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California low carbon fuel policies and natural gas fueling infrastructure: Synergies and challenges to expanding the use of RNG in transportation☆

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ABSTRACT

The emergence of natural gas as an abundant, inexpensive fuel in the U.S. raises the possibility that expanding natural gas infrastructure could enable a transition to other low carbon fuels. We assess how California's existing fuels policies interact with expanding natural gas infrastructure in the state to promote renewable natural gas resource development in the state. We employ a profit-maximizing mixed-integer linear programming optimization to solve for development of natural gas refueling infrastructure incorporating spatial and temporal considerations and estimate the associated expansion in natural gas fuel demand in California. We investigate whether renewable fuel and carbon pollution credit markets create sufficient incentive to promote shifting to renewable natural gas fuel to replace vehicular natural gas demand. An assessment of California's current policies is undertaken and alternative policy options to enhance market efficiency are discussed. These policies include improvements to state regulations of waste disposal, incentives for fleets to shift to sustainable fuel trucks, and mechanisms to lower connection costs for in-state renewable natural gas into the California natural gas pipeline grid.

1. Introduction

California policy makers have sponsored studies to determine whether natural gas (NG) can be a “bridge” to low carbon fuels in the transportation sector (Jaffe et al., 2016). There are a variety of ways that natural gas as a vehicular fuel can reduce emissions in the transportation sector. Given the slightly lower carbon intensity of fossil natural gas as a transport fuel, switching from conventional fuels like gasoline and diesel into fossil natural gas achieves a small reduction in emissions. Industry players, such as Clean Energy, BP and ENN, are investing in natural gas fueling infrastructure to supply the trucking industry, expanding gaseous fuel's ability to scale (Hall, 2014; Shauk, 2014). This infrastructure can also accommodate renewable natural gas (RNG), which has substantially lower carbon intensity, creating a pathway to reduce greenhouse gas emissions from the freight sector. A number of U.S. states, including Oklahoma and Utah, have offered incentives for construction of natural gas refueling infrastructure and to assist in the conversion of government and commercial fleets in switching to natural gas. We look at the potential benefits for California to pursue such policies.

In this paper, we test whether California's existing policies will be effective in promoting the transition of lower carbon renewable natural gas into existing and potential natural gas fueling infrastructure in the state. We consider additional policies that might be effective in reducing barriers to widespread conversion of heavy-duty freight away from oil to transition to renewable natural gas.

We build on work utilizing a geospatial optimization model to assess how natural gas refueling infrastructure and vehicle technology adoption can evolve in the future under various scenarios of low, medium, and high diesel prices and under two different choices for initial stock of natural gas trucks. We add various kinds of renewable natural gas as additional fuel alternative pathway options in addition to fossil natural

Abbreviations: BCF, Billion Cubic Feet; BTU, British Thermal Unit; CARB, California Air Resource Board; LCFS, California Low Carbon Fuel Standard; CO_2, carbon dioxide; CO_2e, carbon dioxide equivalent; CNG, Compressed Natural Gas; dge, diesel gallons equivalent; ege, ethanol gallon equivalent; gge, gasoline-gallon-equivalent; LFG, Landfill Gas; LNG, Liquefied Natural Gas; mmBTU, million British Thermal Unit; MSW, Municipal Solid Waste; RFS, Renewable Fuel Standard; RIN, Renewable Identification Number; RNG, Renewable Natural Gas; WWTP, Waste Water Treatment Plants

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gas fuel and traditional diesel. By doing so, we are able to combine the resulting estimation of vehicular natural gas consumption with new estimates of RNG supply to assess how much RNG can enter into the vehicular natural gas market in California over the next 15 years. Testing different scenarios, we are able to examine what level of carbon prices might be necessary to promote sustainable renewable natural gas pathways despite the high manufacturing costs for RNG when compared to the production costs for fossil natural gas and diesel fuels. We specifically consider how changes in carbon credits, subsidies, and landfill tipping fee structures would influence the outcomes for how much RNG might be deployed into the California commercial trucking market. By doing so, we expand existing literature on refueling network research for planning and designing both natural gas and hydrogen supply chains to study a different alternative fuel, renewable natural gas, in the California context. This allows us to consider specifically the role that carbon pricing plays in promoting alternative fuels infrastructure.

Methodologically, Fan et al. (2017) was the first to utilize supply chain optimization techniques with network suitability analysis to explore possible pathways for alternative fuels to enter the freight sector. This paper adds to these techniques an additional layer of policy analysis to consider scenarios for how existing carbon credits available in California might influence the choice between fossil fuels and a lower carbon substitute, RNG, on an economic, temporal and geospatial basis. We believe this study of the California market holds insights into how carbon pricing intersects with goals to usher low carbon fuels into the on-road freight sector. We acknowledge limitations to our approach because we do not consider how carbon pricing might shift good movements to other transport modes or new efficiency technologies (such as automation and digital logistics planning) not under study in the modeling. We consider those technologies for future work. Finally, in the NG fuel demand model design, all facilities on a given route are assumed to be owned by a single entity with objective of maximizing profits across all stations along the given route. We acknowledge that the single-owner development per route limits the model's widespread application but note that in the United States to date, many regional natural gas routes (and even some national routes) have been developed by a single developer (for example, ENN Group Co. Ltd. in Utah and Clean Energy nationally).

2. Background

California is now is home to about 25% of U.S. liquefied natural gas (LNG) refueling facilities (Alternative Fuels Data Center, 2017a). There are more than a dozen LNG fueling stations for heavy trucks around the state of California and additional expansion is expected. As of May 2017, California had 380 fueling stations marketing natural gas-based fuel. There are approximately 25,000 registered natural gas vehicles in California (California Energy Commission, 2015). The state is home to 334 compressed natural gas (CNG) stations, or about 20% of the total number of CNG stations in the United States. An increasing number of stations sell RNG in the form of CNG, providing additional environmentally friendly options for consumers and businesses.

California is a major entry point for goods entering the United States. Total freight transported on road in California averages four million tons per day and freight movement is responsible for 7% of California's greenhouse gas emissions (California Air Resources Board, 2014; California Department of Transportation, 2012). California consumes approximately three billion gallons of diesel fuel a year in transportation and 17 billion cubic feet (BCF) of natural gas, the majority in heavy-duty trucking (California Energy Commission, 2017). Fan et al. (2017) find that California's natural gas heavy freight fueling system could expand to cover 900 million gallons of dge (diesel gallon equivalent) by 2030, if the number of heavy-duty trucks currently running on natural gas were to double in the coming years. Detailed flow rates vary year to year, but Fan et al. (2017) results find that the Los Angeles region can sustain the highest demand for natural gas fuel, followed by Fresno, Bakersfield and San Jose.

The state is seeking to reduce emissions from this sector to meet its climate and air quality goals. One pathway to reduce emissions in the sector is to substitute renewable natural gas for fossil-based gaseous fuels. Renewable natural gas can be a source for methane that is produced from organic materials or waste streams. It is possible to treat RNG so that it meets existing fossil natural gas pipeline and vehicle specifications. While RNG emits similar levels of greenhouse gases as fossil natural gas when used as a transport fuel, its derivation as a waste product means it provides an overall reduction of lifecycle greenhouse gas (GHG) emissions due to avoided upstream emissions. For example, landfill gas to energy (LGTE) where naturally occurring methane from the breakdown of waste in a landfill is captured and converted to a biofuel avoids harmful releases of pure methane leaks directly from the landfill into the atmosphere.

The existence in California of a liquid carbon pollution market via the Low Carbon Fuel Standard (LCFS) that qualifies both fossil natural gas and renewable natural gas for credits improves the potential for a shift away from diesel trucks to alternative fuels such as natural gas and renewable natural gas. Additionally, the national Renewable Fuel Standard (RFS) program categorizes renewable natural gas as advanced biofuel which generates Renewable Identification Numbers (RINs) which can then be sold to non-renewable fuel providers in order to comply with RFS requirements (Alternative Fuels Data Center, 2017b). The sale of RINs generated from RNG production also subsidizes the production of RNG. In 2014, the California legislature passed a bill promoting sustainable freight.[1] The law authorized the use of Greenhouse Gas Reduction Fund dollars to be spent on technology development, demonstration, pre-commercial pilots, and early commercial deployment of Zero or Near-Zero medium- and heavy-duty trucks. Roughly 20% of the program money in 2017 will be focused on heavy trucks. This amount will increase between 2018 and 2023 to 50% of allocated funds targeting heavy-duty trucks (California Assembly Bill, 2415, 2016).

Subsequently, California's Sustainable Freight Action Plan, released in 2015, calls for maximizing "near-zero emission freight vehicles and equipment powered by renewable energy by 2030." The plan specifically calls for the deployment of "over 100,000 freight vehicles and equipment capable of zero emission operation" (Brown, 2016). Given the time lag expected for the manufacture of hydrogen fuel cell or electric trucks, it is assumed that natural gas trucks powered by RNG will be an important building block to the early adoption of near-zero emission freight vehicles.[2]

There is an existing literature on U.S. biomass resources. Data from Saur and Milbrandt (2014) shows California providing many large candidate sites for landfill gas as well as other sources including solid organic waste collection, wastewater treatment plants and animal manure. Eight of the 25 largest candidate landfill gas sites cited in Saur and Milbrandt (2014) are located in California. Krich et al. (2005) find that there is sufficient biomethane sourced from cows to fuel existing natural gas vehicles in California but suggest that the economics of converting biogas to electricity is more cost effective than upgrading biogas to biomethane. Tunå and Hulteberg (2014) calculate that RNG is more cost effective than producing ethanol from woody biomass.

The potential to build a viable biogas fuel network for transportation is well established in Europe. Engerer and Horn (2010) find that European governments have developed incentives to foster the use of natural gas vehicles for environmental reasons and that use of gaseous renewable energy can be a way to avoid increased imports of natural

[1] The bill specified the creation of the "California Clean Truck and Bus and Off Road Vehicle and Equipment Technology Program".

[2] The Alternative Fuel Data Center and other websites provide a detailed list of subsidies for NGVs or natural gas stations (Alternative Fuels Data Center, 2016; Rhodes, 2013).

gas to supply these vehicles.

In the United States, the equipment required for removing impurities (clean up) and increasing the energy content (conditioning) of renewable natural gas have strong economies of scale, meaning that many of the smaller RNG resources will be more expensive to produce on a per unit basis when compared to fossil natural gas. In addition, interconnection of the feeder pipeline supplying RNG to existing natural gas pipelines have high fixed cost for both the capital investment and the required testing and verification of the RNG supply to ensure that it meets the quality specifications to be allowed access to pipelines. California's quality specifications are the strictest in the U.S. for testing, mixing and compression for RNG injection; presenting an additional barrier for in-state RNG production.

California also has several policies aimed to enhance the development of renewable natural gas. The potential to avert upstream methane emissions that would otherwise have been emitted enhances the commerciality of the use of renewable natural gas under a carbon credit regime. California has passed legislation to incentivize converting biomass to RNG such as the Short Lived Climate Pollutants (SB 1383) strategy (California State Bill, 1383, 2016). SB 1383 requires dairies, livestock production, and landfills to reduce methane emissions by 40% relative to 2013 levels by 2030. The legislation also contains provisions that direct gas companies to complete at least five pilot biomethane projects to demonstrate interconnection with the pipeline network by 2018. Additionally, the legislation requires the California Air Resources Board to establish energy infrastructure development and procurement policies needed to encourage dairy biomethane projects. Additional data on California specific resources of biomass are provided in technical resource assessment by the California Biomass Collaborative (Kaffka et al., 2016).

3. Methodology and data

The problem of developing RNG for the transportation market has three major components which we address with three different models working together to provide a fuller picture of the problem. We employ RNG supply estimates from a Geospatial Bioenergy System Model developed in Jaffe et al. (2016). We model natural gas refueling infrastructure development and natural gas vehicle adoption to project scenarios for vehicular natural gas fuel demand by employing the methodology developed in Fan et al. (2017). We link the supply of RNG and demand for vehicular NG fuel through a fuel policy model that examines how fuels policies in place in California (LCFS and RFS) can impact the price of RNG and encourage alternative fuel adoption. A schematic overview of the how these models interact is presented in Fig. 1.

3.1. Natural gas demand model

We address the demand-side for vehicular gaseous fuel by modeling alternative fuel infrastructure development and vehicle adoption using the methodology set forth in Fan et al. (2017). The geospatial model used in Fan et al. (2017) calculates the potential volumetric capacity for the natural gas transportation market in the United States, as well as optimal location of new and existing fueling facilities under different market conditions and alternative regulatory and policy settings. The model includes existing incumbent geospatial locations for dispensing traditional diesel fuels as a competitive market input and is designed to calculate where and when infrastructure should be deployed over a 20-year time horizon in order to satisfy demand along major trucking corridors across the United States. The modeling solution utilizes supply chain optimization techniques well established in the optimization literature for general facility location development (Drezner and Hamacher, 2002). While much of this literature revolves around point based demand, the model uses a flow-based approach because it best resembles the operations of heavy-duty trucking where fleet drivers refuel on route to a specific destination (Agnolucci and McDowall, 2013; Hwang et al., 2017; Kuby et al., 2017; Kuby and Lim, 2007).

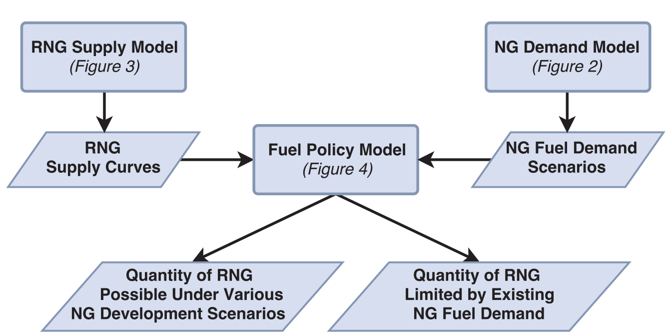

Fig. 1. Modeling schematic overview.

The methodology of this model is described in comprehensive detail in Fan et al. (2017). Here we provide a detailed summary of the methodology, but invite those seeking greater detail to refer to Fan et al. (2017) for further description. A schematic overview of NG Demand Model is presented in Fig. 2.

The model relies on a multistage mixed-integer linear programming network approach to address both spatial and temporal dynamics and to maximize the profit from building and operating LNG liquefaction and distribution facilities during the transition to using more LNG in the heavy-duty vehicle sector or alternatively to build a mix LNG infrastructure and CNG refueling networks that would compete against the incumbent fuel, diesel, in high volume markets. The model solves for the optimal construction of CNG/LNG refueling stations along California highways given inputs of natural gas, diesel, and electricity prices, volumes of truck traffic, candidate station distance to existing pipeline infrastructure, a choice of initial penetration rate of natural gas trucks, route coverage constraint and a 350 mile NG truck range assumption. Once an initial modeling solution is obtained, the model then solves a truck demand model to estimate the number of new truck purchases that will switch into natural gas trucks given the resulting CNG/LNG delivered fuel price which is an output of the optimization model. Based on the number of natural gas truck purchases, the penetration rate of natural gas trucks as a percentage of total trucks is updated and the optimization model then iterates again taking the updated penetration rate and refueling station construction under the first iteration as inputs. This iteration process repeats at roughly five year intervals until 2030.[3]

Parameters for the modeling solution are adjusted for the imposition of specific policy adjustments and incentives, allowing for a comparison of network development results under differing market conditions. The model can be adapted to be responsive to different policy and market scenarios. This is made possible by 1) flexible resource and technology inputs, 2) flexible temporal and spatial data inputs, and a 3) mixed-integer linear supply chain optimization model. For each scenario, the optimal natural gas infrastructure designs are found over a range of market penetration rates, refueling station subsidies, and diesel fuel prices. To simplify the modeling solution and gain computational tractability, we utilize suitability analysis (McHarg, 1995) to select candidate locations based on geospatial industry data on the locations of existing diesel stations on major U.S. highways. We selected critical nodes and links using classical centrality theory of betweenness centrality metrics (Freeman, 1977) and Urban Network Analysis tool (Sevtsuk and Mekonnen, 2012) in addition to k-means clustering algorithms within GIS to handle regions not encompassed by the initial critical nodes effort (Fan et al., 2017).

The objective function of the infrastructure construction submodel is formulated to maximize profit for the entire natural gas supply chain.

[3] The model solves for years 2012, 2015, 2020, 2025, and 2030.

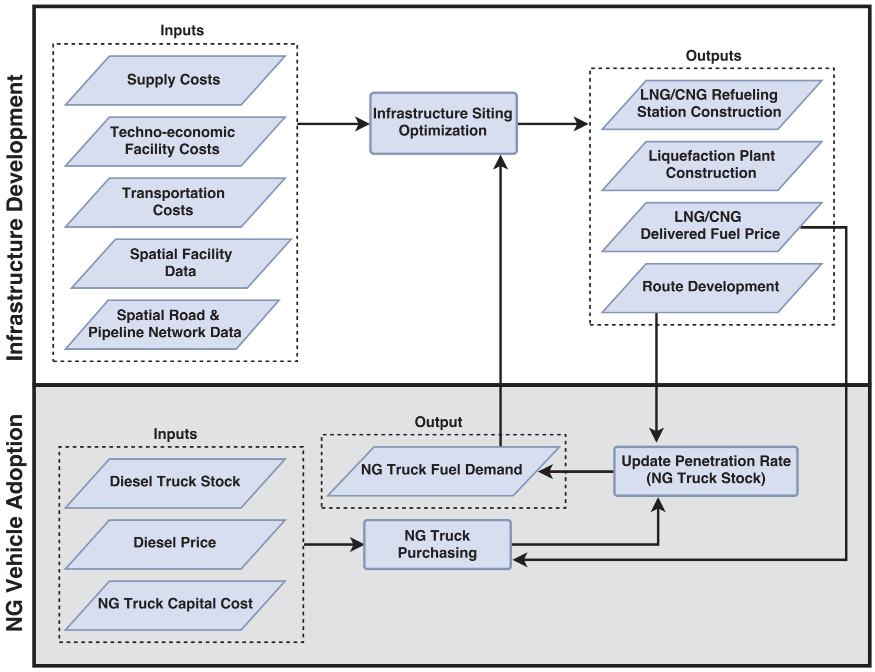

Fig. 2. Schematic overview of NG demand model.

Profit is defined as the annual revenues from the fuel sales less the annual cost of production of the fuel.

Objective:

$$Max\ Profit = \sum_{ij} (RP_j \cdot f_{ij}) + \sum_{lj} (RP_j \cdot f_{lj}) - Cost \tag{1}$$

where

$$\begin{aligned} & Cost \\ & = supply\ cost + station\ fixed\ capital\ cost \\ & + variable\ station\ cost\ (operation\ \ \&\ maintenance\ \&\ electricity\ ) \\ & + pipeline\ transport\ cost\ from\ supply\ to\ station \\ & + LNG\ liquefaction\ plant\ capital \\ & \quad cost\,(includes\ fixed\ operation\ \&\ maintenance) \\ & + variable\ LNG\ liquefaction\ plant\ cost\ (electricity) \\ & + pipeline\ transport\ cost\ from\ supply\ to\ LNG\ plant \\ & + truck\ transport\ cost\ from\ LNG\ liquefaction\ plant\ to\ station \end{aligned}$$

$$\begin{aligned} & \sum_{i} (SP_i \cdot (\sum_{j} f_{ij} + \sum_{l} f_{il})) + \sum_{jt} SFX_{jt} + \sum_{lj} ((SVOM_t + SE_{jt}) \cdot f_{lj}) \\ & + \sum_{ij} (SE_{jt*} \cdot f_{ij}) + \sum_{ij} (PT_{ij} \cdot f_{ij}) + \sum_{ls} (Y_{ls} \cdot PF_{ls}) + \sum_{il} (PE_l \cdot f_{il}) \\ & + \sum_{il} (PT_{il} \cdot f_{il}) + \sum_{lj} (TT_{lj} \cdot f_{lj}) \end{aligned} \tag{2}$$

The objective function shown in Eq. (1) maximizes the profit from producing, delivering, and dispensing LNG/CNG fuel over fueling stations j, liquefaction plants l, and natural gas supply sources i. The profit here is the annual revenue from sales of LNG/CNG less the annual costs of production across all active routes. A route is considered active if refueling stations are constructed along the route at intervals shorter than the maximum range of NG trucks so as to enable the truck to completely traverse the route. The annual revenue is determined by the quantity of LNG/CNG dispensed at CNG stations, f_{ij}, and conventional LNG stations, f_{lj}, times the market price of delivered LNG/CNG fuel, RP_j, which is derived from the retail diesel price at the specific location. The quantity of NG fuel delivered along each route is derived from the annual average truck traffic along the route, converted to an annual quantity of diesel gallons by dividing by the average diesel truck fuel efficiency of 6 miles per gallon and, finally, multiplying the resulting route demand for diesel fuel by the penetration rate along the route to obtain the NG fuel demand along the route.

The annual costs, shown in Eq. (2), are based on the price of feedstock natural gas from each supply hub identified by, SP_i, the station capital costs at location j of technology t, SFX_{jt}, station variable operation and maintenance costs for conventional LNG, $SVOM_t$, electricity price for LNG, SE_{jt}, electricity price for CNG, SE_{jt*}, and the cost of liquefaction plant construction of size s, PF_{ls}. The cost function also accounts for cost of transporting gas by pipeline from supply hubs directly to CNG stations, PT_{ij}, and to liquefaction plants, PT_{il}, and the cost of transporting LNG from liquefaction plant to refueling station via truck, TT_{lj}.

There are a many candidate locations for refueling stations and liquefaction plants based on existing refueling station locations and important locations in the natural gas pipeline network. The optimization model evaluates for every possible combination of station and liquefaction plant construction at every possible size combination the overall profits across all constructed stations and plants. The combination of station/plant construction and size that maximizes profit is returned as the solution to the optimization model. The optimization is subject to a number of constraints which are too lengthy to be included in this paper and can be found in Fan et al. (2017).

Renewable natural gas fuel can be processed to be used interchangeably with fossil natural gas by cleaning and preparing it for injection into the existing natural gas pipeline network. As such, it becomes physically indistinguishable from the wider fossil natural gas pool and can thereby utilize all the same facilities, infrastructure and trucks as fossil natural gas. Because RNG once injected into the natural gas pipeline network is in essence the same as fossil natural gas, its sales and distribution can be modeled using much the same geospatial tools we used for the previous study on natural gas fueling. However, new supply curves need to be added to the modeling. These new alternative supplies must reflect the specific pricing and geospatial differences of RNG resources as compared to fossil natural gas available at purchasing hubs. We must also adapt from a U.S. national model to a California state specific model.

The national model set forth in Fan et al. (2017) compiles the dynamic solution on a state by state basis and then combines the total routes and facilities together. In this paper, we consider infrastructure development on all routes with both endpoints within California as well as routes with one endpoint in California and one in endpoint in the nearby Western States: Washington, Oregon, Nevada, Idaho, Utah, Arizona, and New Mexico.[4] These cross-border routes help to illustrate how the NG refueling network can branch outside of California. Cross-border route development abides by the feasibility constraint in place for within-California routes such that stations may be no more than 350 miles apart. The cost of infrastructure development to these cross-border destinations is included within the California model. Some portion of out-of-state infrastructure development cost could be excluded on the basis that part of the travel is outside the state. We refrained from making such an adjustment because the modeling results indicate that fuel dispensed out-of-state makes up less than 1.5% of total fuel sales. In this study, we utilize all data on available sources for fossil natural gas used in California including fossil natural gas from other states. We do not currently include RNG assessments from outside California.

In the original national modeling solution, demand-side fuel choices included traditional diesel fuel and related incumbent infrastructure or two alternative pathways for natural gas fuel: 1) LNG via centralized conversion facilities and trucking of the liquefied fuel and 2) LNG produced at a modular LNG conversion facility onsite at a refueling station (Fan et al., 2017). In both LNG delivery options, natural gas is delivered to the conversion facilities (either centralized or modular) via the natural gas pipeline network and the source of all natural gas is assumed to be fossil natural gas. In our RNG extension, fuel choices are modified to include diesel fuel and related incumbent infrastructure as well as two pathways for natural gas fuel and four pathways for renewable natural gas. The natural gas pathways include infrastructure either for LNG via centralized conversion facilities and trucking of the liquefied fuel and 2) CNG produced via an onsite compressor at a refueling station. In this paper, natural gas is assumed to be delivered to the conversion facility (either centralized LNG or onsite CNG) via the natural gas pipeline network and we consider multiple possibilities for sources of gaseous fuel; in addition to fossil natural gas, we consider four alternative sources of renewable natural gas all connected to the natural gas pipeline network: 1) RNG from landfill sources, 2) RNG from an aerobic digester of municipal solid waste (MSW), 3) RNG from an aerobic digester of waste water at waste water treatment plants (WWTP), and 4) RNG from an anaerobic digester of dairy manure.

3.2. RNG supply model

For this work, we employ the RNG supply estimates developed in Jaffe et al. (2016) using the Geospatial Bioenergy System Model to optimally locate and size facilities to produce RNG from California's resources based on the costs of procuring, transporting and converting the resource to RNG (Parker, 2012; Parker et al., 2010; Tittmann et al., 2010).

We employ these RNG supply estimates to assess the degree to which renewable natural gas can enter the market for vehicular fuel, what quantity of RNG is available to displace fossil fuel, and what level of price support is required to incentivize RNG production. A schematic overview of the methodology employed in creating the RNG supply estimates is presented in Fig. 3.

Jaffe et al. (2016) collected information on geo-located quantities of biomass for dairy manure, landfill waste in place, municipal solid waste, and wastewater treatment plants and estimated supply curves that consider the cost of capital expenditure for anaerobic digesters and clean-up and upgrading facilities, distance to nearest pipeline, and pipeline and interconnect construction costs for each RNG production pathway. The supply curve estimates also incorporate landfill tipping fees which serve as an offset in the MSW pathway. We utilize these technical estimates of resource availability and costs to determine the quantity of renewable natural gas that could be supplied in California's heavy-duty freight sector under different competitive landscapes and policy conditions. The supply curves are modified by adjusting the input cost functions for each technology pathway.

We also consider the impact of landfill policy on California RNG production. One of the four pathways of RNG production, municipal solid waste, is particularly sensitive to landfill policy. A municipality that disposes of its waste at a landfill will incur a charge for that activity. Alternatively, it could transfer it to a municipal solid waste digester and avoid the cost of paying the tipping fee. Jaffe et al. (2016) assumes the RNG production captures the value of the avoided tipping fee cost. Therefore, the higher the tipping fees in an area, the more economical is the choice to divert waste to a dedicated digester. In our approach, we also adjust the revenue stream available to MSW digesters through increased tipping fees. We determine the tipping fee using the 2015 CalRecycle study of landfill tipping fees across the state (CalRecycle, 2015). Regionally differentiated tipping fees were used based on average tipping fees from the report. In order to assess the impact of policy affecting tipping fees or restrictions to landfill contributions, we increased the tipping fee offset received in the MSW RNG pathway by 20% and recalculated the levelized costs of RNG production in light of a larger possible offset.

A recent CA legislation, SB 1383, prescribes a dramatic change to landfill policy. SB 1383 requires a fifty percent reduction in organic waste contributions to landfill by 2020 and a 75% reduction by 2025 relative to 2014 levels. This quota on organic matter contributions will drive up the cost of finding alternate destinations for organic waste which will significantly improve the economics of RNG production from dedicated municipal solid waste digesters.

3.3. Fuel policy model

We then link demand and supply models with a model that shifts the RNG supply curves relative to the cost of fossil natural gas in accordance with how LCFS credits and RFS RIN prices subsidize specific RNG costs. We assess how the LCFS and RFS policies reduce the price of specific RNG pathways relative to competing fossil natural gas. To accomplish this, we calculate for a given LCFS credit price or a given RFS RIN price, what the resulting per mmBTU price reduction will be for each RNG fuel pathway relative to fossil natural gas in line with methodology used in Scheitrum (2017).[5] Following the calculation of the RNG price reduction, we determine the quantity of RNG that can be supplied at less than or equal to the cost of fossil natural gas. Lastly, the quantity of RNG that can be consumed is constrained by the demand for natural gas as a vehicular fuel which is calculated by the NG demand model. With these demand projections, we assess the quantity of RNG that can be consumed in California under scenarios where vehicular natural gas consumption expands. A schematic overview of the Fuel Policy Model which links to both the NG Demand Model and the RNG supply Model is presented in Fig. 4.

The per mmBTU value of LCFS credits depends on three criteria: 1) the LCFS credit price, 2) the carbon intensity of the fuel pathway (i.e. fossil natural gas, RNG from landfill sources, RNG from dairy sources, etc.) in terms of grams of CO_2e per megajoule and 3) the carbon intensity target. We calculate the per mmBTU quantity of credits generated according to the formula

$$N_p = (Target - CI_p) \times C \tag{3}$$

[4] Examples of cross-border routes include Los Angeles,CA to Las Vegas, NV or San Francisco, CA to Portland, OR.

[5] The RFS requires transportation fuel sold in the United States to contain a minimum volume of renewable fuel. Recently, the U.S. Environmental Protection Agency has classified RNG as qualifying as cellulosic and advanced biofuels in the RFS program. Fossil natural gas does not qualify as biofuel under the RFS (Alternative Fuels Data Center, 2017b).

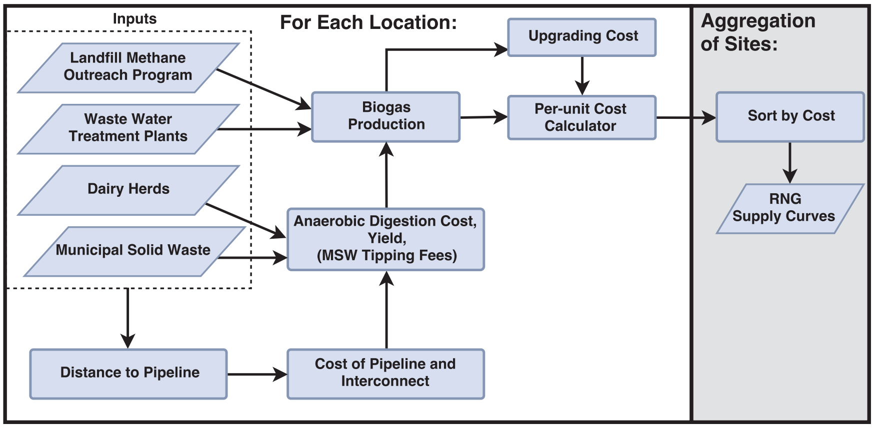

Fig. 3. Schematic overview of RNG supply model.

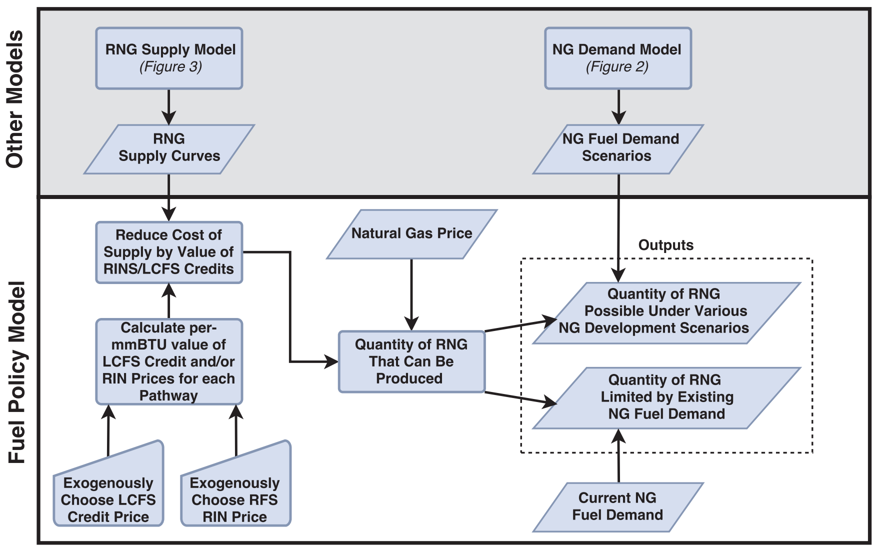

Fig. 4. Schematic overview of fuel policy model.

where N_p is the number of LCFS credits generated per mmBTU, *Target* is the carbon intensity target of the LCFS program, CI_p is the carbon intensity of the fuel pathway in question, C is a constant which converts grams CO_2e per megajoule to credits per mmBTU, and p indicates the fuel pathway (Landfill, MSW, WWTP, or Dairy RNG).[6] Since the sale of fossil natural gas also generates LCFS credits, the relevant value to employ when determining the relative prices of fossil and renewable natural gas is the quantity of credits generated per mmBTU of renewable natural gas in excess of fossil natural gas. The number of credits generated by RNG in excess of fossil natural gas per mmBTU, N_p^*, is given by modifying Eq. (3) to

$$N_p^* = (FossilCI - CI_p) \times C, \tag{4}$$

regardless of where the carbon intensity target is set. *FossilCI* is the carbon intensity of fossil natural gas. The per mmBTU value of the LCFS credits generated in excess of fossil natural gas is then N_p^* multiplied by the LCFS credit price. Given the price support to pathway p in excess of the support received by fossil natural gas, we then shift the supply curves for each of the pathways of RNG production and determine the quantity of RNG that can be produced at a cost less than that of fossil natural gas.

The process for calculating the impact of RIN prices on RNG supply curves is much simpler. All four pathways of RNG are classified the same way under the Renewable Fuel Standard; they are classified as advanced biofuel. The sale of RNG from any of these four sources generates D3 RINs, the most highly priced RINs. The sale of fossil natural gas does not generate any RINs. Therefore, the process to calculate impact of the RFS program on RNG supply curves is as simple as converting the RIN price from dollars per ethanol gallon equivalent to dollars per mmBTU.

Lastly, fossil natural gas can be blended with renewable sources of natural gas to create blends with carbon intensities anywhere in the range from fossil natural gas to the least carbon intensive source, dairy RNG. The carbon intensities of different blends of fossil and renewable natural gas can be estimated using the carbon intensities in Table 1 and using the formula

$$\text{BlendedCI}_p(\theta) = [\text{FossilCI}*(1-\theta)] + [CI_p*\theta], \tag{5}$$

where BlendedCI_p is the carbon intensity of the final blend, *FossilCI* and CI_p are the carbon intensities of fossil natural gas and renewable natural gas pathway p respectively (shown in Table 1), and θ indicates the percentage of RNG in the blend.

3.4. Data

In our optimization model, we employ data similar to the data employed in Fan et al. (2017), but we restrict the analysis to California and consider LNG and CNG as the two options for delivering natural gas fuel. We rely on the Bureau of Transportation Statistics and Freight Analysis Framework for data on annual average truck traffic. For data on the geolocation of U.S. highways, we use the National Highway System per the Federal Highway Administration. Data on the location of

[6] Constant C equals 0.00100587 based on 1,000,000 g per metric tonne and 1,055.87 megajoules per mmBTU.

Table 1
Carbon intensities for fuel pathways employed by the Low Carbon Fuel Standard.

Fuel pathway	Carbon intensity ($g\ CO_2e$ / MJ)
Diesel[a]	102.01
Gasoline[a]	99.78
Fossil CNG[b]	78.37
Landfill CNG[b]	46.42
WWTP CNG[a]	19.34
MSW CNG[a]	−22.93
Dairy CNG[c]	−276.24

[a] California Code of Regulation, Title 17, §95488, Table 6. Carbon intensity for WWTP is the average of two WWTP pathways.
[b] California Code of Regulation, Title 17, §95488, Table 7.
[c] Method 2B Application CalBio LLC, Dallas, Texas, Dairy Digester Biogas to CNG.

natural gas pipelines is from the National Natural Gas Pipeline Network from the National Pipeline Mapping System. Information on natural gas spot prices and locations of natural gas trading hubs are from the Baker Institute World Gas Trade Model (Medlock and Hartley, 2006). The source for the price of diesel and the price of electricity is the U.S. EIA (EIA, 2017, 2016). Information on candidate refueling station locations is from a commercial dataset called “Diesel Truck Stops” and candidate liquefaction plant locations are calculated from the National Natural Gas Pipeline Network as described in Fan et al. (2017). For the RNG supplies, we employ the estimates from Jaffe et al. (2016).

We consider various policy options to support the production of renewable natural gas. We consider the impact of LCFS credits and RIN prices on RNG production. We employ the monthly average LCFS credit price at the end of 1Q 2016 of $120 per metric ton of CO_2 equivalent avoided and determine the quantity of RNG that can be produced at a cost lower than the price of fossil natural gas of $3.00 per mmBTU. Though there is a wide variance in the estimates of carbon intensity of fuels and fuel pathways (Dominguez-Faus, 2015), we employ the carbon intensity values listed in the LCFS rulemaking and rely on specific applications for pathways that are not available in the rulemaking. Carbon intensities employed in the LCFS analysis for diesel, gasoline, fossil natural gas and landfill, dairy, MSW, and WWTP RNG are presented in Table 1 and are from the California Code of Regulation, Title 17 §95488 and an approved application for pathway carbon intensity certification. For RIN prices and their impact on RNG production, we consider RIN credits of $1.78 per ethanol gallon equivalent (ege) based on the 2016 D3 cellulosic biofuel RIN price.

4. Results

4.1. Expansion of natural gas demand in transportation

Our reference case from the modeling where we consider diesel and natural gas prices as of May 2016 shows little to no increase in demand for natural gas trucks. We then adjust the parameters to consider different deltas between diesel and natural gas prices. We run the model with an input of diesel prices as of December 2013 to be a reasonable parameter for moderate diesel prices, and diesel prices as of July 2008 to be a reasonable parameter for high diesel prices to demonstrate impacts during periods when natural gas infrastructure and vehicles faced broader adoption, mindful that the gap between diesel prices and natural gas can also be influenced by falling natural gas prices *relative to* diesel prices.

The scenarios for infrastructure development under a 0.1% initial penetration rate and assuming moderate and high diesel prices are presented in Fig. 5. Natural gas fuel consumption by NG trucks projected in 2030 under a 0.1% penetration rate is 0, 692, and 1,153 BCF/year under low, medium, and high diesel price scenarios, respectively.

This feedback mechanism governing the development of the natural gas refueling network is particularly sensitive to the initial penetration rate of natural gas trucks. Fig. 6 shows the different rates of natural gas refueling infrastructure development under 0.2% initial penetration rate under the low, moderate, and high diesel price scenarios. Natural gas fuel consumption by NG trucks projected in 2030 under a 0.2% penetration rate is 1,845, 123,007, and 239,947 BCF/year under low, medium, and high diesel price scenarios, respectively.

4.2. Adoption of renewable natural gas

Our analysis shows that no RNG from any source – landfill, MSW, Wastewater or animal manure – is commercially feasible without policy intervention when competing against low-priced natural gas. However, the existence of carbon and renewable fuels credits in the California market is sufficient to overcome the underlying market failure where the externality of carbon pollution would remain unassessed. Under a $120 LCFS credit price, we find that 14 BCF/year of RNG can be produced. The quantities possible from landfill, MSW, WWTP, and dairy are 6.3, 1.7, 1.5, and 4.3 BCF/year, respectively. Under a $120 LCFS credit price combined with a RIN price of $1.78 per ethanol gallon, we find 83 BCF per year can be produced. Under the LCFS plus RIN scenario, the quantities possible from landfill, MSW, WWTP, and dairy are 50.8, 16.3, 5.6, and 10.1, respectively.

Minimum levels of price support required to promote RNG production range from $3.75 per mmBTU for landfill up to $26.00 per mmBTU for dairy. Our estimates for levels of price support needed to promote various RNG production pathways are presented in Table 2 below.

We also consider whether additional changes in the level of waste collection tipping fees would promote investment in RNG from municipal solid waste that could be economically diverted to a digester. Any change in the level of landfill tipping fees influences the economics of diverting MSW to a digester. We consider an example where current tipping fees, which vary widely from site to site, were 20% higher than today. In this case, higher tipping fees would be impactful to RNG production levels from MSW sources. Our results suggest that volumes of MSW going to municipal digesters would increase from 1.75 to 12.4 BCF per year under a $120 per metric tonne of CO_2e LCFS credit price if tipping fees were 20% higher.

5. Conclusions and policy implications

5.1. Natural gas fuel adoption

Oil and natural gas prices have been volatile in recent years. In the early 2010s, there was a large cost benefit to fuel switching from diesel to natural gas that has since moderated. We are cognizant that changes in the relative spread between U.S. natural gas and diesel prices will influence how much government intervention is needed to incentivize switching to natural gas trucks. To the extent that California can promote the use of natural gas trucks in secondary and tertiary freight markets, it will be easier to launch a sizable alternative fuels infrastructure in the state. California requires that all trucks that cross into its borders, including cross-national trade with Mexico, meet its environmental vehicle rules and specifications.

There are other barriers to the market as well. Fleet owners worry that supply chains for natural gas vehicles are not yet sufficiently robust to avoid higher maintenance costs, potentially raising fixed operating costs to find mechanics trained to repair natural gas engines. Regulatory uncertainty remains an additional barrier as some California environmental policies have sun-setting elements or may face changes in the future. High injection tariffs and interconnection costs for renewable natural gas in California also inhibit commercial development of RNG and incentivize injection of RNG from other locations outside the state. The Coalition for Renewable Natural Gas estimates that interconnection costs for projects outside California range from $82,000 to $272,000 per connection while California utilities quote

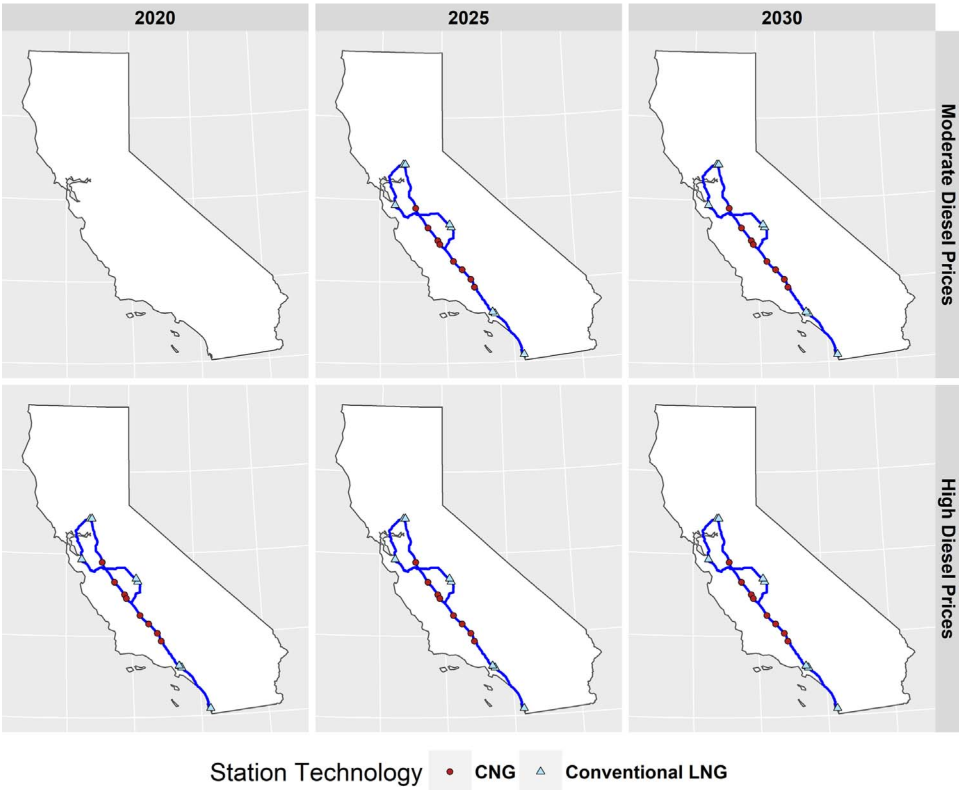

Fig. 5. NG station price development and route deployment, under 0.1% market penetration and two scenarios: moderate and high diesel prices. The blue lines indicate routes that are active for NG trucks due to sufficient station construction to allow for complete end-to-end travel. The blue triangles indicate conventional LNG stations and the red circles indicate CNG stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

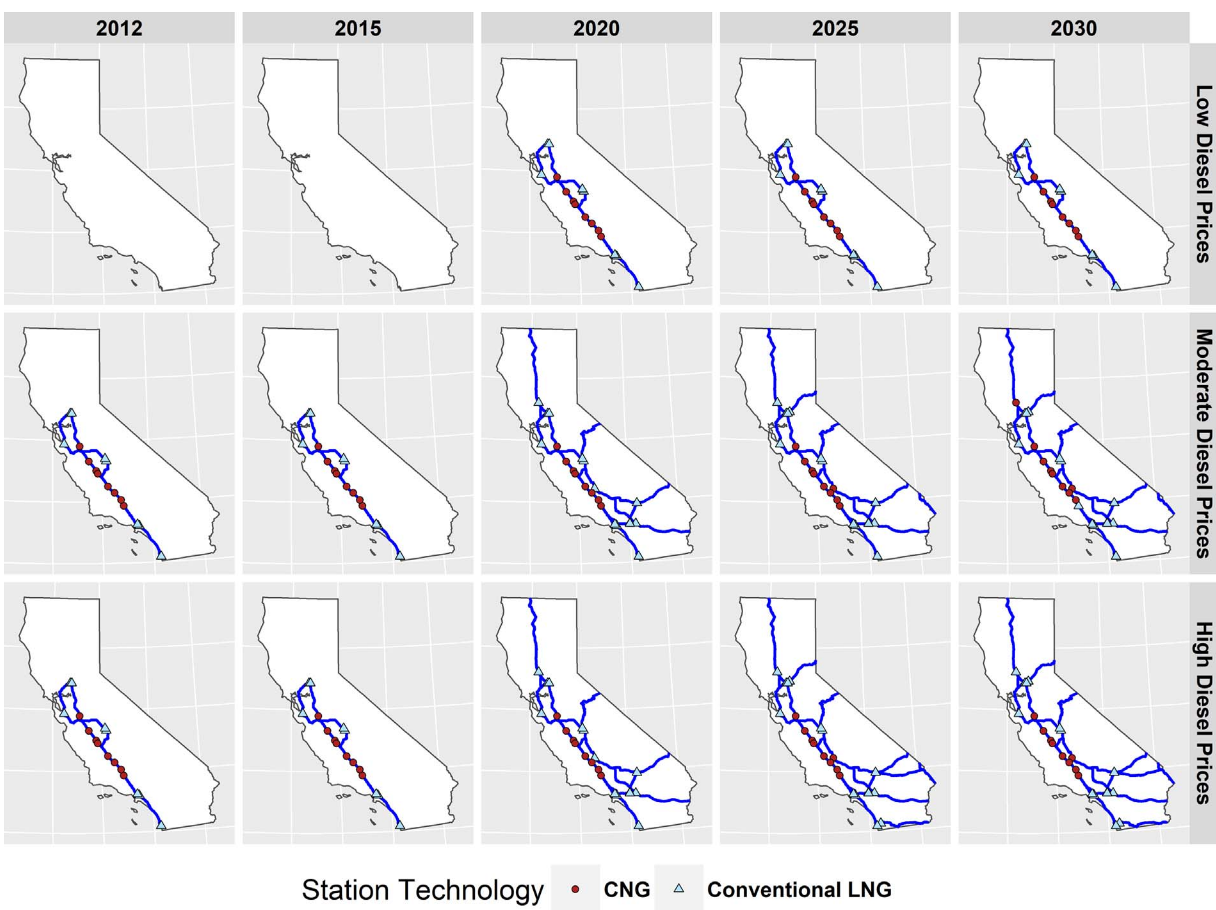

Fig. 6. NG station price development and route deployment, under 0.2% market penetration and three scenarios: low, moderate, and high diesel prices. The blue lines indicate routes that are active for NG trucks due to sufficient station construction to allow for complete end-to-end travel. The blue triangles indicate conventional LNG stations and the red circles indicate CNG stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Levels of price support required to incentivize production by pathway.

RNG production Pathway	Support required to incentivize production over $3.00/ mmBTU market price (2015$)	
	$ per mmBTU	$ per gasoline gallon equivalent
MSW	$11.50	$1.38
Landfill	$3.75	$0.45
WWTP	$5.90	$0.71
Dairy	$26.00	$3.15

interconnection costs as high as $1.5–3 million (Coalition for Renewable Natural Gas, 2013). The process for planning, siting, and constructing RNG facilities is also hindered by competing regulations and permitting bodies.

To achieve the high estimate of RNG production in California of 83 BCF per year, natural gas transportation would have to expand beyond its existing 17 BCF per year. This expansion could result from either a widening of the natural gas-diesel price spread (due to market forces or via market incentives) or by policy intervention that would increase the number of natural gas trucks on California roads in the near term. Our study finds that it would take a doubling of the current heavy-duty natural gas trucking fleet to promote rapid investment in station infrastructure to match potential RNG production. This would likely require either technology cost breakthroughs, regulatory policies restricting fleet choices, or subsidies for purchasing natural gas trucks to grow the network to a large enough volume of trucks to prompt self-generating expansion. There are indications that increased market competition using Chinese manufactured fuel tanks could reduce natural gas truck tank cost by 60–70% but policy intervention is still needed to spur the market.

We consider specifically how renewable natural gas might fare in California as a fuel for trucking given that fuel developers in the state benefit from carbon pollution credits and other incentives for low carbon fuels. We find California's LCFS and the national RFS provide a carbon credit for gaseous fuels from natural gas or RNG and this already serves, in effect, as part of the needed subsidy that can be captured by commercial developers and alters the relative prices in favor of natural gas fuels.

5.2. Impact of existing policy on adoption

Next we analyze what level of existing credits for alternative fuels are sufficient to propel renewable natural gas as an alternative fuel for trucking in California. Our fuel policy model results show that the combination of LCFS credits and RIN prices substantially increases the amount of natural gas fuel and RNG that is commercially feasible in the state. This result confirms that carbon prices can make a significant difference in incentivizing the substitution of lower carbon fuels for fossil fuels.

One takeaway of this conclusion is that it may already be economical for carbon credit markets in California to encourage investment by the private sector in in-state renewable natural gas resources. In particular, we find that large landfills located in Los Angeles, San Diego, Irvine, Sacramento and Livermore could be commercially developed at an LCFS credit value as low as $90 per metric tonne CO2e.

5.3. Policy implications

Our findings are consistent with new commercial interest in RNG in the U.S. In March 2017, BP announced that it was acquiring RNG businesses from Clean Energy in the U.S. (Clean Energy, 2017). Still, while existing incentives such as carbon pricing and incentives to lower interconnections costs will overcome some of these higher-cost hurdles for the use of fossil and renewable natural gas in fueling of trucking in the state of California, our modeling suggests that additional interventions may be needed to drive a larger scale in-state local industry. As discussed above, several programs exist in California to provide subsidies to fleet owners willing to purchase natural gas vehicles. Our modeling suggests that these programs could prove important to encourage additional investment in the local California market. These include the Natural Gas Vehicle Incentive Project by the California Energy Commission (CEC); the Carl Moyer Program, which supports the purchase of cleaner-than-required engines and equipment (California Air Resources Board, 2016); and the California Clean Truck and Bus and Off Road Vehicle and Equipment Technology Program. California's efforts through the above programs are seeking to provide this additional push to get the market in motion. Reducing the uncertainty surrounding access and duration of these programs would likely positively influence market development.

Our study considers whether additional changes in the level of waste collection tipping fees would promote investment in RNG from municipal solid waste that could be economically diverted to a digester. Any change in the level of landfill tipping fees influences the economics of diverting MSW to a digester. The commerciality of RNG is higher in Europe. This is due to many factors including higher prices of incumbent fuels via taxes and other factors. Higher tipping fees for landfilled material in Europe is another factor that has promoted RNG in Europe (CalRecycle, 2015; European Environment Agency, 2013). A 20% increase in tipping fees would raise RNG production from MSW sources by a factor of seven under a $120 per metric tonne of CO_2e LCFS credit price. The higher the tipping fee, the more cost savings in the choice to divert MSW waste to a digester instead of paying to dispose of it in a landfill.

California's government has already tightened limits on the amount of MSW that can be accepted at landfills. This in effect will be as if the state raised tipping fees. But a mandated state-wide minimum floor tipping fee for MSW, if high enough, could be another policy that could stimulate higher diversion of MSW to digesters. By contrast, a tax on landfill operations might be ineffective, depending on the level of competition for landfill services in a particular location. Competition might force landfill operators to reduce underlying tipping fees to make room for the tax.

Another way to render the California natural gas fuel network more commercially feasible is to further reduce the costs of producing RNG fuel, which has lower carbon intensity and therefore qualifies for a larger carbon credit than fossil natural gas. In addition to the LCFS, California also has other policies that can help the development of renewable natural gas. The Short Lived Climate Pollutants strategy (SB 1383) requires dairies, livestock production, and landfills to reduce methane emissions by 40% relative to 2013 levels by 2030. Under the reductions mandated by SB 1383, these facilities will find it more compelling to produce RNG as both a method to generate income and a method for compliance with regulations. However, these measures may reduce the gross quantity of RNG available in California by shifting marginal dairy producers outside of California where they do not face these regulatory compliance burdens. The full impact of this policy requires further study.

In the long run, RNG supplies could be expanded through the use of gasification of woody biomass or power-to-gas technologies for producing methane from excess renewable electricity. The potential for RNG from woody waste resources from California's cities, forests and farms could more than double the supply of RNG. The production of RNG from excess renewable electricity could also be significant. These resources will be valuable as a source of liquid fuels and/or hydrogen in a carbon-constrained world, which may limit their use as RNG.

The carbon intensity of CNG/LNG fuels drastically improves with the addition of RNG. This creates a rationale for government support for both the development of RNG resources for use in freight transportation and the shift toward greater overall use of CNG and LNG in the transport sector. By utilizing RNG, CNG and LNG have the flexibility to reduce the carbon intensity below what is possible with fossil natural gas alone and is not a dead end pathway as California pushes its carbon intensity requirements beyond the rating of fossil-based CNG.

In summary, policy interventions such as waste management policies and carbon credit programs like the LCFS will prove to be integral to the development of gaseous alternative fuels in California. We find that the private sector is well positioned to consider the wide variations in costs for various sources for RNG at different locations and applications and to decide which resources will carry the most attractive return on private capital under various credit and incentive structures. Some investments are already taking place in California, providing some evidence that market participants are pursuing the most fruitful options first. Our findings suggest that research & development, scale economies and learning by doing will enhance the introduction of renewable sources of gaseous fuel over time.

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