Optimal Pathways to Achieve Climate Goals – Inclusion of a Renewable Gas Standard

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Acronyms

AAEE – Additional Achievable Energy Efficiency
AB – Assembly Bill
BAU – business as usual
bcf – billion cubic feet
CAISO – California Independent System operator
CARB – California Air Resources Board
CCS – Carbon Capture and Sequestration
CEC – California Energy Commission
CFC – Chlorofluorocarbon
CI – Carbon Intensity
CO_{2e} – CO_2 equivalent
CPUC – California Public Utilities Commission
DCF - Discounted Cash Flow
DG - Distributed Generation
DR – Demand Response
E3 - Energy and Environmental Economics, Inc.
EV – Electric Vehicle
gge - gasoline gallon equivalent
GHG – Greenhouse Gas
GREET model – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GWP - Global Warming Potential
IEPR – Integrated Energy Policy Report
IPCC - Intergovernmental Panel on Climate Change
IRP – Integrated Resource Plan
IRR - Internal rate of return
ISO – see CAISO
kg – kilogram
kWh – kilowatt hour
LCA – Life Cycle Analysis
LCFS – Low Carbon Fuel Standards
LFG - Landfill Gas
LMOP - Landfill Methane Outreach Program
MACRS - Modified Accelerated Cost Recovery System
MJ – megajoule
mmBtu - million British thermal units
mmscf - million standard cubic feet
mmscfd - million standard cubic feet per day
MMT – Million Metric Tonnes
NREL - National Renewable Energy Laboratory
PV – photovoltaic
PVC - polyvinyl chloride
RCNG - Renewable Compressed Natural Gas
REC – Renewable Energy Certificates
RFS - Renewable Fuel Standard

RGS – Renewable Gas Standard
RIN - Renewable Identification Number
RNG – Renewable Natural Gas
RPS – Renewables Portfolio Standard
SLCP - Short-Lived Climate Pollutant
TOU – Time of Use
TTW - Tank-to-Wheels
ULSD - Ultra Low Sulfur Diesel
USD – United States Dollar
WTT - Well-to-Tank
WTW - Well-to-Wheels
WWTP – Wastewater Treatment Plant

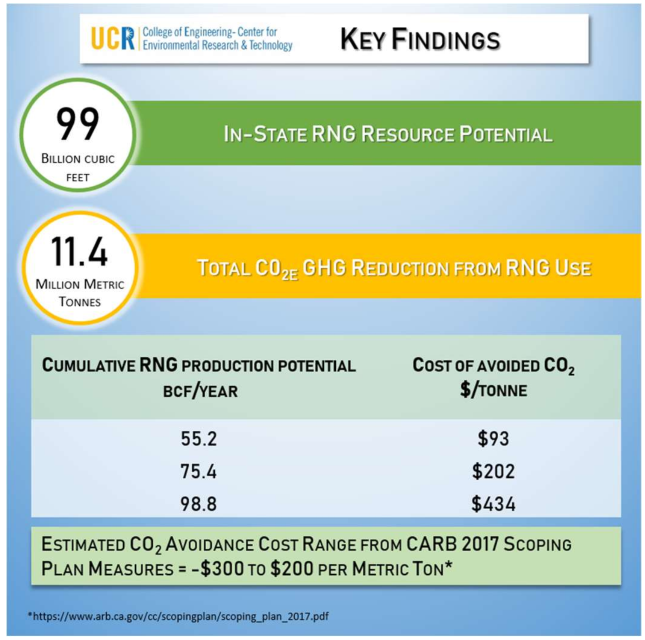
I. Executive Summary

There is broad scientific consensus that current Greenhouse Gas (GHG) emission levels and global surface temperature warming trends demonstrate the need for rapid and significant mitigation of net GHG emissions to the atmosphere. In response, many jurisdictions have aggressively focused on decarbonizing the electricity sector, and significant progress has been achieved in the past two decades. Technology availability and infrastructure compatibility and other factors have played an important role in the ongoing transformation of the electric grid. However, the progress is not easily replicated in other sectors. Continued replacement of fossil energy sources with carbon neutral resources in all the major sectors must occur to achieve California's GHG reduction targets. This effort must also take into account the effects on energy security, cost effectiveness and criteria and air toxic pollutant emissions (local air pollutant emissions). Achieving these complex and sometimes divergent goals requires the ability to understand the nature of long term demands, technology and market developments, resource and infrastructure requirements, and other factors. Diversification of resource and technology options and optimization of approaches and pathways is essential to ensure risk mitigation, and to develop reliable and pragmatic solutions.

The University of California, Riverside's Center for Renewable Natural Gas performed this study to evaluate the role Renewable Natural Gas (RNG) can play in a comprehensive strategy that can be deployed across different sectors, including transportation, building, and commercial and industrial use. This analysis is conducted using a two-step process: first, high percentage of renewables integration into the electric grid was assessed by analyzing Renewables Portfolio Standard (RPS) scenarios. California's RNG production potential, and associated costs and benefits were analyzed in the second step. The RPS analysis is used as a baseline that represents a successful and effective GHG mitigation approach against which a Renewable Gas Standard (RGS) can be compared.

The costs and emission reductions associated with the state's electric sector through current and potential future RPS scenarios were evaluated using the Resolve model. The results provide context to compare the magnitude of emission reductions achievable through a Renewable Gas Standard (RGS) program and the associated carbon abatement costs. RNG production potential is estimated using four feedstock groups: Landfill gas upgrading, animal manure, biosolids from Wastewater Treatment Plants (WWTPs), and food and green waste. A cumulative total of approximately 99 billion cubic feet (bcf) of RNG can be produced annually from a portion of these feedstocks in California. This RNG can result in a reduction of approximately 11.4 Million Metric Tonnes of CO_2 equivalent (MMT CO_2e) GHGs per year with carbon abatement costs ranging from $50 to over $400 per Metric Tonne (MT) of CO_{2e} GHG. *However, <u>a significant amount of the carbon reductions are cost effective based on current circumstances</u>.*

The benefits of replacing fossil fuels with RNG are broad and multifaceted. These include reduced landfilling of waste, criteria and toxic pollutant emission reductions compared to other fossil fuels, and Short-Lived Climate Pollutant (SLCP) emission reductions. A key advantage of RNG compared to other renewable fuels is its potential to make significant contributions immediately in the heavy duty transportation sector. RNG has the unique advantage of a mature, and extensive storage and distribution infrastructure and the availability of NG vehicle technologies. Analysis results show that the carbon abatement costs through RNG use are comparable to other regulatory approaches, including the successful RPS program. An RGS would require increasing percentages of renewable gas to be injected into the natural gas pipeline infrastructure to meet specific renewable percentage targets compared to total natural gas consumption. Such a policy would provide a significant step forward for an enhanced framework and the regulatory driving force that can substantially increase renewable gas production and use in the state. GHG emissions are often intricately tied to the local, national and global economies, quality of life, and other factors. A diverse portfolio of approaches is important in order to achieve sustained, long term emission reductions across sectors and from all source categories. *More importantly, large scale renewable gas production would address some emissions from sources that are unlikely to be mitigated in the near term through other measures*.



Recommendations and next steps to realize RNG's potential role in California's climate strategy:

- Address the key barriers to commercial RNG production and use; and develop strategies to expedite production.
- Further incorporate renewable gas production and other CO_2/methane mitigation strategies as part of an optimal climate mitigation approach that takes advantage of all pathways with high GHG reduction potential.
- Develop an enhanced policy framework that will enable RNG production in significant quantities from in-state resources building on current capture mandates (SB 1383) which can jump start in-state production but produce modest volumes.
- Adopt an RGS with gradual increased percentage thresholds to help provide stable financing for expanded RNG production to assist in cost effective GHG reductions. To further expand RNG supply potential and facilitate cost effective GHG reduction, consider policies that enable continued out of state supply of RNG, not unlike out of state electric resources enabled under current RPS requirements.

Given the far reaching consequences of a potential 2 °C global average temperature rise and the urgency in preventing it, every meaningful GHG reduction strategy must be pursued seriously. RNG can play a unique and significant role without excluding other approaches and represents an immediate opportunity. As the global leader in combating climate change, California is the ideal candidate to demonstrate the realization of RNG's potential.

II. Introduction

There is broad scientific consensus that current GHG emission and global surface temperature warming trends demonstrate the need for rapid and significant mitigation of net GHG emissions to the atmosphere. Current emission trends are continuing along high end emission scenarios and there is a high likelihood of an increase in global average temperature of 2 °C by 2050 compared to pre-industrial levels. Preventing such a rise will require significant and sustained mitigation of GHG emissions in the next 15 years [1-4]. In response, many jurisdictions have aggressively focused on decarbonizing the electricity sector, and progress has been achieved in the past two decades. Technology availability and infrastructure compatibility and other factors have played an important role in this ongoing transformation of the electric grid. However, the progress is not easily replicated elsewhere. Other energy use sectors, including transportation, pose major challenges to decarbonization and well defined approaches are necessary to continue progress in GHG reduction. The electricity sector is also facing potential issues related to renewable generation intermittency and the need for long-term, advanced, high capacity storage. The electric grid must be further modernized in order to integrate very high percentage of renewables into the generation mix.

California has some of the most aggressive GHG mitigation and renewable energy generation targets in the world and will likely mandate further goals and targets on both fronts [5]. Emission reductions and increased renewable energy use will be required across multiple sectors in order to achieve these goals. The electricity sector has made considerable progress in increasing renewable generation over the past few decades and further increases are anticipated. Under the current Renewables Portfolio Standard (RPS), the State's electricity mix will consist of 40% renewables by 2024 and 50% by 2030. Senate Bill 100, approved by the state assembly and senate and pending action by the governor, would accelerate the renewables penetration and achieve a 50% RPS by 2025 and 100% by 2045[6]. Likewise, increased renewables penetration into the grid is the most likely trend across the world partly due to concern over GHG emissions but more importantly due to wind and solar power's cost competitiveness. Besides the 50% RPS, California has a number of other climate and clean energy goals including:

Assembly Bill 32 (AB 32) mandates a GHG reduction target of

- Achieve 1990 emission levels by 2020
- Achieve 80% below 1990 levels by 2050

Senate Bill 32 (SB 32) mandates a GHG reduction target of

- Achieve 40% below 1990 levels by 2030

Executive order S-3-05 sets a GHG reduction target of

- Achieve 80% below 1990 levels by 2050

Governor's pillars (2030 goals)

- Increase renewable electricity to 50 percent
- Reduce petroleum use in vehicles by up to 50 percent
- Double energy efficiency savings achieved in existing buildings and make heating fuels cleaner

- Reduce emissions of short-lived climate pollutants
- Manage farms, rangelands, forests and wetlands to increasingly store carbon

Senate Bill 1383 (SB 1383) mandates a Short Lived Climate Pollutant (SLCP) reduction target of

- Achieve 40% below 2013 levels by 2030 for CH_4 and HFCs
- Achieve 50% below 2013 levels by 2030 for anthropogenic black carbon
- Also provides specific direction for reductions from dairy and livestock operations and from landfills by diverting organic materials.
    - Reduce landfill disposal of organics by 50% below 2014 levels by 2020
    - Reduce landfill disposal of organics by 75% below 2014 levels by 2025

Senate Bill 350 (SB 350) mandates an RPS of:

- Achieve 40% renewables percentage in the State's electricity mix by 2024
- Achieve 50% renewables percentage in the State's electricity mix by 2030

In response to legislation and direction from the governor, the California Air Resources Board (CARB) has prepared and updated a Scoping Plan to achieve the State's climate goals and has also developed a Short-Lived Climate Pollutant (SLCP) Reduction Strategy [5, 7]. The Scoping Plan coordinates the State's efforts including actions and initiatives across various sectors to meet mid and long-term climate goals such as the 2030 GHG targets [5]. The SLCP is included as a component of the current Scoping Plan and the use of RNG as a GHG mitigation strategy is included in both plans.

Significant portions of fossil energy sources must be replaced with carbon neutral resources in all the major sectors in order to achieve California's GHG reduction targets. This effort must also take into account the effects on energy security, cost effectiveness and needed criteria and air toxic pollutant emission reductions. Achieving these complex and sometimes divergent goals in an expedited timeframe requires the ability to understand the nature of long term demands, technology options and limitations, and market developments, resource and infrastructure requirements, and other factors [8]. Diversification of resource and technology options and optimization of approaches and pathways is essential to ensure risk mitigation, and to develop reliable and pragmatic solutions. Developing technologies and mitigation strategies that can be quickly and cost effectively adopted by other jurisdictions, particularly in the developing world, is crucial. This will help maximize the benefits from the state's investments and broaden the positive impact.

A comprehensive approach towards development/utilization of renewable energy resources, efficiency improvements, and emission reduction across sectors is necessary to identify the pathways and scenarios that are practically achievable, cost effective, and sustainable in the long term. California has a number of resources and technologies readily available that can lead to significant GHG reductions while also reducing criteria pollutant and air toxic emissions along with improving waste disposal methods. This study evaluates the role RNG can play in such a comprehensive strategy that can be deployed across different sectors, including transportation, buildings, or commercial and industrial uses. RNG has the potential to play a key role in achieving many of the State's climate targets, most importantly, GHG reduction goals. Establishing a Renewable Gas Standard (RGS) can help achieve these targets in a more cost effective and less disruptive way than otherwise, while not excluding other renewables.

This study also evaluates multiple scenarios involving different RPS and RGS standards to identify viable pathways toward achieving the State's targets. Investments necessary to achieve current and potential future RPS scenarios are calculated along with the GHG emission reductions, and anticipated electricity cost. The RPS scenario assessment was conducted in order to set a baseline against which the costs and emission benefits from a potential RGS can be compared. The production cost for increasing quantities of RNG are calculated along with the GHG emission reductions. Results including the cost of carbon abatement and other parameters are used to recommend best approaches forward.

III. Methods

This section details the background, methods and calculations used to evaluate the resource availability, conversion technologies, deployment costs and timelines, and estimated emission reductions for specific renewables scenarios. Section A presents the analysis of California's renewable portfolio standards and Section B presents an analysis RNG potential and the feasibility of a potential renewable gas standard.

A. Renewables Portfolio Standard (RPS) Evaluation

1. Background

The major technological approaches to GHG emission reductions are reduction/elimination, capture and use, and sequestration. Emission reduction/elimination is achieved through means including efficiency improvements to existing processes, elimination of leaks and wastage, and transitioning to lower carbon intensity options, i.e., renewable energy sources. Examples include energy efficient appliances/lighting, and transition to renewable power sources such as solar and wind. The capture and use approach involves fuel and electricity production from carbonaceous matter that would otherwise result in GHG emissions to the atmosphere. A well-known example is the capture of landfill methane emissions for fuel or power production. The carbon capture and sequestration (CCS) approach involves the capture of GHG emissions from large point sources and sequestering them using long term storage options. Examples include the CO_2 sequestration in underground geological formations.

A number of policy approaches are used to develop and deploy the reduction strategies stated above. Broadly, the policy approaches are grouped as (1) economic instruments, (2) regulatory approaches, and (3) information policies [4]. Economic instruments, also referred to as 'market-based' approaches, use (i) levies and/or incentives to limit emissions and to stimulate transition to alternative technologies. Taxes, fees, and incentives are widely used economic instruments and are collectively referred to as 'price instruments'. Examples include carbon taxes imposed by several jurisdictions. Emission trading approaches, referred to as 'quantity instruments', create a mechanism for GHG trading while imposing individual and/or overall limits. California's successful program, commonly referred to as cap and trade, is an example of such an instrument. Economic instruments create incentives for businesses and individuals to reduce emissions without directly prescribing specific actions or technologies [9].

Unlike economic instruments, regulatory 'command and control' approaches set specific targets or standards that must be met by organizations and/or the general public. These include emission standards, technology standards, and product standards and are often sector specific. Examples include efficiency standards for appliances and vehicles. Information policies involve the development and distribution of high quality, scientifically accurate information on relevant topics, for example, technology and lifestyle choices. The Energy Star program in the United States better enables informed and positive decision-making across society.

Other approaches in addition to those discussed above, are also available. These include government provision of goods and services, and voluntary actions. Government provision examples include public transportation services that use the decision making authority of governmental entities to support emission reductions. Other voluntary actions can be taken by public or private entities and involve commitments that are not necessitated by the law.

GHG emissions are often intricately tied to the local, national and global economies, quality of life, and other factors. The cost and effectiveness of each approach is affected by these factors and are difficult to quantify, especially in the short term [4, 5, 10]. Under many circumstances, economic instruments are acknowledged to be more cost effective on a per ton mitigation basis in the long term than regulatory approaches [4, 11]. However, capturing the full abatement potential is a complex challenge and a diverse portfolio of approaches is necessary, especially due to the urgency of climate change [4, 5, 12].

Renewables Portfolio Standard (RPS) is a regulatory instrument that mandates a certain percent of the jurisdiction's electricity supply to be produced from qualifying renewable sources [13]. Although RPS refers to energy standards, in practice, the term is commonly used to describe California' renewable mandates for the power sector, including in this report. RPS is the most widely used mechanism for encouraging the transition to renewable power. However, RPS is a least cost approach that aims to meet the targets renewable percentages using the least expensive technology and portfolio options. Due to this, RPS is not considered the most effective approach to foster investments in emerging technologies that are considerably more expensive than commercially mature options [13]. RPS does not set a price for either renewable electricity or for avoided carbon but can work in tandem with such economic instruments to support the overall process. A number of compliance mechanisms are used to ensure that the goals are met by power producers and utilities. Renewable Energy Certificates (RECs) are a commonly used mechanism in the United States[1]. A REC is issued when one megawatt hour (MWh) of renewable electricity is generated and delivered to the grid. The REC essentially serves as proof of generation and can then be traded under carbon emission trading programs. The primary objective behind RPS programs are specific energy system goals, although the programs also achieve environmental and administrative goals. RPS policies ultimately eliminate fossil carbon emissions from the electric power sector by deploying carbon free or renewable carbon based technologies.

2. Study Methodology

This study evaluates scenarios under the current RPS policy and potential higher standards where the current generation trend persists and new renewable capacity is added to the grid.

[1] https://www.epa.gov/greenpower/renewable-energy-certificates-recs

Under California's Renewable Portfolio Standard (RPS), the State's electricity mix will consist of 40% renewables by 2024 and 50% by 2030. The California Public Utilities Commission (CPUC) uses the integrated resource planning (IRP) as the umbrella proceeding to 'consider all of the Commission's electric procurement policies and programs and ensure California has a safe, reliable, and cost-effective electricity supply[2].' The goal of the IRP proceedings include identifying a diverse and balanced portfolio of resources that can help 'ensure that California's electric sector is on track to help California reduce economy-wide GHG emissions 40% from1990 levels by 2030' [14]. As part of the IRP proceedings, the CPUC has conducted extensive modeling of California's electric grid including the California Independent System Operator (CAISO)'s balancing authority area to develop a plan to meet the state's GHG goals by optimizing the renewables portfolio. This modeling has been performed using the Resolve model, developed by Energy and Environmental Economics, Inc. (E3), an energy consulting firm [153]. The Resolve model was also used in the CAISO study for Senate Bill 350 (SB 350) to evaluate ratepayer benefits from expanding the CAISO footprint [16]. SB 350 (Clean Energy and Pollution Reduction Act) was signed into law in 2015 and establishes, among other actions, targets for energy efficiency and renewable electricity aimed at reducing GHG emissions [17].

Traditional power system planning approaches are built around the reliability and flexibility offered by traditional fossil resources. These approaches are inadequate in their ability to model high renewables integration into the grid. New tools are under development that can account for the inherent unpredictability and distributed nature of renewable resources. The key requirements for power planning models include the ability to provide adequate temporal, spatial, and operational resolution, ability to manage the necessary computational complexity, transparency and replicability [18]. A number of power system planning models are available including some open source options. We used the Resolve model to evaluate the RPS scenarios discussed below. Resolve (Renewable Integration Solutions model) is an investment and operations planning model aimed at addressing key planning challenges related to high renewables integration into the electric grid [19]. The California Public Utilities Commission (CPUC) made the model available to the public in 2017.

The Resolve model is designed primarily to investigate investment driven by renewable energy targets [20]. The following description of the Resolve model is quoted from the model documentation [21]. "The Resolve model is one of a growing number of models designed to answer planning and operational questions related to renewable resource integration. In general, these models fall along a spectrum from planning-oriented models with enough treatment of operations to characterize the value of resources in a traditional power system to detailed operational models that include full characterization of renewable integration challenges on multiple time scales but treat planning decisions as exogenous. Resolve co-optimizes investment and dispatch over a multi-year horizon with one-hour dispatch resolution for a study area, in this case the California Independent System Operator (ISO) footprint. The model incorporates a geographically coarse representation of neighboring regions in the West in order to characterize and constrain flows into and out of the ISO. RESOLVE solves for the optimal investments in renewable resources, various energy storage technologies, new gas plants, and gas plant retrofits subject to an annual constraint on

[2] http://www.cpuc.ca.gov/irp/
[3] https://www.ethree.com/tools/resolve-renewable-energy-solutions-model/

delivered renewable energy that reflects the RPS policy, a capacity adequacy constraint to maintain reliability, constraints on operations that are based on a linearized version of the classic zonal unit commitment problem as well as feedback from ISO, and scenario-specific constraints on the ability to develop specific renewable resources [20]."

As part of the IRP, E3 has performed modeling analysis of a number of 50% RPS scenarios of the CAISO electric system [20]. This analysis by E3, performed using the Resolve model, evaluate the effect of a number of parameters including load growth forecasts, technology and fuel costs, and GHG emission targets [14]. These modeling results, along with the assumptions and input data have been published by the CPUC [14]. The present study uses these scenarios as the baseline input for our work, including many of the underlying assumptions and forecasts. A brief summary of the key assumptions and inputs, from the CPUC's 2017 IRP documentation [20], are provided below. Details and additional information are available in the appropriate references [14, 20, 224]. However, the analysis performed herein uses the Resolve model to assess high RPS scenarios that have not been publicly evaluated by the CPUC.

The annual load forecasts by Resolve are based on the California Energy Commission (CEC)'s 2016 Integrated Energy Policy Report (IEPR). The Resolve model represents the annual forecast in the form of baseline consumption with a number of demand side modifiers including electric vehicles, energy efficiency, building electrification and other factors [20]. The baseline resources, i.e., existing resources, included in the analysis fall under the categories of conventional generation (thermal sources using fossil fuels), renewables, large hydro, energy storage and demand response. The candidate resources that can be used to build the optimal portfolio include natural gas, renewables, energy storage and demand response (DR). Each candidate resource includes multiple technology options such as combined cycle gas turbine, reciprocating engine, solar, wind, battery storage, pumped storage, shed and shift DR. Details of load and renewable profiles, including electrification and energy efficiency profiles, operating characteristics, reserve requirements, fuel costs and other parameters are available in the CPUC documentation [20].

Resolve also allows the user to enforce a GHG cap on each scenario. As part of the IRP process, the CPUC assessed four GHG emission scenarios based on the upper, middle, and lower range of emissions attributed to the electric sector in the California Air Resources Board (CARB)'s AB 32 Scoping Plan [5, 20, 235]. AB 32 (California Global Warming Solutions Act of 2006), required the CARB to develop a Scoping Plan that will essentially outline California's strategy to reduce GHG emissions to 1990 levels by 2020. The Scoping Plan is updated every five years and now incorporates the strategy for achieving the 2030 GHG target of 40% below 1990 levels. The four Scoping Plan scenarios are listed below [14, 20, 23].

- Default: The electric sector achieves an emissions level by 2030 that is equivalent to the upper end of the range attributed to it in California Air Resources Board (CARB)'s Draft Scoping Plan Scenario (62 MMT by 2030).
- Moderate Share of Economy-Wide Emissions Reductions: The electric sector achieves an emissions level by 2030 that is equivalent to the middle of the range attributed to it in CARB's Draft Scoping Plan Scenario (52 MMT by 2030).

[4] http://www.cpuc.ca.gov/irp/prelimresults2017/
[5] https://www.arb.ca.gov/cc/scopingplan/scopingplan.htm

- Large Share of Economy-Wide Emissions Reductions: The electric sector achieves an emissions level by 2030 that is equivalent to the lower end of the range attributed to it in CARB's Draft Scoping Plan Scenario (42 MMT by 2030).
- Extra Large Share of Economy-Wide Emissions Reductions: The electric sector achieves an emissions level by 2030 equivalent to what is attributed to it in CARB's Alternative 1 scenario (30 MMT by 2030); this implies that additional electric sector investments beyond those included in the CARB's Draft Scoping Plan Scenario are used to achieve the state's GHG emission reduction goals.

The CPUC has selected the Large Share of Economy-Wide Emissions Reductions (42 MMT CO_{2e} GHG) scenario as the base case for IRP assessments. This study also uses the 42 MMT scenario as the base case. The different portfolios for candidate RPS targets are developed using the basic assumptions from this base case scenario. Each scenario analyzed by Resolve involves a number of assumptions and input parameters. Some of the key parameters for 42 MMT scenario are listed below. Curtailment of excess power is allowed under all the scenarios. Additional information and details are available in the IRP documentation [14, 20, 23].

- Electric Vehicle Adoption: CARB Scoping Plan
- Building Electrification: California Energy Commission (CEC) 2016 Integrated Energy Policy Report (IEPR) - Mid Demand
- Hydrogen: No Hydrogen
- Behind-the-meter photovoltaic (PV): CEC 2016 IEPR - Mid PV
- Energy Efficiency: CEC 2016 IEPR - Mid Additional Achievable Energy Efficiency (AAEE) + Assembly Bill 902 (AB 802)
- Existing Demand Response (DR): Mid
- Time of Use (TOU) Adjustment: High
- Workplace Charger Availability: Mid
- Electric Vehicle (EV) Charging Flexibility: Low

3. Results

The CPUC has published a number of Resolve scenarios evaluating 50% RPS portfolios including the input and output files from each scenario [14, 19, 20, 22]. We ran several of the published scenarios using the CPUC input data and were able to replicate the published results. The 50% RPS results discussed below are from the published scenarios. Multiple modeling runs were performed to provide an initial draft sensitivity analysis. The results were used to identify lower cost options, which are presented here. Although the objective of this study is not to identify the lowest cost RPS portfolios, the intent of the authors was to not bias the analysis in favor of alternate approaches to RPS. The RPS analysis is intended to serve as a baseline based on an ongoing and successful program that can be used to assess the costs and benefits of a potential RGS strategy. The RPS scenario results presented here are the most feasible, lower cost options that emerged from the analysis.

The CAISO RPS and emission targets and calculated values for the 50% RPS by 2030 scenario are shown in Figure 1. The state is currently ahead of schedule to meet the RPS and GHG emission reduction targets. The modeling results show significant progress being made on both fronts throughout the analysis period. The total installed generation capacity and the new builds during the evaluation timeframe are shown in Figure 2 and Figure 3 respectively. The biomass resource in Figure 2 represents biopower. RNG was not included as a renewable power generation source.

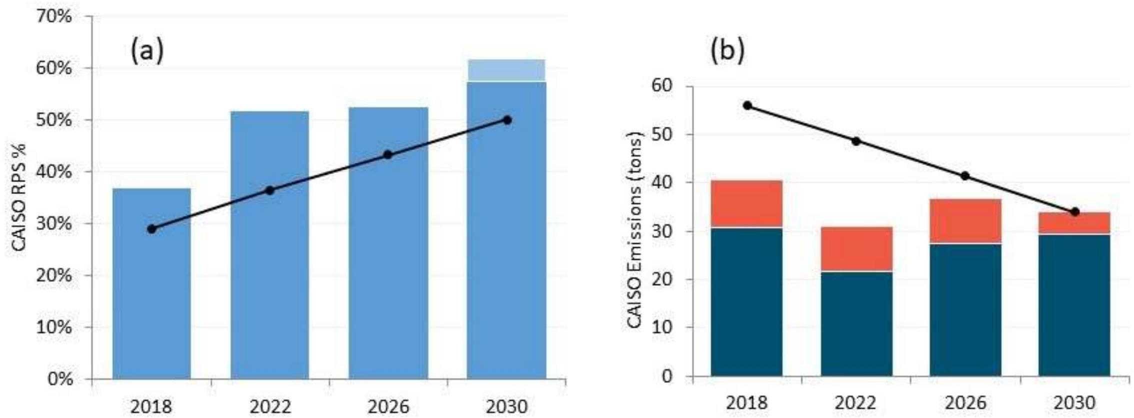


Figure 1 50% RPS by 2030 scenario (a) RPS targets and predicted values; (b) CAISO GHG emission targets and predicted values

(a) Solid line – RPS target; Stacked blocks – Effective RPS (in blue) & banked RECs (in pale blue)

(b) Solid line – Emission target; Stacked blocks – CAISO (in blue) & import emissions (in red)

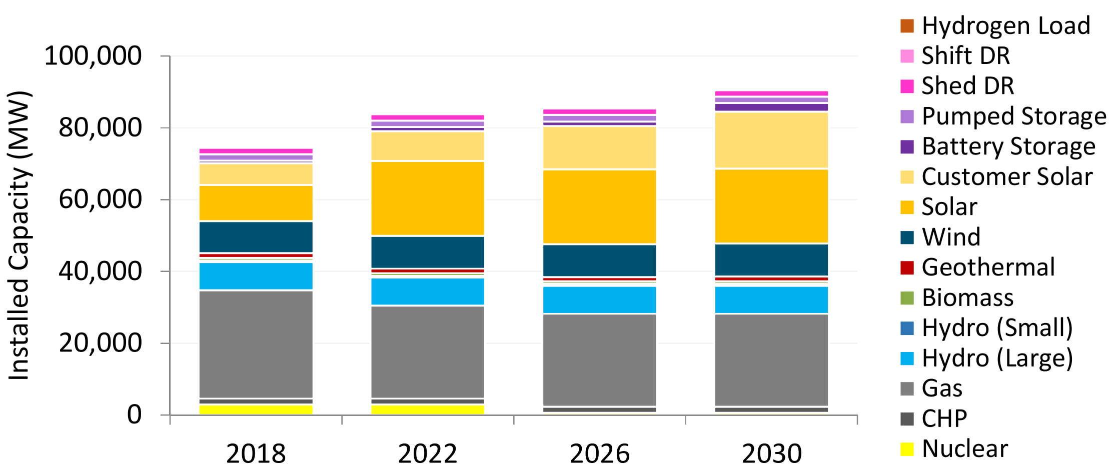


Figure 2 50% RPS by 2030 Total CAISO installed generating capacity

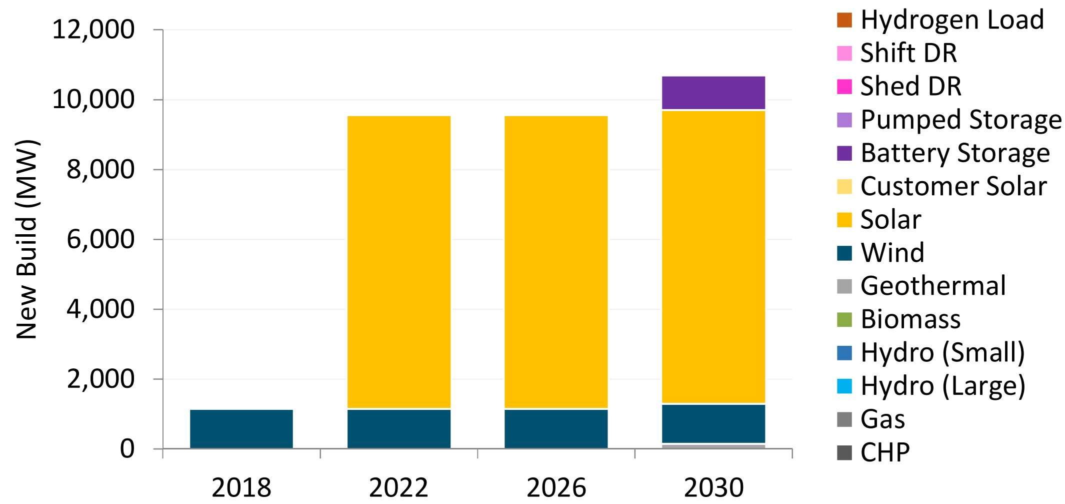


Figure 3 50% RPS by 2030 Total CAISO new build

As the results show, significant fossil generating capacity exists under the 50% RPS scenario. However, new builds over the analysis are only in three categories: wind, solar, and battery storage. The total cumulative investment ranges from $32 to $40 billion dollars over the analysis period. The electric costs increase from a present value of 15.6 to 20 ¢/kWh as shown in Figure 4. This represents a 28% increase over 12 years. By comparison, California's average electric costs increased from 11.35 to 15.23 ¢/kWh from 2004 to 2016, which is a 34% increase. The results anticipate a trend of decreasing electric costs as the cost of solar and wind power have considerably decreased over the years.

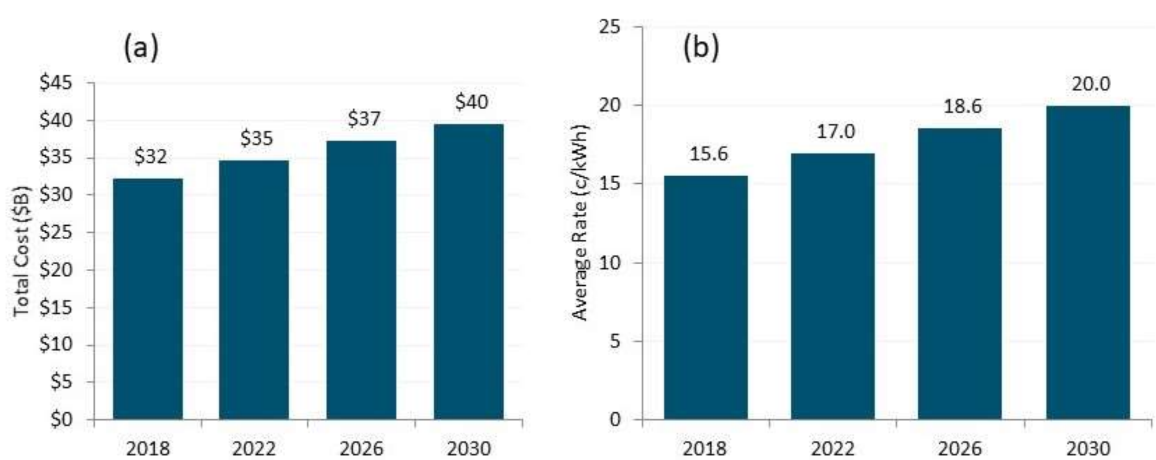


Figure 4 50% RPS by 2030 scenario (a) Total cumulative investment; (b) Electric costs

A number of higher RPS scenarios beyond the current 50% requirement were evaluated. Scenarios beyond 50% RPS target have not been published by the CPUC. The results presented here must be considered a first level assessment of the achievability of a very high RPS target, in this case 80%. The 80% RPS by 2042 was selected as the very high renewables scenario based on the timeline proposed in SB 100 [24]. The total costs, GHG emissions and RPS values for an 80% scenario are shown in Figure 5 and Figure 6. The higher RPS scenarios rely on significant added storage capacities and other mechanisms such as demand response in order to manage the renewable resources and mitigate curtailment. The grid must be further modernized in order to be able to integrate very high percentages of renewables without affecting the reliability and safety of the system. Such efforts are already under way and will need to be consistently pursued over the years [16, 17].

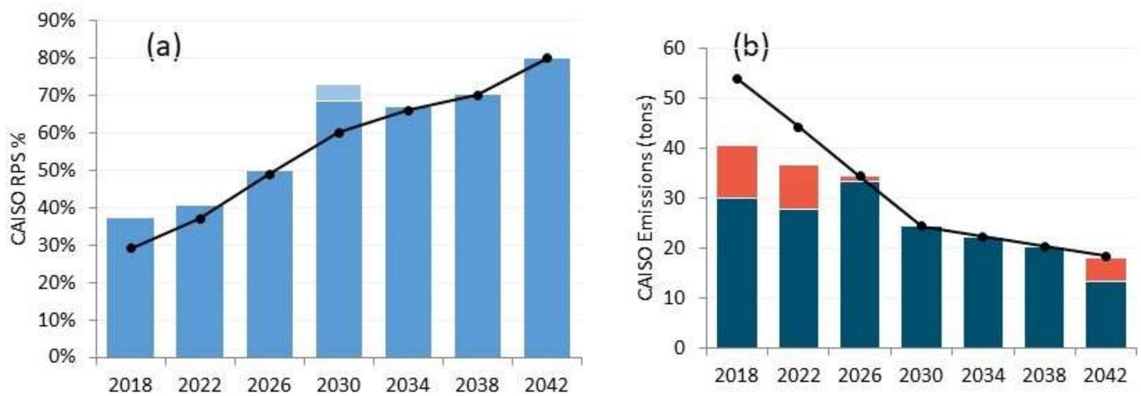


Figure 5 80% RPS by 2042 scenario (a) RPS targets and predicted values; (b) CAISO emission targets and predicted values

(a) Solid line – RPS target; Stacked blocks – Effective RPS (in blue) & banked RECs (in pale blue)
(b) Solid line – Emission target; Stacked blocks – CAISO (in blue) & import emissions (in red)

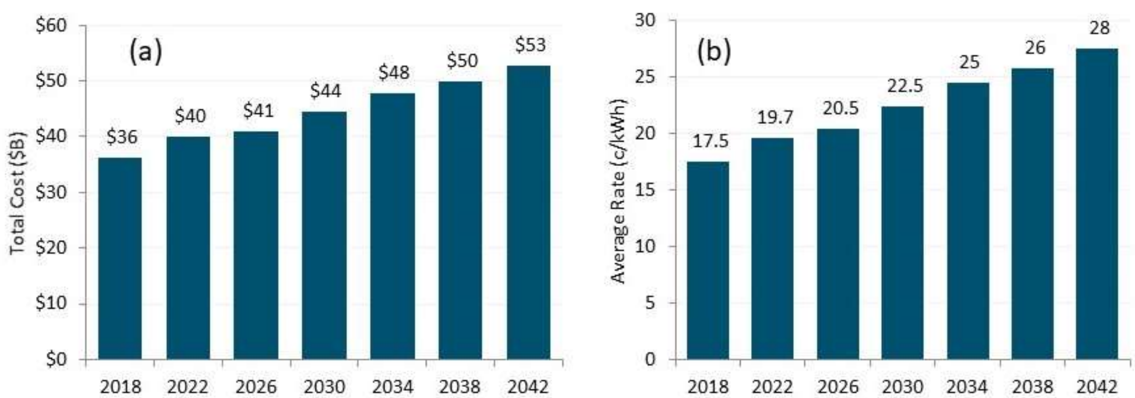


Figure 6 80% RPS by 2042 scenario (a) Total investment; (b) Electric costs

The higher electric costs in 2018 for the 80% RPS indicate that efforts must already be under way in order to meet these costs. Lack of such efforts may lead to substantive back loading of investments which may cause other issues. Results for RPS targets of 50, 60, 70, and 80%, including the GHG emissions, cumulative capital investment and the electricity costs for the respective target years are summarized in Table 1. As explained in the footnote to the Table, the 50% RPS scenario with 30 MMT GHG emissions represents a more stringent GHG cap option compared to the baseline 42 MMT GHG scenario. The results presented are sample cases that explore higher renewable portfolio options and are not intended to be optimal scenarios for the respective RPS values.

Table 1 Selected California RPS scenario results

RPS target	Target year	GHG emissions, MMT CO2e	Total investment, billion USD	Electricity cost, c/kWh
50%+	2030	42	39	19.9
50%*	2030	30	40	20
60%	2030	24.3	41	20.9
70%	2040	19.4	50	26
80%	2042	17.9	53	28

+ Large Share of Economy-Wide Emissions Reductions Scenario: The electric sector achieves an emissions level by 2030 that is equivalent to the lower end of the range attributed to it in CARB's Draft Scoping Plan Scenario (42 MMT by 2030) [23]; * Extra Large Share of Economy-Wide Emissions Reductions Scenario: The electric sector achieves an emissions level by 2030 equivalent to what is attributed to it in CARB's Alternative 1 scenario (30 MMT by 2030); this implies that additional electric sector investments beyond those included in the CARB's Draft Scoping Plan Scenario are used to achieve the state's GHG emission reduction goals [23].

Considerable uncertainty is seen higher RPS scenarios, especially above 50%, with significant variation in new buildouts and costs. Thus the power costs vary widely – the results shown here represent some of the lower cost portfolios. The high renewables scenarios shown here result in up to 10% curtailment of renewables with the curtailment increasing considerably under options without significant storage capacity. All scenarios evaluated result in significant GHG reductions compared to the Business As Usual (BAU) trajectory of 65 MMT CO_{2e} GHG emissions from the electric sector in 2030 presented in the Scoping Plan. The representative 50% RPS case from the Scoping Plan results in 42 MMT CO_{2e} emissions compared to the BAU scenario.

As the carbon intensity of the state's electricity supply decreases along with increasing renewables percentages, the GHG mitigation effectiveness of the investment decreases. Figure 7 shows that the ratio of new renewables investment over each million tons of GHG reduction increases considerably at higher RPS values. These investments do not include routine grid management costs not associated with the renewables mandate. The ratio provides insight into the potential carbon abatement costs for increasing RPS targets.

As with the electricity costs, the marginal CO_2 cost varies significantly depending on specific RPS values and assumptions. For the scenarios evaluated until 2030, the values range from no additional costs at lower values to over 200 $/ton CO_{2e} avoided for the higher RPS scenarios. Carbon mitigation costs of are reported in a number of studies in the literature using a wide range of approaches [11, 25-33]. However, detailed studies evaluating the uncertainties and sensitivities of very high RPS scenarios are currently not available [34]. The costs depend on the underlying assumptions, the benefits estimated, methodology and specific renewable energy scenario. Literature values are in a comparable range with the costs estimated here, although caution should be used in direct comparison since underlying assumptions vary significantly. A relevant study is the evaluation of higher RPS values in California by E3 using the Resolve model [15]. The study estimated a 9-23% rate increase for a 50% RPS by 2030 scenario compared to a 33% RPS, with the implied cost of carbon abatement approximately ranging from $50 to $400 per tonne depending on the specific scenarios and assuming that all costs of a higher RPS are attributed to GHG emission reductions.

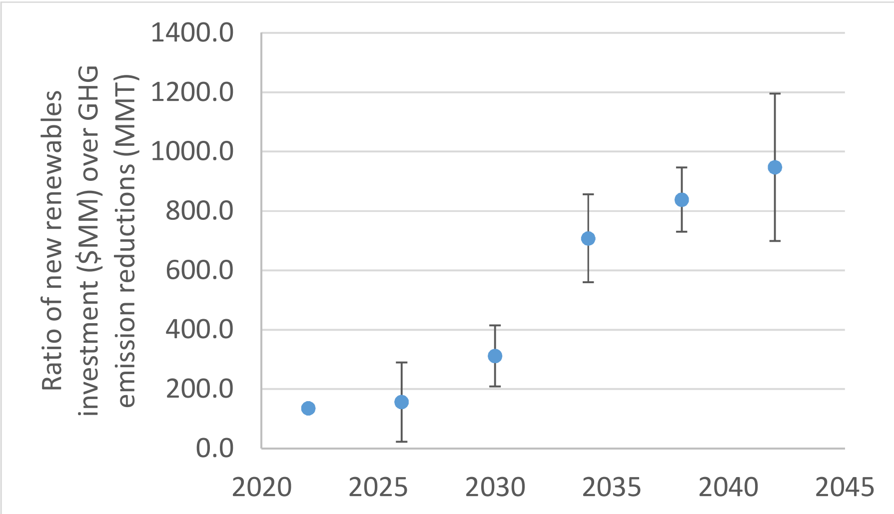


Figure 7 Ratio of new renewables investment over GHG reduction under the 2042 80% RPS scenario

As part of the State's Integrated Resource Planning (IRP) process, the CPUC has recommended GHG planning prices for the load serving entities [23, 35]. The planning prices are based on the marginal CO_2 abatement costs estimated using the Resolve model for the 50% RPS by 2030 with a 42 MMT CO_{2e} emissions scenario from the CARB's scoping plan. The costs range from approximately $17 in 2020 to $150 in 2030 [35]. The scoping plan also provides estimated cost per metric tonne of GHG emission reduction for a number of strategies. Table 2 provides the reduction costs for select strategies from the scoping plan [5]. Details and assumptions used in the calculations are available in the scoping plan. It should be noted that the costs for 5% increased RNG use are estimated by modeling hydrogen blending into the gas pipeline and do not accurately reflect the GHG reduction cost of RNG produced from organic sources [5].

In summary, California's RPS program will integrate significant quantities of renewable generation into the electric grid and will play an important role in the State's climate strategy. The electric sector will achieve significant GHG emission reductions under the current program and potential higher RPS scenarios. Power cost and carbon mitigation costs increase with increasing RPS values and vary widely depending on specific scenarios. Cost alleviation will require modernization of the grid, including increased storage capacities, state of the art demand response, increased electrification, regional integration, resource diversification. Very high renewables scenarios beyond the current targets will pose increasingly complex logistical, technological and economic challenges.

Table 2 Estimated GHG reduction costs of select strategies from CARB scoping plan [5]

Measure	Cost/metric ton in 2030	Cost/metric ton 2021-2030
50% RPS	$175	$100 - $200
Liquid Biofuels (18% CI Reduction Target LCFS)	$150	$100 - $200
Short-Lived Climate Pollutant Strategy	$25	$25
10% increase in RPS + 10 GW behind the meter solar PV	$350	$250 - $450
Liquid Biofuels (25% CI Reduction Target for LCFS)	$900	$550 - $975
30 percent Refinery	$300	$175 - $325
25 percent Industry	$200	$150 - $275
25 percent Oil and Gas	$125	$100 -$175
5% Increased RNG	$1500	$1350 -$3000

B. Renewable Gas Standard (RGS) Evaluation

1. Background

Renewable Natural Gas (RNG) is pipeline quality gas that is fully interchangeable with fossil natural gas but is produced from a renewable feedstock and can be used as a 100% substitute for, or blended with, conventional natural gas streams [36]. RNG can be produced from most renewable carbonaceous feedstocks. However, technological requirements, production efficiencies and costs vary significantly depending on the feedstock and conversion technology. The distributed nature of the feedstocks can limit commercial facility capacities and eliminate potential cost savings due to lack of economy of scale. However, a number of resources can be readily converted into meaningful quantities pipeline quality renewable gas using existing, commercially mature technologies. Additional commercial technologies are needed to economically convert all available carbon resources into a high value gas and advances are anticipated in the near to mid-term. For example, most resources cannot be mixed together and processed in the same facility with a few exceptions such as the co-digestion of food waste with biosolids [37]. This necessitates a feedstock by feedstock and project location approach to commercial development where many factors must be accounted for, including resource type, resource ownership and cost, logistic challenges, infrastructure availability (ex., access to pipelines), technology selection, commercial viability, and permitting requirements. Most of these considerations apply to other renewable energy technologies such as solar and wind as well.

A key objective of this study is to identify resources and technologies that constitute the most cost effective and practically viable pathways to increasing renewable methane production in significant quantities in California. The estimates provided here were developed using the most readily available feedstocks, commercially mature conversion technologies and the most cost effective development strategies. The most competitive cost and emission reduction benefits through RNG use are often realized through the conversion of organic waste matter and by using the RNG for transportation purposes [38].

In the RNG production context, it is useful to classify organic waste into wet and dry waste matter. Wet wastes include very high moisture content feedstocks such as biosolids, cattle manure, commercial food waste (consisting of inedible fats, oils and grease from commercial and industrial facilities), and food and yard waste diverted from landfills. Wet wastes are easily decomposed in anaerobic digestors under moderate process conditions. Dry feedstocks include cellulosic plant matter such as agricultural and forest residues and other biomass that must be converted through thermochemical processes or typically be pretreated to break down the cellulose before bioconversion [39]. Dry resource materials generally offer more concentrated feedstocks and significantly higher fuel production potential but conversion is often expensive relative to wet feedstocks due to additional processing requirements. Renewable methane, along with carbon dioxide and other trace chemicals, is also produced in landfills through waste decomposition over time. Most of the waste matter, when not properly disposed and air emissions controlled, result in methane emissions to the atmosphere.

Currently, RNG is commercially produced through (1) landfill gas upgrading, and (2) wet waste conversion through anaerobic digestion. The estimates presented here are based on the feedstock/resources listed below. Anaerobic Digestion is used to convert the three feedstocks other than landfill gas.

- Landfill gas upgrading
- Animal manure
- Biosolids from Wastewater Treatment Plants (WWTPs)
- Food and green waste

The following sections discuss California's RNG production potential, the carbon intensity of RNG from the above feedstocks, production costs, and associated GHG mitigation.

Renewable Gas Standard (RGS)

Policies to reduce the carbon intensity of energy use sectors and to improve air quality are the main drivers of renewable fuels production. Government support in the form of specific policy measures and incentives has played an important role for renewable fuels production to reach levels that can have a significant impact on net GHG emissions. In this context, a renewable gas standard, similar to the renewable portfolio standard (RPS) for power generation, has been advocated [40, 41]. An RGS would require increasing percentages of renewable gas to be injected into the natural gas pipeline infrastructure to meet specific renewable percentage targets compared to total natural gas consumption. Such a policy would provide an enhanced framework and the regulatory driving force that can substantially increase renewable gas production and use in the state. Besides carbon reduction incentives, the policy would also create certainty in the market and better attract project developers.

This study evaluates potential production in this context, evaluating the cost of production for increasing percentages of RNG addition to the pipeline and storage infrastructure. The results show that a 5% RGS can be met using readily available feedstocks and existing carbon credits under the Low Carbon Fuel Standard (LCFS) and Renewable Fuel Standard (RFS) programs with some refinement. California's LCFS program, originally adopted in 2009, is a technology-neutral standard aimed at reducing the carbon intensity (CI) of the state's transportation fuel pool by at least 10% by 2020[6]. The program sets CI values for fossil and renewable fuels using a Life Cycle Analysis approach. Tradeable credits are issued for low carbon fuels based on the life cycle CI values whereas deficits are imposed for high CI fuels. The RFS is a federal program aimed at reducing GHG emissions while expanding the nation's renewable fuels sector by requiring a certain volume of renewable fuel to replace fossil fuels[7]. The federal RFS program uses credits referred to as Renewable Identification Numbers (RINs) that are generated by renewable fuel producers and can then be traded[8].

Resources are also available to meet higher RGS percentage targets, although at increasing costs of production. The results in the following section are not for all available feedstock, but for select categories and quantities that constitute the most commercially attractive scenarios. Existing policy drivers for RNG include California's LCFS program and the US Renewable Fuel Standard program.

2. Methodology

Carbon Intensities of RNG Pathways

The carbon intensity (CI) of RNG from different sources is based on generic pathways for each resource in California's LCFS program [42]. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is widely used in Life Cycle Analysis (LCA) studies, especially in the United States [43]. The LCFS pathway CI values are calculated using the CA-GREET 2.0 Tier 2 model. The CA-GREET model is a modified version of the GREET model consisting of California specific assumptions.

The key GHGs considered in the LCA are CH_4, CO_2, N_2O, and Chlorofluorocarbons (CFCs). The 100 year Global Warming Potential (GWP) values published by the Intergovernmental Panel on Climate Change (IPCC) in 2007 are used in the calculations [44]. The LCA for fuels is typically performed in two parts, the Well-to-Tank (WTT) and Tank-to-Wheels (TTW) estimates. The final full life cycle emissions and energy consumption information, i.e., Well-to-Wheels (WTW), is obtained by adding the two parts. The Well-to-Tank section accounts for all the fuel production steps such as resource extraction, fuel production, transport, storage, distribution, and marketing. Facility fabrication and facility decommissioning during these steps are not taken into account. The Tank-to-Wheels part takes into account the emissions during the vehicle operation. Vehicle manufacturing and vehicle decommissioning are not taken into account during this stage. Current LCA studies overwhelmingly focus on performance per unit of fuel produced, e.g. MJ, of fuel instead of performance per hectare or other units of the land used. Conventionally, demolition and recycling of the process plants have not been studied in detail [45]. The GHG emissions for each pathway are calculated for each GHG and are reported on a carbon dioxide equivalent (CO_2e) basis using the GWPs.

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[6] https://www.arb.ca.gov/fuels/lcfs/lcfs.htm
[7] https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard
[8] https://www.epa.gov/renewable-fuel-standard-program/renewable-identification-numbers-rins-under-renewable-fuel-standard

Table 3 Carbon Intensities of RNG Production Pathways [46]

Pathway	**kg CO_{2e}/mmBtu**
California ultra low sulfur diesel (fossil fuel)	107.7
Natural gas (fossil fuel)	84.3
RNG - Landfill Gas	36.8
RNG - Wastewater Biogas	8.2
RNG - Food/Green Waste Biogas	-24.2
RNG - Dairy Biogas	-288.2

Table 3 lists the CI values for select pathways. Ultra Low Sulfur Diesel (ULSD) from average crude oil refined in California and North American fossil natural gas are listed for comparison purposes. The dairy biogas and the food/green waste pathways have negative CI values (i.e., greatest climate benefits) due to emission credits as methane destruction is currently not mandated for these pathways [47]. The LCFS credits assigned for low carbon intensity fuels are critical for renewable competitiveness at this time. Incentives such as renewable credits have played an important role in the introduction and commercial production of low carbon intensity fuels and power.

California RNG Potential

Several estimates of current biomass resources in California are available in the literature [48-52]. The estimates vary depending on the assumptions and the data sources. Jenkins et al. [48], conducted a study assessing the potential biomass quantities available and estimated that the state has roughly 30 million metric tonnes (MMT) per year of in-state biomass production. These resources are equivalent to more than 2 billion gasoline gallon equivalents (gge) of energy, equivalent to approximately 253 bcf of RNG. A study conducted by Milbrandt et al. for the National Renewable Energy Laboratory (NREL) estimated the net amount of biomass resources available in California to be 13.4 MMT/yr [53].

Estimates of RNG potential from these resources have also been reported [40, 54]. A 2014 report by the Bioenergy Association of California focused specifically on RNG production potential in the state [40]. The authors report that the state has the potential to generate approximately 284 billion cubic feet (bcf) per year of renewable methane from organic matter. This is more than 10% of California's total natural gas consumption and is equivalent to about 2.2 billion gge of transportation fuels. A 2017 study by Parker et al., estimated a gross RNG potential of 90 bcf per year from wet feedstocks with approximately seventy five percent of the resources being economically viable under current policy [54]. A select list of production potential values reported in the literature are provided in Table 4. The assumptions and calculation methods used to estimate the potential are available in the specific references.

Individual resource estimates are also available, for example the landfill methane project database of US EPA's Landfill Methane Outreach Program (LMOP) and AgSTAR programs offer nationwide databases of landfill gas projects and livestock farm anaerobic digesters respectively [55, 56]. A study by Krich et. al. reported that the state has the potential to produce 23 bcf of methane per year from all the biodegradable sources and the biodegradable components from dairies can alone produce 14.6 bcf per year [57].

Table 4 California RNG Production Potential Estimates in Literature

Reference	Comments	Estimated CA RNG potential, bcf/year
Parker et al., ASU & UC Davis, 2017 [54]	Wet feedstocks	90
Penev et al., JISEA, 2016 [58]	Wet feedstocks, agricultural residues, forestry residues	110
Sheehy & Rosenfeld, ICF, 2017 [41]	Wet feedstocks, agricultural residues, forestry residues	105-208
Levin et al., Bioenergy Association of California, 2014 [40]	Wet feedstocks, agricultural residues, forestry residues	284
American Gas Foundation, 2011 [59]	Wet feedstocks, agricultural residues, forestry residues	52-129

The key assumptions used in RNG production cost estimates are discussed below.

RNG production technology and cost vary widely based on feedstock type, conversion technology, end use purpose and other factors. An important variable is the quantity of feedstock available for processing in a single commercial facility. A number of capital and operating cost estimates are available for different RNG facilities, including both real world cost data from existing plants, and estimates based on anticipated costs [38, 41, 50, 54, 58, 60-62]. This study uses California specific cost data from published studies to evaluate specific production pathways at increasing RGS percentages. All scenarios assume that the RNG is upgraded to pipeline quality and is injected into the nearest natural gas pipeline with sufficient capacity [63]. Pipeline interconnection costs used in this study reflect the current environment in California [54, 61, 62, 64]. The pipeline injection assumption provides conservative production cost estimates and is used to evaluate production costs from all resources using the same basis. In practice, the RNG is likely to be used for a range of applications such as refueling, commercial use, power generation, etc. RNG injected into the pipeline will be blended with fossil gas and will be stored, distributed, and used through the natural gas infrastructure and end use technologies. The ultimate life cycle GHG emissions benefits will be affected by the efficiencies, leakage rates, and governing regulatory requirements of the infrastructure and technologies. These aspects are outside the scope of this study and are not assessed as part of the analysis unless stated in the assumptions.

The production cost estimates were conducted using an Excel based discounted cash flow model. The following assumptions are common for all scenarios. No carbon credits or feedstock tipping fees are assumed in the production cost estimates.

- Plant startup year: 2018
- Project economic life: 15 years
- Analysis Methodology — Discounted Cash Flow (DCF)
- Average annual plant capacity factor: 93%
- Equity financing: 20%
- Debt: 80%
- Interest rate on debt: 6%
- Discount rate: 8%
- Depreciation schedule length: 7 years
- Depreciation type: Modified Accelerated Cost Recovery System (MACRS)
- Internal rate of return (IRR): 12%
- Tax rate: 35%

3. Results

a) *Landfill Gas*

Landfill gas (LFG) upgrading offers the most commercially attractive scenarios for RNG production. Since the gas is collected in the landfills, the capital expenses only involve cleanup/upgrading costs and pipeline interconnection. The available resources are estimated using the LMOP California landfills database [55]. As of June 2018, the database lists a total of 311 landfills in California with 235 landfills with existing collection systems. LFG production rates are available for 191 of the landfills with a number of existing LFG to power projects. The total LFG flow rate from the landfills is approximately 279 bcf. Besides CO_2 and moisture, LFG typically contains contaminants such as sulfur compounds, halogenated compounds, ammonia, silicon compounds and siloxanes. The CH_4 content varies from 45-65%. This report assumes a 50% recoverable CH_4 content in all raw LFG and biogas streams.

The cost of upgrading varies depending on the contaminants present and the technology choices. Meeting pipeline quality standards can be capital intensive and more difficult to achieve for smaller scale projects [65, 66]. The calculations are performed for three plant scales. The most commercially attractive facilities have an average production rate of 2 mmscf per day. The capital costs are estimated to be \$9.80/mmBtu of RNG produced with an estimated operating cost of \$5.2 per mmBtu [67]. The pipeline interconnection cost is impacted by distance to the pipeline and is assumed to be \$1 to \$2 million per project. The next group of projects have an average production rate of 0.75 and 0.5 mmscf per day. The capital costs are estimated using the base values through the six-tenths rule [68]. The interconnection costs include additional pipeline costs for lengths of 20 and 25 miles respectively [69]. As shown in Figure 8, the production cost for pipeline injection varies from \$6.9 to \$12.6 per mmBtu for increasing cumulative RNG production.

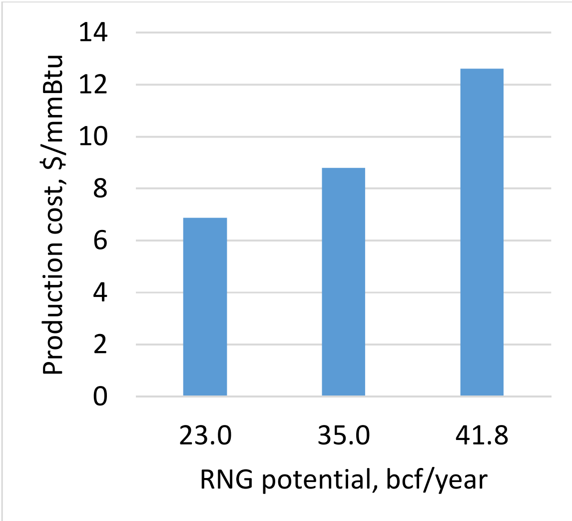

Figure 8 Production cost for RNG via LFG Upgrading

b) Animal Manure Feedstock

The animal manure available in California for energy production is estimated in a number of studies [49, 54, 57, 60-62]. Dairy and livestock methane emissions are an important part of California's Short-Lived Climate Pollutant (SLCP) reduction strategy. Since dairies are currently not mandated to capture and convert the methane emissions, RNG production from manure receives avoided methane credits, resulting in the lowest CI of all biomethane pathways (*Table 3*). Based on available resource estimates, we calculate the RNG potential from animal waste to be 17.8 bcf per year. A biogas yield of 0.24 cubic meters per kilogram of dry waste is assumed. For dairy digester projects, sufficient feedstock availability is often a challenge. A herd size of 10,000 cattle is assumed to produce sufficient manure for a single commercially viable project [60, 61].

For smaller dairies, clusters are created using the 'hub and spoke' approach. The approach is described by Bullard et al., [61] as follows: "The "hub" would involve a centrally located operation where raw dairy biogas could be gathered from a cluster of existing dairy operations. At the hub, the gas could be cleaned and conditioned to sufficient levels for use as fuel for electrical distributed generation (DG), upgraded to pipeline quality "biomethane" and sold as renewable natural gas (RNG) or upgraded for use as renewable compressed natural gas (RCNG) transportation fuel. The "spokes" would involve a gas gathering system of low -pressure polyvinyl chloride (PVC) pipelines that interconnect the cluster of participating local dairies." Based on California dairy data, it is assumed that 1.78 bcf of RNG can be produced from large single dairy projects without the need for a cluster [60]. The second group of projects are based on clusters with a cumulative potential of 8.9 bcf per year. The rest of the projects are smaller sized where clusters do not appear to have competitiveness. The capital cost is estimated to be $9.7 million for a single dairy project with 0.26 mmscf/day of production capacity and $16.2 million for a cluster project with the same capacity. The operating cost is estimated to be 7.5% of the capital costs. The smaller facility costs are estimated from the baseline values using the six tenths rule with an additional $1.5 million for pipeline and interconnection costs per project. Figure 9 provides the production costs and cumulative RNG potential.

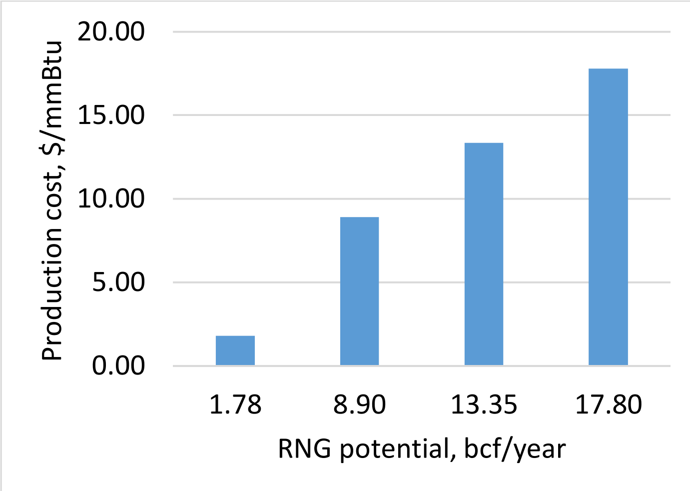

Figure 9 RNG Production cost for Dairy manure AD

c) Biosolids and Food/Green Waste Feedstock

The RNG production potential from AD of Wastewater Treatment Plant (WWTP) biosolids is estimated to be 8.4 bcf per year based on literature data [40, 64]. The project scales are assumed to be 3.6, 1.2, and 0.24 mmscf per day with a digester capital cost of $59 per mmBtu with additional gas clean/upgrading and pipeline interconnection costs [60, 64]. Several WWTPs have recently adapted the co-digestion approach where the biosolids can be supplemented with compatible feedstocks such as food wastes. Figure 10 shows the production cost and corresponding cumulative capacity for biosolids based RNG. For the food/green waste pathway, the total RNG potential is estimated to be 19.3 bcf per year [40, 49]. The digester, upgrading and interconnection costs are assumed to be the same as the biosolids pathway. The production costs and corresponding cumulative capacity for food/green waste based RNG are shown in Figure 11.

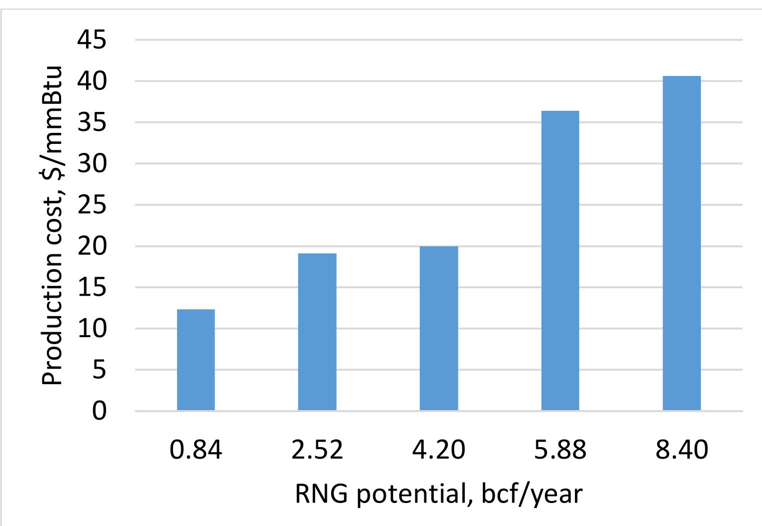

Figure 10 RNG Production cost for biosolids AD

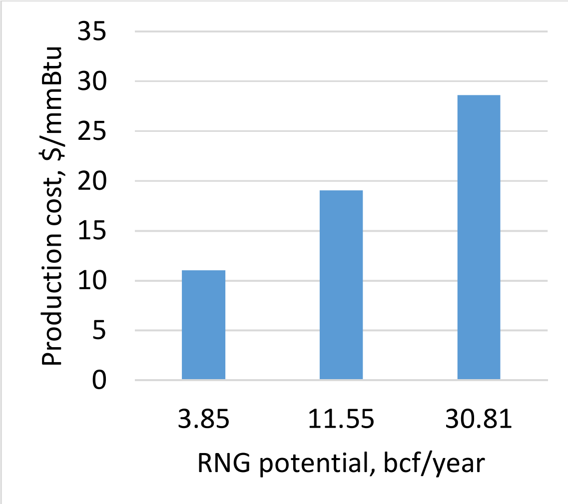

Figure 11 RNG Production cost for food/green waste AD

As the results show, the production costs vary significantly based on resource type, project scale, and other factors. For feedstocks such as biosolids and municipal solid waste that are typically transported to landfills, additional tipping fees often occur. The fees vary based on the location and disposal costs. The combined RNG production potential from the four groups of wet resources considered and the corresponding production costs are shown in Figure 12. The production costs range from approximately $6 to $68 per mmBtu. By comparison, the average 2017 natural gas citygate price was $4.16 [70]. Additional RNG production is technologically feasible, although increasing costs and logistical issues will pose significant challenges. Cellulosic biomass waste conversion through thermochemical technologies such as gasification offer an opportunity to address many of these challenges and considerably increase production potential.

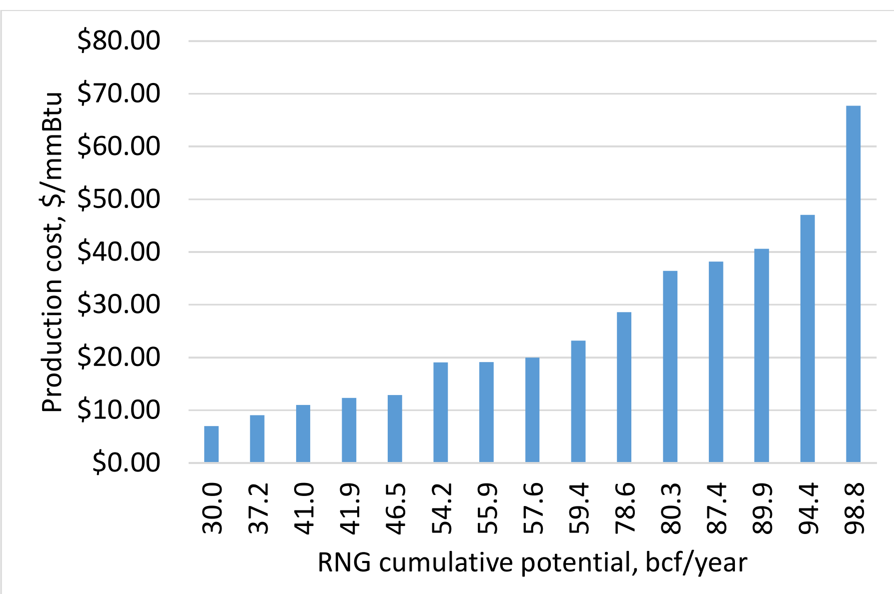

Figure 12 Combined RNG potential and production costs from select wet resources

d) *GHG Emission Reduction*

The GHG emission reductions achieved for each bcf of RNG produced is calculated using the CI values listed in *Table 3*. The net GHG reduction in million metric tonnes (MMT) per year for corresponding annual production numbers for the results described above are shown in Figure 13. The cumulative GHG reductions are equal to 11.4 CO_{2e} MMT. Figure 14 compares the California GHG emissions from forecasted natural gas use through 2030 with and without a 5% RGS assuming a CI value of 84.3 kg CO_{2e}/mmBtu for fossil natural gas [71]. These potential emission reductions are unlikely to be achieved in the near to mid-term through other measures. The total RNG production estimated in this report approximately represents enough volumes of RNG to satisfy a 5% RGS mandate for California. Under such a mandate, 5% of the total natural gas consumption in the state would be derived from the above renewable resources. This would be a valuable and consequential transition towards renewables with significant GHG emission reductions. For example, the state's current 2030 target is to reduce GHG emissions to 260 MMT CO_{2e} from the 2015 levels of 440 MMT CO_{2e}. Figure 15, from the CARB scoping plan, shows the estimated cumulative GHG reductions for select measures [5]. The cumulative GHG reduction of approximately 11.4 MMT CO_2e GHG per year achieved through a 5% RGS can make a meaningful contribution towards the state's GHG goals. It should be noted that the SLCP reduction strategy will capture some of the emission reductions included in the 11.4 MMT CO_2e GHG estimate. Increasing percentages of RNG supplies can play an important role in the overall strategy.

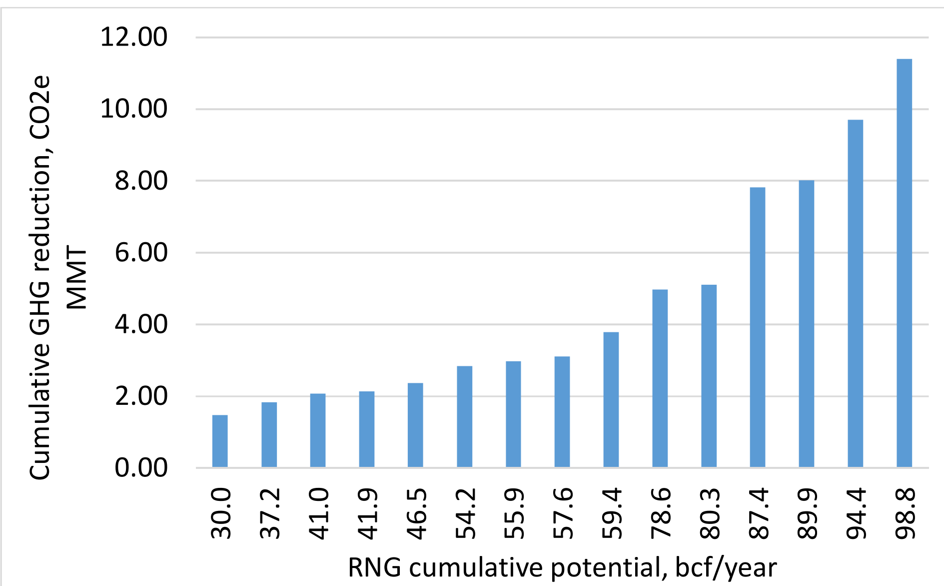

Figure 13 Total annual GHG reduction through RNG production and use

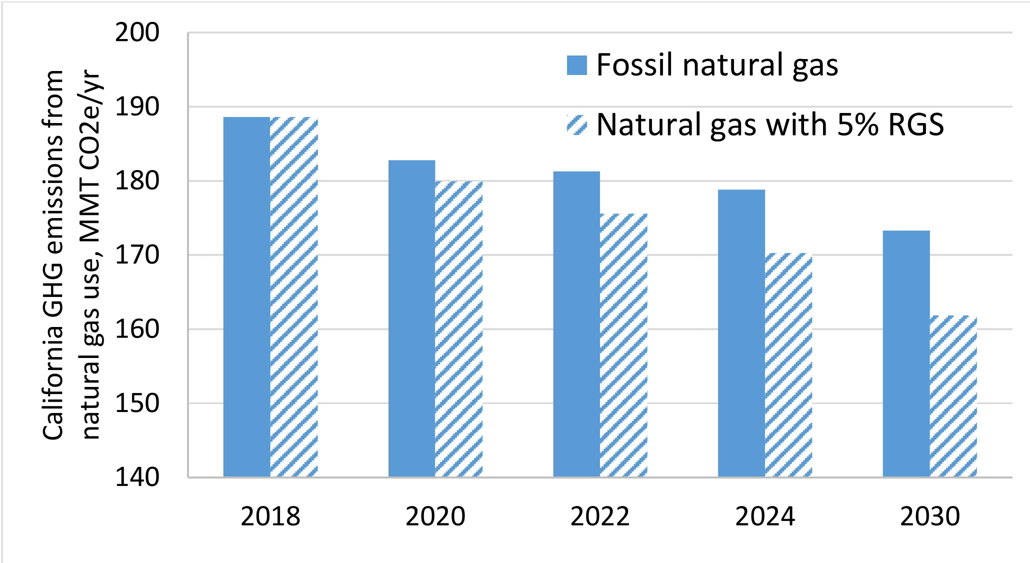

Figure 14 California GHG emissions from natural gas use with and without a 5% RGS

Additional benefits besides the GHG emissions include critical SLCP emission reductions and vastly improved waste management practices. *RNG also represents an important opportunity to reduce GHG and criteria and air toxic pollutant emissions from the heavy duty transportation sector that is heavily fossil fuel dependent*.

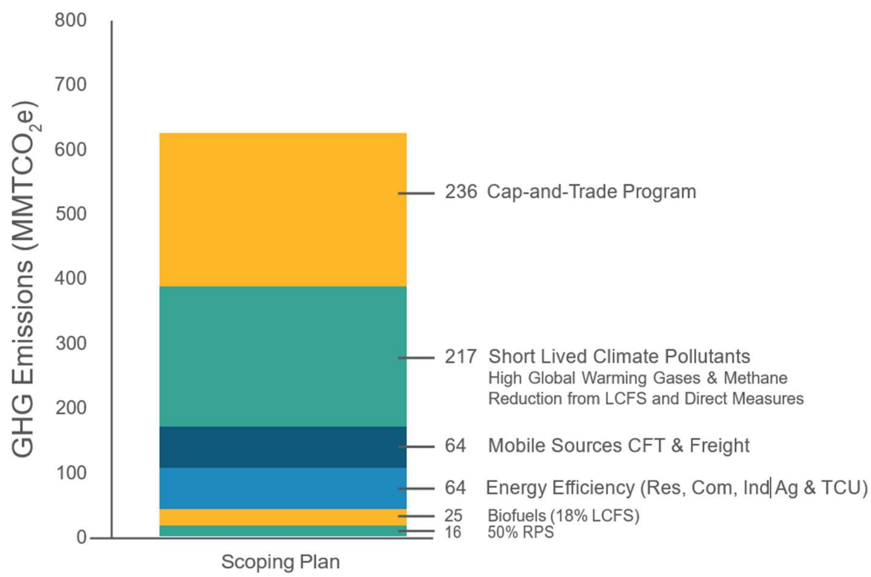

Figure 15 Estimated cumulative GHG reductions by measure from the CARB scoping plan [5]

The sales price of fossil and renewable natural gas is assumed to be $4/mmBtu throughout the calculations. The cost of avoided CO_{2e} GHGs is calculated assuming that each mmBtu of RNG produced received sufficient credits to meet the sales price. For example, if the production cost is $10/mmBtu for a particular batch of RNG, then a credit of $6/mmBtu would be necessary for that batch to be cost neutral. Although LCFS and RFS credits vary, in 2017, average credits of $26-$39 per mmBtu was available for RNG used for transportation through the RFS program whereas $4-$5 per mmBtu of credits were available through the LCFS program. The credit needed on an mmBtu basis for cumulative production potentials are shown in Figure 16 whereas the total credit dollars provided annually are shown in Figure 17. The cumulative credit dollars estimates range from $91 million for 30 bcf/yr to $205 million for 46.5 bcf and $411.5 million for 59 bcf respectively. The costs increase with increased production quantities and credits worth approximately $1.8 billion are estimated to be distributed through the 2030 timeframe for the total projected RNG potential. As the results show, continuation of government incentives or regulatory support is needed to maximize RNG production at this time consistent with the development and deployment cycle of other renewables. From a public policy perspective, this can be done via regulations or incentives or a combination of the two approaches.

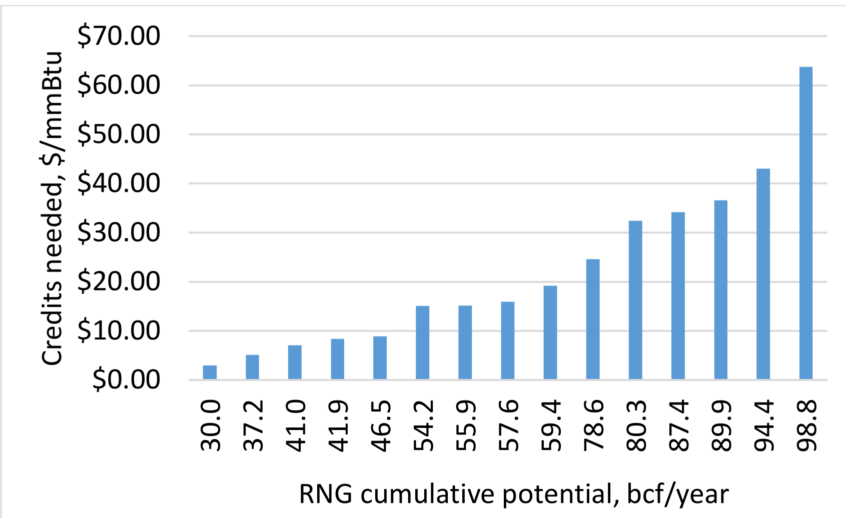

Figure 16 RNG carbon credits necessary to achieve a sales price of $4/mmBtu

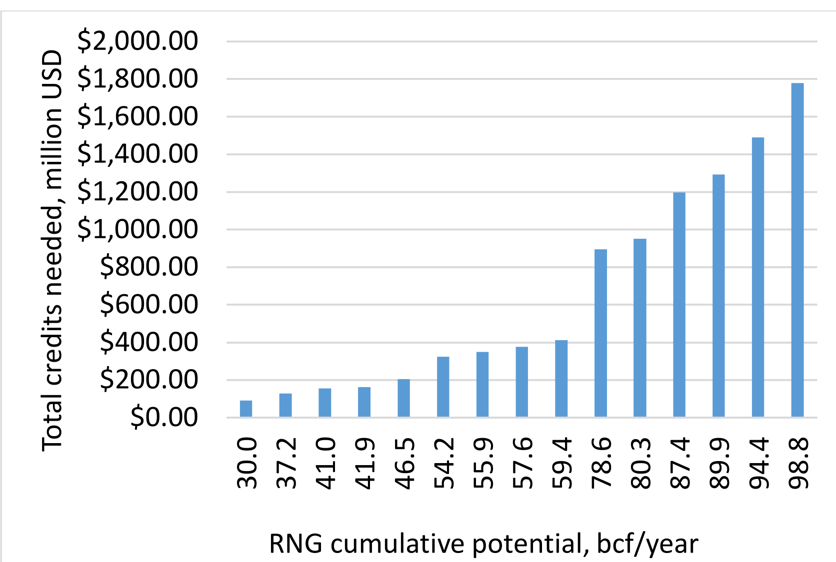

Figure 17 Total annual credit dollars necessary for select wet waste RNG production scenarios through the 2030 timeframe

RNG Production beyond 5% RGS

Current RNG production relies heavily on biological pathways such as anaerobic digestion that are well understood and are commercially mature but have limitations including limited feedstock acceptability, low conversion efficiency, and poor product quality. Two technology options that can enable RNG production in significant enough quantities to be meaningfully beneficial are Thermochemical Conversion and RNG production via water electrolysis (Power to Gas or P2G). Biomass is the most abundant renewable carbon source that can be converted into fuels and chemicals with a zero or very low carbon footprint. Unlike biological processes that only convert part of the biomass, thermochemical processes can generally convert all the carbon in the feedstock [39].Thermochemical conversion technologies such as gasification and pyrolysis can significantly increase RNG production from in-state resources. California's tree mortality rates epidemic and other factors have led to increased wildfire hazards. Thermochemical conversion of forest residues can help manage the issue while producing a renewable fuel. While technologies are available, thermochemical conversion is still undergoing commercialization, and accelerated technology development and deployment efforts are crucial in achieving greatly increased renewable energy production in the near to mid-term.

Converting excess renewable electricity into a gaseous fuel such as hydrogen or methane is very attractive since it offers a means to increase the renewable energy content of the pipeline infrastructure while addressing the well-known grid capacity and curtailment problems associated with electricity transportation. Since methane, and to some extent hydrogen, can be reliably stored for long periods using the existing infrastructure, Power to Gas can significantly 'decarbonize', i.e., reduce the GHG footprint of the State's natural gas supply. Thermochemical conversion and power to gas based RNG can enable increased ***renewable energy use in all major sectors*** including commercial, residential, and transportation.

IV. Results and Discussion

This study evaluates the potential for commercially viable RNG production in California using commercially mature technologies and in-state resources. California has some of the highest renewable methane resource potential in the United States. The resources include wet and dry feedstocks that include a wide range of sustainable, organic carbon sources. Wet feedstocks such as biosolids, cattle manure, and food and yard waste have a high moisture content and often pose a disposal problem. Wet feedstocks are attractive due to their reactivity in digesters and along with landfill gas upgrading, account for all commercial RNG production at present. Dry feedstocks are available in more abundant quantities but conversion is often expensive and involves technology challenges. A comprehensive survey of resource potential was conducted and the data was used to estimate RNG production potential from four groups: Landfill gas upgrading, animal manure, biosolids from WWTPs, and food and green waste. A cumulative potential of approximately 99 bcf of RNG is estimated to be available through the conversion of select quantities of these feedstocks.

The production cost for RNG from each feedstock type was calculated using data from a number of sources, including commercial facilities. The production cost estimates vary widely based on feedstock type, conversion technology, and other factors. An important variable is the quantity of feedstock available for processing in a single commercial facility. The estimates do not include any subsidies or incentives either for feedstock disposal (ex., tipping fees) or for fuel production (ex. LCFS credits). All scenarios assume that the RNG is upgraded to pipeline quality (definition) and is injected into the nearest natural gas pipeline. California specific pipeline interconnection costs are included in the estimates. The production costs vary from approximately $6 to $68 per mmBtu for the selected scenarios with the 99 bcf cumulative production potential. Additional RNG production is possible but at increasing costs and uncertainties. Landfill gas (LFG) upgrading offers the most commercially attractive scenarios for RNG production, although the costs are highly sensitive to feedstock density and vary widely for all feedstocks.

The GHG emissions avoided through RNG production by each feedstock/technology combination is calculated using the California LCFS CI values. All RNG pathways offer significant GHG emission reduction compared to fossil fuel alternatives with dairy biogas and the food/green waste pathways providing the greatest climate benefits due to the avoided methane credits. The 99 bcf RNG is estimated to result in a cumulative GHG reduction of approximately 11.4 MMT CO_2e per year. If currently available LCFS and RFS RIN credits per tonne of avoided CO_2 are granted, the value of the credits are sufficient for many of these RNG production pathways to meet a sale price of $4/mmBtu. Thus, these pathways are likely commercially viable under existing programs and offer an important opportunity to reduce fossil fuel use and mitigate GHG emissions. The average CO_2 avoidance costs for corresponding RNG production quantities are shown in Table 5.

Table 5 Cost of avoided GHG emissions through RNG use

Cumulative RNG production potential, bcf/year	Cost of avoided CO_2, $/tonne
55.2	$93
75.4	$202
98.8	$434

Policy related issues pose some of the biggest challenges to RNG project developers in California. Several policy measures have been adapted by the State that encourage renewable energy generation. However, programs that directly address specific technological and commercial issues related to RNG production are necessary to accelerate commercial production. A statewide renewable gas standard has the potential to address many of the challenges and enable commercial production in significant quantities. An RGS would require increasing percentages of renewable gas to be injected into the natural gas pipeline infrastructure to meet specific renewable percentage targets compared to total natural gas consumption. Such a policy would provide the enhanced framework and the regulatory driving force that can substantially increase renewable gas production and use in the state. Besides carbon reduction incentives, the policy would also create certainty in the market and attract project developers. The results of this study show that a 5% RGS can be met using readily available feedstocks with modification of the existing policy framework.

We also estimated the costs and emission reductions anticipated through current and potential future RPS scenarios for the state's electric sector. This analysis was aimed at identifying a baseline against which the costs and benefits of an RGS strategy can be compared. The results provide context for the magnitude of emission reductions achievable through an RGS program and the carbon abatement costs. We used Resolve, an investment and operations planning model aimed at addressing key planning challenges related to high renewables integration, to evaluate the RPS scenarios. Resolve is the model of choice of the CPUC for high renewables integration planning and is designed primarily to investigate investment driven by renewable energy targets. California RPS targets of 50 to 80% were evaluated using the Resolve model. The assumptions used in devising the scenarios are from the state' scoping plan and have been used to evaluate RPS options as part of the CPUC's IRP process. The 50% scenarios represent current mandates with specific added GHG caps and the other scenarios explore higher RPS possibilities. All scenarios evaluated result in significant GHG reductions compared to the CARB's baseline GHG estimate presented in the Scoping Plan. The baseline case, referred to as the Business As Usual (BAU) emission trajectory results in approximately 65 MMT CO_{2e} GHG emissions from the electric sector in 2030 compared to the 42 MMT CO_{2e} emissions for the representative 50% RPS case. The electricity costs and the marginal CO_2 costs vary significantly depending on specific RPS values and assumptions. Considerable uncertainty is seen higher RPS scenarios, especially above 50%, with significant variation in new buildouts and costs. As part of the State's IRP process, the CPUC has recommended GHG planning prices for the load serving entities. The planning prices are based on the marginal CO_2 abatement costs estimated using the Resolve model for the 50% RPS by 2030 with a 42 MMT CO_{2e} emissions scenario from the CARB's scoping plan. The costs range from approximately $17 per ton of CO_2 in 2020 to $150 per ton of CO_2 in 2030. It is highly likely that under very high potential RPS values, the costs will increase significantly while renewables integration will pose complex challenges. Cost alleviation would increasingly rely on electrification of transportation and other sectors, demand response through shedding and shifting of loads, and considerable storage needs. Implementation timeframes for these mitigation approaches are subject to several external factors including technology advancement and the state's economy.

The results of this study show that *the carbon abatement costs through RNG production are comparable to other regulatory approaches*, including the successful renewables portfolio standard. GHG emissions are often intricately tied to the local, national and global economies, quality of life, and other factors. The cost and effectiveness of each approach is affected by these factors and capturing the full abatement potential is a complex challenge. A diverse portfolio of approaches is important in order to achieve emission reduction from different source categories and to minimize risk. Thus, *an optimal GHG mitigation strategy should incorporate RNG production and use and other complimentary mitigation strategies that represent all the key pathways with high mitigation potential*.

The rate of net CO_2 emissions reduction across the world are significantly slower than the rates needed to avoid an average 2 °C warming. SLCP emission reduction has evolved as a key strategy that can potentially reduce global average climate warming by approximately 0.6 °C by 2050 [7]. California must achieve deep SLCP emissions reduction by 2030 in order to meet the State's GHG emission and air quality targets. RNG has the potential to play a key role in the state's SLCP reduction strategy.

More importantly, an RGS program would address emissions from sources that would not be mitigated through the decarbonization of the electric grid. Agriculture and waste management activities in the state represent an important segment of the GHG emissions, including short lived climate pollutants (SLCP) with high GWP values. Encouraging RNG production from renewable carbon feedstocks will create a sustainable carbon recycling program that will mitigate net emissions to the atmosphere from these sources. In the absence of clean energy production, these emissions will likely remain unmitigated. Methane destruction through combustion, as in landfills, reduce SLCP emissions but represent waste energy that could replace fossil fuels. An RGS program will not only replace fossil fuels in California but will also promote the advancement of conversion technologies that will likely be deployed around the world. Renewable methane is a well-known alternative fuel in many countries and is often produced in both rural and urban regions, albeit using inefficient approaches. Cost effective technology options can increase renewable gas use while reducing biomass burning and fossil fuel use.

Recommendations

The benefits of replacing fossil fuels with RNG are broad and multifaceted. A key advantage of RNG compared to other renewable fuels is its potential to make significant contributions immediately in the transportation sector. RNG has the unique advantage of a mature, and extensive storage and distribution infrastructure and the availability of NG vehicle technologies. By comparison, building up a dedicated hydrogen infrastructure in the U.S. is expected to take decades and cost $70 billion [72]. Fungible (drop-in) liquid transportation fuels (ex. Fischer-Tropsch diesel) from biomass are the only renewable alternative with a mature infrastructure and end use technology availability but are widespread commercial production of such fuels has not been achieved.

The benefits of RNG use beyond GHG emissions reduction include reduced landfilling of waste, criteria and toxic pollutant emission reductions compared to other fossil fuels, and SLCP emission reductions. The climate benefits of RNG will also be realized regardless of the end use technology and location. However, the significant local air pollution reductions will be best achieved through RNG use in the heavy duty transportation sector, especially in non-attainment areas.

Recommendations and next steps to realize RNG’s potential role in California’s climate strategy are:

- Address the key barriers to commercial RNG production and use; and develop strategies to expedite production.
- Further incorporate renewable gas production and other CO_2/methane mitigation strategies as part of an optimal climate mitigation approach that takes advantage of all pathways with high GHG reduction potential.
- Develop an enhanced policy framework that will enable renewable natural gas production in significant quantities from in-state resources building on current capture mandates (SB 1383) which can jump start in-state production but produce modest volumes.

- Adopt an RGS with gradual increased percentage thresholds to help provide stable financing for expanded RNG production to assist in cost effective GHG reductions. To further expand RNG supply potential and facilitate cost effective GHG reduction, consider policies that enable continued out of state supply of RNG, not unlike out of state electric resources enabled under current RPS requirements.

Given the far reaching consequences of a potential 2 °C global average temperature rise and the urgency in preventing it, every meaningful GHG reduction strategy must be pursued seriously. Renewable natural gas can play a unique and significant role without excluding other approaches and represents an immediate opportunity. As the global leader in combating climate change, California is the ideal candidate to demonstrate the realization of RNG's potential.

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