The Design and Economics of Low Carbon Fuel Standards

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Abstract

Low-carbon fuel standards (LCFS) are increasingly common policy tools used to decrease emissions and increase the penetration of renewable energy technologies in the transportation sector. In this paper, we discuss important design elements of the policy, and provide a background on prominent policies that are currently enacted or proposed. The economics of an LCFS are presented using a simple conceptual model, and the economic literature on the policy is reviewed. Important opportunities to build on the extant literature are identified, including studying the role of low carbon fuel standards in spurring technical change, and the interaction of the policy with other federal and state transportation policies.

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1 Introduction

Low-carbon fuel standards (LCFS) are increasingly viewed as viable policy tools to reduce transportation sector greenhouse gas (GHG) emissions and increase the market penetration of low-carbon, alternative fuel technologies. Given that the transportation sector is responsible for over a quarter of US GHG emissions (Environmental Protection Agency, 2015), policies driving emission reductions in the sector must play an important role in any comprehensive climate policy.

An LCFS requires the average carbon intensity (CI), or carbon emissions per unit, of fuel sold in a region to be below a specified standard. Any firm that produces fuel with a CI above the standard generates a 'deficit' in proportion to the difference between the fuel's CI and the standard. Firms must account for any accrued deficits over a compliance period by purchasing credits generated by firms producing fuels with CI's below the standard. Thus, the policy incents production of low-carbon fuels while simultaneously discouraging production of fuels with a high-carbon content such as gasoline and diesel.

In this paper, we discuss important policy designs elements of an LCFS, and provide a brief history of prominent low-carbon fuel standards that have been enacted or proposed in the US and abroad. In addition, we summarize the market effects of an LCFS using a simple economic model, and discuss important contributions on the policy from the economics literature.

Overall, we find that the LCFS literature is scarce relative to that on other environmental policies. We conclude by identifying important areas for future research in the field. In particular, we identify opportunities to study the role of low-carbon fuel standards in driving technological innovation, examine the interaction of the policy with other regional and federal transportation policies, and explore the role of learning in new fuel technologies and its impact on efficient fuel mandate levels. The issues discussed here have implications beyond the transportation sector as similar policies have been proposed or enacted in other markets and settings. For applied economists, studying low-carbon fuel standards presents an opportunity to contribute both to the intellectual capacity of a growing literature as well as to the political and regulatory progress of a policy at the forefront of energy and climate change economics.

2 Regulatory design

Low-carbon fuel standards are currently enforced in California, British Columbia, and Oregon. In addition, legislative efforts and executive actions have been taken to establish standards in Washington and the European Union (Yeh and Sperling, 2013). In this section, we discuss important design decisions that policy makers and regulators must make when enacting an LCFS. We then discuss important developments in the policies already in place and under consideration.

2.1 Designing an LCFS

Enacting an LCFS requires regulators to make a number of important design decisions, all of which require significant regulatory effort (Yeh and Sperling, 2013). Every low-carbon fuel standard currently in place or under consideration is a form of an energy-based LCFS, and the policy is typically designated as a limit on the GHG content per mega-joule (gCO_2/MJ) of fuel sold in a region.[1] Table 1 compares important design elements of an LCFS to those of a renewable fuel mandate, a comprehensive carbon cap-and-trade (CAT) program, and a comprehensive carbon tax.[2] Under an LCFS, a regulator or legislative body must determine long-run and interim emission reduction goals, develop a methodology for calculating fuels' carbon intensities, and design a compliance credit market for regulated parties. The policy is similar in these respects to designing a cap-and-trade (CAT) program. An LCFS is most similar to a renewable fuel mandate, with the main difference between the two being the role of CI's versus fuel categories. Carbon intensity factors play a central role under an LCFS, while fuel categories play a much consequential role under fuel mandates.[3]

By comparison, a carbon tax requires only the designation of CIs to determine fuels' taxable emissions. While determining fuel carbon intensities is not without controversy, taxes represent a relatively simple policy to enact from a regulatory viewpoint. In addition, if unpriced carbon emissions are the only market failure, taxes are an efficient mechanism to correct the externality. For this reason, the performance of alternative policies such as an LCFS is typically compared to that of a carbon tax in the economics literature.

The long-run goals of an LCFS must balance both the potential costs and benefits of achieving the targeted carbon intensity reductions. Large reductions in the average CI of fuels are not possible given the current state of advanced fuel technologies. Increasing the penetration of low-carbon fuel requires progress along a number of fronts including, but not limited to: (i) increasing low-carbon

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[1] Holland et al. (2009) discuss alternative specifications of intensity standards including: (i) a fuel economy-based emissions standard - a standard that limits carbon emissions per vehicle mile traveled; and (ii) an historical baseline LCFS - a standard limiting the average carbon intensity of fuel based on historic fuel consumption. The former is largely similar to an energy-based LCFS; however, the latter is potentially more efficient, as the standard is more easily met by reducing fossil fuel output than a pure intensity standard.

[2] We use the term 'comprehensive' to indicate that the policy covers all emissions for all fuels.

[3] CI values may be used to 'bin' fuels into separate categories under fuel mandates. For example, the US Renewable Fuel Standard (RFS) CI measures to determine whether fuels qualify as 'advanced' biofuels.

Table 1: Designing a Fuel Sector Carbon Policy

Decision	LCFS	Renewable Fuel Mandate	Comprehensive CAT	Comprehensive Tax
Determine carbon reduction goals & compliance pathway?	✓	✓	✓	
Designate qualifying fuels?	L	✓		
Determine fuel carbon intensities?	✓	L	✓	✓
Design compliance credit market?	✓	✓	✓	

*Notes: A 'comprehensive' CAT or carbon tax refers to a policy covering all transportation emissions. CAT = Cap and Trade. 'L' denotes 'limited', indicating the decision typically plays a secondary role in the policy, if any. For example, under an LCFS a regulator may exclude certain fuel pools such as freight and aviation. Under a renewable fuel mandate, a regulator may designate 'carbon intensity' thresholds that firms must meet to qualify for certain categories.

fuel production capacity; (ii) investing in delivery systems to transport low-carbon fuels to markets and fuel terminals; (iii) increasing the availability of the fuels at retail stations; (iv) increasing the market share of alternative fuel vehicles; and (v) increasing consumer demand for alternative fuels. Meeting these objectives requires large advances in both scientific and engineering knowledge, as well as large investments from governments, firms, and consumers in advanced fuel technologies. In addition, the relative importance of each objective varies across fuel technologies. For example, expanding market penetration of high-blend cellulosic biofuel requires progress along all fronts, while expanding the share of electric vehicles primarily requires increasing consumer preferences for the vehicles, and upgrading residential and commercial electric distribution and fueling systems.

Several studies are available from both prominent consulting firms and the academic literature on the technical feasibility of long-run objectives of states' low-carbon fuel standards.[4] These studies require researchers to make long-run projections of future fuel prices, alternative fuel production capacities, investments in alternative vehicle technologies, and fueling distribution infrastructure.[5]

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[4] See e.g., Farrell and Sperling (2007); Yeh et al. (2009); Pont and Rosenfeld (2011); Boston Consulting Group (2012); ICF International (2013); Pont et al. (2014).

[5] The studies vary in their assumptions regarding the role of other fuel policies. For example, ICF International (2013) consider a limited role of the RFS when determining the future availability of advanced biofuel that will be sold in California.

Alternative fuel production costs are typically estimated based on projections assuming a certain degree of learning and forecasts of future feedstock costs. Given the complexity of the task, most studies present only a handful of future compliance scenarios and the results typically do not convey the deep uncertainty surrounding the estimates.

In addition to long-run objectives, regulators typically set interim compliance pathways. Most low-carbon fuel standards require modest reductions in early years and become more stringent over time. For example, California's LCFS requires no more than a 2.5% CI reduction for the first five compliance years. The standard increases rapidly thereafter to reach the long-run 10% reduction target in 2020.[6] As discussed below, the interim pathways can play an important role in parties' compliance strategies, particularly if they are allowed to over- or under-comply from year to year.

Among the most important choices regulators make when designing an LCFS is the method for calculating fuels' carbon intensities. CI assignments represent the carbon-equivalent emissions of producing a fuel.[7] Several engineering models currently exist that vary in their assumptions used to calculate fuel CIs. One of the most controversial aspects of assigning CIs is whether to include estimates of carbon emissions due to changes in land use (Witcover et al., 2013).[8] Land-use change can result in large carbon releases (Searchinger et al., 2008). Land-use change estimates attempt to account for carbon emissions from both direct increases in acreage devoted to energy-crop production as well as indirect changes in total planted acreage due to policy-induced prices increases. Including land-use change estimates has a large effect on the incentive for many biofuels under an LCFS (Rajagopal and Plevin, 2013). Given the complexity associated with calculating CIs and evolving scientific consensus in the life-cycle analysis literature, policymakers often must update the process used to assign fuel CIs, adding to the regulatory complexity of an LCFS.

The market for compliance credits plays a central role in low-carbon fuel standards. Designing a market for the credits is multi-faceted, and requires regulators to make a number of decisions including: (i) determining the parties that are allowed to purchase and sell credits; (ii) setting reporting requirements for credit generation and transfers; (iii) determining the transactional information that is released to the public; (iv) putting in place a system for firms to validate credits;

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[6] The interim targets are subject to change in the current re-adoption process.

[7] Policies vary in how they calculate carbon emissions from producing fuels. For example, California's LCFS estimates emissions based on 'well-to-wheel' emissions, while other policies such as California's Cap-and-Trade program do not include emissions from some portions of the product supply chain and do not include emissions from certain fuels and industries.

[8] Life-cycle estimates also vary in their treatment of emissions from changes in agricultural management practices such as the amount of above-ground biomass left on fields, and from production of co-products, among other factors (Witcover et al., 2013; Murphy and Kendall, 2013).

and (v) determining whether to allow banking/borrowing of credits across compliance years. Because compliance credit markets typically operate 'over-the-counter', it is important for regulators to ensure that parties can find trading partners with relative ease, as well as determine whether credits on the market are valid.[9] Transparency is also essential for the operation of an efficient credit trading market, and regulatory efforts aimed at decreasing transaction costs and increasing transparency in credit trading markets can significantly increase the policy's efficiency (Stavins, 1995).

Deciding whether parties may over- or under-comply from year-to-year can play an important role in determining firms' compliance strategies. Banking allows firms to over-comply with their mandate in any year and carry credits forward to apply towards future compliance obligations, while borrowing allows firms to carry a credit deficit forward that must be made up for in future compliance periods.[10] In general, allowing unlimited banking and borrowing affords firms the most flexibility in determining their optimal compliance strategy and may increase program efficiency (Rubin, 1996).

A related issue is whether to include a cost containment mechanism in the regulation. Cost containment provisions give regulated parties additional compliance options in the event that they are unable to purchase credits for a price deemed reasonable by the regulator.[11] Such measures are increasingly included in carbon policies. For example, California's cap-and-trade market holds special reserve auctions each quarter where parties may purchase allowances for a pre-established price (California Air Resources Board, 2015).[12] Similar market-stability reserve systems have been considered in the European Union's Emission Trading System (Fell, 2015). The California Air Resources Board has proposed including a cost containment mechanism in the LCFS in its current re-adoption process (California Air Resources Board, 2014b). Most cost containment mechanisms entail either directly or indirectly relaxing the policy's stringency. Thus, when setting a cost containment provision a regulator must weigh the economics losses from high compliance costs

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[9] In 2011 and 2012, fraud occurred in the market for biodiesel compliance credits under the RFS. The Environmental Protection Agency has since put into place a system for validating compliance credits.

[10] So long as firms believe the policy will be fully enforced in the future, deficit carry-over will occur if firms believe future compliance costs will be lower than current costs. For example, firms may carry a deficit if they anticipate a low-cost production facility coming online in the future. When deciding whether to allow deficit carry-over, regulators must balance these efficiency gains with the potential that firms may strategically carry deficits if they believed the policy stringency will change in the future.

[11] Lade and Lin (2013) provide an in-depth discussion and compare alternative cost containment mechanisms for an LCFS.

[12] As discussed by Bailey et al. (2012), ambiguity remains regarding the consequences of the reserve being exhausted.

with the prospect that the policy may not achieve its emission reduction targets should firms use the mechanism.

2.2 California's LCFS

California's Low Carbon Fuel Standard was established by Executive Order S-01-07 in 2007 and is administered by the California Air Resources Board (ARB). The policy requires substantial reductions in the carbon intensity of fuels sold in California, with the goal of reducing the average carbon intensity by 10% by 2020. Implementation began in January 2010 with a reporting only year, and regulated parties began holding obligations in January 2011.

Andress et al. (2010) summarize many of the early regulatory details of California's LCFS. The ARB sets itself apart from other jurisdictions by including indirect land-use change estimates in fuel CIs. To obtain a CI, a firm must register with the ARB. If the firm's production process has not already been assigned a CI, the firm must apply for a 'fuel pathway' for its fuel through the Method 2 process developed by the Board (California Air Resources Board, 2010).[13] The Agency uses the CA-GREET model, a life-cycle assessment model, to determine a fuel's carbon intensity value, and the fuel pathway is added to the published carbon intensity lookup table (California Air Resources Board, 2012).[14]

Table 2 provides a sample of carbon intensity values from approved fuel pathways.[15] Alternative vehicle technologies differ in the efficiency that they convert fuel into mechanical energy (Andress et al., 2010). The ARB accounts for this by assigning fuels energy-economy ratios (EERs).[16] To calculate a fuel's CI, regulated parties divide their fuel pathway CI by the EER for the fuel's vehicle technology. The last column of Table 2 makes these adjustments. As can be seen, EERs play an important role for some fuels, especially electricity.

CI assignments for the same fuel can vary dramatically depending on fuel's production pathway. For example, Midwestern corn ethanol produced using conventional practices has a production carbon intensity of 69.40 gCO_2/MJ, while ethanol produced in California with a less energy intensive production process is assigned a CI of 47.44 gCO_2/MJ. In addition, indirect land-use change (iLUC) estimates vary widely across different feedstocks. For example, Biodiesel and renewable diesel

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[13] For pathways similar to current ones, there is a substantiality requirement.

[14] The process for assigning CI's is likely to change with the current LCFS re-adoption process.

[15] CI values are taken from the California Air Resources Board (2012). EER ratios are taken from a December 2014 staff report (California Air Resources Board, 2014b). The values are presented for illustrative purposes and are likely to change in the current re-adoption process.

[16] Other jurisdictions use similar methods to account for differences in vehicle technologies.

Table 2: Example LCFS CI Assignments*

Fuel Pathway		Carbon Intensity Value (gCO_2/MJ)			
Fuel	Production Pathway	CI	iLUC	EER	EER Adj. CI
CARBOB Gasoline	–	99.18	0	1	99.18
ULS Diesel	–	98.03	0	1	98.03
Corn Ethanol	Midwest; 80% Dry Mill; 20% Wet Mill; Dry DGS	69.40	30	1	99.40
Corn Ethanol	California; Dry Mill; Wet DGS; 80% NG; 20% Biomass	47.44	30	1	77.44
Sugarcane Ethanol	Brazilian; Avg. production processes	27.4	46	1	73.40
Hydrogen	Compressed H_2 from central reforming of NG	142.20	0	2.5	56.88
Electricity	California average electricity mix	124.10	0	3.4	36.50
Comp. Natural Gas	California NG via pipeline; compressed in CA	67.70	0	0.9	75.22
Biodiesel	Conversion of Midwest soybeans to biodiesel	21.25	62	1	83.25
Biodiesel	Conversion of waste oils (high energy)	15.84	0	1	15.84
Renewable Diesel	Conversion of Midwest soybeans to renewable diesel	20.16	62	1	82.16

*Notes: CI = carbon intensity value (gCO_2/MJ). iLUC = indirect land-use change. EER = energy economy ratio. EER Adj. CI = CI/EER. EER designates the technical efficiency of an alternative fuel vehicle relative to an internal combustion engine. CI's are taken from a sample of approved fuel pathways from December 2012 (California Air Resources Board, 2012). EER ratios are used from the California Air Resources Board (2014b). The CNG EER is for CNG used in a spark-ignition engine. CI values are presented for illustrative purposes and are likely to change in future rulemakings.

produced from Midwestern soybeans have an iLUC of 62 gCO_2/MJ added to their production process CI due to estimated emissions from land-use changes.[17]

The ARB has overcome a number of important legal challenges since the program's inception. In December 2011, a District Court judge granted a preliminary injunction against the ARB, finding that California's LCFS violated the federal commerce clause due to its life-cycle accounting methods. The injunction was stayed by the Ninth Circuit court, and the ARB has continued enforcement of the policy (Biofuels Digest, 2011; California Air Resources Board, 2013). In September, 2013, the Ninth Circuit Court of Appeals upheld the LCFS, and in June 2014 the US Supreme Court chose not to review the lower court's decision.

In 2013, California's Fifth Appellate District Court found that the LCFS adoption process violated the California Environmental Quality Act (CEQA). The court allowed the ARB to continue enforcing the LCFS, but required the Board to freeze the standard until it readopted the program.[18] The case has resulted in a lengthy re-adoption process, and the Board has used the opportunity to propose a number of amendments to the original regulation. The amendments currently under consideration include: (i) modifying the LCFS compliance schedules for 2015 to 2019; (ii) changing the process for determining fuel CIs; (iii) updating iLUC estimates; (iii) allowing refiners to generate credits for reducing emissions from producing gasoline and diesel; and (iv) including cost containment provisions in the regulation (California Air Resources Board, 2014a,b).

Researchers at the University of California at Davis Institute of Transportation Studies provide regular and timely updates on the progress of California's LCFS (Yeh and Witcover, 2012; Yeh et al., 2013; Yeh and Witcover, 2013, 2014). The updates review important developments in the regulation including the total credit and deficit generation, the composition of generated credits, and compliance credit prices. The most recent issue finds that the average CI of alternative fuels sold in the state fell 15% since the program's inception. While ethanol generates most credits, its share of generation has decreased since 2013 as larger shares of credits are generated by renewable diesel, biodiesel, and to smaller extent, electricity (Yeh et al., 2015).

2.3 LCFS in Other Jurisdictions

British Columbia's Renewable and Low Carbon Fuel Requirements Regulation has been in place since 2010.[19] Carbon-intensity targets were set relatively high in the program's early years, and

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[17] The methods for determining iLUC values are being revised by the ARB in its 2014-2015 re-adoption process and are subject to change.

[18] In addition, the court directed the Board to study whether biodiesel blending results in increased NO_x emissions and ensure the fuel does not violate ambient air quality standards in the state.

[19] British Columbia uses a different life-cycle assessment model, GHGenius, to estimate fuel carbon intensities than California. In addition, the Ministry does not include estimates of indirect land-use change (British Columbia

firms were only required to report fuel CIs through 2012. Enforcement began in 2013 (British Columbia Ministry of Energy and Mines, 2014a). The most recent publicly available data suggests that firms over-complied with the policy's targets through 2012. Credits were primarily generated by low-carbon ethanol; however, biodiesel, renewable diesel and electricity also played an important role in credit generation (British Columbia Ministry of Energy and Mines, 2014c). Unlike California, BC does not provide regular enforcement and credit generation updates, and has yet to release data for the 2013 compliance year.

The Oregon legislature passed an LCFS, known as the Clean Fuels Program, in 2009 and directed the Oregon Department of Environmental Quality (DEQ) to reduce the carbon content of the state's transportation fuels by 10% over a 10 year period. The DEQ began collecting data on fuel use and imports in the state in 2012. On January 7, 2015 the Oregon Environmental Quality Commission adopted rules to begin enforcing the policy, and enforcement began February 2015. In March 2015, Governor Kate Brown signed Senate Bill 324 removing a sunset on the program, and allowing the DEQ to move forward enforcing the regulation (Oregon Department of Environmental Quality, 2015).

In 2009, former Governor Christine Gregoire of Washington issued an executive order directing the state's Department of Ecology (DEC) to assess whether a low-carbon fuel standard could serve as a means of achieving the state's long-run GHG emission reduction goals. Unlike Oregon which has no refining capacity, Washington has a number of large refineries that would likely be adversely impacted by the policy.[20] As such, the DEC has yet to move forward with enforcement activity.

Outside North America, the European Union introduced regulations in 2009 creating a low-carbon fuel standard known as the Fuel Quality Directive (FQD). The FQD has a modest long-run reduction target compared to its North American counterparts, with the goal of reducing the average fuel CI in the EU by 6% by 2020. Final adopting measures have been published by the European Commission after a lengthy public commenting period (European Commission, 2014). The final measures have yet to be adopted by the European parliament; however, the current proposal looks much like those in North America. While the Commission was directed to report on the potential impact of iLUC, it has not yet published a final recommendation for addressing the issue (European Commission, 2015).

Ministry of Energy and Mines, 2013, 2014b).

[20] The DEC has commissioned two studies on the impacts of a potential LCFS in the state (Pont and Rosenfeld, 2011; Pont et al., 2014). The most recent study finds that while average gasoline and diesel prices may increase under the LCFS, the increases would be modest and the overall impacts on the economy would be small but positive. Most positive impacts from the study assume that renewable production facilities will locate in Washington.

3 Economics of an LCFS

Before reviewing the broader economic literature on low-carbon fuel standards, we present a model of an industry facing an LCFS to illustrate the basic market effects of the policy.[21] Consider an economy with both a high- and low-carbon fuel sector. For simplicity, assume consumers are indifferent to the composition of fuel.[22] Suppose the high-carbon fuel is abundant at relatively low prices while the low-carbon fuel is more costly. The solid lines in Figures 1a - 1c graph equilibrium in each market in the absence of an LCFS. The initial equilibrium price, P_0, is determined by the intersection of the fuel demand curve with the blended fuel supply curve in Figure 1c.[23] The equilibrium volumes of the low- and high-carbon fuels are found by observing the supply of each fuel at P_0. In our example, because the low-carbon fuel is relatively expensive, little of the fuel is blended in the initial equilibrium.

Under a binding LCFS, every unit of high-carbon fuel generates a deficit that must be accounted for by purchasing credits from low-carbon fuel producers.[24] Thus, the policy implicitly taxes high-carbon fuel and subsidizes low-carbon fuel. This is illustrated by the dashed lines in Figures 1a and 1b. The implicit subsidy shifts the low-carbon fuel supply curve down in Figure 1a, while the implicit tax shifts the high-carbon fuel supply curve up in Figure 1b. The level of the tax and subsidy is endogenous, and compliance credit prices adjust to the point where the reduction in high-carbon fuel and increase in low-carbon fuel just meets the standard.[25] The high-carbon fuel industry's total tax liability equals the area $C + D + E$. The total tax liability is equal to the subsidy for the low-carbon fuel industry, given by the area $A + B$, illustrating the equivalence between an LCFS and a revenue neutral tax-subsidy scheme (Holland et al., 2009).

Equilibrium under an LCFS is determined by the intersection of the new blended supply curve, represented by the dashed upward sloping line in Figure 1c, with the fuel demand curve. In most cases, an LCFS decreases the volume of high-carbon fuel and increases the volume of low-carbon

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[21] The model is based on work in Holland et al. (2009) and Lade and Lin Lawell (2015).

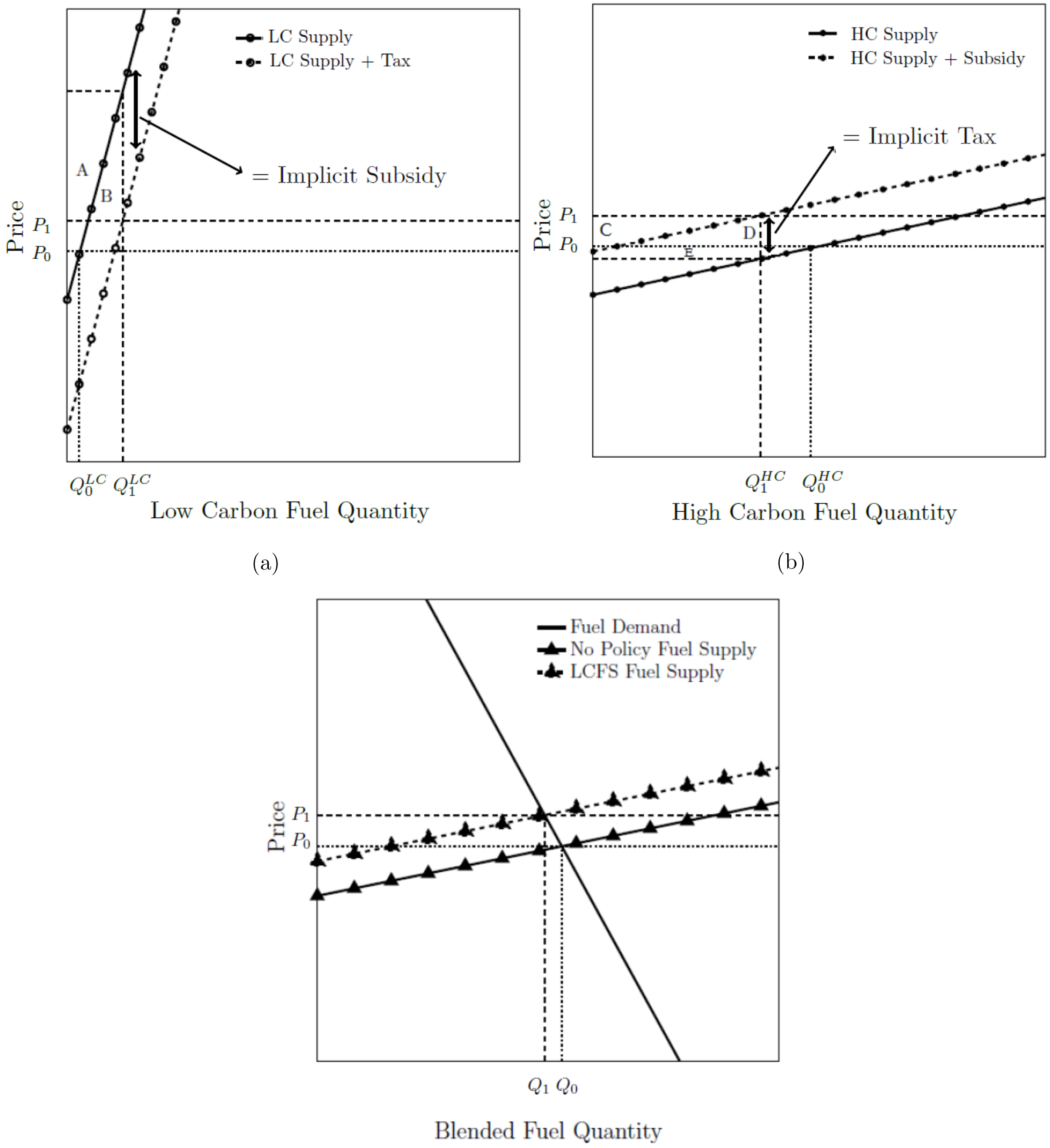
[22] We do not consider blending constraints or quality differences between the fuels. This limits the application of the model to liquid fuels. The model can be extended to a non-liquid fuels case by assuming that the high-CI and low-CI fuels are sold in separate markets. In this case, the two markets become linked through the policy constraint and similar results hold as considered here.

[23] The blended fuel supply curve is equal to the horizontal sum of the low- and high-carbon fuel supply curves.

[24] The model here considers a scenario where the policy is applied to a single jurisdiction. Section 3.1 discusses the results from work studying the implications of an LCFS being applied in multi-jurisdiction setting with incomplete regulation.

[25] The level of the tax/subsidy is a function of the fuels' relative CIs, the LCFS standard, and the compliance credit price (Lade and Lin Lawell, 2015).

Figure 1: Economics of an LCFS



(a)

(b)

(c)

fuel.[26] The effect of the policy on fuel prices depends on the net fuel supply response. Intuitively, if the decrease in high-carbon fuel is fully offset by an increase in low-carbon fuel production, the policy will decrease fuel prices. This requires rather generous assumptions on the curvature of the low-carbon fuel supply curve. Thus, a binding LCFS increases prices in general; however, the price impact is usually small relative to the impact of an emissions tax as the policy induces transfers between producers to achieve its objectives rather than by pricing emissions directly (Holland et al., 2009; Lade and Lin Lawell, 2015).

An LCFS has similar effects when considered in a dynamic setting. When the policy is applied over time and firms are allowed to bank or borrow credits between compliance periods, compliance credit prices will reflect both current and expected future compliance costs. Thus, if firms anticipate high future compliance costs, demand for permits will rise earlier in the program as firms bank credits for future compliance. Thus, the implicit tax-subsidy may increase well before the higher compliance costs are realized (Lade, Lin Lawell, and Smith, 2015).

The efficiency of an LCFS relative to other carbon policies depends on the economic environment in which it is enacted. If unpriced emissions are the sole market failure, a ‘first-best’ policy prescription is to tax all fuels’ emissions. Because an LCFS taxes only the portion of emissions that exceed the standard and subsidizes fuels with emissions below the standard, the policy is generally characterized as ‘second-best’ in the economics literature (Helfand, 1992; Holland et al., 2009). As discussed in the next section, an LCFS may be more desirable when considered in a dynamic setting or in the presence of other market failures.

3.1 A Review of the Literature

3.1.1 Market Effects and Efficient Low-Carbon Fuel Standards

Several papers study the effects and efficiency of an LCFS in alternative market settings. Holland et al. (2009) provide a seminal study of the policy. While the authors show that an LCFS does not guarantee emission reductions, simulations calibrated to represent the US gasoline market find that the policy decreases emissions and increases fuel prices. Average abatement costs, calculated as the loss in consumer and producer surplus divided by the emission reductions achieved by a given standard, demonstrate that the policy is much less efficient at reducing emissions than a carbon tax or cap-and-trade program.

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[26] See Lade and Lin Lawell (2015) for a discussion of when an LCFS may decrease the volume of both fuels. This occurs only in special cases that are unlikely to arise in fuel markets.

Holland et al. (2014) use long-run biofuel supply curves from Parker (2011a,b) to compare a national cap-and-trade program to an RFS and LCFS. The authors find that fuel mandates are more costly than a cap-and-trade program in achieving the same emission reductions. The gains from an LCFS and RFS, however, are found to be relatively concentrated among a small number of counties that produce low-carbon fuel feedstocks, while the costs are spread over a larger number of US counties. The authors argue that this feature of fuel mandates make them more amenable to adoption than a cap-and-trade program. Holland et al. (2015) use the same biofuel supply curves to simulate the effect of various policies on emissions, renewable fuel production, and land use. The authors find that land-use changes and biofuel production increases are modest under cap-and-trade relative to an LCFS or RFS. In both studies, the fuel price impacts of an RFS and LCFS are lower than under a cap-and-trade for all simulations, consistent with the dampened price impact of an LCFS discussed above.

Related work has studied means by which a regulator can increase the efficiency of an LCFS through strategic policy decisions. Lemoine (2013) shows that the efficiency of an LCFS may increase if a regulator optimally sets both the fuel standard and fuels' CI factors. He extends the model in Holland et al. (2009) to a multi-fuel setting where a regulator is uncertain about fuel CIs, and shows the welfare maximizing CI levels do not always correspond to the regulator's true expected value. Lade and Lin Lawell (2015) show that a regulator can increase the efficiency of an LCFS by optimally setting a cost containment mechanism that caps compliance credit prices.

3.1.2 Incomplete Regulation, Leakage, and Market Power

The discussion thus far has considered a case where an LCFS is applied to a single jurisdiction. As discussed in Section 2, an LCFS is most commonly applied in jurisdictions that are connected through trade to other regions that do not have an LCFS, potentially leading to problems arising from incomplete regulation. Incomplete regulation occurs when pollution damages depend on global emissions and a regulation applies only a specific region. In this context, increasing the cost of emissions in a regulated region can shift production to unregulated regions, causing emissions leakage.[27] In addition to leakage, environmental policies may have unintended consequences if regulated firms have market power (Buchanan, 1969; Mansur, 2013).

Holland (2012) studies the relative efficiency of an LCFS in the presence of both incomplete regulation and market power. The author finds that an LCFS may be more efficient than a carbon

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[27] Leakage is a broader problem associated with any regional carbon policy. The issue has been studied in depth the context of other carbon policies like cap-and-trade (Bushnell et al., 2008; Fowlie, 2009; Bushnell and Chen, 2012; Fischer and Fox, 2012).

tax in the presence of either problem. The result is driven by the dampened price effects of an LCFS which incentivizes higher domestic fuel production than would occur under a carbon tax. Rajagopal and Plevin (2013) study the implications of including iLUC in biofuel CIs in an open-economy model. The authors find that including iLUC lowers emissions and raises fuel prices in the domestic economy; however, domestic emission reductions may be offset in part, or in special cases in full, by increased emissions abroad. Lade, Lin Lawell, and Sexton (2015) develop a conceptual model to study the impacts of imperfect competition on the performance of renewable fuel mandates. Overall, the studies suggest that policymakers and regulators must carefully weigh potential adverse consequences of carbon policies in the presence of leakage or market power both when choosing between carbon policies as well as when setting the stringency of a policy.[28]

3.1.3 Policymaking with Multiple Objectives

Policy makers often seek to address multiple objectives with an LCFS including: (i) reducing carbon emissions; (ii) increasing energy security; [29] (iii) minimizing policies' fuel price impacts; and (iv) supporting the development of a domestic low-carbon fuel industry. Rajagopal et al. (2011) compare an LCFS with other carbon policies based on these objectives using an open-economy model. The authors find than an LCFS ranks highly in reducing emissions, limiting adverse impacts on consumers due to lower fuel price impacts, and supporting a domestic low-carbon fuel industry. Using a similar open-economy model with an integrated agricultural and energy sector model, Chen et al. (2014) find that an LCFS leads to a higher penetration of low-carbon biofuel and achieves greater emission reductions than an RFS. These studies suggest that alternative objectives play an important role in policymaking and contribute to the political desirability of low-carbon fuel standards over other carbon policies.

3.1.4 Innovation and Learning

In addition to the criteria above, an important objective of low-carbon fuel standards is to drive innovation in fuel markets and increase the penetration of alternative fuels. Previous theoretical and empirical work in the economics literature supports the notion that technological progress is influenced by regulatory incentives and energy prices (Popp, 2002; Jaffe et al., 2005). The literature

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[28] In addition to the two studies, Kessler and Yeh (2013) study alternative designs for an LCFS aimed at minimize leakage in a multi-jurisdiction setting.

[29] Energy security benefits of an LCFS are studied by Leiby and Rubin (2013) and Leiby (2008).

studying the efficiency of an LCFS when technology is endogenous, however, is relatively limited to date.

Clancy and Moschini (2015) develop a model of a conventional and renewable industry in which innovators make research and development (R&D) investments in a renewable technology based on their beliefs about the prospect of innovation and its future payoff.[30] The authors compare welfare and R&D outcomes under a no policy scenario, a carbon tax, and a fuel mandate.[31] They find that efficient mandates increase when innovation is endogenous, suggesting that regulators should set more stringent standards as the prospect for innovation increases. In addition, the authors find that a carbon tax creates higher profit opportunities when the expected technological gains are large, while mandates may provide a larger incentive for investments in small, incremental innovations. The findings suggest that while policies like an LCFS may provide a larger incentive for incremental innovations such as learning-by-doing, they may play a more limited role in incentivizing investments in 'break-through' technologies than previously thought.[32]

The findings are consistent with recent empirical work studying patent activity. Johnstone et al. (2010) find that quantity-based mechanisms such as mandates are more highly associated with innovation and R&D in older technologies, while price-based policies such as targeted subsidies have a larger impact on innovation in more costly, renewable technologies.

3.1.5 Overlapping Policies and Policy Interactions

Low-carbon fuel standards are one among a suite of carbon policies in place for the transportation sector. Fuel providers and importers in the US must also comply with the federal Renewable Fuel Standard, a biofuel mandate. In addition, California refiners began holding a compliance obligation for fossil fuel emissions under the state's cap-and-trade program in 2015, while non-fossil fuel emissions are exempted (Yeh et al., 2015). These policies are likely to have important interactions with any regional LCFS, and understanding the implications of those interactions will become more pressing as the policies become more stringent over time. To date, the authors are not

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[30] In addition, Chen et al. (2012) study biofuel mandates and low-carbon fuel standards in the presence of learning-by-doing in advanced biofuel production. Fulton et al. (2014) study alternative investment strategies in cellulosic ethanol production of firms in the US biofuel industry.

[31] The authors specify the mandate as a minimum requirement of renewable fuel. As discussed in Lade and Lin Lawell (2015), a fuel mandates has similar market effects as an LCFS.

[32] In similar work outside the fuels market context, **?** develop a model with technological innovation with knowledge spillovers to compare policies aimed at reducing emissions in the electricity sector. The authors find that an LCFS outperforms all policies except for an emissions price.

aware of any papers studying these interactions and their implications for efficient policymaking in the economics literature.[33]

4 Conclusion and Paths for Future Research

A number of opportunities exist to expand the current understanding of the effects and effectiveness of low-carbon fuel standards in transportation fuel markets. Two of the most pressing areas that require further research include the role of the policies in spurring technical change and learning in the low-carbon fuel industry, and the interaction of low-carbon fuel standards with other carbon policies.

As more renewable fuel technologies are developed and the low-carbon fuel standards continue to expand, empirical work in the spirit of Popp (2002) and Johnstone et al. (2010) could test the relative importance of the policies in spurring innovation. In addition, extensions to Clancy and Moschini (2015) may help distinguish the underlying mechanisms by which an LCFS incentivizes technological progress. A deeper understanding of these mechanisms could identify alternative design structures such as instituting a price floor for LCFS compliance credits that may improve the incentive for investments in break-through technologies (Burtraw et al., 2010).

The interaction of low-carbon fuel standards with other carbon policies is perhaps the most pressing omission in the literature. While most efforts to implement an LCFS are at state and regional level, national policies exist that interact with the policy. Studying the policy interactions is essential to understanding the full effect of low-carbon fuel standards in achieving GHG emission reductions. Thus, work in the spirit of Goulder and Stavins (2011) and Goulder et al. (2012) is certainly desirable.

Low-carbon fuel standards are not unique to the transportation sector, and lessons learned from the policies have broad implications. For example, low-carbon fuel standards have been proposed as an tool with which states can meet their requirements under the Environmental Protection Agency's Clean Power Plant Rule. A few papers have already begun to explore the potential effects of these polices on the electricity sector (Linn et al., 2014), as well as the strategic choice faced by states in deciding between a mass and rate-based standard (Bushnell et al., 2014). Overall, studies of low-carbon fuel standards will continue to have broad implications for the design of effective and efficient carbon policies in the US and abroad.

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[33] One exception is Huang et al. (2013) who study the interaction between an LCFS and RFS; however, the authors consider implementation of both policies at the national level and do not study the interaction of a regional LCFS and national RFS.

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