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Article

Market Potential for CO_2 Removal and Sequestration from Renewable Natural Gas Production in California

Jun Wong, Jonathan Santoso, Marjorie Went, and Daniel Sanchez*

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ABSTRACT: Bioenergy with carbon capture and sequestration (BECCS) is critical for stringent climate change mitigation but is commercially and technologically immature and resource intensive. State and federal fuel and climate policies can drive first markets for BECCS in California. We develop a spatially explicit optimization model to assess niche markets for renewable natural gas (RNG) production with carbon capture and sequestration (CCS) from waste biomass in California. Existing biomass residues produce biogas and RNG and enable low-cost CCS through the upgrading process and CO_2 truck transport. Under current state and federal policy incentives, RNG-CCS can avoid 12.4 mmtCO_2e/year (3% of California's 2018 CO_2 emissions), of which 2.9 mmtCO_2/year are captured and sequestered. It simultaneously produces 93 PJ RNG/year (4% of California's 2018 natural gas demand) with a profit maximizing objective, resulting in profits of \$11/GJ. Distributed RNG production with CCS can potentially catalyze markets and technologies for CO_2 capture, transport, and storage in California.

KEYWORDS: *Biogas, Carbon capture, Renewable natural gas, BECCS, Niche markets*

■ INTRODUCTION

Deep decarbonization of the energy system critically relies on bioenergy with carbon capture and sequestration (BECCS) to produce low-carbon and carbon-negative products such as heat, electricity, and fuels.[1] Current BECCS deployment has been lagging the scales envisaged in century-scale climate change mitigation scenarios. Instead, it is limited to a handful of demonstration projects in corn ethanol and waste-to-energy production[2−4]. On the basis of this disparity, some have argued for a "bottom-up" approach to BECCS commercialization based on niche markets, scale-up, regionally appropriate feedstocks, and local policies[5−7]. In these contexts, small-scale (megatonne scale) commercially viable opportunities for BECCS are necessary to promote more widespread adoption of carbon removal. Establishing first markets for BECCS use can incentivize and accelerate innovation in carbon removal. Thus, technology and policy analyses identifying opportunities with existing infrastructure and technologies are critical to building these first markets—doing so enhances mitigation efforts by developing experience in carbon capture, transport, sequestration, and removal.[2]

In recent years, California's waste management policies have supported increased biomass utilization. SB-1383, signed into law in 2016, is a broad methane reduction strategy in California that targets a 40% decrease in methane emissions by 2030 and a 75% decrease in organic waste sent to landfills by 2025. The bill specifically targets dairy emissions; it requires a 40% decrease of dairy production-related methane emissions by 2030. Beyond dairy, the legislation targets a 50% reduction in the level of the statewide disposal of organic waste from the 2014 level by 2020 and a 75% reduction by 2025.[8] SB-1383 necessitates innovative methods to process waste biomass. Anaerobic digestion, electricity generation, biochar production for land application, and composting are all methods that can utilize the available biomass residues to potentially meet the SB-1383 goals. Of these applications, RNG-CCS through anaerobic digestion is a particularly attractive candidate that meets both the organic waste diversion and methane emissions goals while producing carbon-negative fuels and catalyzing first markets for BECCS. Most recently, the California Public Utilities Commission (CPUC) proposed a decision that would dramatically expand RNG production.[9] Here, we explore the viability of RNG-CCS to create first markets for BECCS in California.

California is well positioned for BECCS implementation. The state's economy yields large volumes of waste biomass from agricultural, forestry and urban activities. In total, California produced 54 million bone dry tons (bdt) of biomass residues in 2018.[10] The volume of biomass residues is projected to grow to 71 million bdt per year by 2050.[10] At the same time, California's geography is well suited for CO_2 storage.[11] Over 24,000 km^2 of nonurban area in the Central

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Valley, Bay Area, North Coast, and greater Los Angeles area (10% of California's total land area) is suitable for CO_2 sequestration (Figure 1). In total, the state has over 200 $GtCO_2$ of total sequestration capacity.

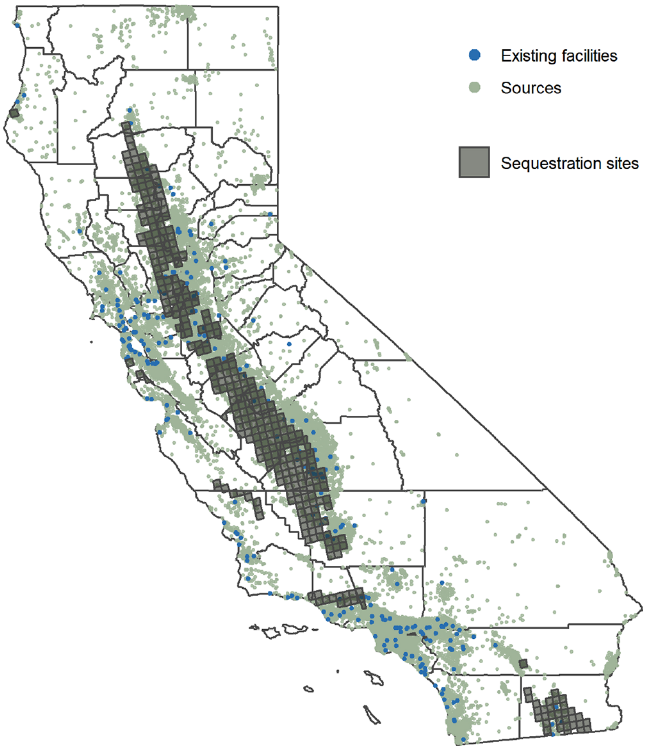


Figure 1. Available biomass residues, existing digesters, and potential CO_2 sequestration sites in California available biomass residues (green), existing anaerobic digesters and landfills (blue), and potential CO_2 sequestration sites (gray) in California. Colocation of residues, existing digesters, and potential CO_2 sequestration sites across California reduces biomass and CO_2 transportation costs.

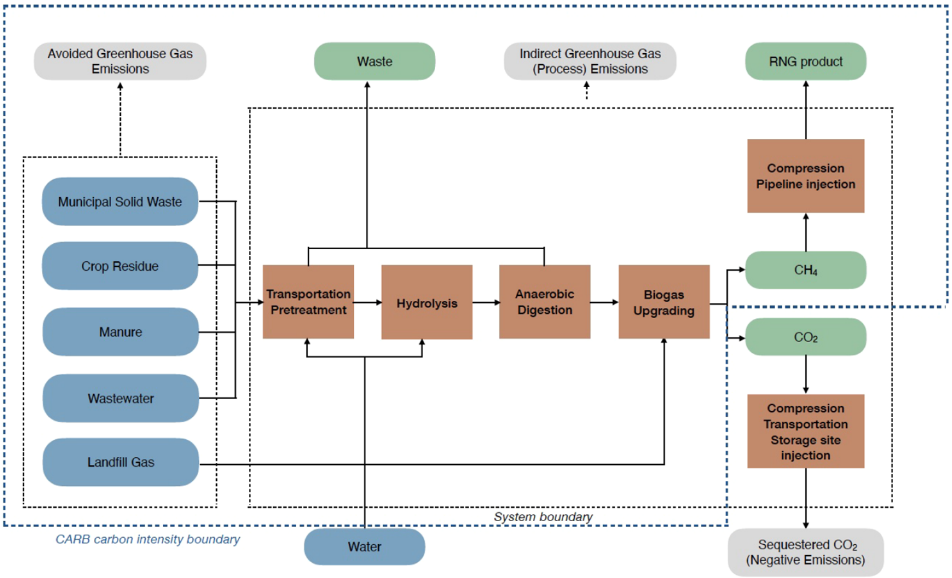
Current state and federal fuel and climate policies can drive first markets for BECCS in California. In particular, California's Low Carbon Fuel Standard (LCFS), federal 45Q carbon sequestration tax credits, and the federal Renewable Fuel Standard (RFS) can all be used to incentivize BECCS. Established in 2011, California's LCFS provides financial incentives for low-carbon and carbon-negative transportation fuels through tradeable CO_2 abatement credits.[12] In 2019, California's Air Resources Board amended the LCFS to allow CCS projects to generate additional LCFS credits.[13] Abatement credits are performance based, proportionate to the carbon intensity reduction relative to a benchmark fossil fuel. Historical credit prices ranged from \$160−\$192 per ton of CO_2 abated between 2018 and 2020.[14] In 2018, the federal government enhanced its existing tax credit for geologic CO_2 sequestration (45Q), providing tax credits of \$50/tCO_2 sequestered for dedicated storage for facilities capturing over 100,000 tCO_2 per year.[15] The federal RFS subsidizes the production of renewable fuels through the distribution of renewable identification number (RIN) credits. Biofuels are eligible to receive different classes of RIN credits on a volume basis (one credit is a gallon gasoline equivalent (GGE)); lignocellulosic biofuels receive D3 credits, which are often traded at higher prices, while "advanced" (noncorn starch) biofuels receive D5 credits. D3 credits have traded at 0.59−2.74 \$/GGE in 2018−2020, while D5 credits have traded at 0.38−0.85 \$/GGE.[16]

The production of RNG for use as transportation fuel coupled with CCS allows producers to leverage the policy incentives described above. Depending on the feedstocks used in the production of RNG, the end product could qualify for either D3 or D5 RIN credits under the approved Q and T pathways. Specifically, pathway Q states that any renewable compressed natural gas produced from biogas from landfills, wastewater treatment facility digesters, agricultural digesters, and separated MSW digesters qualify for D3 credits. Pathway T states that any renewable compressed natural gas produced from biogas from waste digesters qualify for D5 credits. Note that while separated MSW digesters, wastewater digesters, and landfill gas are classified as "cellulosic biofuels" under pathway Q and therefore qualify for D3 credits, in practice, codigestion requires producers to verify the cellulosic content of their feedstock. This process of verifying the cellulosic content of feedstock is often cumbersome. Thus, in our analysis, we assume that only RNG from landfill gas receives D3 credits under pathway Q while RNG from codigestion qualifies for D5 credits under pathway T. The RNG produced for transportation use also qualifies for LCFS credits. In particular, producers will earn credits depending on the carbon intensity of the produced fuel relative to the benchmark fossil fuel. The carbon intensity of a particular production process depends on the feedstocks used, the counterfactual usage of the feedstocks, and the production process. In this analysis, we assume that the carbon intensity of the RNG produced varies only by feedstock type. Because the proposed RNG production process incorporates CCS, the producers would also qualify for 45Q credits for CO_2 sequestered provided the minimum sequestration requirement is met.

Given the policy and resource context, biogas and renewable natural gas production from biomass are growing in California. Anaerobic digestion, a sequence of processes by which microorganisms break down biodegradable material in the absence of oxygen, has been used as a technology for waste management and renewable fuel production. We estimate that 46 anaerobic digester (AD) sites process food waste, municipal solid waste, and dairy waste in California as of 2019[17−19]. Furthermore, 154 existing wastewater treatment plants have onsite digesters, and 52 landfills are equipped with existing landfill gas (LFG) collection systems.[20,21] We estimate roughly 3 million mmbtu of biogas is produced per year from anaerobic digesters and 10 million mmbtu of landfill gas is diverted to various cogeneration projects in California. All but five AD projects in California are generating electricity and/or heat. More recently, producers are starting to upgrade biogas into renewable natural gas (RNG) for injection into California's natural gas distribution system. RNG has entered markets as a low-carbon transportation fuel, in part due to subsidies from the RFS and LCFS. For instance, the Calgren facility in Pixley and the CR&R facility in Perris generate RNG from manure and food waste, respectively.

Despite the recent development of RNG facilities in California, the few existing facilities in California do not incorporate RNG production with CCS despite the fertile policy environment and geologic endowment in California. Biogas contains a mixture of CH_4 and CO_2, along with other trace contaminants (roughly 60% CH_4 and 40% CO_2). The upgrading process separates CH_4 from other components of biogas, producing not only a pure stream of CH_4 but also a

(a) System Flow Chart



(b) Model Flow Chart

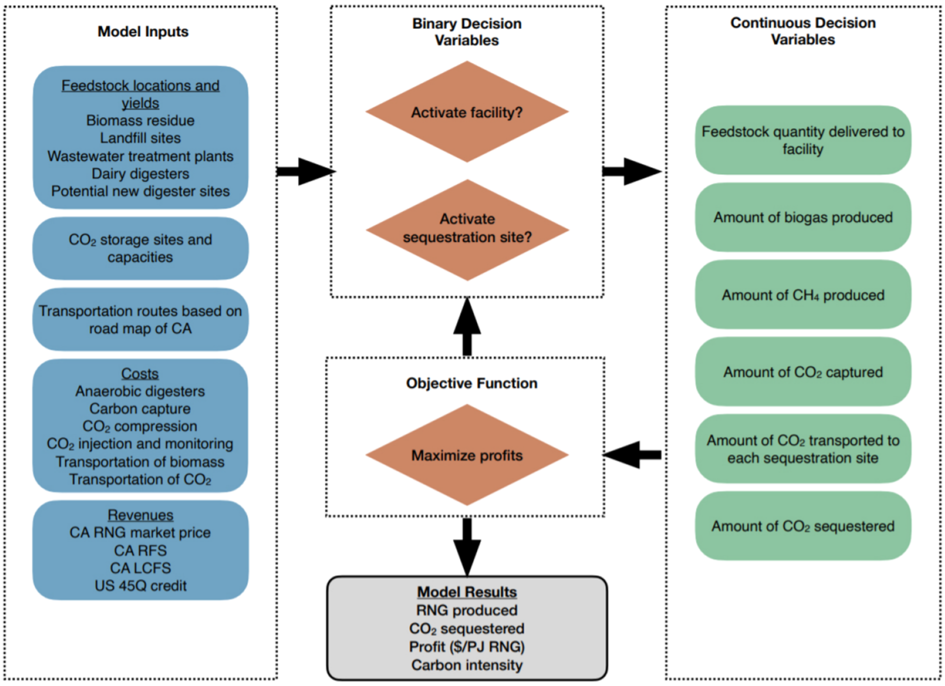


Figure 2. System and model flowchart (a), process flow diagram, and (b) model flowchart for RNG-CCS systems. (A) Major processes in the RNG-CCS system. We consider relevant system boundaries for lifecycle CO_2 emissions assessments consistent with California's Low Carbon Fuels Standard. We consider CO_2 emissions from CO_2 compression, transportation, and sequestration. (B) Major features of our optimization model. Our optimization maximizes total profits, including binary decision variables to activate a particular facility or sequestration site, alongside continuous production decision variables.

relatively pure stream of CO_2. In particular, pressure swing adsorption (PSA) separates the CH_4 and CO_2 in biogas and produces a stream of 75%−98% pure CO_2[22,23]. The relatively pure stream of CO_2 from the biogas upgrading process presents an opportunity for low-cost CO_2 capture, in contrast to CO_2 capture from flue gases where the lower CO_2 concentration results in greater energy requirements and purification costs. To our knowledge, RNG-CCS is relatively understudied in the literature despite the attractive low-cost opportunity for CO_2 capture. Esposito et al.[24] report that the production of food-grade CO_2 (defined as a stream of 99.9% CO_2) from biogas upgrading can be profitable in Italy. While some studies utilize spatial optimization to study the usage of biomass, adding CCS adds another dimension to the spatial optimization problem.[25,26] There are also relatively few previous works using spatial optimization to analyze BECCS' feasibility. Recent works on BECCS spatial optimization include Negri et al.,[27] Sanchez et al.,[2] Sanchez and Callaway,[28] Singh et al.,[29] and Xing et al.[30]

Here, we develop a spatially explicit optimization model to assess the near-term opportunities for RNG production from waste biomass with CCS in California under existing policy incentives (Figure 2). The model incorporates high-resolution geospatial data on existing biomass residues, anaerobic digesters, wastewater treatment plants, landfills, truck networks, and geologic sequestration sites in California. Profitable RNG production with CCS has the potential to catalyze markets and technologies for CCS and BECCS in California.

■ METHODS

We build a spatially explicit optimization model informed by geospatial data on biomass residues, existing anaerobic digesters, wastewater treatment plants, landfills, road networks, and geologic sequestration sites in California (Figure 2). We offer two novel methodological contributions to the literature on spatial optimization of biomass and CCS. We model for codigestion and consider trucking networks for CO_2 transportation. We contend that the codigestion of feedstocks offers greater economies of scale and flexibility to the system. The relatively small amount of CO_2 produced in this context does not justify pipeline construction for the sole purpose of transporting several million tons of CO_2. In particular, California's siting and permitting processes are not conducive for near-term development of CO_2 pipelines. We offer further details below and in the Supporting Information.

Data Development. We compile a database of available biomass residues (feedstocks) in California from various sources. Geospatial data on municipal solid waste (MSW), crop residues, and manure are from Breunig et al.[10] We supplement these with data on wastewater treatment plants and daily average flows from the California Association of Sanitation Agencies (CASA).[21] Lastly, we collect landfill locations and volumes of landfill gas from the U.S. Environmental Protection Agency's Landfill Methane Outreach Program (LMOP).[20] We estimate the current deployment of anaerobic digesters in California using the U.S. Environmental Protection Agency's AgStar database on dairy digesters,[17] Argonne National Laboratory's RNG database,[18] U.S. Environmental Protection Agency's LMOP database,[20] and CalRecycle.[19] We consider locations for new digesters in cities with a population greater than 10,000 and less than 5 km away from an existing natural gas pipeline. Saline aquifer storage capacities and locations are derived from the National Carbon Sequestration Database (SI Text).[31] We use the open source routing machine (OSRM)[32] to calculate the shortest road distance and driving time between point source feedstock locations and facilities and facilities to sequestration sites. To avoid computational limitations, we limit feedstock and CO_2 transport to within 50 miles.

We derive the cost of anaerobic digesters, biogas upgrading, and RNG injection from Parker et al.[25] Biomass transport and CO_2 capture and transport costs are as in Tittmann et al.[33] and Psarras et al.,[34] respectively. CO_2 compression and pumping costs are from McCollum and Ogden.[35] To calculate the costs of CO_2 sequestration in saline aquifers, we supplement the methods of Sanchez et al.[2] with the C2SAFE model for California-specific policy-related costs, such as seismic monitoring.[36] We convert all costs to 2019 US dollars using the Information Handling Services (IHS) Upstream Capital Cost Index. We assume a 15-year project timeline and a 10% internal rate of return. We assume that new anaerobic digesters will have to be built, with the exception for wastewater treatment plants with existing digesters. At wastewater treatment plants with existing digesters, we assume that the existing digester is able to process the local wastewater and that a new digester will be built to accommodate outside feedstocks. Thus, capital cost of anaerobic digesters only apply to nonwastewater feedstocks that cannot be transported while O&M costs apply to all feedstocks.

We assume that all the RNG produced is used as a transportation fuel. Thus, the RNG is eligible to receive renewable identification numbers (RINs) under the Renewable Fuels Standard according to the approved pathways Q and T and Low Carbon Fuel Standard (LCFS) credits.[16] The produced RNG is also eligible to receive 45Q carbon sequestration credits (given the 100,000 tCO_2 captured per year threshold is met) and the market price for compressed natural gas (CNG).

We use biogas yields from Li et al.,[37] but we also compile a range of biogas yields for various feedstocks from a broader literature review (SI Text). We assume that the resulting biogas is comprised of 60% CH_4 and 40% CO_2. To determine the amount of LCFS credits that a RNG source qualifies for, we calculate the amount of LCFS credits gained from the RNG produced without CCS, then add additional credits for each ton of CO_2 sequestered after subtracting the corresponding process emissions required for CO_2 compression, transport, and sequestration. We determine the carbon intensity of the RNG produced from the California Air Resources Board, which varies by feedstock type.[13] Note that this carbon intensity estimated by the Air Resources Board does not include CCS. We determine the RNG carbon intensity by weighting the carbon intensities of the individual feedstocks according to their composition in the feed for codigestion processes. Each ton of sequestered CO_2 also earns LCFS credits. To adjust for the emissions generated from CO_2 compression, transport, and sequestration, we assume that the system uses California grid electricity for capture and compression, with carbon intensity equal to the average California mix in 2018.[38] We also assume for CO_2 transport an emissions factor of 161.8 gCO_2/ton-mile.[39] Note that the feedstock transport emissions factor is already accounted for in the carbon intensity provided by the California Air Resources Board.

Problem Statement and Scenarios. We minimize the net total cost of the production of RNG and sequestration of CO_2 using a mixed integer program to identify cost-effective sequestration opportunities (Figure 2). We treat revenues from policies as negative costs where the objective is some function with the form *Cost* − *Revenues*. This formulation is identical to profit maximization since maximizing is equivalent to minimizing the negative of the objective. We model the detailed costs associated with the RNG-CCS system including the capital and operating costs of anaerobic digesters, biogas upgrading, RNG compression, and CO_2 compression and sequestration. Additionally, detailed road network data allow for the exact calculation costs of feedstock and CO_2 transport costs. The possible revenue sources include the market price of RNG and credit prices of LCFS, RIN, and 45Q. We detail the system boundaries in the SI. In practice, price volatility, policy uncertainty, lifecycle emissions accounting, and tax equity availability will all affect the cost effectiveness of CCS projects that depend on tax credits and tradeable permits. We do not

Table 1. Policy Scenarios

Policies (units)	Baseline	No RFS	No 45Q Threshold	High Policy	Low Policy	Capped LCFS	No LCFS
LCFS (\$/tCO_2)	\$100	\$100	\$100	\$200	\$20	\$100	\$0
RFS (\$/GGE)	\$0.25	\$0	\$0.25	\$1.50	\$0	\$0.25	\$0.25
45Q (\$/tCO_2)	\$50	\$50	\$50	\$50	\$50	\$50	\$50
45Q minimum (tCO_2/year)	100,000	100,000	0	100,000	100,000	100,000	100,000
LCFS Cap (PJ/year)	N/A	N/A	N/A	N/A	N/A	28	N/A

explicitly include other potential revenue streams, such as CO_2 utilization options (enhanced oil recovery or beverage carbonation) or alternative feedstock uses.

We define two binary decision variables that indicate the activation of facilities and sequestration sites, respectively. The six continuous decision variables are the quantity of feedstock delivered to a facility from a source, amount of biogas produced, amount of CO_2 captured from the biogas upgrading process, amount of CH_4 produced from the biogas upgrading process, amount of CO_2 transported to each sequestration site, and amount of CO_2 sequestered at each sequestration site. Our model is implemented in A Mathematical Programming Language (AMPL) and solved using the branch-and-bound model. The model's complexity yields optimality gaps of up to 10% for most scenarios—implying that solutions are feasible but not necessarily optimal. Only in one instance in the sensitivity analysis did the optimality gap exceed 10%.

We simulate the viability of the RNG-CCS system under different policy regimes. The six different scenarios considered are low and high policy support scenarios, a no RFS scenario, a no 45Q minimum threshold scenario, a no LCFS scenario, and a transport CNG-capped LCFS scenario. Table 1 describes the assumed policy credit prices in each scenario. The policy incentives are lowered such that LCFS credits are \$20, with no RFS credits and 45Q credits of \$50 in the "low policy scenario." This scenario simulates a weak policy environment in which renewable fuels are not subsidized as heavily. In contrast, the "high policy" scenario simulates a strong policy environment in which renewable fuels are more heavily subsidized. In this scenario, we extend the policies to their allowed maximum: LCFS credit price of \$200, RFS credit price of \$1.50, and 45Q staying at \$50. Due to the uncertain future of the RFS, we also simulate a no RFS scenario, where all other credits remain the same as the baseline, but RFS credits are nonexistent (i.e., \$0). Great uncertainty surrounds the Renewable Fuel Standards past 2022, as the U.S EPA will have discretion over the mandates of the RFS. In particular, some lawmakers have expressed the desire to "sunset" the RFS.[40] In the "transport-CNG-capped LCFS" scenario, we relax the assumption that all the RNG produced is used as transportation fuel in California. We place a limit on how many LCFS credits can be earned—up to the 2019 demand of CNG as transportation fuel (i.e., each mmbtu of RNG and its associated sequestered CO_2 up until the 2019 demand earns LCFS credits, and each mmbtu thereafter does not earn LCFS credit). To broaden the policy implications federally, we simulate a no LCFS scenario where all other credits remain the same as the baseline, but LCFS credits are nonexistent (i.e., \$0). Because projects in other states (which presumably would not be sending CNG to California) will not earn LCFS credits, simulating whether existing federal policies can incentivize a robust RNG-CCS build-out is crucial. Lastly, we simulate a "no 45Q minimum threshold scenario," in which we remove the minimum CO_2 captured threshold required to be able to earn 45Q credits. Burns and Jacobson[41] argue that removing the threshold would enable greater cost reductions and a more rapid progression along the BECCS learning curve. Altogether, these scenarios extend the implications of the baseline model to better illustrate of the importance of federal and state policy incentives and design on small-scale BECCS systems such as RNG-CCS.

Data Access. National Carbon Sequestration data on saline aquifers are available from the National Energy Technology Laboratory.[31] The Landfill and Outreach Program data are available from the U.S. Environmental Protection Agency.[20] The existing agricultural digester database in the United States can be found at the U.S. EPA AgStar database.[17] Our model and a reproduction kit is available on GitHub (https://github.com/carbon-removal-laboratory/Biogas-CCS).

■ RESULTS AND DISCUSSION

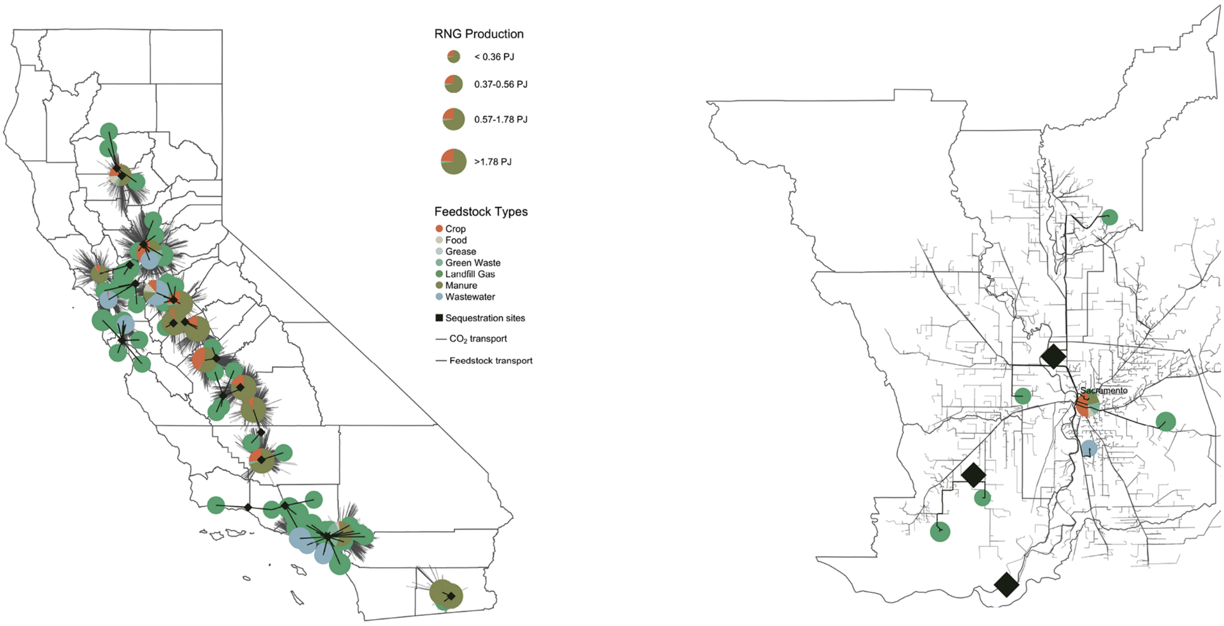
To characterize the optimal deployment of RNG production with CCS in California (RNG-CCS) under current policy conditions, we present key model outputs—RNG produced, CO_2 sequestered, costs, revenues, and profits—under a range of policy scenarios (Figure 3). Policy scenarios are constructed around recent prices available under Section 45Q, California's LCFS, and the federal RFS (Table 1).

We use as a basis the estimated 54 billion bdt of biomass residues available from crop residues, municipal waste, and manure per year in California in 2020.[10] Additionally, exisiting landfill gas facilities and wastewater treatment facilities collect 5.3 million m^3 landfill gas and 2.8 million gallons of wastewater per day, respectively. Together, these sources can produce up to 150 PJ RNG per year or 6.5% of the natural gas demand in California in 2018 and 5 million tons CO_2 per year for potential sequestration.[42]

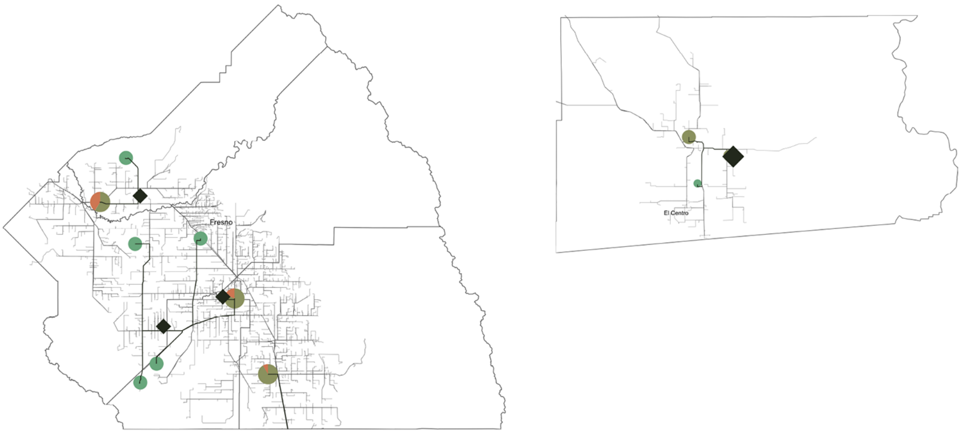
In the baseline scenario, 79 facilities profitably produce 93 PJ of RNG per year (63% of the total RNG potential from biomass residues) and sequester 2.9 million tons of CO_2 per year in 18 sequestration sites. Figure 3 shows the distribution of these facilities and sequestration sites across the state. Of the 79 facilities, 13 are new facilities, 8 are existing wastewater treatment plants with constructed additional capacities, and 58 are landfills. The volume of CO_2 sequestered at each site ranges up to 515,000 tons of CO_2 per year, and the median sequestration site is shared among three RNG facilities, with each facility transporting CO_2 an average of 26 miles. The amount of RNG produced makes up roughly 4% of current natural gas usage in California or roughly 3 times the current demand for utilizing natural gas as transportation fuel. The baseline scenario results in 12.4 million tons of CO_2 avoided per year, including 2.9 million tons of CO_2 sequestered per year.

The baseline utilizes municipal solid wastes (MSW) heavily; facilities annually process a total of 156,500 bdt of food waste, 700,000 bdt of green waste, and 28,600 bdt of grease, with an average transport distance of 20 miles. The system takes

(a) California (b) Sacramento Area



(c) Fresno Area (d) Imperial County



(e) Southern California (f) Bay Area

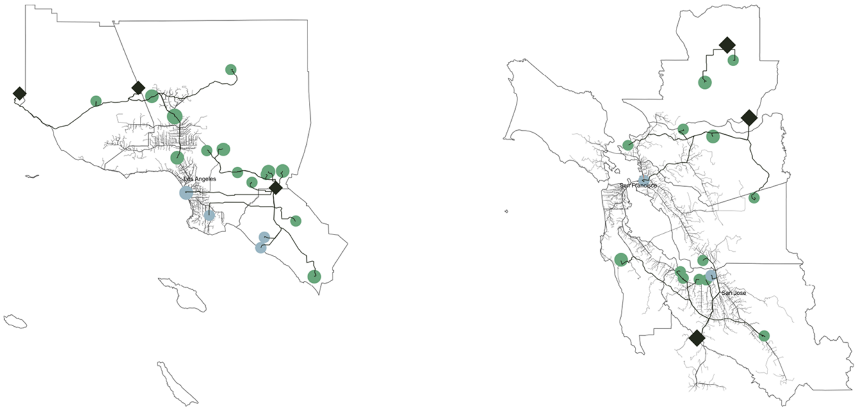
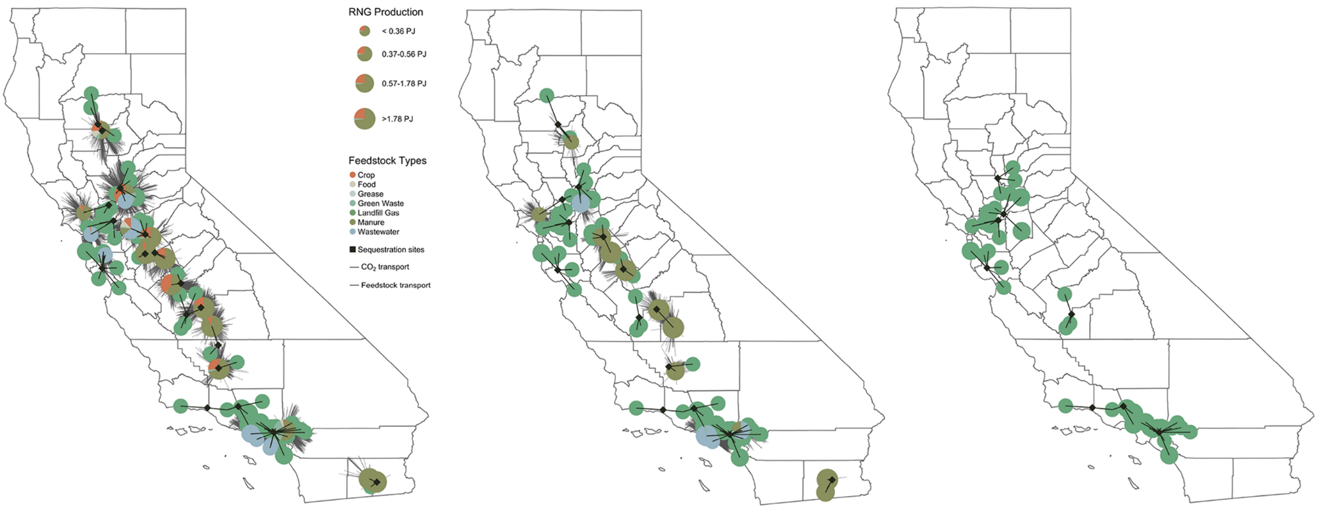


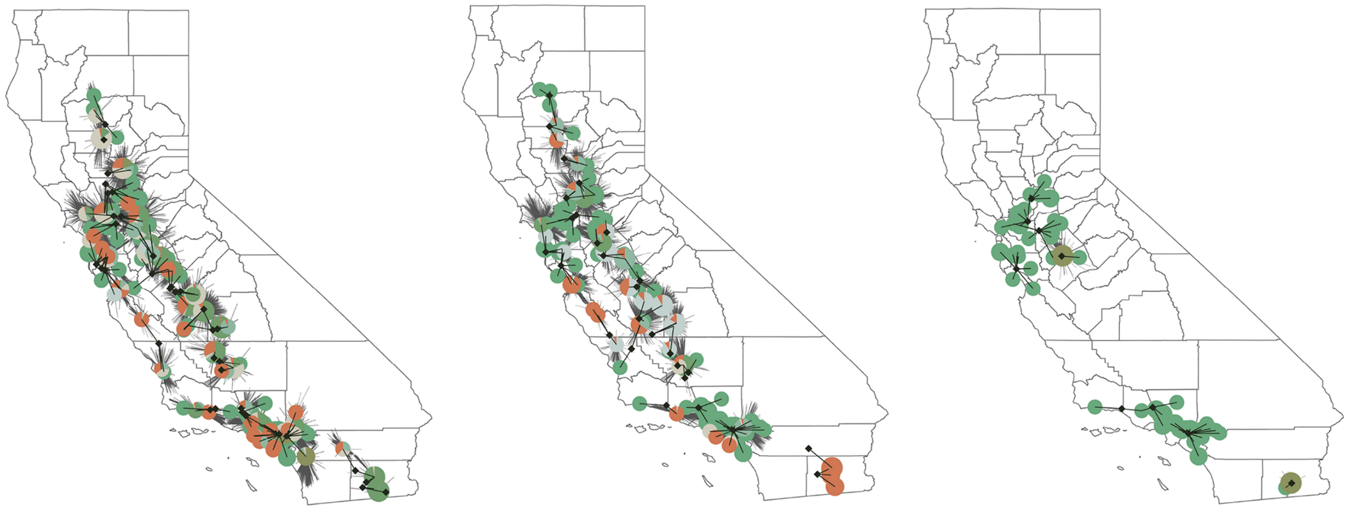
Figure 3. Baseline RNG-CCS system in (a) California and (b−g) in prominent regional agglomerations. Across California, RNG-CCS systems produce 119 PJ of RNG from 85 facilities per year and sequester 4.1 million tCO_2 in 19 sequestration sites per year. In panels (B−G), we focus on the emerging regional agglomerations. Extensive biomass residue and CO_2 sequestration collection networks are formed, enabled by small-volume truck transportation.

advantage of the colocation of agricultural activity and sequestration sites in the Central Valley; 2.5 million bdt of available crop residues and 8.9 million bdt of manure are utilized. On average, crop residues are transported 26 miles,


(a) Baseline

(b) No RFS

(c) Low Policy


(d) High Policy

(e) No 45Q Threshold

(f) LCFS Cap

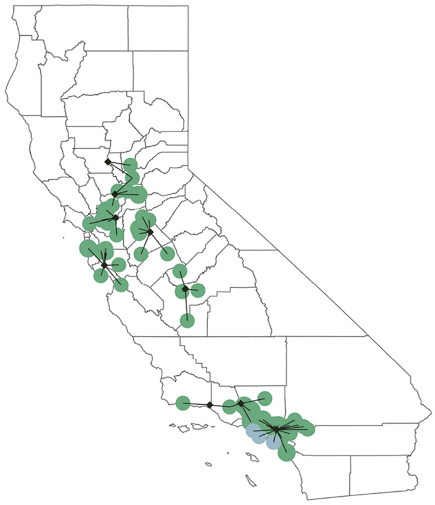

(g) No LCFS

Figure 4. RNG-CCS systems for various policy scenarios: (a) baseline, (b) no RFS, (c) low policy, (d) high policy, (e) no 45Q minimum threshold, (f) LCFS cap, and (g) no LCFS. RNG-CCS systems are robust to varying levels of policy support.

and manure feedstocks are transported 15 miles from source to processing facility.

Our model generates regional networks that exploit the diversity of feedstocks in the state in the optimal baseline scenario. Facilities tend to cluster near urban regions with readily available MSW. Broadly, we observe five distinct regions of agglomeration within California: in urban regions such as the greater Los Angeles area, Bay Area, Sacramento

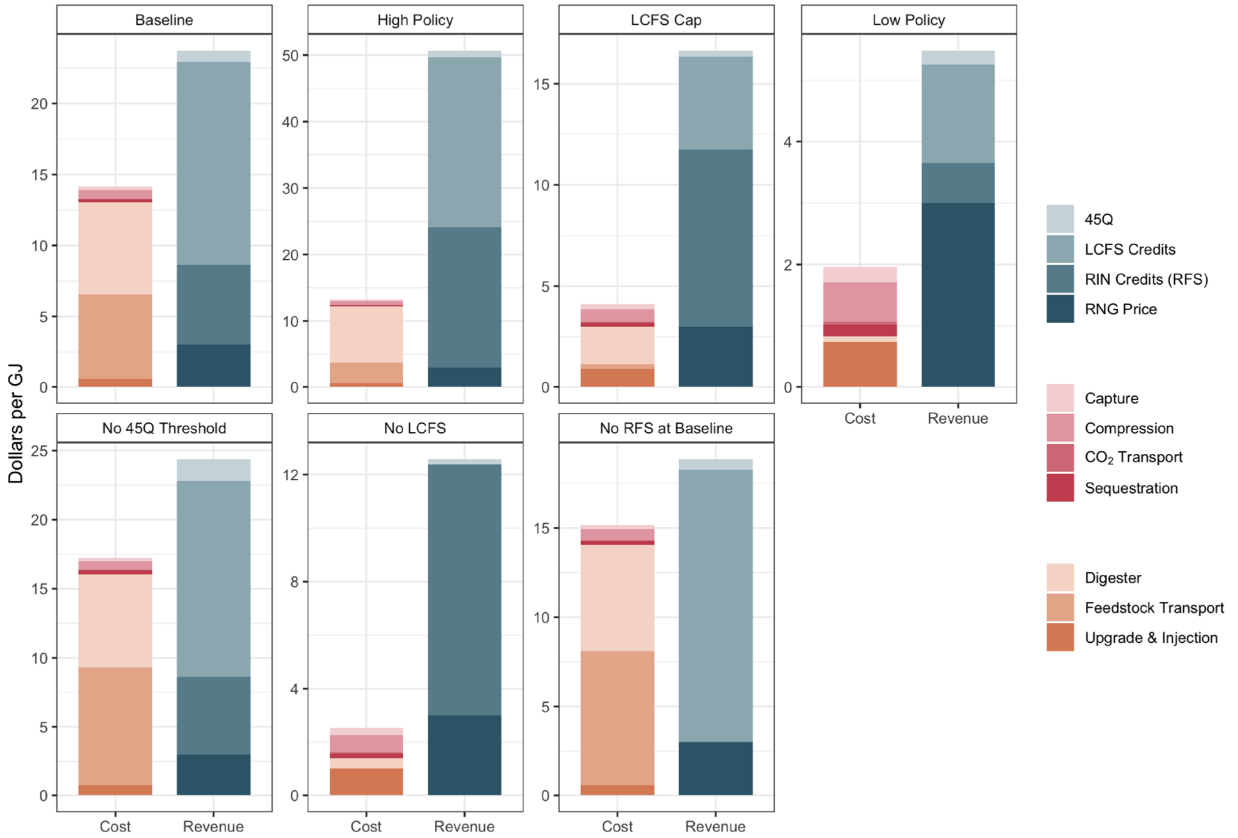


Figure 5. Costs and revenues (\$/GJ) for RNG-CCS system for various policy scenarios. Costs are separated into two technology categories: CCS-related (red) and biomass processing-related (orange). Across all scenarios, CCS-related costs are a small fraction of total costs. Revenues from the LCFS make up a large share of revenue across all scenarios other than the capped LCFS and no LCFS scenarios.

Valley, and agricultural regions around Bakersfield and Imperial County (Figure 3). CO_2 sequestration is economically feasible in all regions due to the regional availability of sequestration sites.

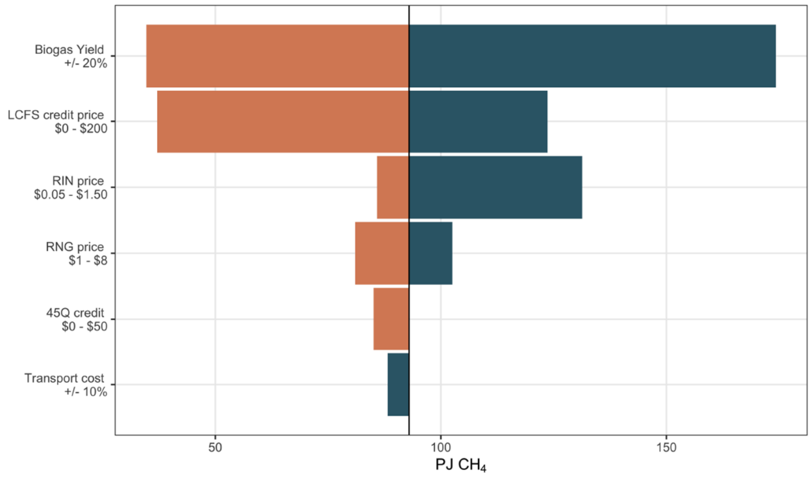
In the optimal scenario, we see significant heterogeneity in feedstock utilization across different parts of California. Landfill gas plays a significantly larger role in urban regions such as the Bay Area and greater L.A. area compared to agricultural regions in the Central Valley. In the Bay Area, landfill gas produces 87% of the total RNG, compared to 6.5% in Fresno. Overall, landfill gas makes up roughly 39% of the total RNG production. In contrast, manure produces 70% of the total RNG in Fresno and 99% in Imperial County, taking advantage of the livestock in these regions. The ability of the RNG-CCS system to process all varieties of biomass residues makes for an attractive option to produce carbon-negative fuels across California.

The baseline results above suggest that the current policy climate is sufficient to incentivize a robust build-out of RNG-CCS systems in California. However, since the system relies on policy incentives to generate revenue, its viability is susceptible to fluctuations in policy regimes. To probe the sensitivity of the system to varying levels of policy support, we consider the six policies described in the Methods section: high policy, low policy, no RFS, no 45Q minimum threshold, no LCFS, and transport RNG-capped LCFS.

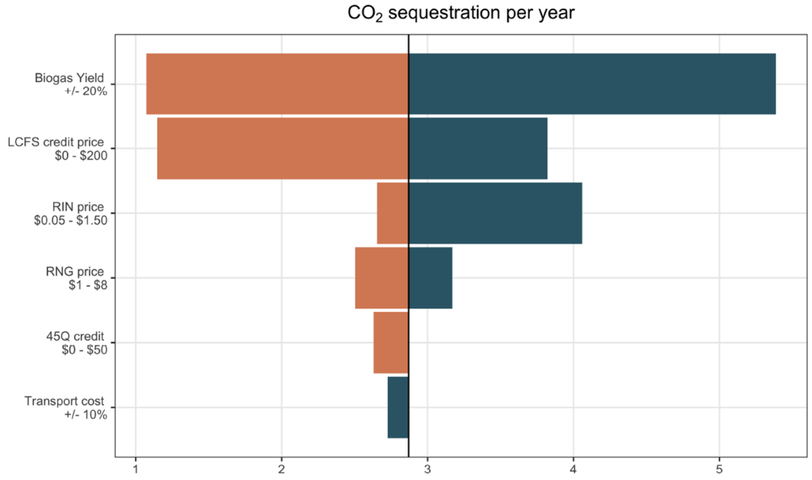
In the favorable policy environment of the "high policy" scenario, 4 million tons of CO_2 are sequestered in 36 sites, and 130 PJ of RNG is produced per year from 121 facilities. With significantly lower policy support in the "low policy" scenario, we still find that 1 million tons of CO_2 is sequestered in eight sites, and 32 PJ of RNG is produced per year from 37 facilities. Without RFS at baseline, we find that the baseline levels of LCFS and 45Q credits are sufficient to sustain a similar level of RNG-CCS build-out in California as the baseline scenario. We still sequester 2.3 million tons of CO_2 in 14 sequestration sites and produce 73 PJ of RNG from 61 facilities (Figure 4). This represents a 22% decrease in RNG production from the baseline scenario. Removing the minimum threshold 100,000 tons of captured CO_2 for 45Q eligibility does not increase the RNG-CCS build-out in an optimal scenario. Instead, production is distributed over a greater number of facilities. Here, 95 facilities produce 90 PJ of RNG and sequester 2.8 million tons of CO_2 in 27 sequestration sites. When capping LCFS credits to 2019 transport CNG demand, 60 facilities produce 39 PJ of RNG and sequester 1.2 million tons of CO_2 in nine sequestration sites. Removing LCFS credits completely, 54 facilities produce 37 PJ of RNG and sequester 1.1 million tons of CO_2 in nine sequestration sites. The feedstock mix is different in the two limited LCFS scenarios. While landfill gas dominates the share of RNG produced in both scenarios, manure is used much more heavily in the capped LCFS scenario compared to wastewater in the no LCFS scenario. This is because the limited LCFS will still incentivize the use of manure, which has a highly negative carbon intensity, compared to the low cost option of using existing digesters fitted for wastewater at wastewater treatment plants in the no LCFS scenario.

Profits range from \$3 to \$32/GJ under low and high policy support environments, respectively (Figure 5). Without the

(a) CH_4 production per year



(b) CO_2 sequestration per year



(c) Profits per year

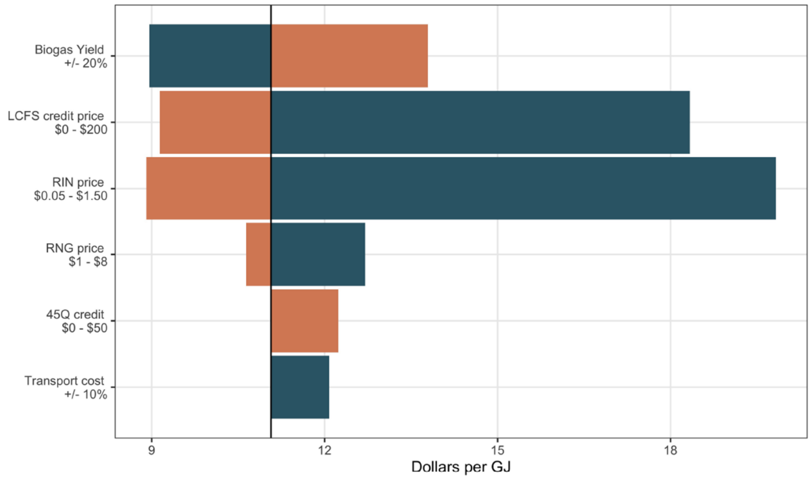


Figure 6. Parametric sensitivity analysis of yearly (a) CH_4 production, (b) CO_2 sequestration, and (c) profit. We vary biogas yield, LCFS price, RIN credit price, RNG price, 45Q credits, and transport cost. Average profits rarely fall below the baseline of \$12/GJ but can reach as high as \$37/GJ when RFS prices are at their highest.

RFS, we find that profits decrease compared to the baseline from \$11 to \$7.4/GJ. Profits remain roughly similar when we remove the minimum 45Q threshold, earning an average of \$11.50/GJ. LCFS credits to remain a significant source of revenue across all scenarios. Especially without the RFS in the baseline case, LCFS credits make up an overwhelming majority (81%) of the revenues earned. However, the RNG-CCS build-out is still robust when LCFS credits are limited, earning \$11 and \$9/GJ in the capped LCFS and no LCFS scenarios, respectively. Surprisingly, CCS-related costs are small relative to biomass processing-related costs across all scenarios, making up roughly 10% of the total baseline cost. Biomass processing-related costs dominate. Levelized digester costs account for nearly 45% ($6.50/GJ) of the total baseline cost, and feedstock transport costs account for 42% ($5.93/GJ) of the total baseline cost. Across varying levels of policy support, we find that the RNG-CCS system is still able to profitably produce carbon-negative transportation fuel.

We find above that federal and state supports for carbon sequestration are large drivers of, and critical to, near-term BECCS deployment. To examine the marginal impact of various policies, we perform sensitivity analysis parametrically. Figure 6 shows the results of the sensitivity analysis. At the baseline, existing policies are capable of incentivizing a robust network of RNG-CCS systems in California while generating $11/GJ of profits. We find that CO_2 sequestration and RNG production are most sensitive to LCFS credit prices relative to other policy drivers. All else being equal, when LCFS credits are reduced from $100 to $0/t$CO_2$, we sequester 1.1 million tons of CO_2, compared to 2.9 million tons of CO_2 at the baseline and produce 37 PJ of RNG compared to 93 PJ at the baseline. When LCFS credits are $200/t$CO_2$, we sequester over 3.8 million tons of CO_2 and produce 123 PJ of RNG. The RFS also appears to be an efficient policy driver to incentivize carbon-negative systems. CO_2 sequestered ranges from 2.6 to 4 MtCO_2/yr per year, and RNG production ranges from 89 to 131 PJ per year while incentivizing profits upward of $19/GJ when we vary the RFS credit price. Taken together, the results suggest that LCFS and RFS are important drivers of RNG-CCS systems in California. While the LCFS is only officially extended through 2030, California Governor Newsom issued an executive order in 2020 to the California Air Resources Board to extend the LCFS beyond 2030.[43]

The 45Q tax credit plays a complementary role to LCFS and RFS credits. As it is currently designed, for a facility to claim 45Q credits, it has to capture at least 100,000 tons CO_2 per year. Some argue that the minimum threshold should be removed to lessen project finance risks and accelerate the small-scale innovations in CCS.[41] In this context, we find that the 100,000 ton capture minimum constraint is not a deterrent, as the levels of RNG produced are similar across the two scenarios. While the "no minimum" scenario observes more active facilities (95 vs 79) for a similar amount of RNG production, it also observes more active sequestration sites (27 vs 18). It appears that the minimum capture threshold acts as an agglomeration force without sacrificing RNG production or CO_2 sequestration potential—pushing production into a fewer number of facilities and requiring less drilling and fewer active sequestration sites. However, in other contexts, the threshold might act as a significant obstacle in pilot projects with relatively newer technologies or that do not produce transport fuels and thus rely more significantly on 45Q credits.[44]

California is well suited for systems such as the RNG-CCS system presented here. The feedstock heterogeneity across regions and availability of potential sequestration sites throughout the state create rich opportunities for low-cost and near-term carbon-negative systems. Moreover, fuel production with CCS could be an important part of the energy supply mix that satisfies low-carbon fuel mandates in California and the United States. Other low-carbon and carbon-negative fuel technologies with CCS such as ethanol coupled with CCS, enhanced oil recovery (EOR), direct air capture with EOR (DAC-EOR), and many others, could become important under current policy conditions[2,45].

We stress that RNG-CCS is not a substitute for electrification in California; at baseline, it produces only 4% of current natural gas demand. If we do not electrify and decarbonize effectively, E3 PATHWAYS suggests that the baseline RNG production would meet only 7% of the overall natural gas demand. In contrast, if California electrifies effectively, the baseline RNG production would meet 14% of the overall natural gas demand. Despite this, RNG-CCS still holds the potential to catalyze first markets for BECCS in California and is an attractive source of low-carbon transportation fuel.

RNG-CCS can promote broader CCS deployment in California. We find that sharing sequestration sites across different CCS projects can further lower the capital cost of CO_2 sequestration while ensuring effective monitoring and verification. Existing efforts by the U.S. Department of Energy's C2SAFE program aim to sequester 50 million tons of CO_2 over 20−30 years.[36] Furthermore, sequestration and abatement credits to drive CCS first markets can develop experience, project financing, policies, and business models for CCS. Within California, the Central Valley is prime to emerge as a hub for CCS. Baker et al.[11] describe the central valley as "ready to go" to address CO_2 storage needs. Further work is necessary to enable sequestration at sites near urban areas, which we assume cannot be utilized here.

We note several key limitations to our current modeling framework. First, we assume that the natural gas produced can be injected into the natural gas pipeline network in California. However, depending on feedstock input and upgrading technologies, further RNG upgrading to remove any trace amounts of N_2, H_2, H_2S, O_2, and siloxanes may be required. Further, many existing natural gas pipelines lack adequate capacity.[46] We also consider only one type of waste management in California: anaerobic digestion. Composting is another viable waste management policy. We do not evaluate the trade-offs between composting biomass residues and using biomass residues to produce RNG via anaerobic digestion. We assume that any potential CH_4 emissions from leakage in the natural gas system are negligible to the climate impacts of reduced GHG intensity of the RNG and sequestered CO_2. However, Grubert[47] finds that RNG systems could be climate intensive depending on the methane feedstock. The analysis in this paper is on a yearly basis, but biomass residues, especially agricultural residues, are seasonal. That is, in reality, digesters need to be outsized relative to the model-predicted size for intermittent large inflows while sitting idle for some time. Lastly, we consider a global optimization. That is, we optimize for one collective objective function instead of individual firm objective functions. Firms make decisions individually, not globally, and a facility-level optimization might yield different results. The significant economies of scale involved obviate a need for cost sharing or redistribution to ensure the profitability and impact of an RNG-CCS system at a facility scale. However, we would argue that ex ante it is not obvious that neither a generator-by-generator nor a system-wide optimization framework is more realistic than the other. For example, a system-wide optimization framework allows for the formation of shared sequestration sites, which can reduce the amount of drilling activity and active sequestration sites in the state. Moreover, these digesters will likely not be small-scaled family farm digesters but instead owned by larger companies with multiple farms or multiple landfills. Finally, while we perform both parametric sensitivity analyses and nonparametric scenario analyses to better understand the impacts of federal and state policies on RNG-CCS build-out, we are unable to solve for a “minimum credit” to incentivize RNG-CCS in this context since formulating such a problem would necessitate an intractable nonlinear problem.

Profitable RNG production with CCS potentially catalyzes markets and technologies for CO_2 capture, transport, and removal in California. In particular, RNG with CCS can address both the waste management and climate mitigation needs in California. Producing up to 93 PJ of RNG, sequestering up to 2.9 million tons of CO_2 per year, and avoiding a total of 12.4 million tons of CO_2 per year, RNG-CCS can stimulate a robust carbon-negative system while providing a profitable first market for BECCS. The deployment of RNG-CCS systems in California can accelerate efforts for BECCCS internationally and in California. As California considers a broad range of carbon removal strategies to meet its goal of net neutrality economywide in 2045, we suggest that RNG-CCS could play an early and prominent role. More broadly, the potential success of RNG-CCS in California could lead to further innovation and investment in BECCS beyond state borders and substantially impact the federal climate policy landscape.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c02894.

Information as mentioned in the text (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Daniel Sanchez − *Department of Environmental, Science, Policy, and Management, University of California, Berkeley, Berkeley, California 94720-3114, United States;* orcid.org/0000-0001-9281-5685; Email: sanchezd@berkeley.edu

Authors

Jun Wong − *Kenneth C. Griffin Department of Economics, University of Chicago, Chicago, Illinois 60637, United States*

Jonathan Santoso − *Department of Chemical and Biomolecular Engineering, University of California, Berkeley, Berkeley, California 94720-1462, United States*

Marjorie Went − *Department of Chemical and Biomolecular Engineering, University of California, Berkeley, Berkeley, California 94720-1462, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.1c02894

Notes

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