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Can ethanol alone meet California's low carbon fuel standard? An evaluation of feedstock and conversion alternatives

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Abstract
The feasibility of meeting California's low carbon fuel standard (LCFS) using ethanol from various feedstocks is assessed. Lifecycle greenhouse gas (GHG) emissions, direct agricultural land use, petroleum displacement directly due to ethanol blending, and production costs for a number of conventional and lignocellulosic ethanol pathways are estimated under various supply scenarios. The results indicate that after considering indirect land use effects, all sources of ethanol examined, except Midwest corn ethanol, are viable options to meet the LCFS. However, the required ethanol quantity depends on the GHG emissions performance and ethanol availability. The quantity of ethanol that can be produced from lignocellulosic biomass resources within California is insufficient to meet the year 2020 LCFS target. Utilizing lignocellulosic ethanol to meet the LCFS is more attractive than utilizing Brazilian sugarcane ethanol due to projected lower direct agricultural land use, dependence on imported energy, ethanol cost, required refueling infrastructure modifications and penetration of flexible fuel E85 vehicles. However, advances in cellulosic ethanol technology and commercial production capacity are required to support moderate- to large-scale introduction of low carbon intensity cellulosic ethanol. Current cellulosic ethanol production cost estimates suffer from relatively high uncertainty and need to be refined based on commercial scale production data when available.

Keywords: greenhouse gas emissions, life cycle carbon intensity, biofuels, transportation fuels, life cycle analysis, well-to-wheel analysis, ethanol production cost, land use

S Supplementary data are available from stacks.iop.org/ERL/5/014002/mmedia

1. Introduction

California is developing a series of initiatives and regulations to reduce greenhouse gas (GHG) emissions from primary GHG emitting sectors including transportation, electricity, and building and appliances. Transportation is the largest contributor, accounting for about 40% of California's total GHG emissions (CEC 2007). Approximately 70% of GHG emissions from the transportation sector are associated with gasoline, which is almost entirely consumed by light-duty vehicles (LDVs) (Farrell and Sperling 2007). In order to reduce GHG emissions from the transportation sector, the Governor of California issued the low carbon fuel standard (LCFS) in January 2007, which calls for a reduction in the average fuel carbon intensity (AFCI) (measured on a life cycle (LC) basis) of the State's transportation fuels of at least 10% by 2020. The LCFS was adopted on 23 April 2009.

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While other options are available to achieve the LCFS, increased ethanol use is likely to play a dominant role due to, ethanol's compatibility with the existing vehicle fleet and refueling infrastructure, its large-scale use mandated under renewable fuel standard provisions of the Federal Energy Independence and Security Act (EISA) of 2007 and its production capacity both in the US and Brazil. Hence, the analysis in this study focuses on evaluating the impacts of increasing ethanol use to a level sufficient to meet the targeted AFCI under the LCFS, and the insights developed are likely to be useful even if other options gain traction.

While ethanol use can potentially reduce GHG emissions relative to petroleum derived fuels, LC GHG emissions from ethanol vary significantly depending on the feedstock and the conversion technologies employed. Hence, in this study we analyze the LC GHG emissions from ethanol produced using a number of feedstock-processing pathways. While the LCFS is focused on GHG emissions, consideration of broader sustainability issues has been part of the California discussions (e.g., Yeh *et al* 2009). Further, using GHG emissions as the single metric may be a poor guide for policy because of other simultaneous considerations, including energy security, fuel costs, and competition for agricultural land between food and fuel arising from large-scale biofuel production. California's State Alternative Fuels Plan recommends mechanisms to concurrently address multiple state policies in an integrated fashion: petroleum reduction, GHG reduction and in-state biofuel production (CEC 2007). In response, this study investigates impacts on petroleum displacement directly due to ethanol blending, direct agricultural land requirements, and ethanol costs in addition to GHG emissions. Since the quantity of ethanol produced from a single feedstock may not be sufficient to meet the AFCI, various scenarios of ethanol supply from a combination of sources are analyzed. Further, Executive Order S-06-06 from the Office of the Governor of California, sets a target of a minimum 20% of biofuels including ethanol and biodiesel produced from renewable sources within California by 2010, which increases to 40% by 2020 and to 75% by 2050 (State of California 2006). In view of the mandated preference for biofuels produced within California, the potential for using biomass resources within the State for ethanol production and its implications are also assessed.

Assuming that the targeted 10% reduction in the AFCI of total energy demand of California's LDV fleet in 2020 will be achieved only by using combinations of gasoline and ethanol, this study examines the following specific questions. (1) What are the LC GHG emissions implications of ethanol produced from various feedstocks using conventional and emerging conversion technologies relevant to the 2020 time frame? (2) How does ethanol produced from various feedstocks compare in terms of petroleum displacement directly due to ethanol blending, direct agricultural land requirement, and ethanol production costs? (3) What is the potential ethanol production from existing lignocellulosic (hereafter referred to as cellulosic) biomass resources in California, and to what extent can in-state cellulosic ethanol contribute to reducing the AFCI of California's LDV fuels? (4) What potential combinations of the ethanol sources are feasible for meeting the LCFS and what are their implications? (5) How would the exclusion of indirect land use change (iLUC) effects, and/or the inclusion of potential improvements in corn and sugarcane ethanol production technologies influence these fuels' relative performance?

Studies by the California Air Resources Board (CARB 2009a) and Farrell and Sperling (2007) have analyzed options for achieving California's LCFS. This analysis addresses a number of the limitations of these studies. For example, Farrell and Sperling do not include detailed economic analysis. While CARB includes economic analysis for the compliance paths developed, the economic analysis is not fully consistent with its LC GHG analyses; for example, production costs for three cellulosic ethanol pathways (corn stover, wood chips and municipal solid waste (MSW)) are estimated but the carbon intensity calculations consider only cellulosic ethanol pathways from forest residue and farmed trees. The current study uses consistent pathways for estimating both LC GHG emissions and ethanol production costs. The study also includes several additional pathways not modeled by CARB (2009a), namely, ethanol from California hardwood residues and agricultural residues, California softwood residues (using thermo-chemical conversion), California MSW, and Midwest corn stover. Unlike previous studies, this study analyzes the feasibility of meeting the local biofuel targets set by the Executive Order S-06-06, in addition to the LCFS. Finally, it estimates agricultural land use and petroleum displacement effects for various compliance pathways in addition to GHG and cost implications. Hence, this study provides a relatively more comprehensive and consistent analysis.

2. Methods

The analysis has five main components: (1) identification of potential ethanol feedstock and conversion pathways relevant to the time frame of the LCFS; (2) life cycle inventory (LCI) modeling of GHG emissions and petroleum use of the selected pathways; (3) assessment of California's in-state ethanol production potential using local biomass feedstocks; (4) financial analysis to estimate the minimum selling price of ethanol produced using the selected pathways; and, (5) combining the above for environmental and cost analysis of various potential ethanol supply scenarios to meet the LCFS. Methods used for each of these components are briefly described below. More details are available as supplementary data (available at stacks.iop.org/ERL/5/014002/mmedia).

2.1. Ethanol feedstocks and conversion pathways

Ethanol required to meet the LCFS can be produced within California or elsewhere, using a variety of feedstock and conversion pathways. The analysis includes the pathways shown in table 1. These represent current commercial ethanol technologies as well as future technologies expected to be ready for commercial deployment before 2020 (NAP 2009). For ethanol production using mature technologies (i.e., ethanol

Table 1. Ethanol pathways examined.

Ethanol pathway	Feedstock and location	Conversion process	Ethanol production location
Midwest corn ethanol	Corn produced in US Midwest[a]	Dry mill (80%) and wet mill (20%)	US Midwest
California corn ethanol	Corn produced in US Midwest	Dry mill (natural gas as process fuel)	California
Brazilian sugarcane	Sugarcane produced in Brazil	Fermentation of sucrose	Brazil
Midwest corn stover ethanol	Residue generated from corn production in US Midwest	Dilute acid pretreatment followed by enzymatic hydrolysis and fermentation[b]	US Midwest
California agricultural residue ethanol	Agricultural residues generated in California	Dilute acid pretreatment followed by enzymatic hydrolysis and fermentation (same process as corn stover)	California
California hardwood residue ethanol	Hardwood forest residues generated in California	Dilute acid pretreatment followed by enzymatic hydrolysis and fermentation	California
California softwood residue ethanol	Softwood forest residues generated in California	Indirect steam gasification followed by alcohol synthesis[c]	California
California MSW ethanol	MSW generated in California	Dilute acid hydrolysis in a gravity pressure vessel followed by fermentation of glucose to ethanol[d]	California

[a] The Midwestern states included are Wisconsin, Iowa, Nebraska, Illinois, Indiana, Minnesota, Ohio, Michigan, and South Dakota.
[b] Aden *et al* (2002). [c] Phillips *et al* (2007). [d] Kalogo *et al* (2007). MSW = municipal solid waste.

from corn and sugarcane), the LC GHG emissions for the relevant pathways are taken directly from CARB's regulation (2009a). However, implications of potential improvements in dry mill corn ethanol and sugarcane ethanol processes are discussed in section 3.6.

Unlike corn and sugarcane ethanol, no commercial cellulosic ethanol plants are currently operating. Therefore, the ethanol conversion technologies employed for agricultural and forest residues in the present study are based on design specifications for biochemical (Aden *et al* 2002) and thermo-chemical (Phillips *et al* 2007) processes envisioned by the process developers at the National Renewable Energy Laboratory (NREL) for *N*th plants; development costs associated with initial plants are excluded for *N*th plants. As Aden *et al* (2002) examine only corn stover as a feedstock, modifications are made to the ethanol and co-product yields in the case of the biochemical process, to reflect differences in composition of feedstocks other than stover. Conversion of MSW to ethanol is modeled based on a gravity pressure vessel process developed by GeneSyst Inc. (GeneSyst 2009, Kalogo *et al* 2007). Chester and Martin (2009) analyze a MSW to ethanol process based mainly on NREL's dilute acid process for corn stover conversion; however our model is based on the GeneSyst process because it was developed and tested specifically for MSW and takes into account the relatively low lignin content of MSW (see the supplementary data available at stacks.iop.org/ERL/5/014002/mmedia for a more detailed discussion of other differences from Chester and Martin (2009)). A more general point to note is that a number of competing cellulosic ethanol conversion technologies and unit process alternatives are currently under development, for example, dilute acid versus concentrated acid versus ammonia fiber expansion options for biomass pretreatment (Eggeman and Elander 2005, Sendich *et al* 2008), and a hybrid thermo-chemical–biochemical pathway proposed by Coskata (2009). Which conversion pathway(s) will ultimately prove dominant by 2020 is uncertain. As indicated in Spatari *et al* (2009), there is considerable uncertainty regarding preferred technologies and their operating parameters, all of which will influence the environmental performance of the cellulosic ethanol pathways. Since information on many of these new technologies is proprietary, our analysis is based on published studies. Ethanol from dedicated energy crops is not analyzed because studies indicate that initially cellulosic ethanol production will use cheaper agricultural and forest residues as feedstock, and production of ethanol from dedicated energy crops is likely to be minor even by 2020 (Collins 2007, Ferris and Joshi 2008, EIA 2009).

2.2. *Life cycle assessment of ethanol pathways*

Detailed LCI models are developed to estimate the GHG emissions and petroleum requirements for the ethanol pathways shown in table 1. CARB is using a modified version (hereafter referred to as CA-GREET) of Argonne National Laboratory's GREET model to estimate the direct emissions for LCFS-related fuels (CARB 2009b). For consistency, we also use the CA-GREET 1.8b model for modeling the ethanol pathways in table 1 that are not currently included in CARB's carbon intensity lookup table (CARB 2009a). The LC activities included in CA-GREET are feedstock production, feedstock transportation, conversion to ethanol, ethanol transport, storage and distribution, and vehicle use (the well-to-wheel (WTW) stages).

The functional unit for the analysis is 1 MJ of fuel produced and used by a representative LDV. As in CA-GREET, GHG emissions (CO_2, CH_4, N_2O), are aggregated into CO_2 equivalent (CO_2eq) based on 100 year global warming potentials. Co-product credits for each of the pathways are estimated using the displacement method or an energy-value-based method (details are provided in the supplementary data available at stacks.iop.org/ERL/5/014002/mmedia). Although only LC GHG emissions are regulated under LCFS, LC petroleum use and direct agricultural land use are estimated as additional policy relevant performance metrics.

In addition to direct LC GHG emissions, the adopted LCFS regulation includes carbon emissions from iLUC. Increased global biofuel demand is expected to lead to

conversion of land from other uses to agricultural production, resulting in CO_2 emissions from the release of carbon sequestered in these soils and vegetation (CARB 2009a, Searchinger *et al* 2008). However, whether iLUC emissions should have been included in the regulation, and determination of appropriate methods for estimating iLUC emissions are subjects of current ongoing debate, as evidenced by a number of letters, both for and against inclusion of iLUC in the LCFS, written by various stakeholders and scientists to the Governor of California, CARB, and the US Environmental Protection Agency (EPA) (Bioenergy-Wiki 2009). The LCFS, which includes iLUC, was filed with the Office of Administrative Law (OAL) on 25 November, 2009 and is awaiting OAL approval (as of December 2009). There will be an expert working group who will report on the land use issues and indirect effects by January 2011 (CARB 2009c, 2009d). We first analyze the scenario where the current CARB estimates of iLUC emissions are included, but also present the implications of excluding iLUC emissions as the iLUC values may change in the future and analysis of AFCI without iLUC can provide relevant insights.

Three of the eight pathways examined in this work (Midwest corn ethanol, California corn ethanol, Brazilian sugarcane ethanol) are currently represented in the CA-GREET model. The additional pathways we model within CA-GREET 1.8b are ethanol produced from; (1) California hardwood forest residue using biochemical conversion, (2) California agricultural residue using biochemical conversion, (3) California softwood residue using thermochemical (gasification) conversion, (4) California MSW using a gravity pressure vessel process, and (5) Midwest corn stover using biochemical conversion. Details of the key process parameters are discussed in the supplementary data (available at stacks.iop.org/ERL/5/014002/mmedia) and presented in table SI-1 (available at stacks.iop.org/ERL/5/014002/mmedia). In estimating GHG emissions from the MSW ethanol pathway, we assume that MSW is a waste material and has no feedstock production related GHG emissions. However, as Kalogo *et al* (2007) and Christensen *et al* (2009) discuss, avoided GHG emissions for waste material feedstock conversion can vary depending on the assumed disposal alternatives and the system boundary considered. Various components of MSW (e.g., paper, food waste, wood waste) have a number of disposal alternatives available, such as recycling, composting, landfilling with or without landfill gas recovery either for flaring or for electricity generation. For simplicity, and to avoid multiple GHG values for a single pathway, we assume no feedstock production related GHG emissions for MSW. Our approach is consistent with the CA-GREET GHG estimation procedures for forest residues, prior MSW studies (e.g., Chester and Martin 2009) and practice under Chicago Climate Exchange protocols.

2.3. California biomass inventory

In view of the mandated preference for biofuels produced within California (under Executive Order S-06-06), and the likely lower cost of using local biomass resources that avoids long distance transportation of bulky biomass, we assess biomass resources within California separately. The California biomass feedstocks inventoried include; agricultural and forest residues and cellulosic fractions of MSW (see the supplementary data table SI-2 available at stacks.iop.org/ERL/5/014002/mmedia). Data on gross production and total 'technically available amounts' after accounting for current uses of agricultural and forest residues are estimates from a study of statewide biomass resources conducted by the California Energy Commission (CEC 2005). The technically available amounts estimated in the study take into consideration the following factors; terrain limitations, environmental and ecosystem requirements (e.g., maintenance of soil fertility and prevention of soil erosion), collection inefficiencies, and a number of other technical and social constraints, which limit the amount of biomass that can actually be collected. Not all the technically available biomass is likely to be available for conversion to ethanol. We assume 50% of technically available agricultural and forest residues (after considering current uses) are available for ethanol production (see note (c) of table SI-2 available at stacks.iop.org/ERL/5/014002/mmedia). The quantities of agricultural and forest residues available in 2005 are used as reasonable estimates of their availability in 2020, because the amounts of residues are unlikely to change significantly in the absence of major structural changes in the primary agriculture and forest industries. Under these assumptions, 1.6 million dry metric tons (t) of agricultural residues and 5.9 million dry t of forest and mill residues are estimated to be available annually for ethanol production by 2020.

Californians disposed an average of 1 t of MSW per capita in the state's landfills in 2007, at an estimated diversion rate of 58% (California Integrated Waste Management Board 2009). Cellulosic materials (mixed paper and organics) made up approximately 51% of the total MSW landfilled. We assume that the average disposal rate per capita will remain unchanged through 2020 and estimate the total quantity of MSW disposed in 2020 at 42.5 million t based on the projected California population of 42.5 million (US Census Bureau 2005); 40% of which i.e., 17.0 million t, is assumed to be available for ethanol production.

2.4. Financial analysis and ethanol minimum selling price

The minimum ethanol selling price (MESP) (delivered at California's bulk terminals) is defined as the lowest acceptable price after accounting for feedstock costs, operating costs, capital cost, income tax, transportation and distribution costs, co-product revenues, and a specified after-tax return on equity investment (12% in this analysis). The MESPs for each of the pathways listed in table 1 are estimated using discounted cash flow procedures similar to those used by NREL researchers (Aden *et al* 2002, Phillips *et al* 2007), but, using updated values for key parameters such as feedstock costs and ethanol yields. Other parameters, namely plant and equipment life, depreciation methods, financing (100% equity in our analysis) and tax rates are made consistent across all pathways (table SI-3 available

at stacks.iop.org/ERL/5/014002/mmedia). Details of the modeled plant sizes for each of the pathways and estimated cost categories, along with data sources, are provided in table SI-4 (available at stacks.iop.org/ERL/5/014002/mmedia). Although economies of scale influence ethanol production cost, this study does not attempt to determine optimal plant sizes, which may vary depending on local conditions and technologies employed. Plant capacities are based on the original studies, from which the cost data were obtained. Feedstock cost reflects the delivered cost of biomass feedstock to ethanol plants. Because agricultural and forest residues are not currently collected for large-scale industrial use in the US, their delivered costs are based on Walsh (2008), which estimates supply costs for various cellulosic biomass feedstocks including forest and agricultural residues. Since standards such as the LCFS do not affect production costs, in this analysis we consider only the private producer costs of ethanol and do not include external costs associated with carbon emissions, which can become relevant producer costs if internalized through carbon taxes or cap and trade programs. For example, Plevin and Mueller (2008) in their analysis of the effect of CO_2 regulation on ethanol production costs, examine a carbon emission reduction trading program within the LCFS and assign a price of \$50 $t^{-1}CO_2$ for such credits. While the LCFS will have a trading program in LCFS-related carbon emission reduction credits, several key issues remain unresolved, such as whether only iLUC-related credits or both direct and iLUC credits should be made tradable, and whether to allow offsets and credit imports from activities outside of the LCFS (CARB 2009d, 2009e). Given the uncertainty about the credit trading program and the market price of such credits, we consider only the private production costs of ethanol supply as noted above. We also do not include the prevailing Federal Volumetric Ethanol Excise Tax Credit (VEETC) for corn ethanol in estimating producer costs because these credits expire in 2010 and their renewal is uncertain (GAO 2009) given the ethanol mandates under the EISA 2007 and prevailing fiscal conditions.

2.5. Potential ethanol supply scenarios for meeting the LCFS

The LCFS uses 2010 as the baseline year against which a 10% reduction in the AFCI of California's transportation fuels is mandated by 2020 (CARB 2009a). The baseline AFCI of gasoline fuels is set at 95.9 g CO_2eq MJ^{-1}. The 2010 baseline gasoline consists of 10% (vol.) ethanol and 90% California reformulated gasoline blendstock for oxygenate blending (CARBOB), which is the gasoline blendstock currently blended with ethanol to form a finished gasoline. The target AFCI for gasoline or fuels used to substitute for gasoline is set as 86.3 g CO_2eq MJ^{-1} by 2020. CARB projects a total fuel use of 54.1 billion liter gasoline equivalent (lge) (14.3 billion gallon gasoline equivalent) by California's LDV fleet in 2020 (CARB 2009a). In estimating future fuel use, CARB has taken into account measures that would result in a decrease in the amount of fuel used, including implementation of the Pavley (AB 1493) standard, which requires reductions in GHG emissions of new LDVs beginning with the 2009 model year and is expected to result in an increase in the fleet-wide average fuel economy of gasoline vehicles by about 24% by 2020 (CARB 2004, 2009a).

Three potential scenarios are analyzed, each comprised of two or three sub-scenarios of ethanol supply for meeting the LCFS. All scenarios are designed to achieve exactly a 10% reduction in the AFCI of California's LDV fuels in 2020. For each sub-scenario, different combinations of ethanol and gasoline blendstock (CARBOB) are used to satisfy the projected total fuel demand. However, it should be noted that the scenarios are not predictions of future events: rather they are meant to illustrate the impact various ethanol supply options can have on, ethanol volume requirement, petroleum displacement directly due to ethanol blending, weighted average ethanol cost, and direct agricultural land requirement.

The first scenario considers the case where cellulosic ethanol is not available, to reflect the possibility that technical and economic challenges to commercial scale production are not overcome by 2020. In that case, the LCFS ethanol demand can be met by 'conventional' sources, either Brazilian sugarcane ethanol or Midwest corn ethanol. Sugarcane ethanol from Brazil is expected to be the lower cost alternative, but may face import restrictions (or high import tariffs) for US domestic political reasons. Therefore, three sub-scenarios are presented, 1A ($BR_{sugarcane}$_w/o_tariff) and 1B ($BR_{sugarcane}$_w_tariff) where only Brazilian ethanol (without or with tariff) is used to meet the LCFS and 1C (MW_{corn}) where only Midwest corn ethanol is used (table 2).

In the second scenario, we assume that cellulosic ethanol from various feedstocks becomes commercially available at the estimated MESPs and the quantities produced are limited by the corresponding feedstock availability. In this scenario we assume that ethanol with the lowest production cost (MESP) will be used sequentially until the LCFS is met. Here, two sub-scenarios are analyzed, 2A (LP_w/o_tariff), where no import tariff is imposed on Brazilian sugarcane ethanol, and 2B (LP_w_tariff), where the currently imposed tariff of \$0.14 l^{-1} (\$0.54 gal^{-1}) on Brazilian ethanol continues until 2020.

In view of the mandated preference for California produced biofuels in Executive Order S-06-06, in the third scenario, we analyze the case where ethanol produced using California biomass is used first, the balance of the ethanol requirements are then met using sequentially the lowest MESP sources outside of California. Similar to previous scenarios, two sub-scenarios, without import tariff (3A: CA_{eth}_w/o_tariff) and with import tariff (3B: CA_{eth}_w_tariff) are analyzed.

2.6. Agricultural land requirement, petroleum reduction potential and average ethanol cost

For each of the sub-scenarios, the total direct agricultural land requirement, petroleum reduction directly due to ethanol blending and weighted average ethanol cost are estimated as detailed below. It is assumed no additional agricultural land is required for residue (agricultural, forest or MSW) derived ethanol, which is consistent with the treatment of biofuels produced from 'waste' products in the literature (e.g., Searchinger *et al* 2008). The amount of agricultural land

Table 2. Ethanol supply scenarios.

Compliance path	Scenario (and abbreviation)
'Conventional' ethanol	1A. Brazilian sugarcane ethanol only, without import tariff ($BR_{sugarcane}$_w/o_tariff)
	1B. Brazilian sugarcane ethanol only, with import tariff of \$0.14 l^{-1} ($BR_{sugarcane}$_w_tariff)
	1C. Midwest corn ethanol only (MW_{corn})
'Low-cost' ethanol	2A. Sequential use of ethanol with lowest production cost, without tariff on Brazilian ethanol (LP_w/o_tariff)
	2B. Sequential use of ethanol with lowest production cost, with tariff on Brazilian ethanol (LP_w_tariff)
California produced ethanol first	3A. California produced ethanol supplemented with ethanol with lowest production cost produced outside of CA, without tariff on Brazilian ethanol (CA_{eth}_w/o_tariff)
	3B. California produced ethanol supplemented with ethanol with lowest production cost produced outside of CA, with tariff on Brazilian ethanol (CA_{eth}_w_tariff)

directly needed to grow the feedstock for ethanol production is estimated for the scenarios that use ethanol derived from crops (corn or sugarcane) as one of the fuels to meet the LCFS (equation (1)).

$$Q_{\text{land}} = \sum Q_{\text{EtOH_}i}/(Y_i \times Y_{\text{EtOH_}i}) \tag{1}$$

where Q_{land} = total direct agricultural land requirement (ha y^{-1}); $Q_{\text{EtOH_}i}$ = quantity of ethanol from crop i required by a given scenario (l); Y_i = yield of crop i (t ha^{-1} y^{-1}), three year (2006–2008) average yield of nine Midwestern states is used for corn (9.5 t ha^{-1} y^{-1} (152 bu ac^{-1} y^{-1})), 2005/2006 Brazilian average yield is used for sugarcane (72.6 t ha^{-1} y^{-1}); $Y_{\text{EtOH_}i}$ = ethanol yield from crop i (l t^{-1}).

The petroleum reduction directly due to ethanol blending is calculated for each scenario relative to a baseline gasoline case, where the total energy demand of California's LDV fleet in 2020 is assumed to be met by using the 2010 baseline gasoline only (equation (2)). The 2010 baseline gasoline is used for the comparison because this gasoline (containing 10% ethanol) is expected to be the average LDV fuel used in California by 2020 if the LCFS were not implemented. Moreover, CARB does not provide an estimate of the carbon intensity of 2020 gasoline under a business-as-usual case. The petroleum reduction directly due to ethanol blending is estimated based on the LC (WTW) petroleum input (we calculate petroleum input throughout the LC using the method in CA-GREET). For example, producing 1 MJ of CARBOB requires 1.11 MJ of petroleum input, whereas producing 1 MJ of Midwest corn ethanol requires 0.12 MJ of petroleum input. Therefore, displacing 1 MJ of CARBOB with Midwest corn ethanol reduces the petroleum required by 0.99 MJ. The method estimates the petroleum reduction based only on the in-state gasoline/ethanol demand and does not take into account potential derived effects due to relative price/demand changes in global fuel markets (e.g., rebound effect as discussed by Stoft 2009).

$$R_{\text{petroleum}} = \Big[\sum (PI_j \times A_j) - \sum (PI_{k_\text{baseline_gasoline}} \times A_{k_\text{baseline_gasoline}})\Big]/E_{\text{petroleum}} \tag{2}$$

where $R_{\text{petroleum}}$ = petroleum reduction directly due to ethanol blending (l of petroleum), PI_j = WTW petroleum input needed to produce fuel j (ethanol or CARBOB) (MJ/MJ), A_j = energy content of fuel j in a given 2020 ethanol scenario, which meets the LCFS (MJ), $PI_{k_\text{baseline_gasoline}}$ = WTW petroleum input needed to produce fuel k (k refers to ethanol component or CARBOB used in the baseline gasoline) (MJ/MJ), $A_{k_\text{baseline_gasoline}}$ = energy content of fuel k in baseline gasoline required to meet the estimated demand of California's LDV fleet in 2020 (MJ), $E_{\text{petroleum}}$ = energy intensity of petroleum (MJ l^{-1} of petroleum).

The weighted average ethanol cost for each scenario is estimated using equation (3).

$$\overline{P_{\text{ethanol}}} = \sum (Q_j \times P_j) \Big/ \sum Q_j \tag{3}$$

where $\overline{P_{\text{ethanol}}}$ = weighted average ethanol cost in a given scenario (\$ l^{-1} of ethanol), Q_j = quantity of ethanol j in a given scenario (l), P_j = cost of ethanol j (MESP plus tariff, if applicable) (\$ l^{-1}).

3. Results and discussion

3.1. Life cycle results for ethanol pathways

Table 3 presents the LC GHG emissions and petroleum use for the various ethanol pathways. The LC GHG emissions for Midwest average corn ethanol, and California corn ethanol are taken directly from CARB's regulation (2009a), while the LC emissions for Brazilian sugarcane ethanol are based on the average value estimated by CARB in its recent update (CARB 2009b). Life cycle GHG emissions for the other pathways are modeled within CA-GREET, using data collected in this study, as noted above. For corn and sugarcane derived ethanol, emissions from iLUC adopted by CARB are included (no iLUC effect is allocated to ethanol derived from residues and MSW biomass, as noted earlier).

As can be seen from table 3, average Midwest corn ethanol has the highest LC GHG emissions among all ethanol pathways investigated. With an iLUC value of 30 g CO_2 MJ^{-1} adopted by CARB, Midwest average corn ethanol has higher GHG emissions than both the gasoline blendstock and the 2020 target carbon intensity of gasoline fuels (86.3 g CO_2eq MJ^{-1}), which makes it unviable as an option for meeting the LCFS. With iLUC effects, California corn ethanol and Brazilian sugarcane ethanol have higher LC GHG emissions than all lignocellulosic ethanol pathways, but lower emissions than the 2020 target carbon intensity. California corn ethanol has lower

Table 3. Life cycle (well-to-wheel) GHG emissions and petroleum use for gasoline and ethanol.

Ethanol/gasoline pathways	LC GHG emissions (g CO_2eq MJ^{-1} of fuel)	LC petroleum use (MJ petroleum/ MJ fuel)
Midwest corn stover ethanol	−8.3	0.08
CA hardwood residue ethanol	−5.9	0.15
CA agricultural residue ethanol	15.0	0.08
CA softwood residue ethanol	18.6	0.17
Brazilian sugarcane ethanol	66.0 (20.0)[a]	0.13
CA MSW ethanol	40.2	0.01
CA corn ethanol	80.7 (50.7)[a]	0.15
Midwest average corn ethanol	99.4 (69.4)[a]	0.12
CARBOB[b]	95.9[a]	1.11
CaRFG[c]	95.9 (93.4)[a]	1.11
2020 LCFS target AFCI	86.3[a]	

[a] Values taken from CARB (2009a, 2009b). Values in parentheses represent direct GHG emissions only (i.e., emissions from iLUC are not included).
[b] CARBOB is gasoline blendstock for oxygenate blending. Values for petroleum use and GHG emissions are taken from CARB (2009b).
[c] CaRFG is California reformulated gasoline. Values in the table are for a CaRFG, which uses a blend of 80% Midwestern average corn ethanol and 20% California corn ethanol (dry mill, wet DGS) to meet the 3.5% oxygen content by weight (approximately 10% ethanol by volume) (CARB 2009b). The calculated GHG emissions values are equal for CARBOB and CaRFG according to CARB (2009a).

LC GHG emissions than Midwest corn ethanol, in large part because in California all ethanol is produced from dry mills using natural gas for process fuel and the co-product of the process is sold as wet DGS (i.e., no drying energy is required) (CARB 2009a, 2009b)). In contrast, in the Midwest, ethanol is produced from either dry or wet mills. Some of the wet mills use more carbon intensive fuels for process energy (e.g., coal) and the majority of co-products from dry mills in the Midwest are dried (CARB 2009a, 2009b).

The LC GHG emissions of lignocellulosic ethanol range from −8.3 to 40.2 g CO_2eq MJ^{-1}, depending on feedstock and conversion technologies. Midwest corn stover and California hardwood residue ethanol have negative GHG emissions mainly because the co-product (electricity) is assumed to displace the Midwest and California average electricity generation mix, respectively. Although the GHG results of the ethanol pathways vary greatly, all ethanol pathways require far less petroleum input than gasoline does on a LC basis.

If CO_2 emissions associated with iLUC are not included, all ethanol pathways have lower LC GHG emissions than gasoline and the 2020 target carbon intensity of LDV fuels. Without iLUC, the LC GHG emissions of Brazilian sugarcane ethanol are comparable to those of California agricultural residue and softwood forest residue ethanol, and much lower than those of Midwest average corn ethanol.

3.2. California cellulosic ethanol potential

Table 4 summarizes the estimated in-state cellulosic biomass feedstock availability and ethanol production potential for California. A more detailed breakdown is available in table SI-2 (available at stacks.iop.org/ERL/5/014002/mmedia). The estimated ethanol production of 4.1 billion l (i.e., 2.9 billion l of baseline gasoline equivalent[4]) can meet 5.3% of projected energy demand of California's LDV fleet in 2020 (54.1 billion l baseline gasoline equivalent, see section 2.5). The weighted AFCI of California cellulosic ethanol is estimated to be 20.1 g CO_2eq MJ^{-1} based on the LC GHG emissions (table 3) and ethanol potential of each ethanol pathway (table 4). Blending this amount of California ethanol with gasoline blendstock (i.e., CARBOB) results in an average ethanol percentage of 7.7% (by volume) in the gasoline fuel, which has an AFCI of 91.9 g CO_2eq MJ^{-1}, a 4.3% reduction from the baseline of 95.9 g CO_2eq MJ^{-1}.[5]

Compared to these estimates, Farrell and Sperling (2007) estimate that between 9.1 and 11.7 billion l of ethanol can be produced from California in-state cellulosic feedstocks; the difference arises mainly because of their assumption that 100% of all technically available agricultural residues, forest residues and landfilled MSW can be used for ethanol production. In comparison, we assume that 50% of available agricultural and forest residues after adjusting for current uses, and 40% of landfilled MSW, can be used for ethanol production. Hence, ours can be considered as more conservative estimates.

3.3. Minimum ethanol selling price

The estimated MESPs (production cost of ethanol), not including taxes, subsidies or tariffs, range from \$0.33 to \$0.59 l^{-1} of ethanol (table 5). MSW derived ethanol has the lowest MESP among all ethanol pathways, mainly due to its negative feedstock cost (−\$0.41 l^{-1} of ethanol) which arises because landfills charge tipping fees for accepting MSW. However, this negative feedstock cost does not include MSW sorting/separation costs which are necessary to convert MSW into an acceptable feedstock for ethanol production. These sorting costs are included under processing costs in our estimates. It should be noted that the negative feedstock cost is unlikely to persist if there is a large demand for MSW from competing uses. Brazilian sugarcane ethanol has the second lowest MESP if no tariff on imported ethanol is imposed. The MESPs of ethanol derived from agricultural and forest residues are higher than those of Brazilian sugarcane ethanol, ranging from \$0.48 to \$0.52 l^{-1}. Ethanol from corn has the highest

[4] As per CARB (2009a), the efficiency of an E85 flexible fuel vehicle is assumed the same as that of a conventional gasoline internal combustion engine vehicle. Hence, it is assumed that 1 MJ of ethanol can displace 1 MJ of gasoline for LDV applications.

[5] Percentage reduction in AFCI $= \{\frac{CI_{CARBOB}\,Q_{CARBOB}+\sum(CI_{ethanol}\,Q_{ethanol})}{Q_{total}} - CI_{baseline_gasoline}\}\{CI_{baseline_gasoline}\}^{-1}$, where CI_{CARBOB} = carbon intensity of CARBOB (g CO_2eq MJ^{-1}), Q_{CARBOB} = quantity of CARBOB required (MJ), $CI_{ethanol}$ = carbon intensity of a given California cellulosic ethanol pathway (g CO_2eq MJ^{-1}), $Q_{ethanol}$ = quantity of a given cellulosic ethanol (MJ), Q_{total} = total energy requirement of California's LDV fleet in 2020 (MJ), $CI_{baseline_gasoline}$ = carbon intensity of baseline gasoline (i.e., 95.9 g CO_2eq MJ^{-1}).

Table 4. California cellulosic ethanol potential by 2020.

Feedstock	Feedstock available for conversion to ethanol (million dry t y^{-1})	Ethanol yield (l dry t^{-1})	Ethanol production potential (million l y^{-1})
CA agricultural residues	1.6	366	586
CA forest residues (softwood)	3.5	334	1170
CA forest residues (hardwood)	2.4	390	936
CA MSW	17 (million t)	85 (l t^{-1})	1445
Total			4137

Table 5. Minimum ethanol selling price (MESP) (in 2007 dollars). (Note: Number of significant digits in the table reflects the general convention of reporting costs in the energy literature (e.g., EIA 2009) and not necessarily the precision of the estimates).

Ethanol pathway by feedstocks	MESP ($ l^{-1} of ethanol)
CA MSW	0.33
Brazilian sugarcane	0.37
CA hardwood residue	0.48
CA softwood residue	0.50
Midwest corn stover	0.51
CA agricultural residue	0.52
Midwest average corn	0.56
CA corn	0.59

MESP due to the high feedstock costs, which are \$0.40 $l^{-}1$ and \$0.49 l^{-1} for Midwest average corn ethanol and California corn ethanol, respectively. While these estimates are based on best, publicly available data at the time of the study, inferences need to be tempered by the uncertainty in these estimates, especially for the cellulosic ethanol pathways which are not at commercial scale. For example, a 20% increase in production costs of the cellulosic pathways results in higher MESPs for all cellulosic ethanol options compared to Midwest average corn ethanol, with the exception of CA MSW.

3.4. Potential ethanol supply scenarios for meeting the LCFS

In developing the ethanol supply scenarios, we assume that there are no constraints in using high proportions of ethanol in terms of consumer acceptability, vehicle fleet composition, or fuel supply–distribution–refueling infrastructure. However, below we discuss the potential problems with this assumption.

Under the above assumption, a key driver of ethanol use is the price of gasoline. If realized gasoline prices are higher than the MESP of ethanol (plus tariff, if relevant) (in \$/liter gasoline equivalent), ethanol producers will be willing to sell ethanol and fuel producers/blenders will be willing to buy it, and all the available ethanol will be used in the LDV fleet. Because the total available quantity of ethanol will likely exceed the quantity required to meet the LCFS, the LCFS would not be a binding constraint in the above case. If the gasoline price is lower than the projected ethanol production cost, the LCFS becomes relevant as a constraint, and relatively more expensive ethanol will be blended in just sufficient quantity to meet the LCFS. However, the total quantity and mix of ethanol used (in terms of feedstock source and conversion process) to meet the LCFS depends on the relative GHG emissions reduction, ethanol market price and production quantity limits due to feedstock availability or production capacity. The market price of ethanol will be determined by complex interactions between gasoline price, ethanol production costs (MESPs), ethanol production capacity, LC GHG emissions, and other factors[6].

The regulated parties under the LCFS, the transportation fuel providers, have to demonstrate that the mix of fuels they supply meets the AFCI standard for each annual compliance period (taking into consideration any credits/deficits, banking and trading permitted under the Standard). At the same time ethanol quantity mandates under EISA must be met. On one hand, fuel providers may be willing to pay a price premium for low carbon intensity ethanol because it assists them to meet the LCFS and puts less demand on their refueling infrastructure. On the other hand, low carbon intensity ethanol may make meeting EISA quantity mandates more difficult. Final consumers may be indifferent between ethanol from various sources (and their carbon intensities) and choose fuels based on relative prices and possible inconvenience due to lower driving range and scarcity of E85 refueling stations. The demand elasticities for ethanol will vary depending on the number of E85 flexible fuel vehicles (FFVs) on the road and refueling infrastructure in place. In view of these complexities, we do not attempt to model or project actual quantities and the mix of ethanol that might be used in California. Instead, we assume that ethanol with the lowest production cost (MESP) will be used sequentially until the LCFS is met under each of the scenarios and limit our analysis to estimating the weighted average ethanol costs for each scenario.

The sources and required amounts of ethanol, the average volumetric percentage of ethanol in LDV fuel blends, direct agricultural land requirement, petroleum reduction directly due to ethanol blending, and weighted average ethanol cost for the scenarios in table 2 are shown in table 6. Note that iLUC effects are included for corn and sugarcane derived ethanol. Importantly, using average Midwest corn ethanol to meet the LCFS is not an option as its GHG emissions are higher than the 2020 target AFCI (assuming current production methods and the iLUC value adopted by CARB). The quantity of ethanol required to meet the LCFS varies depending on the scenario (from 8.1 to 24.9 billion l).

[6] Other factors may include the ethanol blend wall in conventional vehicles (e.g., currently 10% ethanol by volume), number of FFVs, number of refueling stations with E85, consumer demand elasticities for E85 and gasoline, ethanol mandates (both conventional and advanced biofuel) under EISA 2007, subsidies/tax credits for renewables, and the LCFS credit trading program and its interactions with the potential general carbon trading market.

Table 6. Ethanol demand, direct agricultural land requirement, petroleum reduction directly due to ethanol blending, and average ethanol cost for each scenario (with iLUC effects). (Note: BR = Brazilian; MW = Midwest; CA = California; sc = sugarcane; MSW = municipal solid waste; hw = hardwood; sw = softwood; stover = corn stover; ag = agricultural.)

Scenario	Ethanol demand for blending (10^9 l y^{-1})	Ethanol source (10^9 l y^{-1})	Average vol. of ethanol in fuel blends (%)	Ag. land required (10^6 ha y^{-1})	Petroleum reduction directly due to ethanol blending (10^9 l y^{-1})	Weighted average ethanol cost (\$ l^{-1} of ethanol)
1A $BR_{sugarcane}$_w/o_tariff	24.9	BR sc: 24.9	41	4.0	14.5 (29%)	0.37
1B $BR_{sugarcane}$_w_tariff	24.9	BR sc: 24.9	41	4.0	14.5 (29%)	0.51
1C MW_{corn}			Not an option to meet the LCFS			
2A LP_w/o_tariff	23.7	CA MSW: 1.4 BR sc: 22.3 (CA ethanol: 6%)	40	3.6	13.8 (27%)	0.37
2B LP_w_tariff	8.1	CA MSW: 1.4 CA hw residue: 0.9 CA sw residue: 1.2 MW corn stover: 4.6 (CA ethanol: 43%)	15	0	4.9 (10%)	0.47
3A CA_{eth}_w/o_tariff	19.1	CA MSW: 1.4 CA hw residue: 0.9 CA sw residue: 1.2 CA ag residue: 0.6 CA corn: 0.9 BR sc: 14.1 (CA ethanol: 26%)	33	2.5	11.1 (22%)	0.40
3B CA_{eth}_w_tariff	9.0	CA MSW: 1.4 CA hw residue: 0.9 CA sw residue: 1.2 CA ag residue: 0.6 CA corn: 0.9 MW corn stover: 4.0 (CA ethanol: 56%)	16	0.2	5.4 (11%)	0.48

In Scenario 1, where cellulosic ethanol technology is not yet commercially feasible, the LCFS can still be met using Brazilian sugarcane ethanol, but 24.9 billion l of Brazilian ethanol needs to be imported. Since California corn ethanol has a higher cost than Brazilian ethanol even with the current import tariff of \$0.14 l^{-1}, the inclusion of the import tariff (Scenario 1B) increases the average ethanol cost from \$0.37 to \$0.51 l^{-1}, but will not increase the use of California corn ethanol. Under Scenario 2A, where projected quantities of cellulosic ethanol become commercially available at the MESPs and no tariffs are imposed on imported ethanol, a relatively small quantity of MSW ethanol produced in California will be supplemented by Brazilian sugarcane ethanol. Under Scenario 2B, where import tariffs are imposed on Brazilian ethanol, cellulosic ethanol from other California sources and Midwest corn stover become less expensive and will completely displace Brazilian imports. California in-state ethanol increases from 6% to 43% of ethanol demand. The volume of ethanol required to meet the LCFS also decreases significantly due to the lower LC GHG emissions of cellulosic ethanol. The imposition of the import tariff increases the average ethanol cost compared to the no-tariff case. The tariff leads to substitution with higher cost cellulosic ethanol, but the overall volume percentage of ethanol required to meet the LCFS decreases significantly (from 40% to 15%) due to the lower LC GHG intensity of cellulosic ethanol. In Scenario 3, where local California ethanol is mandated to be used first, Brazilian ethanol will be used to meet residual requirements for meeting the LCFS. However, if import tariffs are imposed, Brazilian ethanol will be substituted with Midwest corn stover ethanol. Such substitution lowers the overall ethanol content from 33% to 16% but increases the average ethanol cost. Import tariffs allow the possibility of meeting the Executive Order requirements of 40% local biofuel use by increasing the percentage of California ethanol from 26% to 56%.

The overall percentage of ethanol blended in gasoline ranges from 33% to 41% for scenarios using Brazilian sugarcane ethanol (i.e., Scenarios 1A, 1B, 2A, 3A) in contrast to 15% and 16% in scenarios without Brazilian ethanol (when the tariff is assumed). The former scenarios will require a large increase in the number of E85 FFVs and associated increase in E85 refueling infrastructure along with ethanol pricing attractive enough for consumers to select E85. There are many factors that will come into play to determine the fuel/vehicle mix in California in 2020 (penetration of alternative fuels/energy carriers, penetration of vehicles other than gasoline or E85 FFVs, expansion of ethanol production capacity, blending capacity and availability of appropriate gasoline blendstock, future regulatory initiatives, etc). We limit our discussion to briefly address FFVs and refueling stations but note that the other issues are important and should be investigated.

We estimate that a minimum of[7] 35% of California's LDV fleet would need to be FFVs under Scenarios 1A and 1B, where the largest amount of ethanol (i.e., 24.9 billion l of ethanol) will need to be blended with gasoline blendstock. Currently, there are approximately 400 000 FFVs in California (∼1.5% of the LDV fleet) (CEC 2009). Reaching the required level of FFVs by 2020 is unlikely, but not entirely unachievable. A large increase in FFV sales in the State would be required, an estimated 7% y^{-1} growth rate from 2010 to 2020 (based on the VISION-CA model (UC Davis 2007)). At this growth rate, 46% and 81% of new LDVs sold in 2015 and 2020, respectively, will need to be FFVs. In addition, drivers would need to choose E85 for their driving. Their preference will depend on the factors such as those discussed above including fuel price and convenience. The estimated FFV share of sales required to reach the 35% goal is much more aggressive than that estimated for the Business-As-Usual (BAU) Scenario in VISION-CA, where a FFV sales growth rate of 0.7% y^{-1} is assumed, resulting in 9% and 12% of new LDV sales to be FFVs in 2015 and 2020, respectively (UC Davis 2007). This implies California would need to mandate FFV capability in the majority of new LDVs sold in the State[8]. The additional cost to manufacture a FFV compared to a gasoline vehicle is estimated at $100 per vehicle (CEC 2009). If the allowable blend volume of ethanol in gasoline for use in gasoline LDVs were increased to 15%, as has been put forward to the US Environmental Protection Agency (Federal Register 2009)[9], the percentage of LDVs that are FFVs in Scenario 1 could be lower (minimum 31%). However, this will still require an aggressive market penetration of FFVs in the next decade.

Currently, 36 public refueling stations offer E85 in California (USDOE 2009). Because FFVs can run on gasoline or any blend up to E85, consumers will not be 'afraid' of running out of fuel before locating a station, but they will not choose E85 unless it is their preference (e.g., lower actual or perceived price, convenience, or for some consumers, because they perceive it to be 'environmental preferable'). (Greene 2008, p 175) reports, 'empirical and theoretical studies indicate that once the fraction of stations offering an alternative fuel passes about 25%, there are very small incremental benefits to adding more stations. Intuitively, once a consumer has decided on a preference for E85, the search process is much more efficient than a random search, both because of learning and because of the relative redundancy of existing gasoline stations'. As a first-order approximation, we assume 30% of California's existing stations should have E85 available, resulting in an estimated 3000 refueling stations offering E85 by 2020 (about 10 000 stations are currently operating in the State (CEC 2008)). This would be a very large increase by 2020 even though significant investments in ethanol infrastructure are planned in the State (CEC 2009).

For the scenarios with import tariffs on Brazilian ethanol (average ethanol blend 15–16%), we estimate that a minimum of 7% of California's LDV fleet need to be FFVs in 2020. A growth rate of FFV sales of ∼0.7% y^{-1}, similar to that estimated for the BAU scenario is required. If the allowable level of ethanol in gasoline for use in gasoline LDVs were increased to 15%, the LCFS can potentially be met without an increase in the number of FFVs.

In terms of direct agricultural land requirement, using Brazilian sugarcane ethanol alone to meet the LCFS requires 4.0 million ha of land being allocated to sugarcane production annually. This amount of land is equivalent to 52% of total land used for sugarcane cultivation in Brazil in 2007 (EPA 2009). Although Brazil reportedly has a considerable area of unused arable land (EPA 2009), concerns have been raised about expanding sugarcane production into environmentally sensitive land, e.g., Brazilian Cerrado (Fargione *et al* 2008). In contrast to crop-based feedstock, using residues as feedstock for ethanol production can significantly reduce land requirements. Scenarios 2B and 3B suggest that the LCFS can be met with no or very minor change in agricultural land use, but requires the successful commercialization of cellulosic ethanol.

In addition to reducing GHG emissions, lessening the dependence of the transportation sector on petroleum is an important energy security policy goal. The petroleum reduction directly due to ethanol blending for each scenario is shown in table 6. The more ethanol that is required to meet the LCFS in a given scenario, the more petroleum reduction can be achieved. Hence, the scenarios that include Brazilian sugarcane ethanol have the highest petroleum reduction potential (between 22% and 29%). However, switching from imported petroleum to imported ethanol does not reduce US dependence on foreign energy. Other scenarios can reduce annual petroleum use by approximately 10% for California.

3.5. Implications of excluding indirect land use change effects on ethanol supply scenarios

Although iLUC effects are included under the current LCFS regulation, the topic continues to be controversial. While there is general agreement that iLUC effects are important, critics question if appropriate methods for estimating these effects for regulatory purposes are available (Bioenergy-Wiki 2009, GAO 2009). The existing LCFS regulation that includes iLUC emissions essentially rules out using corn ethanol as an option to meet the LCFS and is likely to increase dependence on imported Brazilian ethanol. At the same time, the renewable fuel provisions under EISA mandate a significant increase in ethanol in commerce, although cellulosic ethanol technology is not yet commercial. These factors are likely to generate pressures for reconsidering the regulations or delaying the compliance deadlines (although there has been some discussion in California about the possibility of offsetting land use change—see CARB (2009d

[7] We assume two ethanol/gasoline blend levels will be available, E10 and E85. For Scenarios 1A and 1B, the volume of E85 required in the gasoline fuel pool is ∼25.2 billion l, and the amount of E10 is ∼35.3 billion l. After adjusting for heating value differences, E85 accounts for ∼35% of total fuel energy demand of California's LDV fleet in 2020. Assuming FFV owners will drive 100% of vehicle miles traveled on E85 and drive equivalently (same mix of vehicles, distances driven, etc) to non-FFV owners, a minimum 35% of the LDV fleet will need to be E85 vehicles by 2020.

[8] We are aware that sales of E85 FFVs are restricted in California due to an issue associated with the State's evaporative emissions standards (Weverstad 2009). The above assumes resolution of this issue.

[9] USEPA has postponed its ruling on increasing the ethanol blend wall to 15%, to Spring 2010 because vehicle trials with E15 are still ongoing.

p 343, 344)). In view of the ongoing debate about the iLUC effects, we analyze the implications on the ethanol scenarios of excluding iLUC emissions and summarize these. More detailed information is available in table SI-7 (available at stacks.iop.org/ERL/5/014002/mmedia).

Without iLUC effects, corn ethanol becomes a viable option to meet the LCFS (table SI-7 available at stacks.iop.org/ERL/5/014002/mmedia). Since corn ethanol has higher WTW GHG emissions compared to other ethanol pathways, using corn ethanol alone (Scenario 1C: MW_{corn}) requires far more ethanol (46% by volume) to be blended with gasoline than other scenarios. Obviously, this will require large increases in the number of FFVs. Using large amounts of corn ethanol also reduces direct petroleum use by 16.5 billion l annually, a 32% reduction compared to using gasoline only (2010 baseline gasoline). Other scenarios reduce petroleum use by between 4.9 and 6.0 billion l annually.

In terms of direct agricultural land requirement, using conventional crop-based ethanol (Scenario 1) to meet the LCFS requires between 1.6 and 7.1 million ha of land being allocated to feedstock production annually. Using corn ethanol alone to meet the LCFS has the greatest agricultural land requirement of 7.1 million ha (Scenario 1C, MW_{corn}), which is equivalent to about 140% of total harvested corn acreage in Iowa in 2008. Compared to corn ethanol, using Brazilian sugarcane ethanol alone to meet the LCFS requires only 1.6 million ha of agricultural land.

The weighted average cost of ethanol ranges from \$0.37 l^{-1} (Scenario 1A) to \$0.56 l^{-1} (Scenario 1C). The lowest cost and highest cost options use Brazilian ethanol without a tariff and Midwest corn ethanol, respectively. The results indicate that the minimum 40% in-state biofuel goal can be achieved either by mandating the use of California produced ethanol or imposing tariffs on imported ethanol; between 43% and 57% of the ethanol required to meet the LCFS will be from within California under Scenarios 2B (LP_w_tariff), 3A (CA_{eth}_w/o_tariff), and 3B (CA_{eth}_w_tariff). These scenarios have ethanol blend volume levels of 15%–18%.

3.6. Implications of corn and sugarcane ethanol productivity improvements on ethanol supply scenarios

While production of corn and sugarcane and the processes that convert these two feedstocks to ethanol are considered mature technologies, several potential improvements in both feedstock production and conversion have been discussed in extant literature (e.g., USDA 2009, Macedo *et al* 2008, Mueller 2007). These include an increase in corn yield from 9.5 t ha^{-1} in the base case to 11 t ha^{-1}, annual reduction in farming energy use at the rate of 1.85%, increased fertilizer utilization efficiency, increased energy efficiency and the use of natural gas and biomass in dry mills. Similarly, projected improvements in the sugarcane ethanol pathway include, an increase in sugarcane yield from 87 to 95 t ha^{-1}, increase in cane sucrose content from 14.2% to 15.3% (increasing ethanol yields), and increased and more efficient use of bagasse and field waste in distilleries (see the supplementary data section 4 available at stacks.iop.org/ERL/5/014002/mmedia). Assuming these potential improvements are achieved in the 2020 time frame, we re-estimate LC GHG emissions, direct agricultural land use, petroleum use and MESP for corn and sugarcane ethanol pathways and discuss the implications.

With these improvements, the WTW GHG emissions including iLUC emissions decline to 80.1 g CO_2eq MJ^{-1} from 99.4 g CO_2eq MJ^{-1} for Midwest corn ethanol, and to 60.2 g CO_2eq MJ^{-1} from the average value of 66 g CO_2eq MJ^{-1} for sugarcane ethanol (table SI-8 available at stacks.iop.org/ERL/5/014002/mmedia). Both fuels have lower GHG emission intensities than the 2020 target carbon intensity of gasoline fuels (with inclusion of iLUC effects), making them viable options for meeting the LCFS. The improvements also lower the MESP of Midwest corn ethanol by \$0.01–\$0.55 l^{-1} and of sugarcane ethanol by \$0.05–\$0.32 l^{-1}. Based on these estimates, the ethanol supply options with and without iLUC effects are reevaluated (see the supplementary data section 6 available at stacks.iop.org/ERL/5/014002/mmedia).

With these improvements, in Scenarios 1A and 1B the Brazilian sugarcane ethanol requirement decreases to 20.9 billion l (from 24.9 billion l in the base case with iLUC), and the direct agricultural land use declines to 2.9 million ha y^{-1} (from 4.0 million ha y^{-1}), see table SI-9 (available at stacks.iop.org/ERL/5/014002/mmedia). Producing the required 47.2 billion l of corn ethanol in Scenario 1C, requires 10.3 million ha of land, almost twice the total corn acreage harvested in Iowa in 2008. Even with these improvements, using corn ethanol increases the average ethanol cost significantly, by \$0.09 l^{-1} compared to using Brazilian ethanol (with tariff). The average ethanol percentage in fuels will be as high as 70%. The magnitude of the effects on vehicle mix, infrastructure, land use and fuel cost, suggest that even with these improvements in the corn ethanol pathway, depending only on corn ethanol to meet the LCFS is not a feasible option. These effects are less severe if iLUC effects are excluded (see table SI-10 available at stacks.iop.org/ERL/5/014002/mmedia): the required corn ethanol volume in Scenario 1C will be 16.3 billion l, a 65% reduction compared to the scenario with iLUC, the average ethanol volume in the fuel blend declines to 28% (from 70%) while the average ethanol cost remains at \$0.55 l^{-1}. Another alternative is to actively develop and promote cellulosic ethanol because of its lower LC GHG emissions, potentially lower ethanol production cost (compared to corn ethanol), lower direct agricultural land use, and lesser requirements for fleet composition and infrastructure.

The ethanol costs considered in the scenarios do not include the prevailing Federal VEETC for corn ethanol because these credits may be terminated or modified in the near future, however, continuation of these subsidies is unlikely to change the basic conclusions of this analysis, primarily because using corn ethanol as currently produced will not be an option to meet the LCFS due to its high GHG emissions. A LCFS credit trading program in combination with VEETC subsidies may facilitate corn ethanol use by allowing the purchase of carbon offsets with the subsidy.

4. Conclusions

The LCFS becomes relevant as a constraint only when gasoline prices are lower than the projected ethanol costs (in \$ l^{-1} gasoline equivalent), in which case, relatively more expensive ethanol will be blended in just sufficient quantity to meet the LCFS. The above analyses suggest that displacement of a portion of gasoline with ethanol is a feasible option to attain the AFCI target specified in the LCFS, although using Midwest corn ethanol will not be an option under current regulatory and productivity conditions. The fraction of ethanol that needs to be blended with gasoline can vary significantly (from 15% to 41%), depending on the feedstock used for ethanol production and associated LC GHG emissions. The quantity of ethanol that can be produced from renewable sources within California is insufficient (on its own) to meet the AFCI target, but can be supplemented with other ethanol sources. The goal of a minimum 40% locally produced ethanol by 2020 is achievable under policy scenarios that either mandate the use of California produced ethanol or impose tariffs on imported ethanol.

Projected improvements in the corn ethanol pathway can reduce the LC GHG emissions of this pathway below the AFCI target, but the necessary changes in direct agricultural land use, fleet composition and infrastructure pose major challenges. Similarly, exclusion of iLUC effects will enable Midwest corn ethanol to be an option to meet the LCFS, but the impacts on agricultural land use and required changes in vehicle fleet mix and infrastructure are more adverse than for other options. Despite these disadvantages, using corn ethanol to meet the LCFS has the potential to significantly lower the direct petroleum use of California's LDV fleet. Utilizing lignocellulosic ethanol to meet the LCFS is more attractive than utilizing Brazilian sugarcane ethanol due to the projected lower direct agricultural land use, dependence on imported energy, expected ethanol cost, required refueling infrastructure modifications and penetration of flexible fuel E85 vehicles. However, significant advances in cellulosic ethanol technology and commercial production capacity are required to support moderate- to large-scale introduction of low carbon intensity cellulosic ethanol. Moreover, current production cost estimates suffer from relatively high uncertainty and these estimates need to be refined based on data from commercial scale production when they become available.

In their documentation, CARB uses single values to represent iLUC effects for ethanol pathways. This method does not appear to take into account potential technology and productivity improvements. For example, the iLUC effect for corn ethanol is estimated by CARB as 30 g CO_2eq MJ^{-1}, based on an average corn yield of 9.5 t ha^{-1} (151.3 bu ac^{-1}). Methods to update the iLUC values should be clearly stated in the LCFS documentation and should acknowledge how the values would change with future increases in crop yield and process improvements. Our analysis of projected improvements in both corn farming and conversion technologies indicates considerable potential reduction in GHG emissions, sufficient to make corn ethanol a viable option for meeting the LCFS, even after including iLUC effects. Similarly, projected improvements in the sugarcane ethanol pathway can further reduce its carbon intensity. There is no consensus on assumptions and assessment methods for estimating the indirect effects of global land use change (GAO 2009), and therefore policies employing iLUC will need to be periodically reviewed to reflect actual GHG profiles of biofuels. Such periodic reviews will also promote improvements in productivity, technology and agricultural practices by rewarding them.

It is important to note some of the limitations of our study. First, we focus only on ethanol as a potential low carbon fuel to meet the LCFS, whereas many other fuel/propulsion systems will likely be used in combination with ethanol to meet the LCFS. As noted earlier, the scenarios examined are not predictions of future events; rather they are meant to illustrate likely impacts of the scenarios if they were to be implemented to meet the LCFS. Future research is needed to identify the 'preferred' compliance strategy from environmental, social and economic perspectives. Second, the analysis is based on point estimates drawing on the best available information, but does not model uncertainty around these estimates; instead some potential scenarios are analyzed. Although these point estimates are often reported with two decimal place accuracy, the differences among scenarios may not be statistically significant, hence judgment should be used in decision-making based on reported differences. Due to the pre-commercial nature of cellulosic ethanol, there is considerable uncertainty in the environmental and cost performance of these pathways and the associated results should be considered with this in mind. Third, our study evaluates only a limited set of metrics which are relevant to the LCFS and to ethanol. While the LCFS does not explicitly require the reporting of sustainability measures, biofuels should receive policy support when they can make positive contributions to important objectives such as energy security, biodiversity, GHG emissions, and the sustainability of the food supply (Tilman *et al* 2009). Finally, we do not consider infrastructure issues, although producing and blending moderate to large amounts of ethanol would require changes to existing infrastructure and to industry practices.

In spite of the limitations of the analyses, insights from the study are expected to be of interest to those directly involved in the California LCFS, as well as stakeholders in other jurisdictions that are considering the implementation of similar LC-based regulations. The inclusion of metrics other than solely GHG emissions offers insights potentially relevant for avoiding unintended consequences.

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