91	Ox Mountain SLF	11.40	2739.15
92	Ponderosa SLF	0.00	2564.14
93	South Chollas Landfill	0.00	2388.72
94	Yuba-Sutter Landfill	0.00	2342.15
95	Palos Verdes Landfill	6.00	2336.66
96	McCourtney LF	0.00	2277.74
97	Fresno Sanitary Landfill	0.00	2266.34
98	City of Santa Clara LF	0.75	2122.95
99	Ascon & Desser Landfills	0.00	2122.85
100	Hanford SLF	0.00	2122.08
101	City of Ukiah Solid Waste Disposal Site	0.00	2083.51
102	Mojave-Rosamond SLF	0.00	2049.32

103	Anderson Solid Waste Disposal Site	0.00	2009.79
104	Mission Canyon Landfill	0.00	2007.32
105	Fairmead Solid Waste Disposal Site	0.00	1963.05
106	City of Corona LF	0.60	1875.64
107	City of Lompoc SLF	0.00	1803.02
108	City of Clovis LF	0.00	1796.39
109	Oro Grande LF	0.00	1772.59
110	Watsonville City Solid Waste Disposal Site	0.00	1740.03
111	City of Paso Robles LF	0.00	1727.11
112	Mariposa County SLF	0.00	1715.54
113	Ostrom Road Landfill	3.20	1696.67
114	Pacheco Pass SLF	0.00	1692.84
115	Allied Imperial Landfill	0.00	1691.70
116	Desert Valley Monofill Landfill	0.00	1639.88
117	Redwood SLF	0.00	1635.88
118	Zanker Road (Nine Par) SLF	0.00	1587.70
119	Ramona LF	0.00	1583.00
120	Yuba-Sutter Disposal Area	0.00	1556.95
121	Camp Roberts Solid Waste Disposal Site	0.00	1459.65
122	Hillside Solid Waste Disposal Site	0.00	1429.93
123	Neal Road LF	2.16	1415.43
124	Rock Creek LF	0.00	1379.23
125	Cummings Road Landfill	0.00	1329.75
126	Union Mine Disposal Site	0.21	1326.96
127	John Smith Road Solid Waste Disposal Site	0.00	1277.87
128	Coalinga Disposal Site	0.00	1236.20
129	Southeast Regional Solid Waste Disposal Site	0.00	1227.75
130	University of California at Davis SLF	0.00	1201.82
131	Vandenberg Air Force Base LF	0.00	1158.87
132	Amador County SLF	0.00	1147.16
133	McFarland-Delano SLF	0.00	1141.86
134	Industry Hills Sheraton Resort	0.50	1127.12
135	Billy Wright Disposal Site	0.00	1106.81
136	Tuolumne County Central SLF	0.00	1061.98
137	City of Santa Maria Refuse Disposal Site	1.00	1054.33
138	Eastlake SLF	0.00	1015.33
139	Blythe Disposal Site	0.00	1005.19
140	Glenn County LF Site	0.00	1002.17
141	Duarte LF	0.00	1001.60
142	Eastern Regional LF	0.00	995.44
143	Boron SLF	0.00	959.31
144	Johnson Canyon Landfill	0.00	949.96
145	Orange Avenue Disposal Inc.	0.00	948.12
146	Calexico Solid Waste Disposal Site	0.00	943.43
147	Las Pulgas LF	0.00	936.01
148	Ben Lomond Solid Waste Disposal Site	0.00	930.46
149	Bishop Sunland	0.00	913.60
150	San Onofre LF	0.00	895.33
151	Chicago Grade LF	0.00	881.42
152	Crescent City SLF	0.00	847.55
153	Healdsburg Landfill	0.00	843.38
154	Marsh Road LF	1.58	807.39
155	Arizona Street LF	0.00	773.57

156	Chestnut Avenue SLF	0.00	761.55
157	Yreka Solid Waste LF	0.00	751.74
158	Central Contra Costa SLF	0.00	735.38
159	Corral Hollow LF	0.00	734.01
160	Mitsubishi Cement Plant Cushenbury LF	0.00	729.79
161	U.S.M.C. 29 Palms Disposal Site	0.00	728.19
162	Hesperia Refuse Disposal Site	0.00	663.39
163	Apple Valley Disposal Site	0.00	633.03
164	Bass Hill LF	0.00	627.68
165	Earlimart Disposal Site	0.00	593.59
166	Edwards Air Force Base-Main Base LF	0.00	556.76
167	Jamacha Landfill	0.28	545.14
168	Exeter Disposal Site	0.00	538.31
169	City of Redding/Benton LF	0.00	499.41
170	Twentynine Palms Disposal Site	0.00	498.63
171	Big Bear Refuse Disposal Site	0.00	497.89
172	NAS, Lemoore SLF	0.00	496.04
173	Brawley Disposal Site	0.00	430.65
174	Lenwood-Hinkley Refuse Disposal Site	0.00	428.32
175	Lewis Road SLF	0.00	410.88
176	Phelan Refuse Disposal Site	0.00	401.43
177	Trona-Argus Refuse Disposal Site	0.00	375.93
178	Benton Crossing SLF	0.00	375.84
179	Santa Clara LF	0.85	340.56
180	Imperial Waste Site	0.00	322.65
181	French Camp Landfill	0.00	319.03
182	Lebec SLF	0.00	312.46
183	Gopher Hill SLF	0.00	306.86
184	Casa Grande Site	0.00	295.43
185	Anza Disposal Site	0.00	288.50
186	Beale Air Force Base SLF	0.00	281.05
187	Yucaipa Refuse Disposal Site	0.00	274.70
188	Independence Disposal Site	0.00	252.80
189	Caspar Refuse Disposal Site	0.00	250.71
190	Twin Bridges LF	0.00	234.60
191	Holtville Disposal Site	0.00	229.17
192	Needles Solid Waste Disposal Site	0.00	227.24
193	Big Oak Flat LF	0.00	223.51
194	Benton SLF	0.00	205.55
195	Sierra Army Depot	0.00	199.98
196	Kern Valley LF	0.00	199.55
197	Chalfant SLF	0.00	187.94
198	Walker SLF	0.00	187.94
199	Borrego Landfill	0.00	183.95
200	City of Willits Disposal Site	0.00	180.42
201	Oasis Disposal Site	0.00	179.64
202	Lost Hills SLF	0.00	171.86
203	Dixon Pit LF	0.00	171.32
204	Upland LF	0.00	170.22
205	California Street LF	1.00	168.43
206	Baker Refuse Disposal Site	0.00	161.86
207	Tecopa Disposal Site	0.00	160.45
208	Chester SLF	0.00	146.57

209	Black Butte Solid Waste Disposal Site	0.00	146.13
210	Lone Pine Disposal Site	0.00	140.90
211	Buttonwillow SLF	0.00	138.13
212	Pumice Valley SLF	0.00	135.57
213	Cloverdale LF	0.00	131.96
214	Evans Road LF	0.00	130.60
215	Brand Park LF	0.00	129.60
216	Loyalton LF	0.00	126.93
217	Portola LF	0.00	125.10
218	Jolon Road SLF	0.00	122.11
219	Foxen Canyon SLF	0.00	116.90
220	Mecca LF II	0.00	104.64
221	West Marin Sanitary Landfill, Inc.	0.00	102.79
222	Westwood Disposal Facility	0.00	102.78
223	Hay Road Landfill, Inc.	1.60	97.78
224	Salton City Cut & Fill Site	0.00	89.82
225	Palo Verde Cut & Fill Site	0.00	81.79
226	Herlong Disposal Facility	0.00	77.85
227	Hot Spa Cut & Fill Site	0.00	77.10
228	Alturas SLF	0.00	70.87
229	Tulelake SLF	0.00	66.11
230	Morongo Disposal Site	0.00	62.15
231	Niland Cut & Fill Site	0.00	61.52
232	Coastal LF	2.55	58.95
233	Rio Vista SLF	0.00	56.20
234	Lucerne Valley Disposal Site	0.00	56.05
235	Bridgeport SLF	0.00	55.30
236	Shoshone Disposal Site	0.00	54.42
237	South Coast Refuse Disposal	0.00	48.13
238	Santa Monica Landfill	0.00	47.70
239	North Belridge Solid Waste Disposal Site	0.00	47.31
240	Pitchess Honor Rancho LF	0.00	42.15
241	Stonyford Disposal Site	0.00	37.59
242	Valley Tree & Construction Disposal Site	0.00	36.28
243	Camp San Luis Obispo LF	0.00	36.08
244	New Cuyama SLF	0.00	36.08
245	Furnace Creek	0.00	34.32
246	Desert Center LF	0.00	33.43
247	McCloud Community Services District LF	0.00	32.65
248	Annapolis LF	0.00	29.57
249	Laytonville Refuse Disposal Site	0.00	29.54
250	Berryessa Garbage Service Disposal Site	0.00	28.10
251	Bieber Disposal Facility	0.00	28.10
252	Glennville LF	0.00	27.90
253	Ocotillo Cut & Fill	0.00	26.92
254	San Nicolas Island LF	0.00	26.73
255	Intermountain Landfill, Inc.	0.00	23.93
256	Kennedy Meadows Disposal Site	0.00	23.17
257	California Valley LF	0.00	20.01
258	Weed Solid Waste Disposal Site	0.00	16.33
259	Two Harbors LF Site	0.00	14.77
260	Yermo Disposal Site	0.00	13.46
261	Newberry Springs Disposal Site	0.00	12.09

262	San Antonio South Shore Disposal Site	0.00	9.62
263	Ravendale Disposal	0.00	8.38
264	Cecilville Disposal Site	0.00	7.26
265	Madeline Disposal Facility	0.00	7.22
266	Balance Rock Disposal Site	0.00	7.06
267	Cedarville LF - East	0.00	6.90
268	Happy Camp Solid Waste Disposal site	0.00	6.86
269	Hotelling Gulch Disposal Site	0.00	6.53
270	Lava Beds Disposal Site	0.00	6.53
271	Rogers Creek	0.00	6.53
272	Kelly Gulch Solid Waste Disposal Site	0.00	6.21
273	Goldstone Deep Space Comm Complex	0.00	6.16
274	Eagleville Disposal Site	0.00	5.91
275	Fort Bidwell LF	0.00	5.91
276	Lake City LF	0.00	5.91
277	Clipper Creek	0.00	5.09
278	Oroville LF	0.00	3.85
279	Metro Water District - Iron Mountain	0.00	0.89
280	Simpson Paper Company Landfill	0.00	0.10
281	Buena Vista Disposal Site	3.18	0.00
282	Coyote Canyon SLF	21.00	0.00
283	Crazy Horse Landfill	1.40	0.00
284	Mission Hills	7.50	0.00
285	Savage Canyon LF	2.00	0.00
286	Sunnyvale LF	1.20	0.00
287	Potrero Hills SLF	9.60	0.00
288	Bakersfield Sanitary Landfill	0.00	0.00
289	Bonsall Landfill	0.00	0.00
290	CWMI - KHF (MSW Landfill B-19)	0.00	0.00
291	Forward Inc. Landfill	0.00	0.00
292	Aerojet Liquid Rocket Company LF	0.00	0.00
293	Calaveras Cement-Division of Flintkote Company	0.00	0.00
294	City of Palo Alto Refuse Disposal Site	0.00	0.00
295	Clover Flat Landfill	0.00	0.00
296	Collins Pine Company Landfill	0.00	0.00
297	Deep Springs College Disposal Site	0.00	0.00
298	Diamond LF	0.00	0.00
299	E.O.D. #2	0.00	0.00
300	Edwards Air Force Base-Rocket Propulsion LF	0.00	0.00
301	Hanford Recycling Disposal Site	0.00	0.00
302	Harold James Inc. Tire Disposal Site	0.00	0.00
303	Louisiana-Pacific Disposal Site	0.00	0.00
304	Montecito Memorial Park	0.00	0.00
305	Owens Fiberglas Co.	0.00	0.00
306	Picacho Cut and Fill Site	0.00	0.00
307	Red Hill SLF	0.00	0.00
308	Santa Fe Energy Resources, Inc. LF	0.00	0.00
309	Santa Rosa Geothermal Company LF	0.00	0.00
310	Speckertt Disposal Area	0.00	0.00
311	Tennant Solid Waste Disposal Site	0.00	0.00
312	Texaco Oil Disposal Site "C"	0.00	0.00
313	Weaverville LF Disposal Site	0.00	0.00
314	West Seventh Street Disposal Site	0.00	0.00

Californa Wastewaster Treatment Plant Inventory

ID No.	WWTP	Current MW Capacity	Unused Mg CH_4/yr
1	Hyperion WWTP	0.00	30581.48
2	Rio Dell City WWTF	0.00	15598.12
3	Healdsburg City WWTP	0.00	14271.75
4	Sac City Combined WW Collection/TRT Sys	0.00	11141.38
5	Sacramento Regional WWTP	4.30	10003.52
6	Ukiah City WWTP	0.00	8165.62
7	Point Loma WWTP & Ocean Outfall	4.50	7374.37
8	Oroville WWTP	0.00	6134.92
9	Clovis WWTF	0.00	5273.83
10	Redway POTW	0.00	4944.83
11	OCSD Plant 1~/~OCSD Plant 2	6.98	4460.69
12	Joint Water Pollution Control Plant, Carson	18.00	4294.02
13	Sonora Regional WWTP	0.00	3969.54
14	Turlock WWTP	1.20	3701.52
15	San Jose Creek Water Reclamation Plant	0.00	3567.28
16	Donald C. Tillman WWRP	0.00	3335.54
17	PRODUCED WATER RECL PROJECT	0.00	3224.36
18	CENTRAL CONTRA COSTA SD WWTP	0.00	3048.92
19	SF-SE Water Pollution Control Plant, N-Point & Bayside	2.00	2788.94
20	CDF&W Iron Gate Hatchery WWTS	0.00	2765.19
21	CAWELO RESERVOIR B	0.00	2738.96
22	City of Livermore Water Reclamation Plant~/~DUBLIN SAN RAMON SD WWTP~/~EBDA COMMON OUTFALL~/~HAYWARD WPCF~/~ORO LOMA/CASTRO VALLEY SD WPCP~/~Raymond A. Boege Alvarado WWTP (Union SD)~/~SAN LEANDRO WPCP	0.00	2564.27
23	Phillips 66 (formerly ConocoPhillips) San Francisco Refinery, Rodeo	0.00	2522.61
24	Colton/San Bernadino STP, RIX	0.00	2506.31
25	Los Coyotes WRP	0.00	2468.03
26	Portola WWTP	0.00	2318.54
27	Stockton Regional WW Control Facility	0.00	2209.04
28	Modesto WQCF WW Land Disposal (secondary trtmt)	0.00	1947.16
29	Santa Rosa Subregional Water Reclamation Facility	0.00	1813.83
30	Modesto Water Quality Control Facility (primary trtmt)	0.00	1742.18
31	Margaret H. Chandler WWRF	0.00	1736.45
32	EBMUD WPCP	4.30	1645.13
33	South Bay International WTP	0.00	1629.03

34	Long Beach WRP	0.00	1600.33
35	Lincoln City WWTF	0.00	1574.86
36	Los Angeles-Glendale WWRP	0.00	1501.76
37	Terminal Island Water Reclamation Plant	0.00	1479.67
38	MRWPCA REG TRTMT & OUTFALL SYS	0.00	1443.94
39	Valencia Water Reclamation Plant	0.00	1415.56
40	BUENA SD, SHADOWRIDGE WRP~/~CARLSBAD WRF~/~ENCINA WPCF~/~Encina Ocean Outfall~/~VALLECITOS WD MEADOWLARK WRP	0.00	1323.18
41	Malaga CWD WWTF	0.00	1293.97
42	FSSD SUBREGIONAL WWTP	0.00	1282.49
43	Willits City WWTP	0.00	1264.47
44	Riverside City WWRF	1.05	1261.79
45	PALO ALTO REGIONAL WQCP	0.00	1252.23
46	SBSA WWTP	0.00	1083.05
47	Calistoga City Dunaweal WWTP	0.00	1066.75
48	SAN MATEO WWTP	0.00	1040.74
49	VICTOR VALLEY MUNI WTP	0.00	892.24
50	Simi Valley WWRP	0.00	848.14
51	City of Livermore Water Reclamation Plant~/~EBDA COMMON OUTFALL	0.00	839.99
52	VISALIA WWTF	0.00	838.33
53	Pomona Water Reclamation Plant	0.00	833.00
54	Auburn WWTP	0.00	820.52
55	Ventura WRF	0.00	797.23
56	NAPA SD WWTP (Soscol Water Recycling Facility)	0.00	762.25
57	Dry Creek WWTP	0.00	760.66
58	Millseat Facility	0.00	753.24
59	DELTA DIABLO SD WWTP	0.00	748.50
60	Whittier Narrows Water Reclamation Plant, El Monte	0.00	743.94
61	Burbank WWRP	0.00	722.13
62	Clear Creek WWTP	0.00	689.45
63	VALLEJO SFCD WWTP	0.00	663.14
64	Michelson WWRF	0.00	662.12
65	Easterly WWTP	0.00	656.14
66	Oxnard Wastewater Treatment Plant	1.00	646.93
67	IEUA Carbon Canyon WWRF~/~IEUA Regional Plant No. 1~/~IEUA Regional Plant No. 4~/~IEUA Regional Plant No. 5	0.00	643.23
68	El Dorado Hills WWTP	0.00	624.04
69	Tapia WRF	0.00	616.77
70	Pleasant Grove WWTP	0.00	569.40
71	McKinleyville WWTP	0.00	555.58

72	NORTH SAN MATEO COUNTY SANITATION DISTRICT WWTP	0.00	546.57
73	Forestville Water District	0.00	544.50
74	Lake of the Pines WWTP	0.00	522.86
75	RICHMOND REFINERY	0.00	516.46
76	HARRF DISCH to San Elijo Ocean Outfall	0.36	508.08
77	CALEXICO CITY WWTP	0.00	506.19
78	SCRWA WWTP	0.00	502.85
79	Saugus Water Reclamation Plant	0.00	502.28
80	South San Francisco-San Bruno WQCP	0.41	491.54
81	SWA Mountain Gate Limestone Quarry	0.00	491.47
82	SeaWorld, San Diego	0.00	485.00
83	SHELL MARTINEZ REFINERY WWTP	0.00	478.81
84	Yuba City WWTF	0.03	478.12
85	PETALUMA ELLIS CREEK WATER RECYCLING FACILITY (NPDES Permit)	0.00	477.60
86	RICHMOND WPCP~/~WEST COUNTY AGENCY OUTFALL~/~WEST COUNTY WW DISTRICT WPCP	0.19	468.34
87	Tracy WWTP	0.00	459.08
88	Alturas Municipal WWTP	0.00	457.26
89	Golden Eagle Refinery WWTP	0.00	456.17
90	Shasta Lake WWTF	0.00	445.88
91	Manteca WW Quality Control Facility	0.00	435.95
92	CENTRAL MARIN SAN. AGCY. WWTP	0.29	427.61
93	WRCRWA Regional WWRF	0.00	426.54
94	USS POSCO Industries - NPDES/SUB15	0.00	424.66
95	Merced WWTF	0.00	422.94
96	Colton WRF	0.00	416.92
97	NOVATO AND IGNACIO WWTP	0.03	407.55
98	BURLINGAME WWTP	0.20	402.44
99	South Bay WRP	0.00	401.73
100	Eureka City Elk River WWTP	0.00	398.11
101	Woodland Water Pollution Control Facility	0.00	395.19
102	CITY OF SAN CLEMENTE WRP~/~City of San Clemente Segunda Deshecha Runoff Plant~/~LATHAM WWP~/~SCWD GW Recovery Facility~/~SMWD OSO CREEK WRP~/~SMWD-CHIQUITA WRP~/~SOCWA 3A RP~/~SOCWA San Juan Creek Ocean Outfall~/~San Juan Capistrano GW TP	0.00	393.92
103	Deer Creek WWTP	0.00	386.44
104	Corona WWRF No. 1	0.00	382.33
105	EVMWD Regional WWRF	0.00	375.67
106	EL TORO WD WRP~/~IRWD LOS ALISOS WRP~/~Irvine Desalter Project Potable WT System~/~Irvine Desalter Project Shallow GW	0.00	368.00

	Unit~/~SOCWA Aliso Creek Ocean Outfall~/~SOCWA COASTAL TP~/~SOCWA Regional TP		
107	Chico Water Pollution Control Plant	0.14	364.46
108	GOLETA SD WWTP	0.00	357.21
109	Crystal Creek Aggregate	0.00	334.16
110	EBMUD Orinda Filter Plant	0.00	333.29
111	Dales Facility	0.00	333.25
112	San Andreas WWTP	0.00	331.36
113	CALERA CREEK WATER RECYCLING PLANT	0.00	322.13
114	EL TORO WD WRP~/~IRWD LOS ALISOS WRP~/~Irvine Desalter Project Potable WT System~/~Irvine Desalter Project Shallow GW Unit~/~SCWD Aliso Creek Water Harvesting Project~/~SOCWA Aliso Creek Ocean Outfall~/~SOCWA COASTAL TP~/~SOCWA Regional TP	0.00	321.78
115	Lake Wildwood WWTP	0.00	320.41
116	Brawley City WWTP	0.00	302.48
117	Henry N. Wochholz WWRF	0.00	301.49
118	PASO ROBLES WWTP	0.00	300.02
119	Coachella SD WWTP	0.00	297.04
120	Stillwater WWTF	0.00	294.27
121	California Men's Colony WWTP	0.00	291.07
122	Davis WWTP	0.08	287.90
123	El Centro City WWTP	0.00	284.01
124	Hill Canyon WWTP	0.42	280.30
125	ATWATER WWTF (5C240100001)	0.00	278.55
126	LOMPOC REGIONAL WRP	0.00	275.46
127	Abalone Farm, The	0.00	274.35
128	South San Luis Obispo SD WWTP	0.00	272.84
129	City of PINOLE WWTP	0.00	271.68
130	COACHELLA VALLEY WD WWTP	0.00	267.50
131	Sterling Caviar LLC, Elverta	0.00	263.67
132	SF - OCEANSIDE Water Pollution Control Plant	1.00	243.81
133	Valley SD WWTP	0.00	243.18
134	Camarillo WRP	0.00	233.20
135	White Slough Water Pollution Control Facility	0.00	227.49
136	SASM WWTP	0.00	225.26
137	Bear Valley WWTP	0.00	222.15
138	Hangtown Creek WRF	0.00	220.55
139	ATWATER REGIONAL WWTF	0.00	218.44
140	Beaumont WWTP No. 1	0.00	208.01
141	Ojai Valley WWTP	0.00	202.98

142	SCWA Graton CSD	0.00	194.45
143	Aerojet Interim GW Extraction & Treatment System	0.00	194.38
144	SONOMA VALLEY COUNTY SD WWTP	0.00	193.57
145	SUNNYVALE WPCP	0.75	190.32
146	Imperial ID El Centro GS	0.00	190.17
147	Ironhouse WWTF	0.00	188.34
148	Brentwood WWTP	0.00	177.92
149	LAS GALLINAS WWTP	0.05	177.10
150	Southern Region Tertiary Treatment Plant	0.00	175.61
151	GET H-B and SGSA Groundwater Extraction and Treatment System	0.00	175.60
152	Galt WWTP & Reclamation Facility	0.00	161.23
153	Windsor Town WWTP	0.00	157.40
154	Arcata City WWTF	0.00	157.18
155	Jackson City WWTP	0.00	153.71
156	Edward C. Little Water Recycling Plant	0.00	149.36
157	Volta Facility	0.00	149.28
158	Placer Cnty SMD No 1 WWTP	0.00	149.01
159	Planada WWTF	0.00	148.11
160	CARPINTERIA SD WWTP	0.00	146.56
161	Grass Valley City WWTP	0.00	138.26
162	SAUSALITO MARIN CITY STP	0.00	136.79
163	SAM WWTP (Sewer Authority Mid-Coastside Wastewater Treatment Plant)	0.00	134.57
164	PISMO BEACH WWTP	0.00	134.37
165	Red Bluff WW Reclamation Plant	0.00	133.80
166	SAN LUIS OBISPO WWTP	0.24	133.46
167	J.F. Enterprises Worm Farm	0.00	131.19
168	Ray Stoyer Water Recycling Facility	0.00	128.82
169	Olivehurst WWTP	0.00	125.59
170	Discovery Bay WWTP	0.00	124.83
171	UC Davis Main WWTP	0.00	122.40
172	CA DEPT OF CORRECTIONS CENTINELA WWTP	0.00	121.76
173	MT. VIEW SANITARY DISTRICT WWTP	0.00	121.26
174	Crescent City WWTP	0.00	116.58
175	North Fresno WWRF	0.00	113.62
176	Fallbrook Public Water District Plant 1	0.00	111.97
177	Mount Shasta WWTP	0.00	108.05
178	Imperial City WWTP	0.00	103.21
179	Pactiv Molded Pulp Mill	0.00	101.19
180	Anderson WPCP	0.00	100.54
181	CALIPATRIA CITY WWTP	0.00	95.74

182	Calmat Sanger Plant	0.00	95.22
183	Linda Cnty Water District WWTP	0.00	94.56
184	MORRO BAY/CAYUCOS WWTP	0.00	94.38
185	Montecito SD WWTP	0.00	90.36
186	CUTLER-OROSI WWTF	0.00	90.27
187	Scotts Valley WWTP	0.00	87.58
188	Royal Mountain King Mine	0.00	87.53
189	AMERICAN CANYON WWTP	0.00	86.13
190	Mariposa WWTP	0.00	85.49
191	Placer Cnty SMD No 3	0.00	84.71
192	Biggs WWTP	0.00	80.69
193	San Elijo Water Reclamation Facility	0.09	80.26
194	Fortuna City WWTP	0.00	76.84
195	WAWONA WWTF	0.00	75.80
196	RODEO Sanitary District WWTP	0.00	62.50
197	Lee Lake WD WWRF	0.00	61.76
198	Willows Wastewater Treatment Plant	0.00	61.11
199	Corning WWTP	0.00	60.21
200	Live Oak City WWTP	0.00	60.00
201	SF ARPRT MEL LEONG TP-SANITARY WASTE	0.00	56.25
202	MARIN CSD 5 - TIBURON WWTP	0.00	52.98
203	Bell Carter Industrial WWTP	0.00	52.82
204	Cloverdale City WWTP	0.00	51.13
205	Quincy WWTP & Collection System	0.00	51.02
206	UC Davis, Bodega Marine Lab (NPDES)	0.00	49.09
207	Sweetwater Authority Groundwater Demin	0.00	48.95
208	SCWA Russian River CSD	0.00	47.82
209	BALSAM MEADOWS HYDRO PROJECT	0.00	47.64
210	SPX Marley Cooling Technologies (on Wagner)	0.00	47.10
211	SAN JOSE/SANTA CLARA WPCP	8.80	46.76
212	Holtville City WWTP	0.00	45.84
213	Fort Bragg City WWTP	0.00	45.52
214	Mountain House WWTP	0.00	44.20
215	Heber PUD WWTP	0.00	43.80
216	YOUNTVILLE / CA VETS HOME WWTP	0.00	39.31
217	Williams WWTP	0.00	38.19
218	Paradise WTP	0.00	37.35
219	Colusa WWTP	0.00	36.24
220	Nevada City WWTP	0.00	36.23
221	Rio Vista Beach WWTF	0.00	36.07
222	Kiefer Landfill GW Extraction & Treatment Plant	0.00	34.88

223	Avalon WWTF	0.00	34.15
224	Angels City WWTP	0.00	34.07
225	Sierra Pacific Industries - Arcata Division Sawmill	0.00	33.50
226	El Portal WWTF	0.00	33.26
227	McVan Area Poso Creek Oil Field	0.00	33.19
228	VALERO BENICIA REFINERY	0.00	33.11
229	Palomar Energy Center	0.00	32.75
230	Deuel Vocational Institution	0.00	31.64
231	EL ESTERO WWTP NPDES	0.70	29.97
232	Corona WWRF No. 3	0.00	29.94
233	Cottonwood WWTP	0.00	29.18
234	Empire Mine State Historic Park	0.00	28.11
235	TREASURE ISLAND WWTP/DOD	0.00	27.84
236	Collins Pine Chester Sawmill	0.00	24.32
237	Occidental CSD	0.00	23.56
238	CARMEL AREA WWTP	0.12	23.02
239	Temporary Ocean Water Desalination Demonstration Project	0.00	23.01
240	Bella Vista WTP	0.00	22.69
241	Clear Creek WTP	0.00	22.28
242	Donner Summit PUD WWTP	0.00	20.23
243	GENERAL ELECTRIC GWCS	0.00	19.88
244	Colfax WWTP	0.00	19.87
245	Klondike, Dutch & Telegraph Tunnel Mines	0.00	18.68
246	WESTMORLAND CITY WWTP	0.00	18.05
247	Lincoln Village Center GWT System	0.00	17.75
248	Copper Cove WWRF	0.00	17.35
249	Center for Aquatic Biology and Aquaculture	0.00	16.98
250	Dunsmuir STP	0.00	16.72
251	Thunder Valley Casino WWTP	0.00	16.14
252	Miners Ranch WTP	0.00	15.65
253	US Navy Naval Air Facility WWTP	0.00	15.42
254	Northwest WWTF	0.00	15.24
255	San Juan Bautista WWTP	0.00	14.19
256	DG Fairhaven Power	0.00	14.05
257	Covelo POTW	0.00	13.93
258	Lake California WWTP	0.00	13.24
259	Scripps Institution Of Oceanography	0.00	12.30
260	HERITAGE RANCH WWTP	0.00	12.09
261	SUMMERLAND WWTP	0.00	10.84
262	IMPERIAL ID GRASS CARP HATCHERY	0.00	9.91
263	Bell Carter Plant 1	0.00	9.56

264	RHODIA INC - NON15, NPDES, SLIC	0.00	8.72
265	Hammonton Gold Village WWTP	0.00	8.69
266	SEELEY CWD WWTP	0.00	8.39
267	Shelter Cove POTW	0.00	8.06
268	Treatment Plant #1	0.00	7.50
269	UNI-KOOL ABBOTT ST	0.00	7.17
270	ROCKWELL INTERNATIONAL GROUNDWATER CLEANUP SYSTEM	0.00	6.79
271	Mendocino City CSD	0.00	6.49
272	LA SALINA WWTP, OCEANSIDE OCEAN OUTFALL~/~Mission Basin Desalting Facility~/~Oceanside Ocean Outfall~/~SAN LUIS REY WRF	0.56	6.02
273	Mineral WWTP	0.00	5.58
274	AVILA WWTP	0.00	5.45
275	Stallion Springs WWTF	0.00	5.42
276	Niland SD WWTP	0.00	5.26
277	Delleker WWTP	0.00	5.09
278	Sierra Conservation Center WTP (NPDES)	0.00	5.03
279	Country Life MHPRV Asset Partners LP WWTP	0.00	3.50
280	Pico Rivera Facility	0.00	3.32
281	CHEVRON ESTERO MARINE TERMINAL	0.00	3.09
282	SAN SIMEON WWTP	0.00	2.83
283	Indian Springs Geothermal Project	0.00	2.70
284	CUYAMA CSD WWTP	0.00	2.62
285	BIG BASIN WWTP	0.00	2.11
286	Imperial CCD WWTP	0.00	1.91
287	Peter M Ormand Date Gardens MHP	0.00	1.48
288	Shasta Lake WTP	0.00	1.24
289	MARIN CSD 5 PARADISE COVE WWTP	0.00	1.18
290	Cascade Shores WWTP	0.00	1.14
291	BIG CREEK POWERHOUSE NO 1 WWTF	0.00	0.92
292	Mendocino Cnty WWD#2-Anchor Bay	0.00	0.44
293	McCabe USD WWTP	0.00	0.34
294	DUBLIN SAN RAMON SD WWTP	1.50	0.00
295	SANTA CRUZ WWTP	1.32	0.00
296	WATSONVILLE WWTP	0.67	0.00
297	Rialto WWRF	0.90	0.00
298	HAYWARD SHORELINE MARSH~/~Raymond A. Boege Alvarado WWTP (Union SD)	0.50	0.00
299	BENICIA WWTP	1.00	0.00
300	MILLBRAE WWTP	0.25	0.00
301	ENCINA WPCF~/~Encina Ocean Outfall~/~VALLECITOS WD MEADOWLARK WRP	0.75	0.00

302	Phillips 66 Company, Santa Maria Refinery (formerly ConocoPhillips)	0.40	0.00
303	Visalia Cleanup-Snyder General	0.50	0.00

APPENDIX B: Economic Model

		48	49	50	51	52	53	54	55	56	57	58	59
		1.06 MW Recip	130 kW Microturbine	Small GT (5.5MW)	3 MW Conventional Combined Cycle (CC)	1.4 MW Fuel Cell	Heat Recovery Unit (Marginal	H2 Production (FC; Marginal Impact Only)	Natural Gas Boiler	Onsite CNG Production	Onsite LNG Production	Onsite SMR (500 kg H2/ day)	Pipeline Injection
1	Gross Capacity	1.06	0.13	5.5	3	1.4	1	0.2775	2.1	0.61	0.256	0.82	12.2
2	Annual Capacity Factor	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
3	Instant Cost ($/kW)	1900	3800	2400	1500	3300	50	1830	40	450	600	1450	305
4	FOM ($/kW-yr)	30	20	25	14.44	150	3	90	5	25	30	10	20
5	VOM ($/MWh)	18	22	12	15	10	1	0	1	15	20	25	20
6	HR (MMBtu/MWh)	11.221	13.5	12	7.85	8.06	0	5.2177	3.412	3.412	3.412	11.919	0
7	HR Degradation	0.0024	0.0024	0.001	0.0024	0.009	0.05	0.009	0.05	0.0024	0.0024	0.0024	0.0024
8	Capacity Degradation	0.0024	0.0024	0.001	0.0024	0.009	0.001	0.009	0.001	0.0024	0.0024	0.0024	0.0024
9	Debt Term (Yrs)	12	12	12	12	20	10	20	10	12	12	10	20
10	Economic Life (Yrs)	20	20	20	20	20	20	20	20	20	20	10	20
11	Federal Tax Life (Yrs)	20	20	15	20	10	10	10	15	20	20	20	20
12	State Tax Life (Yrs)	20	20	15	20	20	15	20	15	20	20	10	20
13	Ad Valorem Tax Rate	0.01098	0.01098	0.01098	0.01098	0.01098	0.01098	0.01098	0.01098	0.01098	0.01098	0.01098	0.01098
14	Annual Starts	25	25	150	25	4	0	0	0	0	0	25	0
15	Start-Up Fuel (MMBtu/MW)	2.8	2.8	2.8	2.8	10	0	0	0	0	0	2.8	0
16	Plant Losses	0	0	0.034	0	0.0693	0	0	0	0.0693	0.0693	0	0.0693
17	TX Losses	0	0	0	0	0	0	0	0	0.033	0.0925	0	0.033
18	Transformer Losses	0	0	0	0	0	0	0	0	0	0	0	0
19	TX Cost ($/MWh)	0	0	0	4.3	0	0	0	0	0	0	0	0
20	Fuel Type	1	1	1	1	1	7	0	8	1	1	1	6
21	GDA Eligibility	0	0	0	0	0	0	0	0	0	0	0	0
22	CSI PBI Eligibility	0	0	0	0	0	0	0	0	0	0	0	0
23	Ownership Type	0	0	0	0	0	0	0	0	0	0	0	0
24	Annual Starts	25	25	150	25	25	0	25	0	0	0	0	0
25	CO2 Emission factors (tons CO2/MMBTU fuel)	0.0585	0.0585	0.0585	0.058	0.0585	0	0.0585	0.0585	0.0585	0.0585	0.0585	0.0585
26	CO2 released (tons CO2)	0	0	0	0	0	0	0	0	0	0	0	0
27	Renewable Resource Percent	0	0	0	0	0	0	0	0	0	0	0	0