Impact of Intensity Standards on Alternative Fuel Adoption: Renewable Natural Gas and California's Low Carbon Fuel Standard

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ABSTRACT

Natural gas is a rapidly growing transportation fuel. While fossil natural gas is only slightly cleaner than conventional fuels, it provides a vector to introduce renewable natural gas (RNG) which can yield substantial emissions reductions. This paper considers RNG supply estimates from four possible sources: dairy manure, municipal solid waste, wastewater treatment plants, and landfill gas along with other major transportation fuels to evaluate the impact of California's Low Carbon Fuel Standard (LCFS) a first of its kind fuel intensity standard. A static, multi-market, partial equilibrium, numerical model of the California fuel markets assesses the economic surplus and climate impact responses to the LCFS policy and compares the efficiency of the LCFS to a hypothetical carbon tax. Results indicate LCFS policy is sufficient to incentivize substantial quantities of RNG production. The LCFS approaches the efficiency of a carbon tax as the LCFS policy becomes more stringent when combined with a price ceiling.

Keywords: Renewable Natural Gas, Methane Abatement, Fuel Standards

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1. INTRODUCTION

Transportation in the United States is almost entirely powered by fossil fuels and is responsible for significant contributions to greenhouse gas emissions (Pachauri et al., 2014). Transportation is the subject of myriad emission-reducing policies and regulations such as those addressing fuel economy, tailpipe emissions, and the mandated blending of biofuels in the gasoline supply.[1] While these programs have largely been successful at achieving their stated goals, transportation remains a major source of greenhouse gas (GHG) emissions, making up 26% of all emissions in the United States (EPA, 2016b). Efforts to further reduce the climate footprint through the use of additional biofuels have been inhibited by the "blend wall"; the technological limitation precluding blends of over 10% ethanol from use in most gasoline engines. For many other alternative fuels, significant adoption depends upon the transformation of the vehicle fleet, which will take many years given the long vehicle replacement interval.[2] Natural gas provides a real possibility for near-term

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[1] See, for example, the Energy Policy and Conservation Act of 1975, the Clean Air Act Amendments of 1977, and the Energy Policy Act of 2005.

[2] The average lifetime of passenger cars and light trucks is 16 and 18 years, respectively (Bento, Roth and Zuo, 2013).

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reductions in transportation emissions, particularly through the employment of natural gas produced from renewable sources.

While natural gas makes up a small portion of fuel consumption, it is steadily growing mostly due to low prices of natural gas. Adoption of natural gas freight vehicles is already employed by several major freight fleets such as Cisco, Pepsi, Walmart, Frito-Lay, HEB, Trimac Transportation, Truck Tire Service Corporation (TTS), Verizon, UPS, AT&T, Food Lion, and Ryder (Jaffe et al., 2015). This phenomenon of expansion of natural gas into the heavy-duty trucking sector has been studied in Krupnick (2011), Knittel (2012), and Fan et al. (2017).

The current level of vehicular natural gas consumption presents a ready market for the introduction of renewable natural gas (RNG) (Energy Information Administration, 2016d). RNG is considered to be an extremely low-carbon (in some cases negative carbon) fuel because it is produced via the recovery of methane that would otherwise emit into the atmosphere and its consumption displaces the consumption of fossil natural gas or some other fossil fuel. Methane is a potent greenhouse gas having approximately 25 times the impact on climate as CO_2 (IPCC, 2007). Therefore, capturing emissions of methane, converting them into less harmful CO_2 via combustion, and displacing the combustion of fossil natural gas significantly reduces GHG emissions. Further, natural gas fuel emits far less particulate matter and pollutants that adversely affect air quality and public health compared to gasoline and diesel (U.S. Department of Energy, 2018). This paper does not assess the impacts on air quality or public health, though this can be assessed in future research.

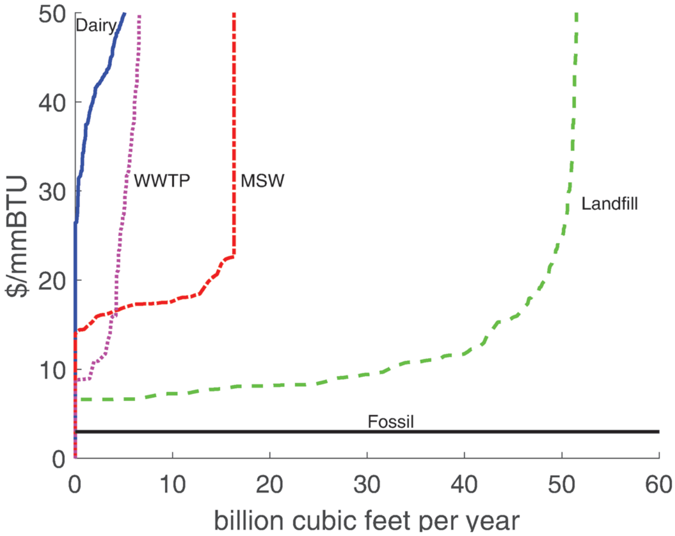
The most promising RNG production pathways are the capturing and upgrading of (1) landfill gas and the anaerobic digestion and upgrading of (2) dairy manure, (3) municipal solid waste (MSW), and (4) waste water at waste water treatment plants (WWTP). California State Bill 1383 (SB 1383), specifically targets the reduction of methane from the dairy sector. SB 1383 (2016) requires the dairy sector to reduce methane emissions by 40% relative to 2013 levels by 2030. This amounts to a reduction of roughly 9.4 million metric tonnes of CO_2e (California Air Resources Board, 2016a).[3] The landfill sector is required to reduce contributions of organic matter to landfills by 50 percent relative to 2014 levels by 2020 and by 75 percent relative to 2014 levels by 2025. Diversion of organic waste to dedicated MSW digesters is one way to accomplish this requirement. The extent to which RNG production can achieve these goals, the quantity of RNG that can be produced and introduced into transportation, and the degree to which emissions can be reduced is largely unknown. To answer these questions, I rely upon estimates of California RNG supplied by Parker et al. (2017). RNG supply curve estimates are presented in Figure 1 with price in dollars per mmBTU and quantity in billion cubic feet (bcf) per year.[4] In this paper, I evaluate the response of California RNG production to an existing California transportation policy, the Low Carbon Fuel Standard (LCFS).

The Low Carbon Fuel Standard sets a target for the carbon intensity (quantity of greenhouse gas emitted per unit of energy consumed) of the transportation sector. Consumption of fuels which have carbon intensities above (below) this target generates deficits (credits). Deficits must be offset by purchases of credits. The carbon intensity target is set exogenously by the state and the price of credits is determined endogenously by the supply and demand for credits in the LCFS credit market. I first present a demonstrative, analytical model to illustrate the features of the LCFS policy in comparison to a carbon tax, which is more familiar to most readers. The analytical model indicates that the response of RNG is highly sensitive to credit price. Evaluation of RNG supply

[3] Carbon dioxide equivalent measures different greenhouse gases in terms of the equivalent amount of carbon dioxide that would be required to be emitted (or avoided) to have the same climate impact.

[4] 1 bcf of natural gas is equal to 1 million mmBTU of natural gas.

Figure 1: Renewable Natural Gas Supply Curve Estimates



Source: Parker et al. (2017).

response to LCFS policy requires a robust model which includes an endogenous determination of credit price.

One limitation of the LCFS is that it applies only to the transportation sector. There may be better opportunities to employ RNG such as heating homes. The scales of this end use is so large there would be effectively no limitation on the quantity of RNG that could be consumed. In the transportation sector, the quantity of RNG that can be consumed is constrained by the number natural gas powered vehicles in use in transportation. Alternatively, RNG could be used to generate electricity which would avoid much of the substantial expense of connecting to the natural gas pipeline network and could offset electricity produced from relatively high emitting sources such as coal-fired power plants. However, The option of employing the captured gas in electricity generation is limited due to new legislation limiting emissions from stationary electricity generation sites (Parker et al., 2017).[5] Therefore, I limit the focus of this paper to the impact on transportation fuels.

In this paper, I construct a numerical, static, multi-market, partial-equilibrium model of California transportation fuels. The model considers the markets for gasoline, diesel, ethanol, biodiesel, natural gas, and renewable natural gas. The fuels considered make up 99.9% of California's transportation fuel consumption. In this model, I estimate the quantity, price, economic surplus, and emissions responses of these fuels to the LCFS policy. The numerical model includes many extensions that build upon previous efforts to model LCFS policy (Holland, Hughes and Knittel, 2009; Lade and Lin Lawell, 2015a,b; Chen et al., 2014; Huang et al., 2013; Rubin and Leiby, 2013). First, by relying on the RNG supply estimates presented in Parker et al. (2017), I include natural gas and RNG which have been absent from previous studies. Second, I extend beyond a two-fuel gasoline-ethanol model as employed by Holland, Hughes and Knittel (2009) and Lade and Lin Lawell (2015a,b) to a more comprehensive consideration of the California fuels market. By expanding be-

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5. The majority of potential RNG production sites would be located in areas classified as as extreme nonattainment for federal 8-hour ozone standards and nonattainment for federal PM2.5 emissions. On-site electricity generation at potential RNG production sites would be categorized as new stationary sources of pollution and therefore subject to tremendous burdens in terms of permitting and approval.

yond gasoline and ethanol, I capture the impact of other major conventional fuels on the LCFS credit market and provide a more complete representation of credit price determination. Without considering these other fuels any modeling of credit market equilibrium would be incomplete. Third, rather than assume perfect substitution of vehicle fuels, I impose constraints that reflect the limitations of the existing vehicle fleet. That is, I adopt the methodology developed by Anderson (2010) to model consumer choice fuel switching between gasoline and E85 and adapt this method to the diesel-biodiesel market. Allowing for substitution across fuel groups would result in a slower rise in credit prices. Results from Bento, Roth and Zuo (2013) suggest that consumers overreact to fuel prices when purchasing replacement vehicles and, over the long-term, the response to subsidized fuels may be significant. Lastly, I model the implementation as it exists in California, rather than consider a hypothetical LCFS policy. Therefore, the results are directly relevant to policymakers.

To evaluate the economic efficiency of the LCFS policy, I compare it to a hypothetical carbon tax. The hypothetical carbon tax I consider applies to all sectors of the economy and employs the same carbon intensity assessments as employed in the LCFS. Consequently, this hypothetical carbon tax accounts for the full lifecycle advantage of negative carbon fuels. Typically, a carbon tax prices the positive content of carbon in a fuel. Fuels that have negative carbon intensity assessments due to the full lifecycle accounting would simply be exempted from the tax. The carbon tax considered in this analysis allows for the full lifecycle analysis of fuels to be accounted for. The apparent subsidization of negative carbon fuels under the carbon tax is the manifestation of avoided taxation elsewhere in the economy. This choice is justified due to the passing of California's SB 1383 which specifically targets the sectors likely to yield fuels with negative carbon intensities for reduction in methane emissions.

In 2015, natural gas fuel made up less than one percent of CA vehicle fuel consumption, but was responsible for generating almost fifteen percent of credits in that year. Models which allow for perfect substitution between fuels implicitly assume complete fuel choice flexibility by all vehicles. Assuming perfect substitution may have merit in the long term, but it is not ideal in understanding market response from the current equilibrium. In the short term, the choices of vehicle fuel a consumer may consider are constrained by the technological limitations of their existing vehicle.[6]

The numerical model reveals two interesting features of the California LCFS policy. First, I find an extremely narrow window of intensity targets that yield an interior solution to the equilibrium in the carbon credit market. The second policy revelation highlights the relative efficiency of the LCFS policy as compared to the hypothetical carbon tax. Previous literature has shown the LCFS to be economically inefficient relative to a carbon tax (Holland, Hughes and Knittel, 2009; Lade and Lin Lawell, 2015a). However, the results of this model reveal that when combined with a price ceiling, the LCFS approaches the efficiency of carbon tax as the policy becomes more stringent. This corroborates the results identified in Lade and Lin Lawell (2015b). At the time the LCFS policy was introduced, it was proposed in lieu of a transportation carbon tax for pragmatic reasons as it was understood that a carbon tax proposition would encounter greater political opposition (Sperling and Yeh, 2009).[7]

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[6] While there are "bi-fuel" vehicles which can easily switch between gasoline-ethanol fuel blends and natural gas fuel, these vehicles make up less than 0.1% of transportation energy consumption (Energy Information Administration, 2019). Many bi-fuel vehicles run entirely on gasoline-ethanol blends and were purchased to deliberately take advantage of a poorly designed alternative fuel incentive scheme in Arizona (Milloy, 2000).

[7] For a more detailed background o the policy motivations of the LCFS, see Farrell and Sperling (2007a) and Farrell and Sperling (2007b).

The following section provides a broad overview of transportation fuels in California including major policies that govern transportation fuels. Section 3 provides background on the LCFS policy and outlines the carbon intensity assessment procedure, credit and deficit generation, and trading in the credit market. Section 4 presents an analytical model of LCFS in contrast to a carbon tax. Section 5 describes the numerical model and parameter calibration. Section 6 presents the results of the numerical model detailing the supply response of RNG to the LCFS, changes in emissions and economic surplus, and comparison of policy efficiency relative to a hypothetical carbon tax. Section 7 discusses these results and Section 8 concludes.

2. BACKGROUND

The overwhelming majority of transportation fuel consumed in California is derived from petroleum and fossil sources. According to the California Air Resources Board (2016d), the 2015 California fuel consumption mix was 71% gasoline, 21% conventional diesel fuel,[8] 6% ethanol, 2% biodiesel and renewable diesel, 1% natural gas, less than 0.10% electricity, and almost zero hydrogen fuel. Gasoline mainly serves the passenger light-duty vehicle market and diesel mainly serves the freight and heavy-duty market (California Energy Commission, 2016; Davis, Diegel and Boundy, 2016).

Gasoline and diesel are fossil fuels and are considered to be high-carbon fuels, whereas ethanol is a plant-derived fuel that substitutes imperfectly with gasoline. The climate impact of ethanol fuel relative to fossil fuel varies depending on the feedstock and efficiency of the production path. The U.S. Environmental Protection Agency classifies corn starch-derived ethanol as conventional biofuel, sugarcane and corn stover-derived ethanol as advanced biofuel, and ethanol derived from grasses, wood matter, and crop residue as cellulosic biofuel (EPA, 2016a).

Ethanol enters the transportation market primarily as a gasoline-ethanol blend. Nearly all gasoline sold in the United States is sold as a 10% ethanol blend known as E10 (Energy Information Administration, 2016a). With few exceptions, all gasoline vehicles on the road can run on a gasoline-ethanol blend containing up to 10% ethanol. Not all vehicles can run on blends greater than 10% ethanol and thus, this presents an upper limit to the concentration of ethanol that can be mixed into the blend which is sold for broad consumption. A subset of vehicles operating today are equipped with "flex-fuel" technology that allows the use of blends containing up to 85% ethanol, E85. Only about 10% of vehicles in operation are equipped with flex-fuel technology which limits the capability of E85 to replace gasoline fuel consumption (Energy Information Administration, 2016b).

Biodiesel and renewable diesel are the available alternatives to diesel fuel that can be utilized in existing diesel engines. Biodiesel substitutes almost perfectly for diesel. Generally speaking, any diesel-powered vehicle can run on biodiesel (Wang et al., 2000). Renewable diesel is a perfect substitute for diesel fuel; all diesel vehicles can run on renewable diesel. The market penetration of biodiesel does not face the same technological limitations as exhibited in flex-fuel vehicles in the gasoline-ethanol market. Since both biodiesel and renewable diesel are produced from biomass, their carbon intensities are much lower than conventional diesel fuel. I make the simplifying assumption to treat biodiesel and renewable diesel as the same fuel in the policy response model.

Natural gas from any source currently comprises a small portion of California fuel consumption and mainly serves the same vehicle classes as diesel fuel. Penetration of Wider adoption

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[8] Conventional diesel fuel is derived from petroleum and is typically known simply as "diesel" or "fossil diesel."

of natural gas fuel requires the development of a more widespread refueling network and a greater adoption of natural gas vehicles (Fan et al., 2017; Scheitrum et al., 2017).

Landfills naturally emit methane as the waste-in-place decomposes over time. Most landfills in California fall under regulation that requires them to capture the natural emissions of methane and flare the gas or use it to create electricity or transportation fuel (EPA, 2016a). The option to produce electricity is unlikely due to restrictions on new stationary sources of pollution due to air quality concerns (Jaffe et al., 2016). While flaring is certainly the cheapest way to convert methane into the less potent CO_2, it does not displace any fossil fuel consumption and the routine use of flaring is discouraged. California has signed on to the World Bank Initiative to end the routine flaring of methane gas by 2030 (World Bank, 2015). While the initiative focuses on the oil and gas industry, it is reasonable to assume that policymakers in California will aim to end the practice elsewhere. For these reasons, Parker et al. assume RNG production to be directly injected into the pipeline system in their supply estimation (Parker et al., 2017). Another option to reduce the methane output of landfills is the anaerobic digestion of organic waste matter, municipal solid waste (MSW). By diverting organic matter from being contributed into a landfill and, instead, feeding it into a purpose-built anaerobic digester, the organic material can be converted into methane more efficiently. SB 1383 mandates the 50% reduction of landfill disposal of organic waste by 2020 and the 75% reduction by 2030 relative to 2014 levels indicating a policy preference for the MSW pathway.

The anaerobic digestion of manure from dairies and feedlots in California provides the opportunity to substantially reduce methane emissions. Agriculture makes up about 8% of California GHG emissions and livestock production makes up two-thirds of the emissions from agriculture. Currently, livestock producers face no requirement to collect and flare the methane emissions from their herds. As in the case of landfills, flaring is also unlikely to be a methane abatement option for dairies. In contrast to the MSW pathway, manure has a significantly lower methane yield, which leads to higher costs of conversion (Parker et al., 2017). Additionally, SB 1383 specifically mentions the production of biomethane (RNG) via digesters and direct injection into the pipeline network as a solution to emissions reduction and an avenue for policy compliance. Waste water treatment plants, the last pathway to be considered, already have anaerobic digesters in place for the purpose of reducing the nutrient load of the effluent stream. The supply estimate for the WWTP pathway considers WWTP sites with anaerobic digesters in place that are not currently generating electricity.

All RNG must be cleaned and upgraded prior to injection into the pipeline system. Gas upgrading cost varies depending on the source. Injection into the pipeline network requires the construction of a pipeline spur from the production site to the nearest natural gas transmission line as well as the construction of a pipeline interconnect. Capital expenditure on upgrading equipment and pipeline connection is a considerable fixed cost which leads to economies of scale.

Electricity supplies less than 0.1% of the energy consumed in transportation and hydrogen fuel provides less than 0.0001% of transportation energy. Increasing the market share of hydrogen and electricity as vehicle fuels is predicated on the expansion of refueling infrastructure and turnover of the passenger vehicle fleet, both of which require long timelines. Modeling the LCFS impact on long-term transition of fleet technology is beyond the scope of this analysis.

3. LOW CARBON FUEL STANDARD POLICY MECHANISM

California's LCFS policy was enacted by Gov. Schwarzenegger in 2007, the regulation went into effect in 2011, and was re-adopted in 2015. The drafting of the regulation is largely based on technical and policy analysis of Farrell and Sperling (2007a,b). The LCFS policy has the stated goal of reducing the carbon intensity of transportation fuel by 10% by 2020 (California Air Resources Board, 2016c). Similar LCFS policies are also in place in Oregon, British Columbia, and the European Union.

The implementation of a Low Carbon Fuel Standard requires the determination of two parameters, the carbon intensity target and the credit price. For a given carbon intensity target, the sale of fuels with carbon intensities above the target generates deficits and the sale of fuels with an intensity below the target generates credits, bothin proportion to the deviation from the target. Next, a price for credits must be established. The implementation in California is designed to be "revenue neutral." That is, the state determines the carbon intensity target and provides a market in which participants can trade credits. In the LCFS credit market, high-carbon fuel providers purchase credits from low-carbon fuel providers. High-carbon fuel providers must purchase enough credits to offset the deficits generated by their fuel sales. The LCFS credit price results from the market equilibrium that equates credits with deficits. This policy is considered "revenue neutral" since wealth is transferred from high-carbon fuel producers to low-carbon fuel producers.

The revenue neutrality of this policy has one important caveat. As a cost containment measure, a price ceiling is imposed on credits at \$200 per metric tonne of CO_2e. At this price, credits can be purchased from the state agency. Sales of credits by the state agency does result in revenue to the government, but these funds are required to be spent on alternative fuel investment.

Lastly, credits can be banked and carried forward into the future to offset future deficits. Literature on commodity storage suggests that allowing for credit banking will bias credit prices upward when the policy is less stringent. Withdrawing credits will bias prices downward when the policy becomes more stringent, until the bank of credits is exhausted (Brennan, 1958). In the numerical model in this paper, I do not examine the consequences of banking permits for future use. Rubin and Leiby (2013) include this feature in their analysis of LCFS compliance scenarios and find that banking smooths out compliance costs. This issue reappears in Section 6.1 where the deviation between simulation results and actual policy outcomes is discussed.

3.1 LCFS Carbon Intensities

The overall goal for the Low Carbon Fuel Standard is to reduce the average carbon intensity of transportation fuel use. Carbon intensity targets for the years 2011 to 2020 are set forth in the LCFS Final Regulation order and are presented in Table 1. The carbon intensity targets are based on achieving a 10 percent reduction in carbon intensity of both gasoline and diesel fuel by 2020.[9]

Carbon intensity values associated with alternative fuels pathways are established in one of two ways. First, for a set of core fuel pathways, the California Air Resources Board has established the carbon intensity values as listed in the LCFS Final Regulation.[10] Fuel providers can either accept the carbon intensity that matches their pathway (if one exists) or they may seek approval of additional fuel pathways or sub-pathways by submitting an Method 2 Carbon Intensity Application where their specific pathway's carbon intensity is assessed (California Air Resources Board, 2016b).

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[9] The average carbon intensity (CI) requirements for years 2011 and 2012 reflect reductions from base year (2010) using the CI for crude oil supplied to California refineries in 2006. The average carbon intensity requirements for years 2013 to 2015 reflect reductions from revised base year (2010) CI values using the CI for crude oil supplied to California refineries in 2010. In 2015 the LCFS was readopted and the CI modeling updated. The average carbon intensity requirements for years 2016 to 2020 reflect reductions from revised base year (2010) CI values.

[10] California Code of Regulation Title 17, § 95488, Table 6.

Table 1: Average Carbon Intensity Requirements (gCO_2e / MJ)

Year	Fuels that Compete with Gasoline	Fuels that Compete with Diesel
2010	Reporting Only	Reporting Only
2011	95.61	94.47
2012	95.37	94.24
2013	97.96	97.05
2014	97.96	97.05
2015	97.96	97.05
2016	96.50	99.97
2017	95.02	98.44
2018	93.55	96.91
2019	91.08	94.36
2020+	88.62	91.81

Source: California Code of Regulation Title 17, § 95484

In this paper, I rely on the carbon intensity values reported in the LCFS Final Regulation for the municipal solid waste, wastewater treatment plant, and landfill sources.[11] Since a carbon intensity value of RNG from the anaerobic digestion of manure is not available in the LCFS Final Regulation, I rely on an approved pathway for dairy digester biogas.[12] Carbon intensity values used in this paper are reported in Table 2.

Table 2: Carbon Intensity Values of Fuel Pathways

Fuel Pathway	Carbon Intensity $\frac{gCO_2e}{MJ}$	Tax (Subsidy)[a]
Diesel[b]	102.01	\$0.40 / diesel gal
Gasoline[b]	99.78	\$0.21 / gasoline gal
E10[b,e]	98.00	\$0.16 / gasoline gal
E85[b,e]	84.67	(\$0.19)/ gasoline gal
Biodiesel	35.44	(\$1.56)/ diesel gal
Fossil CNG[c]	78.37	(\$0.05)/ gasoline gal
Landfill CNG[c]	46.42	(\$1.09)/ gasoline gal
WWTP CNG[b]	19.34	(\$1.94)/ gasoline gal
MSW CNG[b]	–22.93	(\$3.34)/ gasoline gal
Dairy CNG[d]	–276.24	(\$11.59)/ gasoline gal

[a] Implicit tax (subsidy) is calculated assuming the 2020 carbon intensity target as presented in Table 1, a \$200 credit price, and an EER of 0.9 for natural gas fuels.
[b] California Code of Regulation, Title 17, § 95488, Table 6. Carbon intensity for WWTP is the average of two WWTP pathways.
[c] California Code of Regulation, Title 17, § 95488, Table 7.
[d] Method 2B Application CalBio LLC, Dallas Texas, Dairy Digester Biogas (Bakersfield, CA) to CNG (Pathway Code: CNG056).
[e] California Air Resources Board Media Request, July 28, 2016.

The carbon intensities for each fuel listed in Table 2 are the Well-to-Wheels (WTW) value or the full lifecycle value of emissions accounting for all upstream emissions known as Well-to-Tank (WTT), and all vehicular emissions known as Tank-to-Wheels (TTW). Upstream emissions include all steps involved in feedstock production and transport, and finished fuel production, transport, and dispensing. The carbon intensity of gasoline and diesel are roughly the same at about 100 grams of CO_2e per megajoule (gCO_2e / MJ). The carbon intensity of natural gas is about 20 percent less than

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[11] California Code of Regulation Title 17, § 95488, Tables 6 and 7.

[12] Method 2B Application CalBio LLC, Dallas Texas, Dairy Digester Biogas (Bakersfield, CA) to CNG (Pathway Code: CNG056), approved January 22, 2016, http://www.arb.ca.gov/fuels/lcfs/2a2b/apps/Calbio-122115.pdf

gasoline and diesel on a per-unit-of-energy basis. This is why natural gas is sometimes referred to as “clean burning” in relation to gasoline and diesel. The carbon intensity is largely dependent on the molecular carbon content of the fuel.[13] I compute E10 and E85 carbon intensities to be 98.0 and 84.67 $gCO_2e\ /\ MJ$, respectively, based on the carbon intensity of gasoline per California Code of Regulations (2015) as well as the 2015 average carbon intensity of ethanol fuel per the California Air Resources Board (2016d). I rely on the carbon intensity for biodiesel of 35.44 $gCO_2e\ /\ MJ$ based on the 2015 volume weighted average carbon intensity of biodiesel and renewable diesel.

3.2 LCFS Credit/Deficit Generation

The mechanism by which credits and deficits are generated depend not only on the carbon intensity of the fuel in question and the carbon intensity target specified by statute, but also the efficiency with which the fuel is utilized. Each fuel is assigned an energy economy ratio (EER) relative to gasoline or diesel fuel. Different vehicle powertrains use the energy in fuel to varying degrees of efficiency. While a plug-in electric vehicle can be up to four times more efficient than a gasoline powered vehicle, a natural gas powered truck is only 90 percent as efficient as a diesel powered truck in terms of miles per unit of energy.[14] An assessment of compliance outlooks prepared by ICF International (2013) indicates the vast majority of natural gas fuel will be used in heavy duty and off-road applications and, consequently, I employ the 0.9 EER to the natural gas transport sector in the policy response model.

After establishing carbon intensities of fuel pathways, the average carbon intensity target and energy economy ratios, fuel providers (suppliers and blenders) then generate LCFS credits (deficits) according to the formula

$$Credits = \left(CI_{target} - \frac{CI_{fuel\ pathway}}{EER_{fuel}} \right) \times E \times C \tag{1}$$

where *Credits* are in metric tonnes of CO_2e, CI_{target} is equal to the the average carbon intensity requirement for that year, $CI_{fuel\ pathway}$ is the carbon intensity value for the fuel pathway, EER_{fuel} is the energy economy ratio for the fuel, E is the quantity of energy supplied in megajoules, and $C = 10^{-6}\frac{MT}{g}$ is a constant to convert credits from units of grams of CO_2e to metric tonnes of CO_2e. Deficits are generated as negative credits.

3.3 LCFS Credit Market Equilibrium

The third and final aspect of the Low Carbon Fuel Standard policy intervention is resolving the credit market equilibrium. High-carbon fuel providers are obligated to comply with the LCFS and they generate deficits according to the formula in Equation 1. These obligated parties must then purchase an equal amount of offsetting credits from producers of low-carbon fuels. The market price of credits is determined by trading to ensure that credits equal deficits. There is an important caveat to the calculation of the credit market equilibrium. As a cost containment measure, the LCFS sets a maximum credit price of \$200 per credit. At this price, credits may be purchased directly from the state.

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[13] Natural gas, CH_4, has a lower ratio of carbon to hydrogen than gasoline, C_8H_{18}, or diesel, $C_{12}H_{23}$, and therefore, fewer carbon emissions per unit of energy.

[14] California Code of Regulation Title 17, § 95485, Table 5.

4. ANALYTICAL MODEL

In Figure 2, I present a simplified model of the credit generating market. Let the target average carbon intensity be 95 gCO_2e. In this case, fossil natural gas with a carbon intensity of 78.37 will generate LCFS credits as its EER-adjusted carbon intensity falls below this target. Fossil natural gas will generate 0.0084 LCFS credits per mmBTU which I denote by $\alpha_F = 0.0084 \frac{MT\,CO_2e}{mmBTU}$.[15] Now consider a hypothetical renewable natural gas pathway with a carbon intensity of 50 gCO_2e; fuel from this representative pathway will generate 0.0416 LCFS credits per mmBTU, $\alpha_R = 0.0416 \frac{MT\,CO_2e}{mmBTU}$. The renewable fuel generates roughly five times as many LCFS credit as fossil natural gas for the same quantity of energy. The per-mmBTU subsidy received by each pathway is $\tau\alpha_i$, where τ is the LCFS credit price per metric ton of CO_2e and i signifies the pathway. In this case, the RNG pathway will receive five times the subsidy as fossil gas per unit of energy for the same LCFS credit price.

Figure 2: RNG Response to LCFS Credit Prices

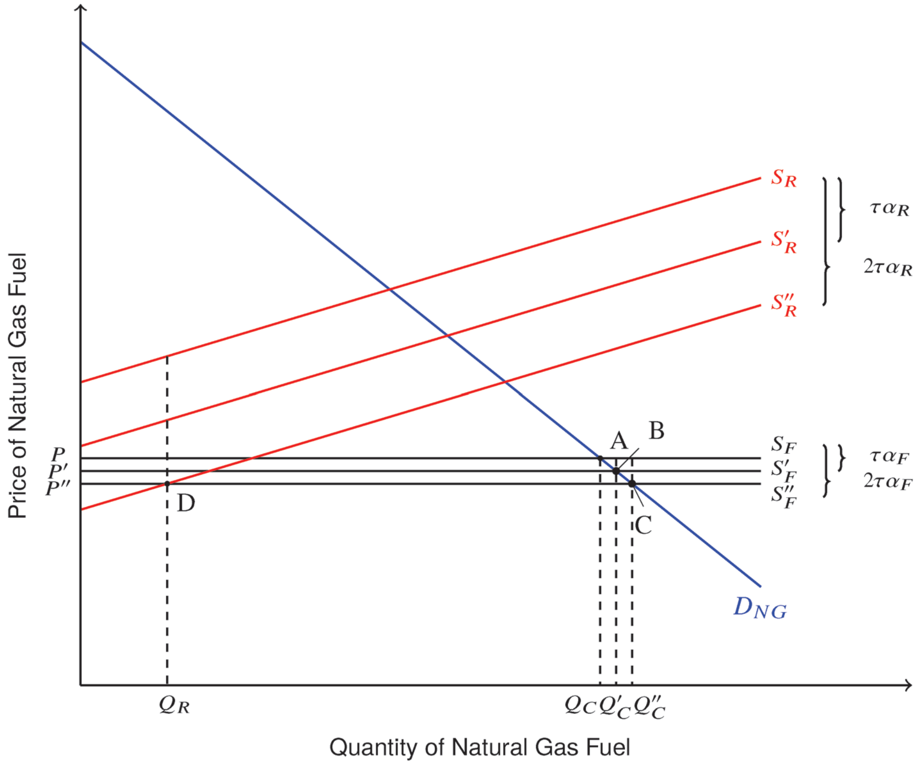

Figure 2 shows the market for natural gas in transportation as it is impacted by the LCFS policy. Demand for natural gas fuel is shown as D_{NG} and there is no distinction made between the different pathways of natural gas fuel from the consumer's perspective. Supply of the renewable

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[15] Under a 95 CI target, fossil natural gas will generate $\left(95-\frac{78.37}{0.9}\right)\times 10^{-6} = 0.00000792$ LCFS credits per MJ or approximately 0.0084 LCFS credits per mmBTU based on 1,055 MJ per mmBTU.

fuel is represented by S_R and supply of fossil natural gas is represented by S_F. The initial equilibrium occurs at point A. I assume the supply of fossil natural gas is perfectly elastic because the LCFS program affects only natural gas used in transportation and the transportation share makes up less than one percent of total natural gas consumption in California (California Energy Commission, 2013).[16] In the absence of the LCFS program, demand for natural gas in transportation is satisfied entirely by fossil natural gas, the lowest cost pathway to provide this fuel. Much like the indirect land use (ILUC) effect of biofuels (Searchinger et al., 2008), fossil natural gas in transportation has indirect emissions by raising the price of fossil gas for power generation and encouraging power generation from coal sources (Sexton and Eyer, 2016). As RNG displaces fossil gas in the transport sector, this frees up fossil gas for power generation which indirectly reduces coal consumption.

Next, I introduce the LCFS policy where credits are trading at τ dollars per $MT\ CO_2e$. In that case, fossil natural gas generates $\tau\alpha_F$ dollar per mmBTU in LCFS credit value which shifts the supply curve down by $\tau\alpha_F$ to S'_F. The renewable natural gas pathway generates $\tau\alpha_R$ dollar per mmBTU in LCFS credit value which shifts the supply curve down to S'_R. After the introduction of the policy with a credit price of τ, the equilibrium price of natural gas falls from P to P' yet the subsidy on renewable natural gas is insufficient to incentivize production of renewable natural gas at the price P'. The equilibrium occurs at point B.

By doubling the LCFS credit price to 2τ, the fossil natural gas supply curve shifts to S''_F, the renewable natural gas supply curve shifts to S''_R, and the equilibrium to point shifts from B to C. In this case, renewable natural gas supplies volume Q_R at point D and fossil gas makes up the remainder $Q''_C - Q_R$. In this example, it requires a substantial credit price for renewable natural gas to be supplied to the market which highlights the sensitivity of RNG production to the LCFS credit price.

Now suppose instead of the LCFS policy as the instrument to reduce GHG emissions, I introduce a hypothetical carbon tax and evaluate its impact on the natural gas and RNG transportation fuels. This hypothetical carbon tax relies on the same carbon intensity assessments as in the previous example. Under this carbon tax, the fossil natural gas will generate 0.0919 metric tons of CO_2e per mmBTU, $\beta_F = 0.0919$ and renewable natural gas will generate 0.0586 metric tons of CO_2e per mmBTU, $\beta_R = 0.0586$. A carbon tax of τ dollars per metric ton of CO_2e will increase the price of each pathway, i, by $\tau\beta_i$ dollars per mmBTU. In Figure 3, I present the RNG response to a carbon tax equal to τ and 2τ as in Figure 2. Before any tax is imposed, the market clears at point A. After imposing a carbon tax of τ dollars per metric ton of CO_2e, the market clears at point B and the tax is not sufficient to induce any RNG production. With a carbon tax of 2τ the market clears at point C and the tax does induce some RNG production, equal to volume Q_R at point D. Notice that the overall consumption of natural gas fuel from any pathway has decreased from Q_C to Q''_C. The carbon tax achieves emissions reductions in two ways. First, it reduces consumption of natural gas altogether by increasing the price of fuel. Second, it induces switching out of fossil natural gas and into renewable natural gas changing the relative prices in line with the relative carbon intensities.

The analytical model illustrates the sensitivity of RNG production to LCFS credit prices in particular, and the importance of credit price on quantity response of all fuels in general. A modeling approach which examines the LCFS policy implications under the exogenous choice of credit price fails to capture the important consequences of the LCFS credit price. Even an examination of LCFS policy response to the exogenous choice of credit price that examines the entire range of credit prices from \$0 to \$200 per metric tonne of CO_2e does not provide any information regarding the likelihood of policy outcome.

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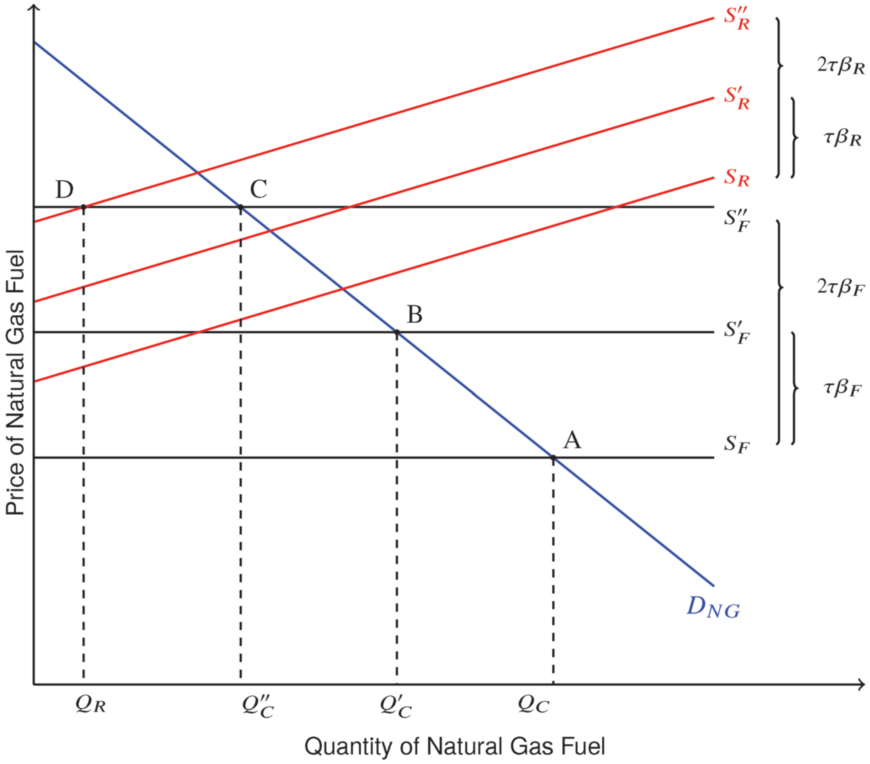
[16] The residual elasticity of supply of natural gas for transportation fuel ranges between 28 to 89 based on a total natural gas supply elasticity between 0.1 and 0.42 and total natural gas demand elasticity of –0.11 to -.024 from estimates in [?]

Figure 3: RNG Response to Carbon Tax



5. NUMERICAL MODEL

In order to capture the important consequences of the LCFS credit price and to assess the LCFS policy impact, I construct a static, multi-market, numerical model of all the major transportation fuels and calibrate this model to actual 2015 California transportation fuel data. I evaluate the response to LCFS carbon intensity targets from 100 down to 85 gCO_2e / MJ and over the full range of credit prices from \$0 to \$200 per metric tonne of CO_2e. To compare the economic efficiency of the LCFS policy, the numerical model also evaluates the response to a hypothetical carbon tax which relies on the same carbon intensity assessments as employed in the LCFS regulation. The carbon tax is evaluated under carbon prices ranging from \$0 to \$200 per metric tonne CO_2e. This numerical model accounts for deficit generation by high-carbon fuels and credit generation by low-carbon fuels. Further, I impose a number of constraints regarding how fuel switching may occur between markets.

I am examining the policy impact in the near- to intermediate-term horizon which precludes the examination of vehicle choice and fleet turnover. Changing the makeup of technologies employed in California's vehicle fleet can lead to much larger adoption of alternative, low-carbon fuels. However, this transition will take place over the long-term and is left for future work. The average age of U.S. cars is 16 years and average age of trucks is 18 years (Bento, Roth and Zuo, 2013). My analysis reveals interesting policy consequences that will manifest in the near-term, long before any substantial transition of the vehicle fleet technology makeup. Further, gasoline and diesel vehicles make up 99% of new vehicles purchased (Keith, Houston and Naumov, 2019). Additionally, recent evidence suggests that consumers do respond to fuel price changes when purchasing new vehicles and through this mechanism, the LCFS program may encourage a vehicle fleet transition in the long run (Bento, Roth and Zuo, 2013). My simulation identifies a rapid increase in credit prices resulting in hitting the price ceiling by 2017. Actual credit prices have taken until 2019 to consistently bind at the ceiling. This simulation does not allow for perfect substitution between vehicle fuels as has been employed in previous analyses of the impact of LCFS policy. Rather, the markets are separated into three fuel groups which allow for substitution within a group, but not between groups. For example, in order to substitute between groups, owners of gasoline vehicles would need to replace their vehicles (or pursue costly retrofit procedures) to be able to switch into RNG fuel. These fuel groups are the gasoline-ethanol blend group containing E10 and E85 fuels, the diesel group which contains conventional diesel and bio/renewable diesel, and the natural gas group which contains fossil natural gas and RNG.

The evaluation of these deficit and credit generating fuels introduce new complexities into the model that are not featured in the fossil/renewable natural gas fuel switching decision. Since renewable natural gas is nearly identical to fossil natural gas, there is no energy-density disadvantage to consider when choosing one fuel over the other. Further, RNG is injected into the pipeline network and is immediately comingled with fossil natural gas. There is no guarantee that a consumer purchasing RNG for their vehicle will receive physical molecules of natural gas produced from renewable pathways. The consumer may not even know if their refueling station has contracted to deliver RNG or not, as the decision takes place behind the scenes between refueling station operators and RNG producers.

The fuel switching decision in the gasoline-ethanol fuel group (between E10 and E85) and in the diesel fuel group (between diesel and bio/renewable diesel) happens at the individual driver level. Unlike the case of renewable natural gas, a consumer must explicitly decide to purchase E85 for their vehicle rather than E10 (similarly for biodiesel over diesel). Since E85 contains about 25% less energy than E10, the decision to purchase E85 depends on the energy-adjusted relative price of the fuels, the inconvenience of finding an E85 station, the inconvenience of more frequent refueling, but also, the possible satisfaction of purchasing a “green” fuel (Anderson, 2010; Salvo and Huse, 2013). The consumption of E85 is limited to a subset of gasoline-powered vehicles known as “flex-fuel” vehicles (Energy Information Administration, 2016b). Between 5% and 10% of vehicles in the United States have flex-fuel technology (Energy Information Administration, 2019). The characteristics of the diesel/biodiesel fuel switching decision are similar to that of the E10/E85 market. Biodiesel contains about 10% less energy than conventional diesel, users of biodiesel face the same inconvenience of lower availability of biodiesel refueling stations and requiring more frequent refueling, and also users may benefit from the satisfaction of purchasing “green” fuel. The key difference between the diesel-biodiesel market and the E10-E85 is that all diesel engines can run on biodiesel.

To model the fuel switching behavior for these fuel types, I employ the methodology developed by Anderson (2010) and expand this method from the E10-E85 fuels market to the diesel-biodiesel market. Anderson considers an individual household utility function where utility is quasilinear in fuel. The utility function is specified as

$$U\left(e,g,x\right)=\left(e+rg\right)+x, \tag{2}$$

where $\left(\cdot\right)$ is strictly increasing and strictly concave, e is consumption of E85, g is consumption of E10, x is consumption of all other goods, and r is the rate at which the household converts gallons of gasoline to gallons of ethanol-equivalent. In this specification, E85 and E10 are perfect substitutes. Given the budget constraint

$$y - p_e e - p_g g - x = 0, \tag{3}$$

where the price of x is normalized to 1, each individual household will be at a corner solution consuming either only ethanol or only gasoline. Whether a household is consuming ethanol or gasoline is determined by their value of r and the ratio of prices of gasoline and ethanol, p_g / p_e. When $r < p_g / p_e$, the household will consume ethanol exclusively. For a household that cares only about mileage, their value of r will equal the relative mileage of E10 over E85 and the household will simply choose the fuel that is cheaper on a cost-per-mile basis. However, other considerations affect a household's decision whether or not to purchase ethanol. The inconvenience of finding refueling stations that offer E85 as well as the need to make more frequent refueling stops when running E85 can dissuade a household from choosing the fuel, yielding a higher value for r, suggesting the household will avoid E85 even when in cases where it is the cheaper fuel per mile. Conversely, if a household places more weight on the "green" aspects of ethanol fuel, this will yield a value for r below the mileage ratio.

The share of households choosing ethanol is then determined by the distribution of r, $h(r)$, the ratio of prices, p_g / p_e, and the portion of vehicles that are of flex-fuel technology, ϕ. Households with a value of r less than p_g / p_e will consume ethanol exclusively. The share of fuel that is consumed as ethanol is given by the cdf of r, $H(r)$, evaluated at p_g / p_e multiplied by the share of vehicles capable of consuming ethanol, ϕ.

5.1 Model Calibration

The numerical model is calibrated to parameterize the supply and demand equations of each fuel and to calibrate the parameters that govern fuel switching as per the Anderson model. I calibrate the model to observed 2015 California equilibrium data for prices, quantities, alternative-fuel-capable vehicle shares, alternative fuel choice fractions, and carbon intensities.

For natural gas, I rely on the California citygate price in December 2015 of \$3.00 per mmBTU per the Energy Information Administration (2016c) and the 2015 consumption in transportation quantity of 17 billion cubic feet per the California Energy Commission (2013). For E10 and diesel, I rely on the California 2015 average prices of \$3.22/gallon and \$3.02/gallon respectively from the Energy Information Administration (2016e) and the consumption quantities of 15.1 billion gallons and 3.5 billion gallons per the California Air Resources Board (2016d) and California Board of Equalization (2016). For E85, I rely on the California 2015 average price of \$2.66/gallon per E85Prices (2016) and consumption quantity of 11.1 million gallons per Elam et al. (2015) as of 2014. The price of biodiesel of \$3.40/gallon was obtained from the Department of Energy as the national October 2015 price (Bourbon, 2016) and the consumption quantity of biodiesel of 291 million gallons is per the California Air Resources Board (2016d).[17]

The share of gasoline powered vehicles in California which are capable of running on E85 is quite low. Nationally, about ten percent of gasoline vehicles are equipped with "flex-fuel" technology enabling the use of E85. In California, the share of vehicles with flex-fuel technology may be as low as 6.6 percent. In this study, I choose the value of ten percent as the share of gasoline vehi-

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[17] Quantity information for biodiesel is based on the sum of biodiesel and renewable diesel sold in California in 2015.

cles with flex fuel technology, ϕ_{flex_fuel}. All diesel engines can run on biodiesel without modification; therefore, the share of biodiesel capable vehicles, $\phi_{biodiesel}$, is 1.0 (Wang et al., 2000).

The last consideration of the fuel switching model is to calibrate the distribution of $r_{ethanol}$, the rate of conversion of gasoline to ethanol-equivalent gallons, and $r_{biodiesel}$, the rate of conversion of diesel to biodiesel-equivalent gallons. I calibrate the distribution of $r_{ethanol}$ for the gasoline-ethanol market, by setting the mean of the distribution equal to the mileage ratio of E10 to E85 and computing the variance based on the observed share of E85 fuel consumed at the observed California E10-E85 price ratio, 1.138 percent. This calibration procedure yields the distribution $r_{ethanol} \sim N(1.35, 0.0612)$.[18] I follow the same procedure for the diesel market and find the distribution $r_{biodiesel} \sim N(1.1, 0.1491)$ at the observed price ratio of diesel to biodiesel and the observed share of biodiesel of 7.78 percent. In the numerical model, the E85 choice fraction and biodiesel choice fraction will adjust as the relative prices E10 to E85 and diesel to biodiesel change in response to different credit targets and credit prices.

The model calibration inputs are summarized in Table 3. While there is a sizable literature devoted to estimating the price elasticity of gasoline demand, there is a gap where it applies to estimating the price elasticity of demand of natural gas as a transportation fuel. Further, estimates of the price elasticity of demand for diesel are much less common than those for gasoline. Based on two commonly cited studies of the price elasticity of diesel, I establish a range of –0.7 to –0.07 (Dahl, 2012; Johansson and Schipper, 1997).

Table 3: California Fuel Market Parameters

Variable	Description	Value
Price of Natural Gas	P_{NG}	\$3.00/mmBTU
Price of E10 blend	P_{E10}	\$3.22/gal
Price of E85 blend	P_{E85}	\$2.66/gal
Price of Diesel	P_d	\$3.02/gal
Price of Biodiesel	P_b	\$3.40/gal
Quantity of Natural Gas	Q_{NG}	17 billion cubic feet
Quantity of E10 blend	Q_{E10}	15.1 billion
Quantity of E85 blend	Q_{E85}	11.1 million gallons
Quantity of Diesel	Q_d	3.5 billion gallons
Quantity of Biodiesel	Q_b	291 million gallons
Share E85-enabled vehicles	$\phi_{flex-fuel}$	10%
Share biodiesel-enabled	$\phi_{biodiesel}$	100%
Initial E85 choice fraction	$H\left(\frac{P_g}{P_e}\right)$	1.38%
Initial Biodiesel choice fraction	$H\left(\frac{P_d}{P_b}\right)$	7.78%

Consistent with the gasoline elasticity estimate meta-analyses of Espey (1996), Dahl and Sterner (1991), and Graham and Glaister (2004), as well as more recent estimates by Hughes, Knittel and Sperling (2006) and Lin and Prince (2013) I employ a price elasticity of demand of –0.2 for all fuels considered in this study. As a sensitivity test, I have run the model under assumption of demand elasticities at the bounds of –0.7 and –0.07 as well as under the assumption of ethanol and

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[18] This distribution compares to the distribution specified by Andersen of $r \sim N(1.35, 0.10)$ which was calibrated to the Minnesota market.

biodiesel supply elasticities of 3.0 and find this has no meaningful impact on the timing or rate at which equilibrium credit prices climb toward the ceiling.

5.2 Natural Gas Group Calibration

Parker et al. (2017) is the basis of my estimate of the supply of renewable natural gas. Renewable natural gas has been addressed in previous analyses of LCFS policy only in terms of scenarios-based analyses that make an exogenous assumption on the portion of the natural gas transportation market that will be fueled by RNG.[19] This paper is the first to employ estimates of RNG supply in terms of market response to fuels policy. For the supply of fossil natural gas, I assume it to be perfectly elastic at the equilibrium price of $3.00/mmBTU. I assume the supply to be perfectly elastic because I am only considering the supply of natural gas for use in transportation which makes up less than one percent of California total natural gas consumption.

I assume demand to be linear and to have an elasticity of –0.2 at the equilibrium price of $3.00 per mmBTU and equilibrium quantity of 17 billion cubic feet per year.[20]

5.3 Gasoline-Ethanol Blend Group Calibration

The calibration of the gasoline-ethanol blend market containing the E10 and E85 fuels requires the specification of parameters that govern the demand and supply for both fuels, plus the mechanism governing fuel switching between the two blend options. Aggregate E85 demand is specified as the product of (1) number of households, (2) the share which have flex-fuel vehicles, (3) the fraction that choose E85, and (4) the average per household consumption of E85. The aggregate ethanol demand equation is

$$Q_e\left(P_e,P_g\right)=N\phi H\left(\frac{P_g}{P_e}\right)\bar{q}\left(P_e\right), \tag{4}$$

where $\bar{q}_e\left(P_e\right)$ is the expected per household consumption of E85 for households that choose E85 (Anderson, 2010). The type of fuel is determined by the ratio of prices, and the extent of consumption is determined by the absolute price.

I then simplify equation 4 to

$$Q_e\left(P_e,P_g\right)=\phi H\left(\frac{P_g}{P_e}\right)\bar{Q}_e\left(P_e\right), \tag{5}$$

where $\bar{Q}_e\left(P_e\right)=N\bar{q}\left(P_e\right)$, and specifies the aggregate demand for E85 fuel given all households choose E85, ϕ reduces this demand to only households that have the technology to choose E85, and $H\left(\frac{P_g}{P_e}\right)$ reduces the demand further to only those households that do choose E85. I set the elasticity of unconstrained aggregate demand, $\bar{Q}_e\left(P_e\right)$, to –0.2 as described in Section 5.2. Lastly, I calibrate the linear function for $\bar{Q}_e\left(P_e\right)$ such that the demand curve has an elasticity of –0.2 at the observed price of E85 and the equilibrium quantity yields a quantity that, once multiplied by ϕ and $H\left(\frac{P_g}{P_e}\right)$ at the observed price ratio, equals the observed E85 consumption.

I repeat the procedure for the E10 market to calibrate the equation

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[19] See for instance ICF International (2013).

[20] Natural gas price elasticity of demand is consistent with Arora (2014) estimate of overall natural gas price elasticity of demand.

$$Q_g\left(P_e, P_g\right) = \left[1 - \phi H\left(\frac{P_g}{P_e}\right)\right]\bar{Q}_g\left(P_g\right), \tag{6}$$

where $\bar{Q}_g\left(P_g\right)$ specifies the aggregate demand for E10 fuel given all households choose that fuel type. The resulting parameters for the unconstrained aggregate demand equations for E10 and E85 are specified in Table 4.

Table 4: Gasoline-Ethanol Aggregate Demand Parameters

Parameter	Value (millions)
$\bar{Q}_e$: intercept	11,707
$\bar{Q}_e$: slope	–734
$\bar{Q}_g$: intercept	15,978
$\bar{Q}_g$: slope	–827

The supply of both E10 and E85 are assumed to be linear, with elasticities of 0.3 based on the estimate of gasoline supply elasticity of 0.289 by Coyle, DeBacker and Prisinzano (2012) and the estimate of ethanol supply elasticity of 0.258 by Luchansky and Monks (2009).

5.4 Diesel-Biodiesel Calibration

I specify the fuel switching model of the diesel-biodiesel model in a similar fashion to the E10-E85 market described in Section 5.3. It is important to note that there are two drop-in replacements for diesel fuel, biodiesel and renewable diesel, both of which are produced from biomass. I make the simplifying assumption to treat both biodiesel and renewable diesel as the same diesel alternative fuel and do not distinguish between the two in our fuel switching model. As in Section 5.3, I specify the aggregate biodiesel demand equation to be

$$Q_b\left(P_b, P_d\right) = \phi_{biodiesel} H\left(\frac{P_d}{P_b}\right)\bar{Q}_b\left(P_b\right), \tag{7}$$

and the aggregate diesel demand equation to be

$$Q_d\left(P_b, P_d\right) = \left[1 - \phi_{biodiesel} H\left(\frac{P_d}{P_b}\right)\right]\bar{Q}_d\left(P_d\right), \tag{8}$$

where the parameters for the unconstrained aggregate demand equations for biodiesel, $\bar{Q}_b$, and diesel, $\bar{Q}_d$, are presented in Table 5. The supply of both diesel and biodiesel are assumed to be linear, with elasticities of 0.3 based on the estimates for gasoline and ethanol stated above.

Table 5: Diesel-Biodiesel Aggregate Demand Parameters

Parameter	Value
$\bar{Q}_b$: intercept	4,485,595,997
$\bar{Q}_b$: slope	–219,882,157
$\bar{Q}_d$: intercept	4,554,569,534
$\bar{Q}_d$: slope	253,031,641

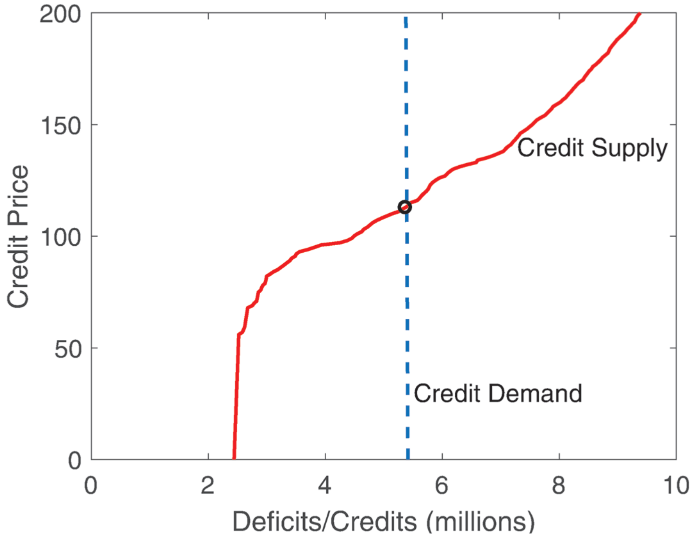
6. RESULTS

This section presents the results of market response to the LCFS and estimates credits and deficits generated over the relevant range of carbon intensity targets and credit prices. Next, I present the likely path of credit prices and the implications on economic surplus and emissions mitigation. Lastly, I compare the policy efficiency of the LCFS to a carbon tax.

6.1 LCFS Policy Impact

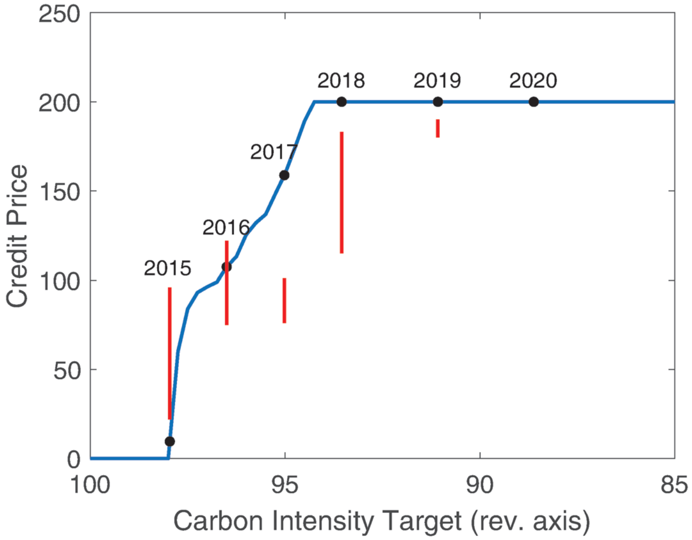
The nature of the LCFS policy requires the evaluation of policy response across not only each possible LCFS credit price ($0 to $200), but also across the relevant range of carbon intensity targets (100 to 85 gCO_2e / MJ). Given the quantity of credits and deficits generated at each combination of intensity target and credit price, I determine the resultant credit market equilibrium. Figure 4 illustrates the credit market equilibrium under a carbon intensity of 95.25 gCO_2e / MJ. In this figure, the supply of credits equals the demand for credits at a price of just under $150 per LCFS credit. This illustrates the need for a comprehensive model incorporating all major fuels to determine credit price. Under each specification of carbon intensity target, the model identifies the equilibrium LCFS credit price.

Figure 4: LCFS Credit Market Equilibrium



I find an extremely narrow window of intensity targets that yield an interior solution to the credit market equilibrium. That is, at choices of carbon intensity target greater than or equal to the current average carbon intensity in the transportation sector, no adjustment is required to meet the target. For intensity targets slightly below the current average carbon intensity, credits are sold to holders of deficits at a price which equates credits and deficits. In this instance, the credit market resolves at an interior solution above zero and below the price ceiling. Further, there is a carbon intensity target such that at the maximum credit price, the supply of credits from low-carbon fuels is insufficient to meet demand for credits by the consumption of high-carbon fuels. At this carbon intensity target and all intensity targets below, the carbon price resolves at the price ceiling and some portion of credits are purchased directly from the government. As noted in Borenstein et al. (2015), the scarcity of low-carbon fuels and the vehicle technology limitations on their adoption yields a situation where the window of market response is limited. The most likely outcomes are a zero credit price, or a price that binds at the ceiling set by statute. Figure 5 shows the path of credit prices as the carbon intensity target declines from 100 to 85 gCO_2e / MJ and indicates the scheduled intensity targets. Carbon intensity target is plotted along the reverse x-axis. Credit price is plotted along the y-axis. Under high carbon intensity requirements, the policy is non-binding and easily met yielding $0 credit prices. As the target declines over time and becomes more stringent, the credit price required to obtain equilibrium in the credit market rises rapidly. At a certain point, the credit price binds at the price ceiling and further reductions in target do not affect the credit price. Result for the scheduled intensity targets for years 2015–2020 are depicted by solid dots. The range of actual monthly credit prices are depicted by the vertical bars indicating the high and low monthly credit prices under the targets for years 2015–2019. The monthly credit price range for 2019 is simply the January and may 2019 credit prices, the most recent available at time of writing.

Figure 5: LCFS Credit Market Equilibria

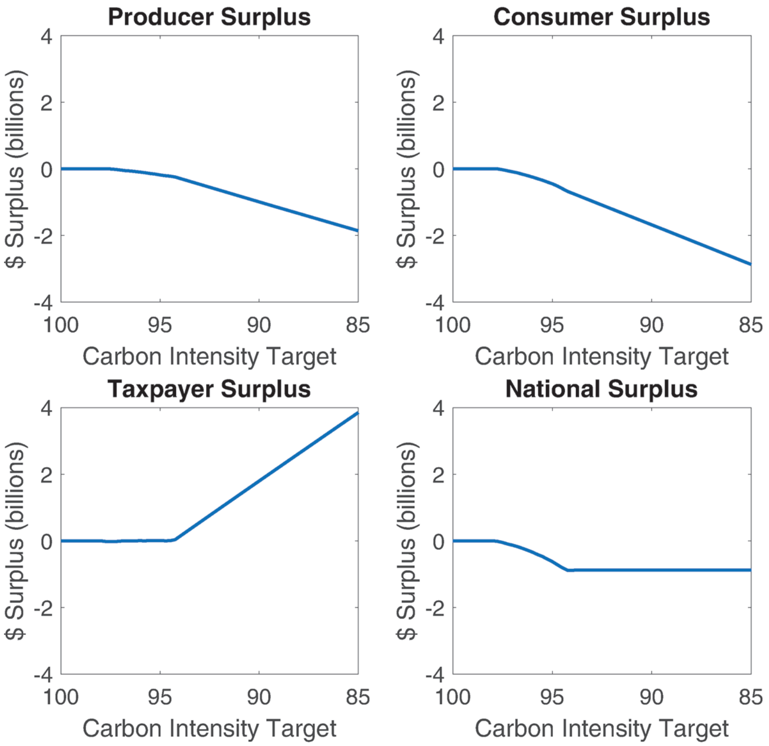


Note that the simulation results indicate that credit prices bind at the price ceiling under the 2017 carbon intensity target. The simulation suggests a more rapid rise in credit prices than we observe in the actual credit price history. This diverges from the actual credit price history where in 2017 credits traded between $75 and $100. The main source of the divergence is the single period nature of the simulation. The actual policy allows for the excess credits to be carried over into the future and spent in later years. This has the effect of raising credit prices early in the policy timeline when targets are easily met and credits are abundant. Banking of credits restricts available supply and increases credit price. As the policy becomes more stringent and credits becomes scarce, obligated parties can withdraw credits banked from earlier years depressing the price below what it would be if the policy required deficits to be offset by credits from within the same year (as is the case in this simulation). For instance, data from the California Air Resources Board show the stock of banked credits has increased from the inception of the policy through 2017. In 2017, contributions to the credit bank ceased and in the final quarter, the credit bank began to deplete. While the policy feature of credit storage has temporarily smoothed out the credit price trajectory, prices are nevertheless bound to reach the price ceiling as the credit bank is soon depleted.

Once the credit price binds at the ceiling, the realized average carbon intensity of the transportation sector fails to meet the intensity target specified by the government. Additionally, the policy ceases to be revenue-neutral as the shortfall in availability of credits is met by sales of credits by the government. Sensitivity of the simulation model is explored in Appendix A.

In Figure 6, I present the equilibrium distributional impacts of the LCFS policy as a function of the carbon intensity target. The revenue neutrality of the policy is evident in the lower-left panel of the diagram. In this panel, the change to taxpayer surplus due to the policy is steady at zero until the credit price ceiling is met and the state becomes a vendor of credits. Below this binding intensity target, the revenue to the government steadily increases as the policy become more stringent and the market must increasingly rely on the state as a source of credits. Producers and consumer are made worse off by this policy in general, but the impact varies by fuel and pathway. Producers of low-carbon fuels benefit greatly from this policy at the expense of producers of high-carbon fuels. Similarly, consumers of natural gas fuel see large benefits in terms of lower fuel price relative to their gasoline-consuming counterparts which suffer increased costs of fuel. Lastly, the lower right panel of the figure shows the total economic impact of the policy before accounting for the value of avoiding emissions. In Section 6.4, I discuss carbon savings and cost to avoid carbon.

Figure 6: Equilibrium Economic Impact by LCFS Carbon Intensity Target



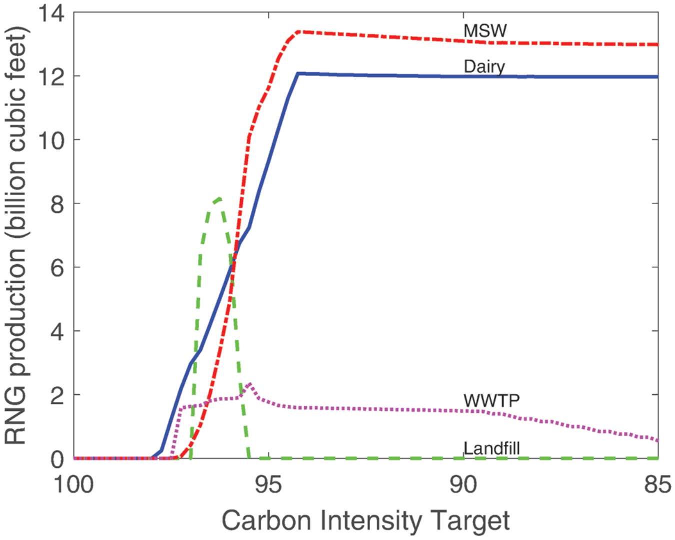
6.2 Policy Implications on Renewable Natural Gas

Representative supply curves of renewable and fossil gas are presented in Figure 1. They show that renewable natural gas is much too expensive to compete against fossil natural gas. These pathways for natural gas production require some form of support relative to fossil gas in order to encourage production. The supply of RNG in response to the LCFS policy is presented in Figure 7

. Given the incentives provided by the LCFS, the scheduled carbon intensity targets and the likely credit prices, dairies and landfills can reduce up to 16% of methane emissions in the short-term, upon construction of the anaerobic digester and pipeline capital. The extent of methane reduction is mainly limited by the capacity of the natural gas vehicle fleet to consume RNG. In the longer-term, as vehicles switch into natural gas fuel, the required reductions in methane emissions can certainly be attained given the existing policy and incentives for renewable natural gas production.

Figure 7 reveals an unusual result where landfill gas is only produced under an extremely narrow window of CI targets. While landfill gas is less costly to produce than the other forms of RNG, its CI score is relatively high compared to the others. Just as renewable sources of natural gas displace fossil natural gas in response to the LCFS policy, once all transportation natrual gas demand is satisfied by renewable pathways, decreasing the CI target leads to increases in credit price which benefits fuels with the lowest CI scores more than fuels with higher CI scores. Once the total transportation demand for natural gas is met by the four RNG pathways, reducing the CI target results in landfill gas being displaced by further adoption of RNG from dairy and MSW sources. This has serious implications for investors considering development of "medium-carbon" fuels as opposed to low-carbon fuels.

Figure 7: RNG Supplied by LCFS Carbon Intensity Target



6.3 Carbon Tax Policy Impact

I present the distributional impacts of the carbon tax policy in Figure 9. Here, the taxpayers are enriched at the expense of losses to producers and consumers. The losses to consumers and producers outweigh the gains in tax revenue, leading to a deadweight loss to the economy. The loss to the economy grows as the price on carbon increases. Valuing the cost of avoiding carbon is addressed in the following subsection.

6.4 Policy Comparison

In this section, I describe the complexity of comparing the LCFS and carbon tax policy instruments, present my basis for comparison, and describe the relative performance of these policy

Figure 8: RNG Emissions Savings by LCFS Carbon Intensity Target

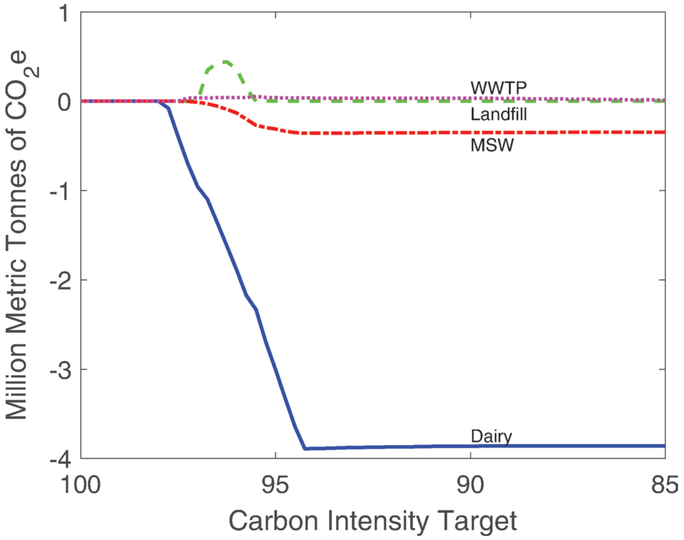
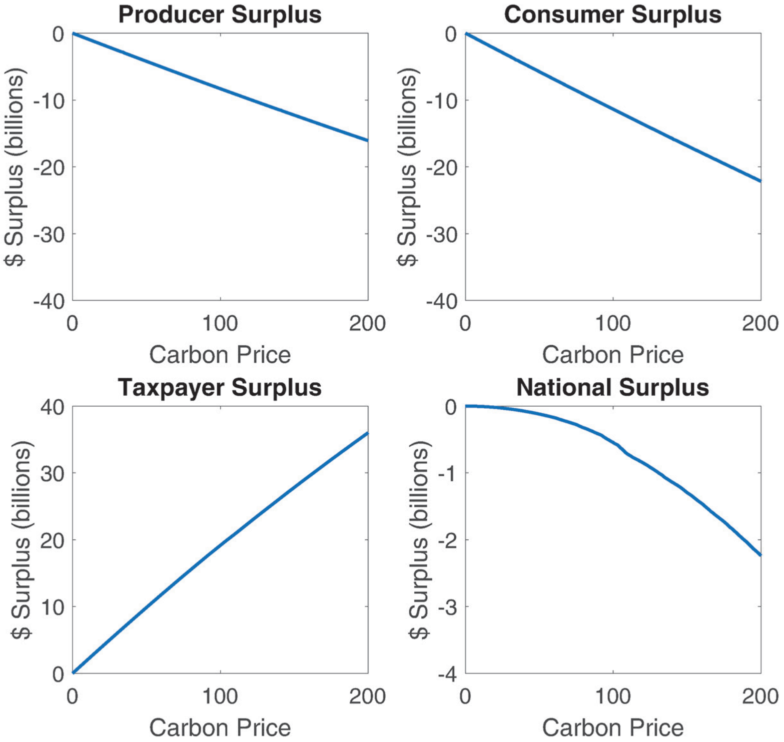


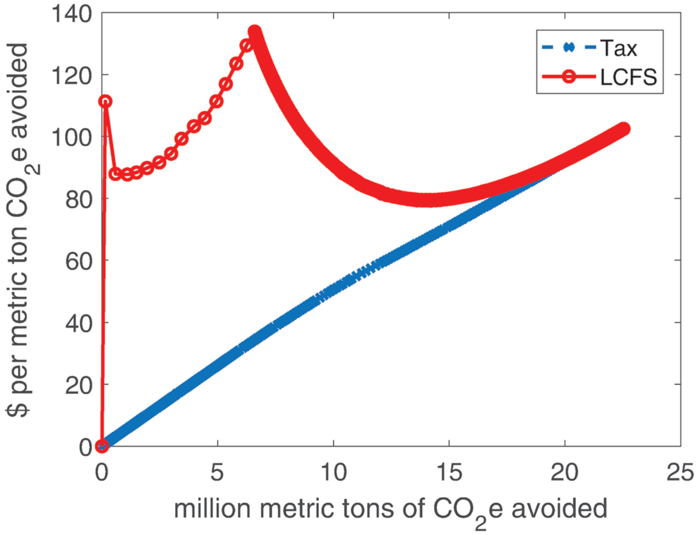
Figure 9: Economic Impact under Carbon Tax



instruments. In order to compare the LCFS and carbon tax policies, they must first be placed on equal footing. For instance, a carbon tax of $100 per tonne is not directly comparable with an LCFS policy with credit prices trading at $100 per tonne. Though they have the same price per tonne of CO_2e generated, the mechanism by which they measure emissions is not equal. The LCFS will understate the emissions by high-carbon fuels and overstate the savings of low-carbon fuels.

The relevant metric to compare the efficiency of these policies is cost to the economy per quantity of CO_2e avoided. That is, dollars of deadweight loss per metric tonne of CO_2e avoided. Figure 10 presents the policy efficiency in terms of $\$DWL$ per MT of avoided CO_2e plotted against the quantity of avoided emissions for the equilibrium results of both policies. The policy efficiencies can then be directly compared for a given reduction in CO_2e by comparing the cost per unit to avoid that quantity of emissions. To achieve a five million metric tonne reduction in CO_2e, the LCFS can achieve this at a cost of \$100 per tonne, whereas a carbon tax can achieve the same reduction for a cost of about \$25 per tonne. However, as the policies become more stringent and the carbon reductions increase, the performance gap between the LCFS and the carbon tax shrinks. This result provides further evidence to support what is suggested in [?] that the efficiency of an LCFS policy with a hard cap on prices can improve as the intensity target decreases.

Figure 10: Policy Efficiency Comparison



7. DISCUSSION

By relying on RNG supply estimates and constructing a model of LCFS response which includes the endogenous determination of credit price, I am able to assess the RNG supply response to LCFS policy. I find that credit prices will likely reach levels that will incentivize large quantities of RNG production. Under likely LCFS credit price outcomes, RNG can supply the entire California vehicular natural gas market with about 8 billion cubic feet per year from dairy, about 13 bcf/year from MSW, and about 3 bcf/year from WWTP RNG production. The LCFS yields a larger RNG production response than a carbon tax. The substantial production of RNG will lead to a reduction of 2.4 million metric tonnes of CO_2e emissions from dairy sources, which meets about 25% of the required emissions reductions required under SB 1383.

It is important to highlight the lack of production of RNG from landfill gas. Landfill gas has the lowest cost of production and is the closest to being able to produce competitively against fossil natural gas. However, the carbon intensity of landfill gas, while lower than that of fossil natural gas, is much higher than the carbon intensity of RNG produced from either MSW sources or from dairy sources. As discussed in Section 6.1, the range of intensity targets which will generate an interior solution for the credit price is very small and the most likely outcome is for credit price to bind at the ceiling of $200 per metric tonne of CO_2e, under most intensity targets. Given such a high LCFS credit price and the much lower carbon intensities of MSW and dairy RNG, the LCFS policy greatly reduces the cost of production of these sources of RNG in contrast to landfill gas. Landfill gas receives a much smaller effective subsidy due to the fact that it generates few credits per unit of energy. Just as RNG production displaces fossil natural gas, landfill natural gas is also displaced by the less carbon intensive sources of RNG.

The quantity of RNG produced is constrained by the demand for vehicular natural gas fuel. Under high LCFS credit prices, a much greater quantity could be produced profitably, but is not produced because use of RNG outside of transportation fuel does not generate LCFS credits. Expanding the use of natural gas in transportation can lead to substantial increases in RNG production, and therefore, methane emission reductions beyond what is presented in the short-term model in this paper.

As has been established in the literature,[21] my results support the finding that the LCFS policy is less economically efficient than an alternative carbon tax. However, the presence of a price ceiling provides many improvements over an unconstrained LCFS policy as was considered in Holland, Hughes and Knittel (2009). Given the limited supply of LCFS credits, the equilibrium credit price is highly sensitive to specification of carbon intensity targets. Therefore, reductions in carbon intensity target below the current average carbon intensity in transportation yields rapidly increasing credit price outcomes. Under intensity targets scheduled for as early as 2018, the LCFS credit price will bind at the price ceiling. The price ceiling limits the price of LCFS credits from resolving at unreasonably high prices and provides certainty to the market. Participants in the fuels markets can reasonably assume that credit prices will remain at or near the price ceiling until a large scale transformation of the California vehicle fleet occurs. Credit price certainty will encourage greater investment into low-carbon fuel production and research and development (Sandmo, 1971). However, just as noted in the carbon tax versus cap-and-trade debate, certainty in credit prices (compliance costs) comes at the expense of giving up certainty in carbon reductions (Metcalf, 2009; Krugman, 2010).

Under a binding credit price ceiling, I show the economic efficiency of the LCFS policy rapidly improving and approaching the efficiency of the hypothetical carbon tax. The main source of inefficiency in the LCFS policy is that the carbon intensity target is set greater than zero meaning that the policy subsidizes fuels which, while still under the target, have positive levels of emissions. As the intensity targets decrease, the efficiency gap between the LCFS and the carbon tax decreases.

8. CONCLUSION

Natural gas is a rapidly growing transportation fuel and while fossil sourced natural gas may not have a significant climate benefit relative to liquid fuels like diesel and gasoline, renewable sources of natural gas have clear advantages in terms of avoiding methane emissions. The production of RNG from matter that would otherwise emit methane into the atmosphere can dramatically reduce greenhouse gas emissions. However, RNG production is very expensive relative to the production of fossil natural gas. Depending on the value placed upon avoiding greenhouse gas emissions, RNG production can be a worthwhile endeavor.

California’s LCFS policy can provide an incentive for substantial quantities of RNG production. RNG produced from dairy and MSW sources can supply the entire market for vehicular natural gas. This amounts to a 2.7 million metric tonne reduction in emissions of which 2.4 comes from the livestock industry. This achieves about 25% percent of the dairy industry’s required re-

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[21] See Holland, Hughes and Knittel (2009) and Lade and Lin Lawell (2015a).

ductions by 2030. While often criticized as an inefficient policy instrument, results indicate the LCFS policy approaches the efficiency of a carbon tax when combined with a credit price ceiling. As the LCFS policy becomes more stringent the economic inefficiency of the LCFS policy quickly decreases.

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