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California's Clean Fuel Future

Assessing Achievable Fuel Carbon Intensity Reductions Through 2030

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Executive Summary

California has long been a global leader in climate policy. Starting with the passage of AB 32 in 2006, California has adopted a strong portfolio of measures to reduce emissions from its economy. Transportation, and the production of transportation fuels, are responsible for over 40% of the state's total carbon emissions. Reducing transportation's climate impact will be critical if the state is to meet its long-term climate goals, and reducing emissions from fuels is a critical part of this effort. California's Low Carbon Fuel Standard (LCFS) is the primary tool the state has to do this.

The LCFS requires fuel suppliers in California to reduce the carbon intensity of their fuels – the amount of carbon pollution per unit of energy – by 10% by 2020, from a 2010 baseline. Fuel providers have a variety of options for compliance. Currently, most credits for the program are generated by blending in lower-carbon liquid fuels into the existing fuel supply. Fuel suppliers can generate credits by taking action themselves, or purchase emission reduction credits from other low-carbon fuel producers. Since it took effect in 2011, the Air Resources Board reports that the LCFS has reduced emissions by the equivalent of over 30 million tonnes of carbon dioxide.

The California Air Resources Board (CARB) is now looking to the future. CARB staff have proposed to extend the program past its current 2020 sunset to 2030, and to increase the carbon intensity reduction target to 20% over that time, along with adjusting the compliance schedule in the interim. They have requested input from stakeholders regarding potential fuel supplies which might allow the state to meet this higher target. In this context, this report evaluates potential LCFS credit supplies through 2030, by building on a modeling framework developed for a 2015 report: *Potential Low Carbon Fuel Supply to the Pacific Coast Region of North America*. The model from the 2015 report was updated to reflect recent developments in low carbon fuel technology, policy and markets. The fundamental question is: how much low-carbon fuel can be expected to be available in California over the 2020-2030 period? In addition, the new work evaluates the effect of over or under-performance by key fuel pathways, relative to their projections, on total credit supply.

The analysis shows that given reasonably expected rates of deployment for low carbon fuel technologies, there will be ample supplies of low-carbon transportation fuel to attain CARB's 20% proposal, and that a higher target would likely be achievable. Under the moderate assumptions modeled in the *Steady Progress* scenario a 2030 target of about 22% would be feasible. Under the more optimistic assumptions included in the *High Performance* scenario, a 2030 target over 26% would be attainable, while scenarios that include optimistic scenarios in a single area would allow a target of 24-25% to be achieved by 2030. Even in the case of some credit generation pathways under-performing expectations, a 20% carbon intensity reduction in 2030 remains achievable.

Under or over-performance of any fuel pathway is not solely a matter of luck or dependent on future energy markets; the development of most of these pathways will be influenced by policy decisions available to regulators now. Through a combination of clear, long-term targets under the LCFS and the use of complementary policy instruments, the eventual outcome of the program can be directed towards the upper range of its potential.

It is important to note that the model used in this study does not consider market effects, nor is it meant to predict actual market behavior. It assesses potential fuel availability, based on current research, and generally makes moderate assumptions about future availability of low-carbon fuels. In addition, potentially significant credit generation pathways that have not yet been included in the regulation have been omitted due to a lack of adequate data or uncertainty about future regulatory design.

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Introduction

California's Low Carbon Fuel Standard (LCFS)[1] is one of the world's most sophisticated and successful policy instruments for supporting carbon intensity reduction in the transportation sector. Established in 2007, the regulation requires that by 2020 the carbon intensity of regulated transportation fuels in California should have been reduced by 10% on average compared to the 2010 baseline. The California LCFS is the first transportation fuel regulation in the world to directly link the value of different transportation energy carriers to a lifecycle assessment of their greenhouse gas performance, and the California Air Resources Board (ARB) has undertaken pioneering lifecycle analysis across a range of fuels and issues to make the implementation of LCFS possible.

Despite the ambitious nature of the targets set by the LCFS, and political and legal opposition to the standard from some stakeholder groups, implementation to date has been successful. By 2015, alternative fuels met 8.1% of Californian transportation energy demand (Yeh & Witcover, 2016), and the California Air Resources Board reports that the program generated 33 million tonnes of carbon emissions reduction credits[2] between the start of 2011 and third quarter of 2017, and a significant credit bank has been built up over this period.

The LCFS is one of a portfolio of measures developed by the California ARB to support compliance with the California Global Warming Solutions Act (AB 32, Chapter 488 Statutes of 2006), which set a target for the state to reduce greenhouse gas (GHG) emissions to 1990 levels by 2020. As 2020 approaches, attention turns naturally to what can be achieved in the next decade. The California Legislature passed SB 32 (Chapter 249, Statutes of 2016), which set a target of a 40% reduction in GHG emissions by 2030 and extended the regulatory authority which authorizes the LCFS.

In March 2018 the California ARB posted draft rulemaking documents ahead of a hearing scheduled for 27 April 2018, in which an adjusted and extended LCFS compliance schedule to 2030 is proposed (see Figure 1). The proposed adjustments set a 2030 requirement for a 20% GHG intensity reduction, with a steady increase in stringency of 1.25% each year starting with the existing 2018 standard. The new schedule, while more ambitious over the full term of the program, delays until 2022 the implementation of the 10% standard currently scheduled for 2020.

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[1] Cf. https://www.arb.ca.gov/fuels/lcfs/lcfs.htm, http://www.energy.ca.gov/low_carbon_fuel_standard/

[2] https://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

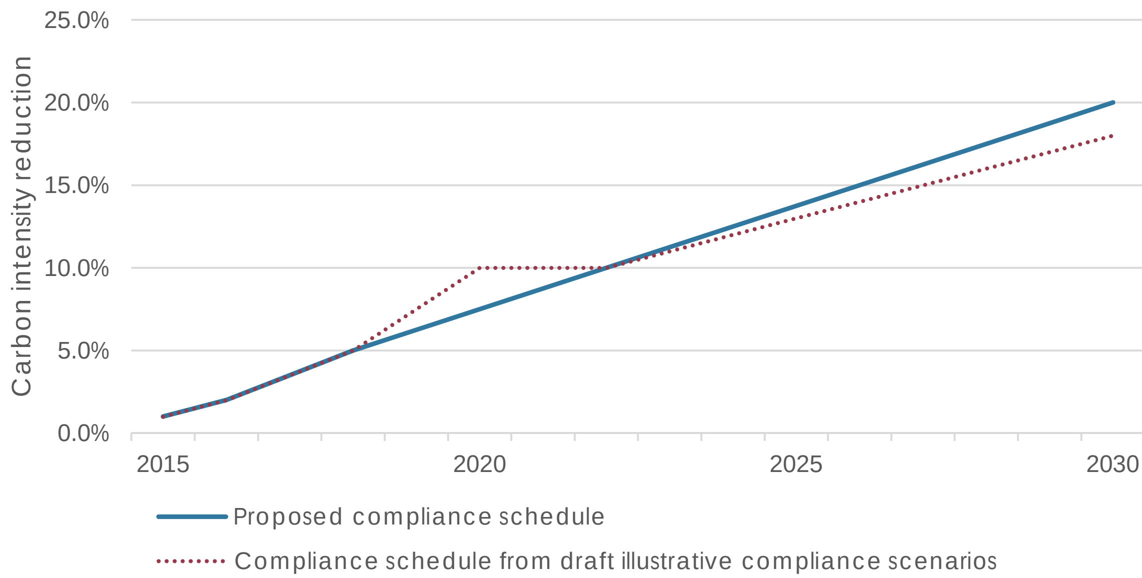

Figure 1 Proposed compliance schedule for the LCFS to 2030

As part of the process of assessing reasonable 2030 targets for the LCFS, ARB staff are actively soliciting feedback from stakeholders. In this context, this report uses a fuel supply modelling framework developed by the International Council on Clean Transportation (ICCT) and E4tech (Malins et al., 2015) to develop California low carbon fuel and greenhouse gas emissions reduction scenarios for 2030. As detailed further in the rest of this report, these scenarios show that given moderate assumptions on future low carbon fuel supply it would be possible to deliver compliance with 2030 targets more ambitious than the 20% reduction in the current proposal. In fact, the moderate, "Steady Progress" scenario shows a carbon intensity reduction of 22% by 2030 is possible. The *"High Performance"* scenario – which assumes accelerated technology deployment - delivers a carbon intensity reduction of over 26% by 2030.

Modelling framework

The modelling presented in this report is based on an updated version of the low carbon fuel supply model documented by Malins et al. (2015). The model, originally used to assess the potential to comply with a Pacific Coast low carbon fuel standard, couples vehicle stock turnover and energy demand modelling with low carbon fuel supply modelling. The vehicle stock and energy demand model is based on VISION 2014, with some elements updated for this report using data from VISION 2017.[3] In the previous study, scenarios were presented showing a range of 2030 transportation fuel carbon intensity reductions for the Pacific region (California, Oregon, Washington and British Columbia) from 14 to 21% (Figure 2).

[3] https://www.anl.gov/energy-systems/project/vision-model

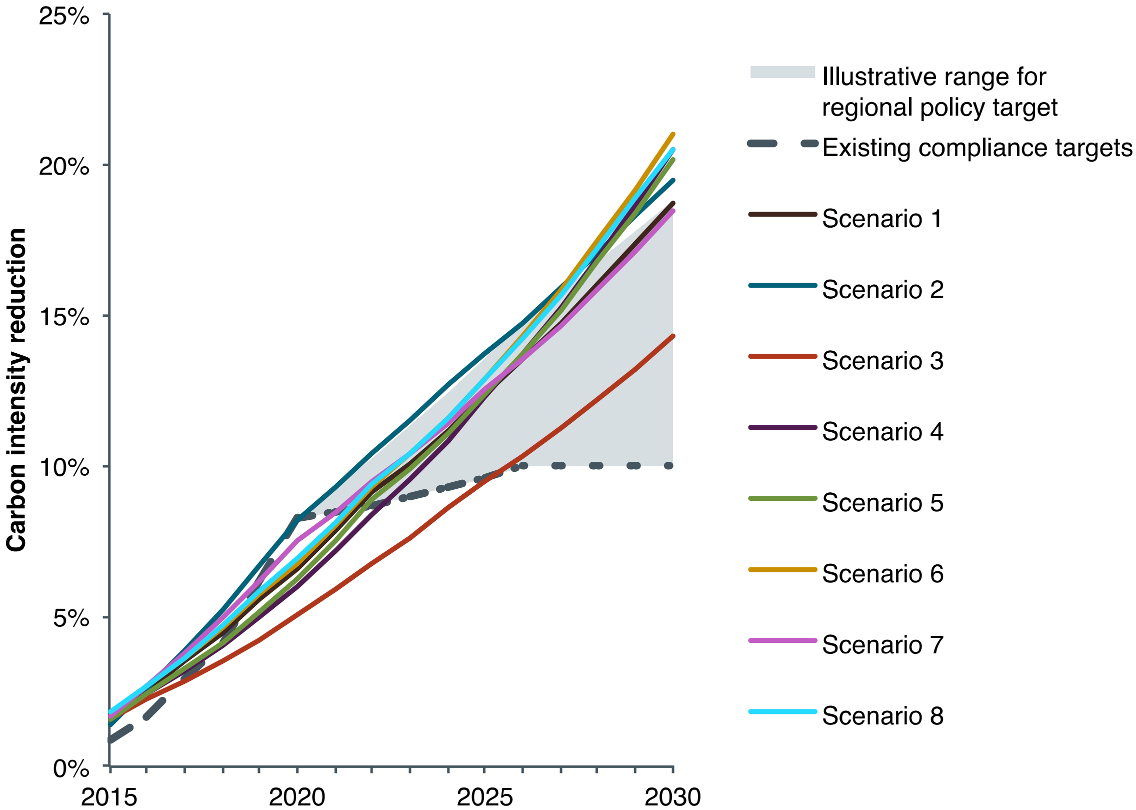

Figure 2 Pacific Coast carbon intensity reduction scenarios from (Malins et al., 2015)

The underlying model is documented extensively in Malins et al. (2015), and the reader is advised to refer to that report to obtain a more detailed description of the model. For this report, the model has been recalibrated to the California market, and various updates have been made to reflect more recent data. Changes to the low carbon fuel supply assessment are detailed below, and model adjustments are documented in Annex A.

The model used in this report is not a compliance model – there are no internal feedback mechanisms by which the model can respond to credit supply shortages or surpluses, and no attempt is made to model LCFS credit prices. Rather, it is a credit supply model, detailing the number of LCFS credits (and hence the level of emissions reduction) that can be generated given certain assumptions about the vehicle fleet and availability of various fuel options and carbon intensity reduction technologies. In the real world, it is intrinsic to the design of the LCFS that suppliers would be expected to take measures to increase the supply of LCFS credits if confronted with a shortfall against compliance targets, or to reduce the supply of LCFS credits if confronted with an over-supplied market.

Low carbon fuel supply assessment update

The results presented in Malins et al. (2015) included credits generated by a range of compliance options including first generation biofuels, second generation biofuels, electric drive vehicles, natural gas vehicles. For some compliance options, such as the use of natural gas and the supply of electricity for electric drive vehicles, the main limitation on the rate of compliance credit generation is the capacity of the vehicle fleet to use those fuels. For others, such as first generation ethanol and biodiesel, the rate of credit generation is limited by the amount of the fuel that can be used at existing standard blend limits, but also by the carbon intensity performance of the fuels being produced. For others, notably drop-in biofuels such as hydrotreated vegetable oil and cellulosic renewable diesel, the main limitation on credit generation is the supply of the fuel to the California market.[4] Assessing potential delivery of carbon intensity reductions therefore requires an assessment along three axes: potential fuel supply; potential fuel demand; and potential fuel carbon intensity.

The cases used as building blocks for low carbon fuel supply scenarios in Malins et al. (2015) reflect various assumptions about development of these fuel pathways to 2030, and are the starting point for the analysis in this report. However, the California fuel market has different characteristics than the Pacific market, and there have been developments in the vehicle and fuel market since 2015 that have been taken into account for new modelling. The ARB has released two sets of illustrative compliance modelling (California Air Resources Board, 2017c, 2018a)[5] containing fuel supply and credit generation scenarios for the LCFS to 2030. Several key issues are discussed in the sections below, while a full review of model amendments is provided in Annex A.

Electric vehicle fleet development

Passenger vehicles

Since 2015, the electric vehicle market has continued to expand. California's 2017 Climate Change Scoping Plan (California Air Resources Board, 2017a) anticipates that there will be 4.2

[4] It should also be recognized that total national and global supply of some fuels is limited by the sustainable availability of the feedstocks required.

[5] The second illustrative compliance scenarios were released part way through this project, and therefore both documents are referred to in this report.

million electric drive vehicles (BEVs, PHEVs and FCVs, but excluding HEVs) by 2030. This compares to a slightly lower 4 million in the whole Pacific region by that year in the 'medium' case in Malins et al. (2015). California's advanced clean cars mid-term review is consistent with the 2017 Scoping Plan, recommending that California should, "Strengthen the ZEV program for 2026 and subsequent model years" (California Air Resources Board, 2017b). The mid-term review notes that, "Since the adoption of the 2018 through 2025 model year standards, manufacturers have been exceeding the annual requirements of the ZEV regulation." As of March 2018, Veloz reported that there had been 380,000 cumulative sales of ZEVs in California.[6]

On 26 January 2018 the Governor of California signed an executive order setting a target of 5 million electric vehicles in the state by 2030 (Office of the Governor of California, 2018) and proposing additional policy actions to deliver this, including an increased appropriation for ZEV rebates. The baseline EV deployment scenario in the model has been updated to reflect the reported 2016 ZEV fleet and deliver 5 million ZEVs by 2030 in line with the Governor's target. The model is calibrated to deliver 2 million ZEVs by 2025, which is considered consistent with the 5 million anticipated in 2030. Sales of ZEVs are divided between battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs) and fuel cell vehicles (FCVs) in line with the 'high demand' case for ZEVs outlined by Bahrenian et al. (2017).

Medium and heavy duty vehicles

Electric drive medium and heavy duty commercial vehicles are not internally modeled by VISION 2014. Given, however, that they are expected to deliver significant numbers of LCFS credits by 2030, it was considered important to add them to the supply model. For the baseline assumptions, annual sales of MD/HD electric vehicles were taken from the proposed regulatory schedule for a medium- and heavy-duty electric vehicle sales mandate detailed by Mobile Source Control Division (2017), as shown in Table 2.

[6] http://www.veloz.org/

Table 2 Number of MD/HD electric vehicle sales assumed in the modeling baseline

Year	% of CA sales	Vehicle sales
2020	0	0
2021	0	0
2022	0	0
2023	2.50%	1,350
2024	5.00%	2,700
2025	7.00%	3,780
2026	8.50%	4,590
2027	10.00%	5,400
2028	10.00%	5,400
2029	13.00%	7,020
2030	15.00%	8,100

For the *MD/HD breakthrough* scenario, an accelerated deployment rate was modelled based on analysis by CALSTART, which is detailed in Annex B.

Given that these vehicles are not natively modeled in VISION 2014, credit generation from these vehicles was estimated by assuming the amount of diesel displaced is proportional to the number of vehicles in the medium and heavy duty fleets respectively. For the baseline it is assumed that EV sales are split 50:50 between medium and heavy duty vehicles. For the *MD/HD breakthrough* scenario, it is assumed that 27% of sales are medium duty and the rest heavy duty, based on the data from CALSTART. In order to be conservative, it was assumed that each electric vehicle would displace 90% of the energy consumption of the average diesel fueled MD/HD vehicle.

Electricity mix

The electricity mix assumption have been updated from the assumptions used in Malins et al. (2015). The 2030 California electricity mix is modelled based on carbon intensity data from CA-GREET (California Air Resources Board, 2016) and on grid mix data from preliminary RESOLVE modelling by the California Public Utilities Commission (California Public Utilities Commission, 2017). In the baseline case, the 2030 grid mix is based on the 42 mmt reference case, with 60% renewables in 2030, plus 9% from hydro and nuclear power. For the scenarios with faster electricity decarbonization (the *High ZEV* and *High Performance* scenarios), the 2030 grid mix is based on the 30 mmt reference case, with 65% renewables.

Renewable Natural Gas

The medium case presented in Malins et al. (2015) assumed that Pacific region transportation could access a renewable gas supply of up to 445 million diesel gallons equivalent (DGEs), and that up to 75% of total natural gas consumed in transportation may be renewable. The ARB illustrative compliance scenarios for 2030 (California Air Resources Board, 2017c, 2018a) assume that 90-100% of natural gas supply to Californian transportation will be renewable by 2020, and show 320 million diesel gallons equivalent (DGE) of natural gas consumption by 2030.

Parker, Williams, Dominguez-Faus, & Scheitrum (2017) provide an assessment of technical and economic potential of renewable natural gas generation in California itself. Of a total identified technical potential of 600 million DGE from landfills, dairies, wastewater treatment and anaerobic digestion of municipal waste, it is found that three quarters (450 million DGE) could be delivered economically given the value of existing incentives. The use of mass balance accounting for renewable natural gas supply allows resources from across the country to generate LCFS credits, but this work shows that in principle all of California's renewable natural gas demand (given a baseline scenario for the number of natural gas powered vehicles) could be generated in-state.

Following the lead of the illustrative compliance scenarios, the previous limit on maximum fractional contribution of renewable natural gas to overall natural gas supply has been removed from the model. The number of natural gas vehicles in the fleet has been better calibrated to the California market, and the maximum potential renewable gas supply scenarios are unchanged from Malins et al. (2015). The assumed carbon intensity of renewable natural gas has been adjusted to reflect the weighted average of dairy RNG (which is assigned a negative carbon intensity) and other sources of RNG. The potential supply of lowest carbon intensity dairy natural gas is limited to the supply level assumed by California Air Resources Board (2017c).

The model is very close to California Air Resources Board (2017c, 2018a) in the amount of natural gas consumption anticipated in the baseline, at 317 million DGE. This is also close to the 310 million DGE given in the 'high demand' scenario by Bahrenian et al. (2017).

Development of the cellulosic biofuel industry

Malins et al. (2015) included a review of the state of the cellulosic biofuel industry in the United States, and a deployment model for cellulosic biofuel production capacity based on work by Plevin, Mishra, & Parker (2014).

In the three years since the previous report, the cellulosic biofuel industry has suffered further setbacks in the U.S. and elsewhere in the world. Notably, several commercial scale cellulosic plants have struggled to debottleneck and have failed to demonstrate commercial production at close to nameplate capacities. The Dupont plant in Nevada[7] IA, Abengoa plant in Hugoton[8] KS, Poet-DSM plant at Emmetsburg[9] IA, and Biochemtex plant in Italy[10] have all experienced major setbacks in delivering target rates of cellulosic ethanol production, with all except the Poet plant reportedly mothballed at the current time.

Given that the rates of capacity expansion anticipated by Malins et al. (2015) have not been realized in the intervening period, the database of expected cellulosic biofuel capacity in the model has been revised to reflect a reduced number of projects, and to adjust expected dates for planned facilities to become operational. This has the overall effect of making the model less optimistic about rates of cellulosic biofuel production expansion in all cases when compared to the earlier work.

As in Malins et al. (2015), it is assumed that, due to the LCFS, California represents the most attractive market for cellulosic biofuel consumption in the U.S., and therefore that a large fraction of overall supply available to California. For the baseline case, that fraction is 60% of total cellulosic fuel produced.

Biodiesel and NOx

In July 2017, ARB approved the additive VESTA 1000 to reduce NOx emissions from blends of diesel with fatty acid methyl ester (FAME) biodiesel, certifying that a B20 blend with 0.3% VESTA 1000 emitted less NOx and particulates in testing than the reference diesel fuel. The availability of this additive removes a regulatory barrier to the use of higher blends of biodiesel in California. The model has been updated to assume a higher starting blend of biodiesel for California (reflecting the implied blend for 2016 documented in the draft illustrative compliance scenario). Higher average biodiesel blends than those used in Malins et al. (2015) are allowed in 2020 and 2030 - of B10 and B15 respectively, with a gradual blend increase through the 2020s.

Hydrotreated vegetable oil renewable diesel t

Potential volumes of renewable diesel from the hydrotreated vegetable oil (HVO) pathway have been increased compared to those modeled in Malins et al. (2015). This reflects that higher

[7] https://www.desmoinesregister.com/story/money/agriculture/2017/11/02/dowdupont-shutters-nevada-cellulosic-ethanol-plant-looks-buyer/824606001/
[8] http://www.biofuelsdigest.com/bdigest/2016/07/18/abengoas-hugoton-cellulosic-ethanol-project-goes-on-the-block/
[9] http://www.argusleader.com/story/news/2017/04/28/poet-accuses-engineering-company-failure-quest-cellulosic-ethanol/100993870/
[10] https://renewablesnow.com/news/mossi-ghisolfi-ponders-sale-of-biofuels-operations-in-italy-report-586538/

volumes of supply have been recorded to California than were anticipated for the whole Pacific region in the previous work, with a 2017 supply of 350 million gallons anticipated for 2017 by California Air Resources Board (2018a), double the medium scenario modeled by Malins et al. (2015). Assumed supply in the updated model is set to peak at 900 million gallons of distillate substitutes (renewable diesel plus renewable jet) in 2025, and then reduce slightly to 2030 as credit generation by other compliance pathways such as ZEVs accelerate. This compares to a total supply of up to 1.65 billion gallons of distillate substitutes assumed in the illustrative compliance scenarios from ARB (California Air Resources Board, 2018a). These volumes of HVO supply remain well within the expected global production capacity as documented by Malins et al. (2015).

While fuel production capacity need not limit the supply of these volumes of renewable diesel to the California market, it is important to note that there may be sustainability implications of large-scale use of by-product, residual and waste lipids (such as used cooking oils, animal fats and distillers' corn oil) that are not captured under the existing lifecycle accounting conventions within the LCFS. This possibility is discussed in more detail by ICF International (2015). In this study, the sensitivity of credit generation to the possibility of changing the methodology for accounting carbon savings from these fuels is explored in one of the sensitivity scenarios by applying an indicative value for indirect emissions from using these materials. This is discussed in more detail below in the explanation of that sensitivity case.

New compliance credit generating options

Since 2015, several additional compliance options have been or are expected to be introduced to the LCFS that were not reflected in Malins et al. (2015). These are:

- Refinery investment credits;
- Refinery renewable hydrogen credits;
- Low complexity/low energy use refinery credits;
- Aviation low carbon fuel credits.

These are in addition to existing crediting opportunities for innovative crude oil extraction and for non-road transportation electricity consumption.

Refinery renewable hydrogen credits

For the modeling baseline, the 'medium' case for renewable hydrogen consumption from Stillwater Associates (2018) is used, giving 750,000 tonnes of emissions reductions a year by 2030. In the *Clean Refineries* scenario, this rate of credit generation is increased to 1.9 million tonnes a year, in line with the high scenario in Stillwater Associates (2018), which is based on assumed rate of credit generation for this compliance option in California Air Resources Board (2017c).

Refinery investment credits

The baseline model assumptions on availability of refinery investment credits are based on the 'medium' case documented by Stillwater Associates (2018). In the *Clean Refineries* scenario, the availability of refinery investment credits is based on the 'high' case in that same report. The analysis by Stillwater Associates (2018) assessed potential for credits from the use of renewable or low-CI electricity, from low-CI process energy, and from electrification at refineries. It also considers the potential for CCS at refineries – this is discussed in more detail below in the section on CCS below.

Low complexity/low energy use refinery credits

This option is assumed to be a minor credit generator. It is assumed that 70,000 tonnes of credits are generated per year, in line with California Air Resources Board (2017c).

Aviation fuel

Advanced alternative fuels for aviation are chemically similar to drop-in substitute diesel fuels (HVO and cellulosic renewable diesel) that are already included in the model. Within the logic of the supply model, increased use of these fuels for aviation will result in reduced availability for road diesel. Given that the per-gallon LCFS credits available for displacing diesel and jet fuel are very similar, we have not introduced explicit modelling of the use of these fuels in aviation – it is assumed that for a given level of fuel supply, the mode to which these fuels are supplied will make only a marginal difference to overall compliance credit generation. It is possible that opening up additional markets for renewable mid-distillate fuels will encourage development of production capacity. Increased market draw for substitute distillate fuels is not explicitly dealt with in the cellulosic fuel production module. A rapid expansion of the use of renewable jet fuel by aviation could therefore result in larger volumes of substitute distillate fuels being produced than is anticipated in the existing model baseline.

Carbon capture and sequestration

The model has also been updated to allow credit generation by the introduction of carbon capture and storage for ethanol and petroleum refineries.

In the model baseline, it is assumed that CCS is introduced only for ethanol refineries in California itself. This baseline assumption is intended to be conservative against the full potential for CCS in the ethanol industry, and to partly reflect the possibility that California may introduce complementary incentives (e.g. through the cap and trade program) that would not be available for out-of-state ethanol refineries.

Based on McCoy (2016) it is assumed that retro-fitted CCS at ethanol refineries can reduce lifecycle carbon intensity of ethanol by 32 gCO_2e/MJ. Given 218 million gallons of ethanol production in California, this results in 567,000 tonnes per year of credit generation. It is assumed that capture capacity grows exponentially from an initial 10,000 tonnes in 2022. For the *Clean Refineries* and *High Performance* scenarios, it is assumed that CCS is also implemented at all starch-ethanol refineries supplying fuel to California by 2030, with credit generation growing exponentially from 20,000 tonnes in 2022.

The baseline scenario also includes 365 thousand tonnes of CCS at refineries by 2030, with an exponential growth from 10,000 tonnes of capacity in 2022, based on Stillwater Associates (2018).

For the *Clean Refineries* scenario only, it is also assumed that CCS is implemented for all Californian steam methane reforming (SMR) units in the oil refining sector at Northern California refineries.[11] Soltani, Rosen, & Dincer (2014) suggest implementing carbon capture after the syngas shift phase of the SMR process. If optimized for CCS, finding that up to 65% of process CO_2 could be captured at this stage. H2A modeling from the DOE[12] anticipates a higher potential CO_2 recovery rate of 81% capture by CCS. The EPA facility level emissions inventory[13] identifies eight relevant facilities in California with combined CO_2 emissions of 5.5 million tonnes per year (Table 3).

[11] The northern refineries have better access to geologically suitable carbon sequestration sites.

[12] https://www.hydrogen.energy.gov/h2a_prod_studies.html

[13] https://ghgdata.epa.gov/ghgp/main.do

Table 3 CO_2 emissions recorded for steam methane reforming in California

Facility	CO_2 Emissions (tonnes/yr)
Shell Martinez Refinery	816,174
Valero Benicia Refinery	948,212
Tesoro Golden Eagle Refinery	562,646
Chevron Richmond Refinery	1,334,862
Air Products & Chemicals Martinez (Shell)	723,983
Air Products & Chemicals Martinez (Tesoro)	264,024
Air Liquide Rodeo (Shell)	769,835
Shell Rodeo	111,304
Total	**5,531,040**

Assuming 60% CO_2 capture, installing CCS for all these facilities would deliver 3.3 million tonnes per year of credits.

The *Clean Refineries* scenario reflects the highest level of CCS ambition modeled for this report, but it is worth noting that there is potential in principle that a successful scaling up of CCS technologies could have a much broader impact on industry in California, and deliver very large numbers of LCFS eligible credits, particularly if post-combustion capture of CO_2 from flue gas is widely deployed. The combination of the LCFS credit and the federal 45Q tax credit could provide well over 125 \$/tCO_2e of value to CO_2 abatement through CCS at the refinery, a value proposition that some commentators believe may prove quite compelling. Capturing 70% of all CO_2 emitted by Bay Area refineries alone could deliver 11 million tonnes of emission reductions, in which case refinery CCS would be comparable to electric vehicles as a source of greenhouse gas emissions reductions. Currently, credit generation by refineries through CCS is limited to 5% of total deficit generation, and this limit would rapidly be met in the event of such widespread adoption of CCS.

Should deployment reach that stage, it would be appropriate to consider whether the limit could be relaxed, ideally in concert with a proportionate increase in ambition of the LCFS compliance schedule in order for the program to continue supporting additional deployment of these technologies. Further detail on the underlying assessment of CCS opportunities is available in Murphy and Martin (2018).

Transportation energy demand

In Malins et al. (2015), vehicle miles travelled (VMT) assumptions were based on the data included within VISION 2014. For this modelling, VMT assumptions for passenger vehicles have been updated in the central case to assume a 6.9% average statewide reduction from 2015 to 2030, reflecting the opportunities for urban VMT reduction in California detailed by ICF (2016).

New vehicle efficiency assumptions are based on data from VISION 2017, which reflect improvements required by corporate average fuel economy (CAFE) standards for 2025. For instance, gasoline internal combustion engine (ICE) fuel economy increases by 32% for cars and 47% for light trucks between 2015 and 2025, while efficiency of new gasoline hybrids increases by 24% for cars and 38% for light trucks. As 2030 standards have not yet been set, the model assumes no significant efficiency improvement from 2025 to 2030, which makes the overall predicted transportation energy demand reduction more conservative than it otherwise would be. The model does not consider any potential feedback between increased ZEV share and reduced fuel economy for other vehicles.

The modelling assumptions used result in an overall transportation energy demand reduction of 19-22% from 2016 to 2030 in the model, depending on scenario. In comparison, the ARB illustrative compliance scenarios with a 20% compliance requirement for 2030 include a transportation energy demand reduction of between 25% and 28% in the low demand case, and between 10% and 13% in the high demand case (California Air Resources Board, 2018a). The modelling here is therefore slightly conservative on potential overall transportation energy demand reductions compared to the low demand illustrative compliance scenarios, but optimistic compared to the high demand scenarios.

Potential indirect emissions of using lipids and fats characterized as by-products, residues or wastes for biofuel feedstock

Currently, within the LCFS no indirect emissions are attributed to biofuels produced from several feedstock materials considered as wastes and residues, in particular biodiesel and renewable diesel produced from used cooking oils/greases, animal fats, and distillers' corn oil. Similar assumptions are made by other regulatory biofuel support mechanisms such as the Renewable Fuel Standard, and in Europe the Renewable Energy Directive. This assumption does not take into account the fact that these lower-value lipids and fats already have economic utilization, in particular in the animal feed industry and in niche oleochemical applications (cf. ICF International, 2015; Malins, 2017; Searle, Pavlenko, El Takriti, & Bitnere, 2017). It is likely that giving full consideration to the market consequences of largescale diversion of these resources would result in the identification of non-negligible indirect emissions resulting from the sourcing of replacement materials for existing uses, somewhat analogous to the indirect land use change emissions associated with land-based biofuel production. In the absence of detailed assessments of these indirect emissions consequences due to displacement in U.S. markets, a scenario is included below in which the indirect land use change emissions value for soy biodiesel is used as a proxy for an appropriate calculated value. This scenario is intended as an illustration of the impact on compliance of potential future adjustments to the LCFS carbon accounting rules to more accurately represent the full lifecycle implications of using these types of material as biofuel feedstock.

This is the only potential methodological adjustment to the LCFS lifecycle assessment that has been considered in this report, which reflects requests by the ARB for additional modeling evaluation on this question. It is important to recognize that as new data becomes available and LCA science develops, there may be changes introduced to the lifecycle values attributed to other fuel pathways, and that these could result in either lower or higher rates of credit generation.

Credit Generation Opportunities Not Modeled

While we have attempted to comprehensively cover likely credit generation under a likely re-adopted LCFS, there are some potential credit generation pathways which we do not explicitly consider which could increase the potential credit supply. These un-modeled pathways may be thought of as a buffer that would expand potential LCFS credit supply beyond what is estimated in this report.

The most impactful of these pathways is likely to be additional credits from renewable and/or "smart" charging, that is, charging which minimizes peak electric loads on the grid. CARB has solicited feedback from stakeholders regarding how either or both of these pathways could be developed, though at present, they are not sufficiently developed to allow modeling. Both pathways could, if implemented, significantly increase the available credits generated by EV charging. We estimate that further reduction to the effective carbon intensity of the electricity supply could deliver an additional 1% to 1.5% carbon intensity reduction in the *Steady Progress* scenario.

Some stakeholders have also requested an LCFS credit pathway for electric bicycles and scooters, which would, if implemented, add a small amount of additional credits to the existing market. Similarly, there are prototype electric aircraft entering the market which could, in the future, be eligible for LCFS credit generation, and credits for zero-emission transportation refrigeration units (TRUs) have been suggested, but are not modelled here. As discussed above, there is also a chance that the emergence of alternative jet fuels could lead to a net increase in the availability of low-carbon distillate substitute fuels to the California market, which has not been explicitly modeled here.

Carbon capture and sequestration has only been evaluated in the context of selected refinery operations or ethanol facilities. It is possible that this under-estimates the potential of CCS to generate credits from other pathways, such as electrical generation units where the resulting energy is expressly being produced for use as transportation fuel, or from other biofuel production facilities.

Neither the exclusion of these pathways from the modelling, nor their discussion here, should be taken to imply any position on their inclusion in the re-adopted LCFS.

Low carbon fuel supply scenarios

Understanding the results

In this chapter, the results of ten scenarios for the low carbon fuel supply to California in 2030 are presented. As discussed above and by Malins et al. (2015), the model used here should be understood as a fuel supply model rather than as a compliance model. This is because the model includes no feedback mechanism from the performance against existing or draft compliance targets on the rate of credit generation – credit generation is determined by assumptions about the amount and type of energy supplied. In the real world, suppliers can be expected to take measures to increase the supply of LCFS credits if confronted with a shortfall against compliance targets, or to reduce the supply of LCFS credits if confronted with an over-supplied market.

Where the scenarios below show an annual supply of credits below the draft targets, this should not be taken to imply that fuel suppliers could not potentially take measures to increase short-term credit supply to allow compliance in such a year. Conversely, where the results of a scenario show a large accumulation of extra credits (under the draft compliance scenario), this should not be taken to imply that we would expect suppliers to keep growing the credit bank indefinitely if the supply of credits exceeds expectations. The rates of credit generation shown in each scenario are implicitly based on an assumption that the LCFS credit value remains significant throughout the period considered. If credit generation was high enough to result in large reductions in credit price, and the compliance schedule was not adjusted, it might be expected that rate of credit generation from some technology options would reduce. In the real LCFS, the credit trading mechanism allows for credit value to adjust to bring overall supply closer to what is needed for compliance, in a way that is not reflected in this model.

The scenarios should therefore rather be understood as a characterization of the number of credits that could be generated under certain technology and deployment assumptions. The comparison to the draft compliance schedule should be considered illustrative rather than predictive.

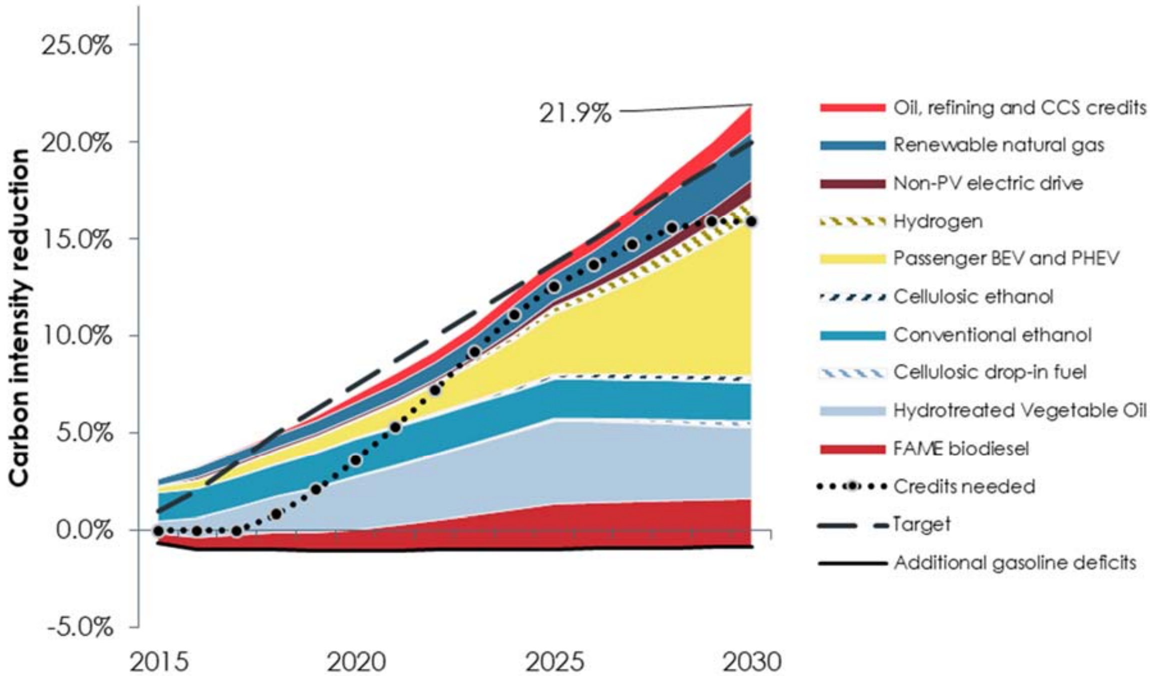

Figure 3 Example of a carbon saving supply chart

For each scenario, two charts and a table are presented. An example of the first type of chart is provided in Figure 3. In these carbon-saving supply charts, a series of ‘wedges’ stacked one on the other represent the % emissions reductions compared to the California fuel carbon intensity baseline that could be delivered from each compliance option in that scenario. The sum of all of these carbon savings is labeled, this number represents the total carbon intensity reduction achievable by 2030 in each scenario. The wedges shown on the chart are as follows:

- Conventional ethanol – ethanol from non-cellulosic feedstocks such as corn, sugarcane and molasses and supplied with gasoline either as an E10 or E85 blend.
- FAME biodiesel – fatty acid methyl ester biodiesel supplied in a blend with diesel.
- Hydrotreated Vegetable Oil – renewable distillate fuels from hydrotreating lipid feedstocks that can be blended with diesel or jet at any rate as ‘drop-in’ fuels.
- Cellulosic ethanol – ethanol produced from cellulosic feedstocks and supplied with gasoline either as an E10 or E85 blend.
- Cellulosic drop-in fuel – fuels produced using biomass-to-liquids technologies from cellulosic feedstocks that can be blended with diesel, jet or gasoline at any rate as ‘drop-in’ fuels.

- Passenger BEV and PHEV – electricity supplied for use by battery electric and plug-in hybrid ZEVs in the passenger vehicle sector.
- Non-PV electric drive - electricity supplied for use by medium and heavy duty vehicles, rail and forklifts.
- Hydrogen – hydrogen supplied for use in fuel cell electric drive vehicles
- Renewable natural gas – biomethane supplied for passenger and heavy duty vehicles[14]
- Oil, refining and CCS credits – carbon savings generated by innovative crude extraction, refinery improvements and carbon capture and sequestration at both petroleum and ethanol refineries.
- Additional gasoline deficits – additional deficits generated in the gasoline pool because the carbon intensity of CARBOB (California Reformulated Gasoline Blendstock for Oxygenate Blending) is higher than the carbon intensity of the gasoline baseline.

It should be understood that this graph shows carbon savings relative to the baseline, not carbon savings relative to the annual compliance schedule. The bottom of the chart starts slightly below zero, reflecting the number of additional deficits expected to be generated due to a slight increase in the carbon intensity of gasoline as compared to the baseline. The emissions reductions generated compared to the 2010 baseline are then layered on, one compliance option after another.

The final wedge, 'oil refining and CCS credits' is an aggregate of several credit generation pathways. These pathways include credits from carbon capture and storage (at both ethanol and petroleum refineries) and additional credits generated by refineries and upstream in the oil supply chain.

Two lines are plotted over the wedge chart. The dashed line shows the draft compliance schedule, peaking with a 20% carbon intensity reduction target in 2030. This is included in the chart to allow the carbon savings generated in that scenario to be compared with the number that would be needed each year for the draft compliance targets. It should again be remembered that the model used is a *supply* model, not a *compliance* model, and therefore there is no LCFS credit price in the model and no feedback in the model on rate of credit generation from the state of the credit market.

The second line, which is dotted, shows the carbon savings that would need to be generated in any given year to meet the draft target, given the number of credits or deficits that are carried over from the previous year. Where there is a positive balance of banked credits, the dotted line is below the dashed line (compliance can be delivered partly using banked credits). In the case

[14] All natural gas supplied for transportation is assumed to be renewable from 2018 onward.

that a deficit is carried over, the dotted line runs above the dashed line, showing the additional savings needed to pay off the deficits previously incurred. Interest is charged in the model on any deficits carried from year to year.

The second type of chart, showing net credits generated each year, (an example is given in Figure 4) is identical in form to a chart include in the CARB draft illustrative compliance scenario spreadsheet (California Air Resources Board, 2017c). It shows the net number of credits or deficits that would be generated each year given the modelled fuel supply (red bars), and the accumulated credit or deficit bank that would be associated with the modelled fuel supply if delivered under the draft compliance targets (blue area). Key results from each scenario are also presented in an associated table in each section.

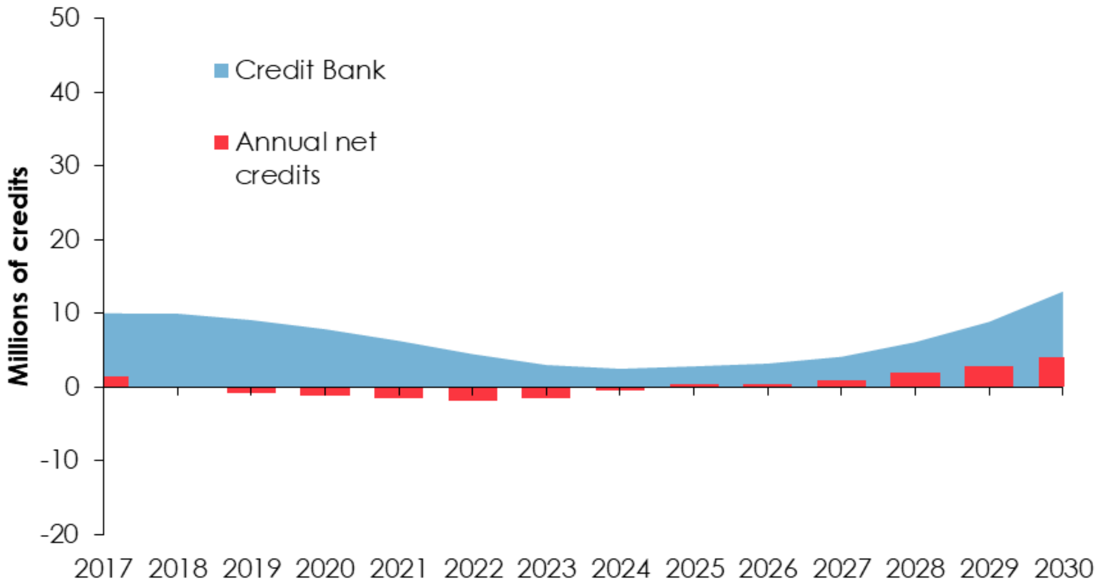

Figure 4 Example credit bank chart

Main scenarios

First, two primary scenarios are presented. In the first, the *'Steady Progress'* scenario, deployment of the various credit generation options develops at a baseline rate that is considered to reflect a reasonable expectation given the current state of technology development portfolio of incentives expected to be available to operators in California and in the U.S more widely. In the second, the *'High Performance'* scenario, it is assumed that several technologies develop more quickly than in the *Steady Progress* case and thus more credit generation would be achievable. In the next section, further sensitivity scenarios are detailed.

Steady Progress

In this scenario, the carbon intensity reduction delivered by 2030 is 21.9%, two percentage points above the draft compliance schedule. Steady progress continues in decarbonization of transportation across the board. The deployment of ZEVs meets the Governor's target of 5 million by 2030, there is gradual progress in commercialization of advanced biofuels, the average carbon intensity of first generation biofuels decreases, and it is assumed that mass balance accounting allows all natural gas supplied for transportation in California to be counted as renewable, utilizing a combination of in-state and out-of-state renewable natural gas supplies.

In the *Steady Progress* scenario, annual consumption of electricity for transportation reaches 19,400 GWh. This is marginally higher than the 18,000 GWh shown in the high demand scenario by the CEC *Transportation Energy Demand Forecast, 2018-2030* (Bahrenian et al., 2017), reflecting the increased level of ambition modeled here for electric passenger vehicles by 2030. Annual consumption of renewable natural gas reaches 320 million gallons diesel equivalent, about the same as the high demand case in Bahrenian et al. (2017), which reaches 310 million gallons diesel equivalent in 2030.

Consumption of distillate-substitute biofuels, biodiesel and renewable diesel/jet[15], also increases in this scenario. From about 400 million gallons in 2016, by 2030 total demand reaches 1.5 billion gallons (600 million gallons of biodiesel blended at B15, and 900 million gallons of renewable diesel or jet fuel). These 2030 volumes are somewhat below those in the CARB illustrative compliance scenarios for a 20% carbon intensity reduction target (1.6 to 2.5 billion gallons in 2030, including alternative jet fuel). Higher volumes could potentially be made available by more rapid growth of cellulosic drop-in fuel production, or by increased supply of hydrotreated vegetable oils.

Total ethanol consumption falls from 1.6 to 1.2 billion gallons, limited by the blend wall (E10)[16]. Cellulosic ethanol production and consumption increases modestly to 120 million gallons by 2030,

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[15] Including distillates from cellulosic biomass-to-liquids as well as hydrotreated vegetable oil.

[16] A 'high alcohol' scenario in which E85 consumption grows more aggressively is discussed below.

and starch ethanol (corn and sorghum) remains the primary source, but continues a trend of reducing carbon intensity including the roll out of carbon capture and storage to California ethanol refineries. A further 30 million gallons of cellulosic biofuel are supplied as drop-in diesel, gasoline and jet fuel.

Figure 5 shows the contribution of various credit generating technologies to achieving compliance with the draft targets. In the very near term, HVO, biodiesel and conventional ethanol remain the largest credit generators. Moving into the 2020s, however, the greenhouse gas emissions reduction delivered by electricity and renewable natural gas increase, as does the generation of credits by refinery improvements and carbon capture and storage (grouped into 'other credits' in the figure).

There is a drawdown of the credit bank between now and 2024, but from 2025 onwards credit generation starts to exceed annual requirements. As shown in Figure 6, from this point on a significant credit bank starts to build up, reaching 13 million by 2030 (Table 4). This suggests that a more stringent compliance trajectory for the final few years to 2030 would be deliverable given these fuel supply assumptions.

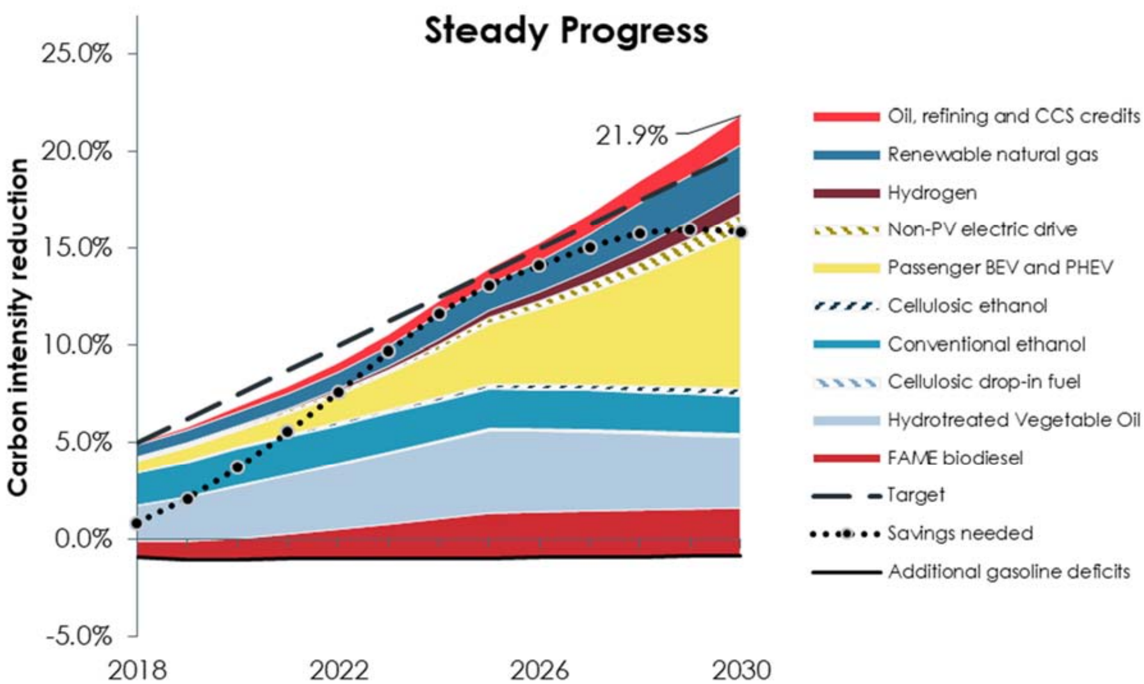

Figure 5 Carbon savings delivered in the *Steady Progress* scenario

By 2030, the carbon intensity reduction delivered is 21.9%, two percentage points above the draft compliance schedule. This strong end-of-decade performance is partly explained by the non-linear growth in consumption of electricity for transportation as the ZEV fleet grows. As can be seen in Figure 5, by 2030 passenger electric vehicles are the largest single credit generating category. By the end of 2030 there are 13 million tonnes of credits in the credit bank.

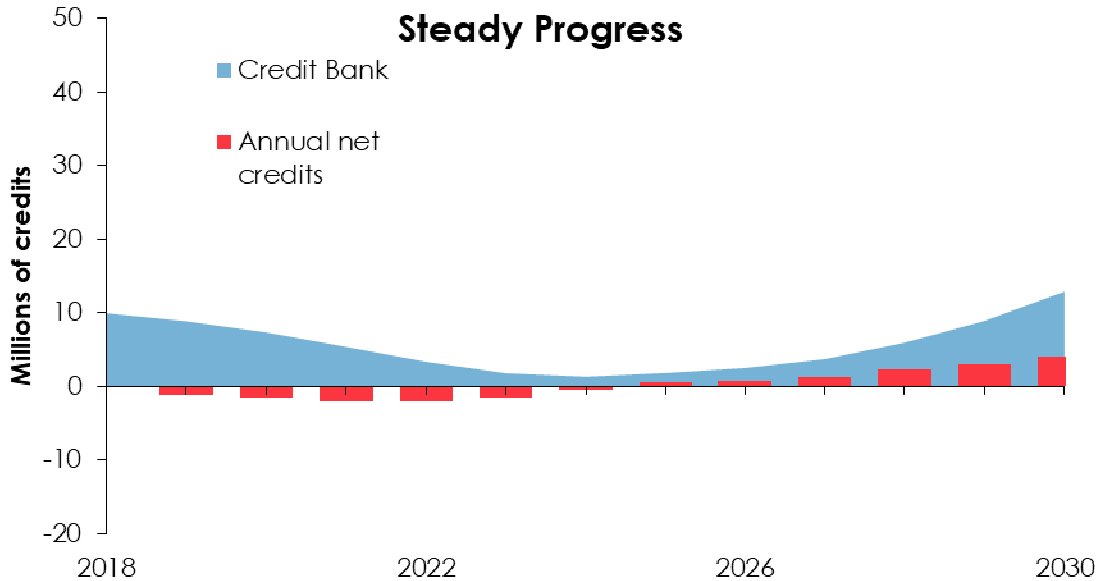

Figure 6 Credit bank evolution for *Steady Progress* scenario under draft compliance schedule

Table 4 Overview of results in the *Steady Progress* scenario

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.8	5.8	13.1
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.6	0.8
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.7	9.2
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.1	2.5	5.2
Cumulative credit generation since 2018 (million tCO_2e)	43.6	153.8	315.0
Annual credit generation (million tCO_2e)	16.3	26.6	36.4
Banked credits at year end (million tCO_2e)	7.3	1.8	12.9
% CI reduction	**6.9%**	**14.0%**	**21.9%**

Additional details of credit generation in the *Steady Progress* scenario are provided in Annex C.

High Performance

This scenario represents the case in which the supply of LCFS credits is significantly enhanced by accelerated technology deployment (compared to *Steady Progress*) across several credit generation options simultaneously. The technology deployment rate assumptions fall between the Steady Progress case and the even faster deployment rates considered in the technology-specific sensitivity cases below. The *High Performance* scenario delivers a carbon intensity reduction of 26.6%, four percentage points higher than in the *Steady Progress* case. The accelerated technology deployment assumptions allows for significantly larger carbon intensity reductions to be delivered by 2030 than in the *Steady Progress* scenario. Specifically the *High Performance* scenario differs from *Steady Progress* by having more aggressive deployment assumptions on cellulosic fuels, passenger ZEVs, heavy duty natural gas vehicles, and on carbon capture at ethanol refineries and green hydrogen use at petroleum refineries.

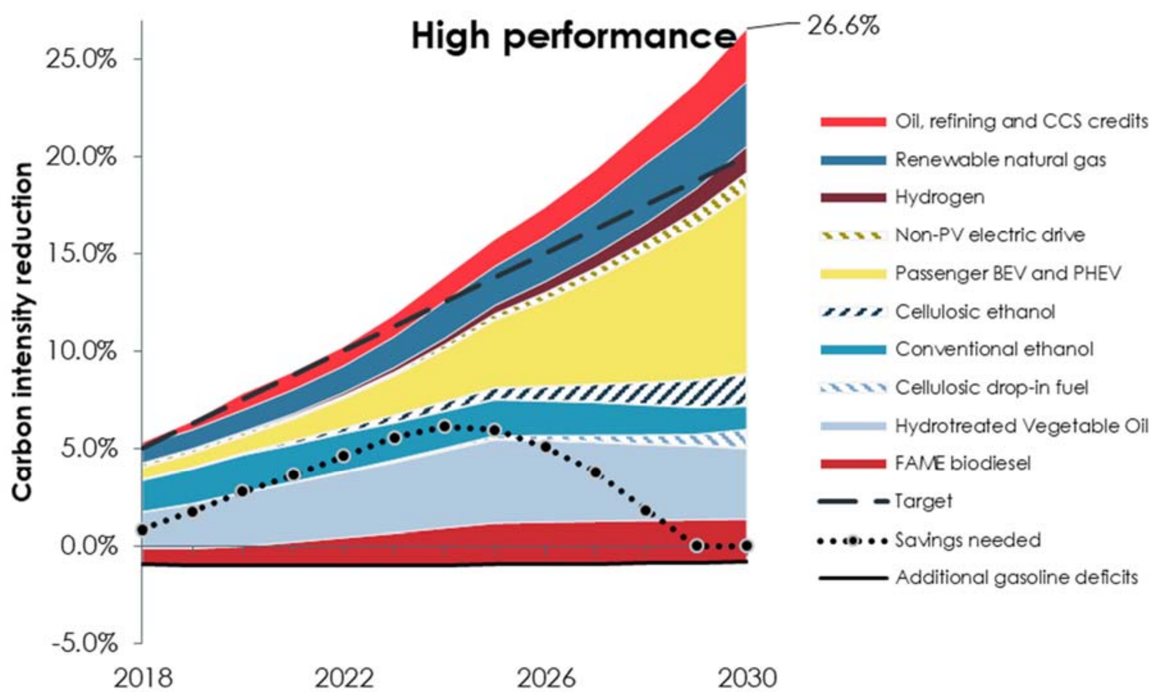

Figure 7 Carbon savings delivered under the *High Performance* scenario

The passenger ZEV fleet grows to 2.3 million vehicles in 2025, and then exceeds the governor's target, reaching 5.8 million by 2030, with ZEVs, including plug-in hybrids, having reached 76% of sales. As noted below in the dioscussion of the *High ZEV* case, this remains well below some esimates of achievable ZEV fleet for 2030 (Southern California Edison, 2017). This results in the cumulative generation of an additional 10 million tonnes of GHG emissions reduction from passenger ZEVs compared to the *Steady Progress* scenario. The natural gas heavy duty vehicle fleet is doubled in size by 2030 compared to *Steady Progress,* allowing an additional 20 million tonnes of cumulative credits to be generated. Simultaneously, the cellulosic ethanol supply reaches over 500 million gallons while the supply of cellulosic drop-in diesel, gasoline and jet fuel reaches 170 million gallons. Whereas in *Steady Progress i*t is assumed that CCS credits for ethanol refineries are generated only by California in-state ethanol producers, in High Performance CCS technology is also adopted by ethanol importers. Finally, whereas in Steady Progress the generation of credits by green hydrogen use in refineries reaches only 750 thousand tonnes a year, in High Performance that rate of generation increases to 1.9 million by 2030 (Stillwater Associates, 2018).

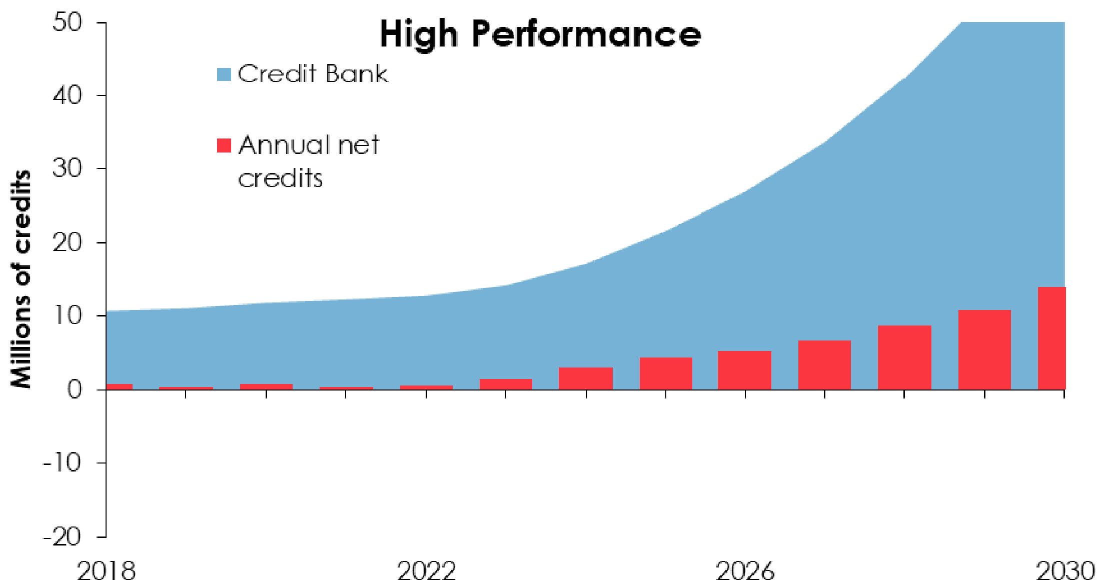

Figure 8 Credit bank evolution for *High Performance* scenario under draft compliance schedule

Taken together, these advances allow an additional cumulative 54 million tonnes of credits to be generated by 2030 than in *Steady Progress* (Table 5), with 9 million more credits a year being generated by the end of the period than in *Steady Progress*. A carbon intensity reduction of 26.6% is delivered, four percentage points higher than in the *Steady Progress* case. As can be seen in Figure 8, when compared to the current draft compliance schedule, these technology deployment successes would result in very large numbers of credits being banked under the proposed compliance schedule. By 2030, more than 10 million tonnes of net credits are being generated annually. Clearly, in practice such large numbers of surplus credits would result in a reduced LCFS credit price, likely reducing the use of some of the credit generation options modelled. Delivering this ambitious rate of decarbonization in practice would therefore require that the compliance schedule be adjusted upwards once the signs of more rapid than expected progress are identified, in order to maintain the role of the credit market in supporting demand for low carbon fuels.

Table 5 Overview of results in the *High Performance* scenario

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.8	6.5	15.5
Credit generation by cellulosic biofuels (million tCO_2e)	0.3	1.5	4.3
Credit generation by HVO and biodiesel (million tCO_2e)	7.9	11.4	8.8
Credit generation by renewable natural gas (million tCO_2e)	2.2	3.5	5.4
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	2.4	3.8	7.7
Additional credits over steady progress (million tCO_2e)	2.2	3.5	8.6
Annual credit generation (million tCO_2e)	18.4	30.1	45.0
Banked credits at year end (million tCO_2e)	11.8	21.6	67.2
% CI reduction	**7.8%**	**15.7%**	**26.6%**

Additional details of credit generation in the *High Performance* scenario are provided in Annex C.

Sensitivity scenarios – strong credit generation

The scenarios presented in this section investigate the sensitivity of the main results to stronger assumptions about the rate of deployment of key individual low carbon technologies, with one assumption adjusted in each case compared to the *Steady Progress* case. The five scenarios consider higher rate of deployment of passenger ZEVs, heavy duty ZEVs, cellulosic biofuels, emissions reductions options at ethanol and petroleum refineries, and in the fifth increased rates of ethanol supply through a higher standard blend and increased use of E85 or other alcohol blends. These scenarios are presented as sensitivity cases to illustrate the effects of credit generation from particularly significant pathways at what we consider to be the higher ends of their likely range. As discussed above, the rate of credit generation in these more optimistic scenarios is not necessarily consistent with the draft compliance schedule – delivering the levels of carbon savings detailed in this section would require not only technological progress, but also ongoing development of the regulatory framework, which would likely need to include tightening the compliance schedule before 2030 in order to support the LCFS credit price.

High ZEV

In this scenario, the governor's target for electric drive vehicle deployment of 5 million vehicles by 2030 is exceeded by even further than was modelled in the *High Performance* scenario. There are 6.7 million ZEVs on the road by 2030, and 90% of new passenger car sales and ZEVs by that year. While this exceeds the Governor's target, it is less than the 7 million vehicles called for in the 'Clean Power and Electrification Pathway' (Southern California Edison, 2017), and the sales rate modeled here is less aggressive to 2025 than projections attributed to Navigant Research and Bloomberg New Energy Finance by California Air Resources Board (2017a).

As one might expect, this accelerated electrification results in strong performance on carbon intensity, with a 24.5% reduction recorded for 2030 (Figure 9). ZEVs are the dominant source of LCFS credits in 2030 in this scenario, accounting for about 50% of total credit generation, and generating 4.7 million tonnes of credits per year more than in *Steady Progress* (Table 6). Annual transportation electricity consumption reaches 24,800 GWh.

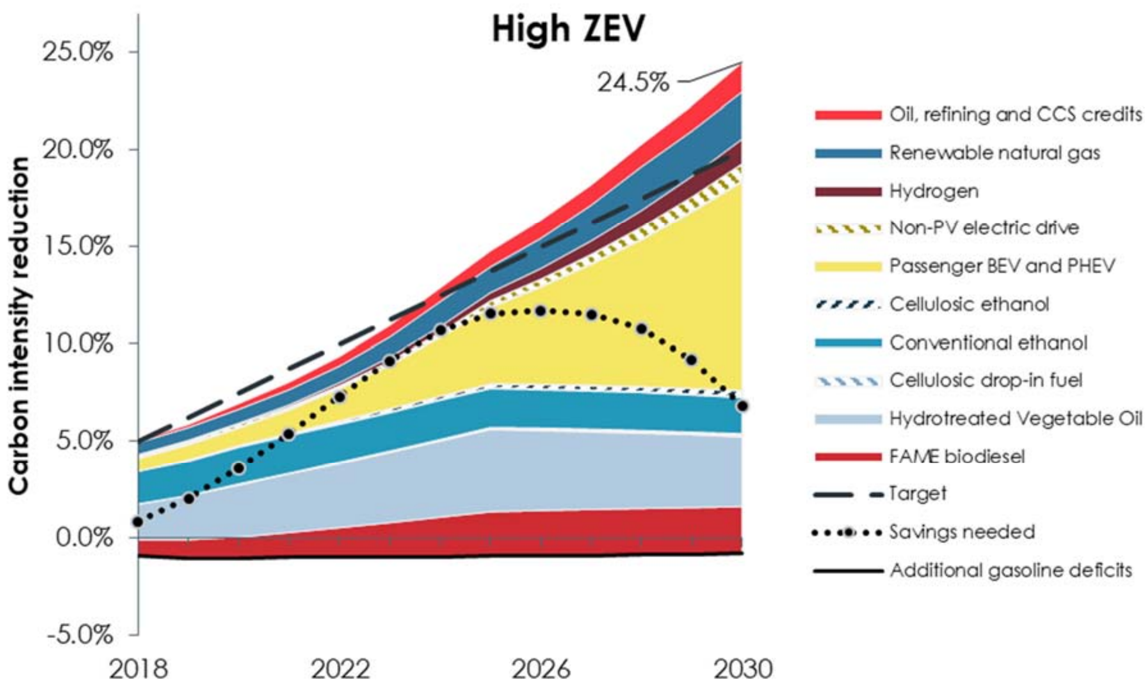

Figure 9 Carbon savings delivered under the *High ZEV* scenario

Even with a very aggressive growth in the ZEV fleet, consumption of liquid fuels remains considerable in 2030, and as can be seen in Figure 9 renewable liquid fuels continue to make an important contribution towards delivering carbon savings. The growth in the ZEV fleet and in electricity use for transportation is not linear, and therefore credit generation in the early part of the 2020s is similar to that in the *Steady Progress* case. From 2025 onward, however, the growth in credit generation results in large credit surpluses and the credit bank reaches about 38 million by 2030.

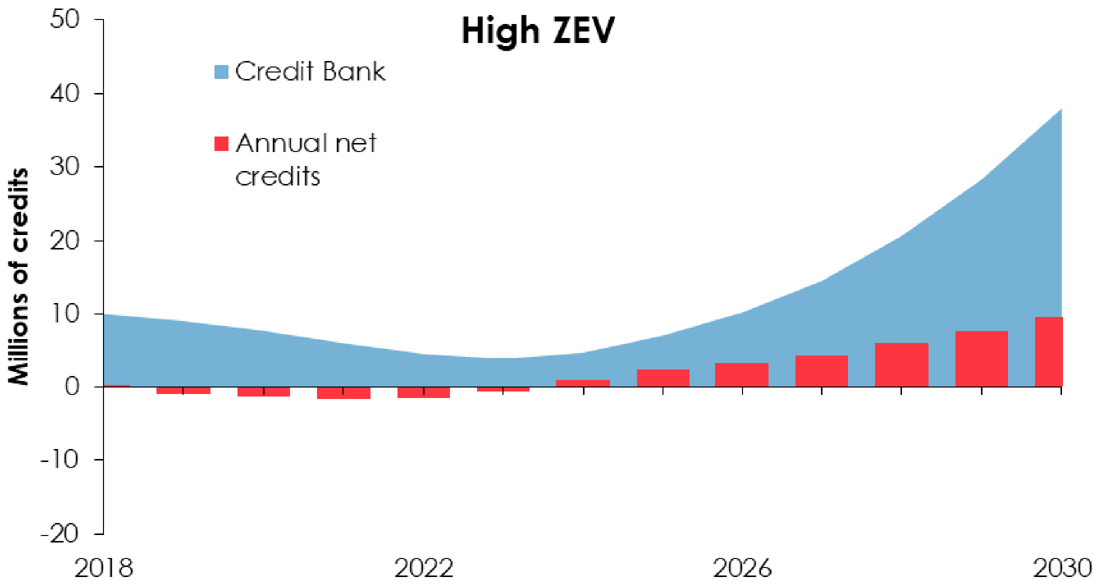

Figure 10 **Credit bank evolution for *High ZEV* scenario under draft compliance schedule**

Table 6 **Overview of results for *High ZEV* scenario**

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	2.0	7.3	17.8
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.6	0.8
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.7	9.2
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.1	2.5	5.2
Additional credits from light duty ZEVs over steady progress (million tCO_2e)	0.2	1.6	4.7
Annual credit generation (million tCO_2e)	16.4	28.2	41.3
Banked credits at year end (million tCO_2e)	7.8	7.1	38.0
% CI reduction	**6.9%**	**14.8%**	**24.5%**

MD/HD Breakthrough

This scenario is similar to the high-ZEV case above, but rather than considering an accelerated roll out of passenger ZEVs, it assesses an accelerated roll out of medium and heavy duty electric vehicles. Based on analysis by CALSTART (see Annex B) if is assumed that the fleet of MD/HV electric vehicles in California grows to 137 thousand by 2030, three and a half times more than in *Steady Progress.*

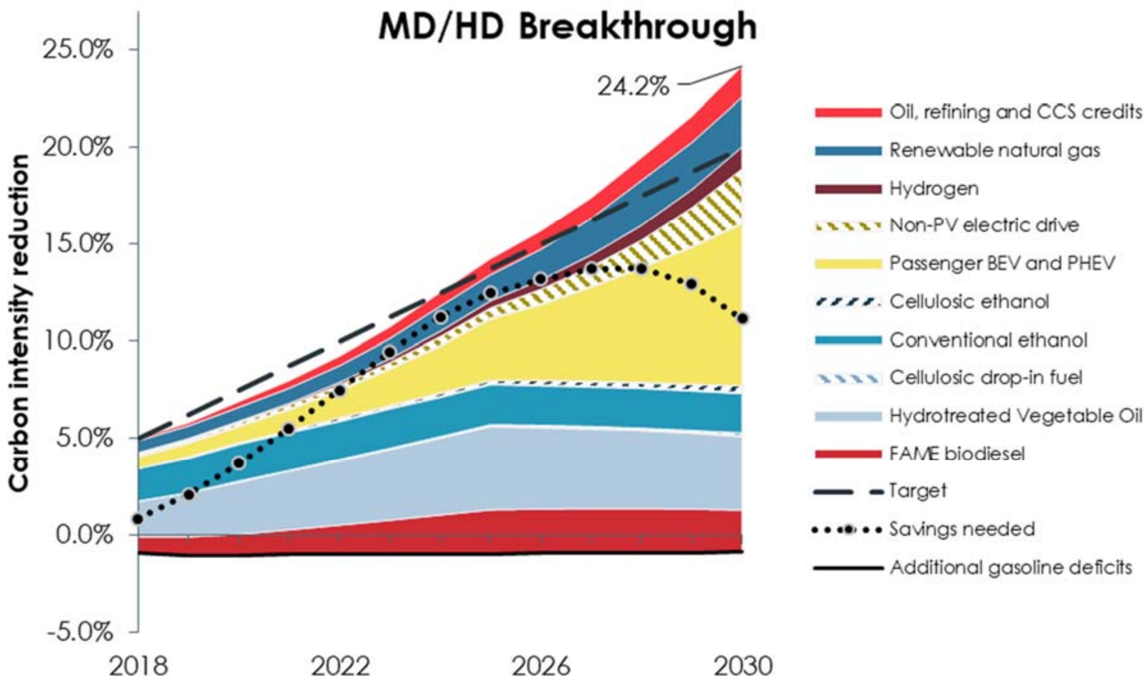

Figure 11 Carbon savings delivered under the *MD/HD Breakthrough* scenario

With this acceleration in MD/HD electrification, electricity supply becomes the largest credit generator in the diesel pool, delivering just under 8 million tonnes per year in 2030 (Figure 11). The credit bank evolution is very similar to that in the *High ZEV* case, with surpluses delivered from 2025 onward growing the bank to 34 million tonnes by the end of the period (Table 7). In 2030, the carbon intensity of the transportation energy mix is reduced by 24.2% compared to the baseline.

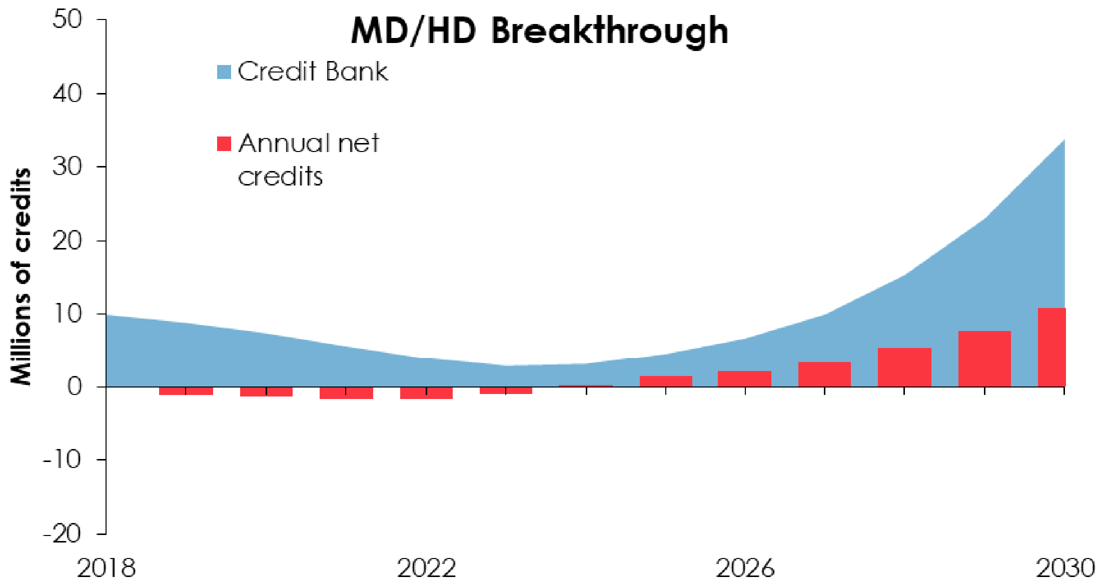

Figure 12 **Credit bank evolution for *MD/HD Breakthrough* scenario under draft compliance schedule**

Table 7 **Overview of results for *MD/HD Breakthrough* scenario**

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.8	5.8	13.1
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.6	0.8
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.6	8.7
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.1	3.4	11.2
Additional credits from heavy duty ZEVs over steady progress (million tCO_2e)	0.1	0.9	6.0
Annual credit generation (million tCO_2e)	16.3	27.4	41.9
Banked credits at year end (million tCO_2e)	7.4	4.6	33.8
% CI reduction	**6.9%**	**14.2%**	**24.2%**

High Alcohol

In this scenario, the emissions reductions delivered by conventional ethanol are maximized by combining a transition from E10 to E20 as the standard gasoline blend with an increase in the use of E85 fuels by E85 compatible vehicles and increased imports of sugar based ethanol. In 2030, 2.4 billion gallons of ethanol are supplied, of which 1.8 billion are starch based, 500 million from sugarcane and molasses based and 120 million are cellulosic. It is assumed, as in the other scenarios, that the carbon intensity for all these ethanol production pathways decreases over time.

As can be seen in Figure 13, the growing ethanol supply results in constant growth of credit generation by conventional ethanol throughout the period assessed. This contrasts with the other scenarios, in which reducing gasoline demand and increased supply of cellulosic ethanol means that conventional ethanol contributes less savings over time.

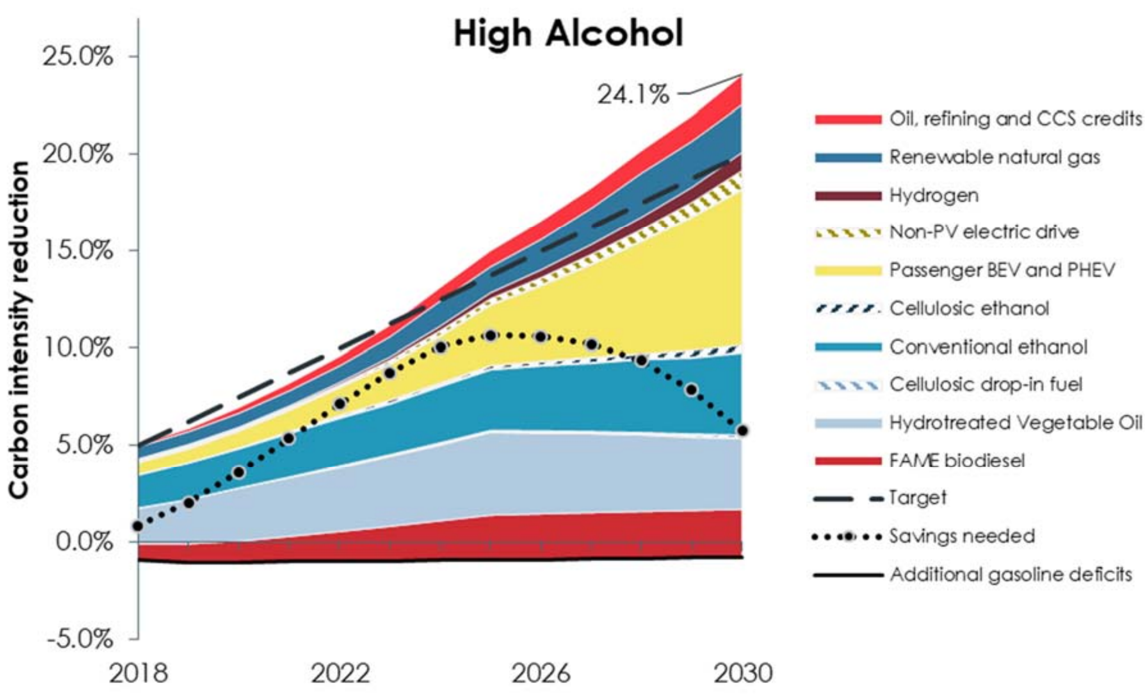

Figure 13 Carbon intensity reductions delivered in the *High Alcohol* scenario

With this larger supply of ethanol, a 24.1% carbon intensity reduction is achieved by 2030. In the modeling, raising the use of ethanol provides additional credits earlier in the compliance period than increasing the supply of electric vehicles. The credit bank grows to 38 million tonnes by 2030 (Table 8).

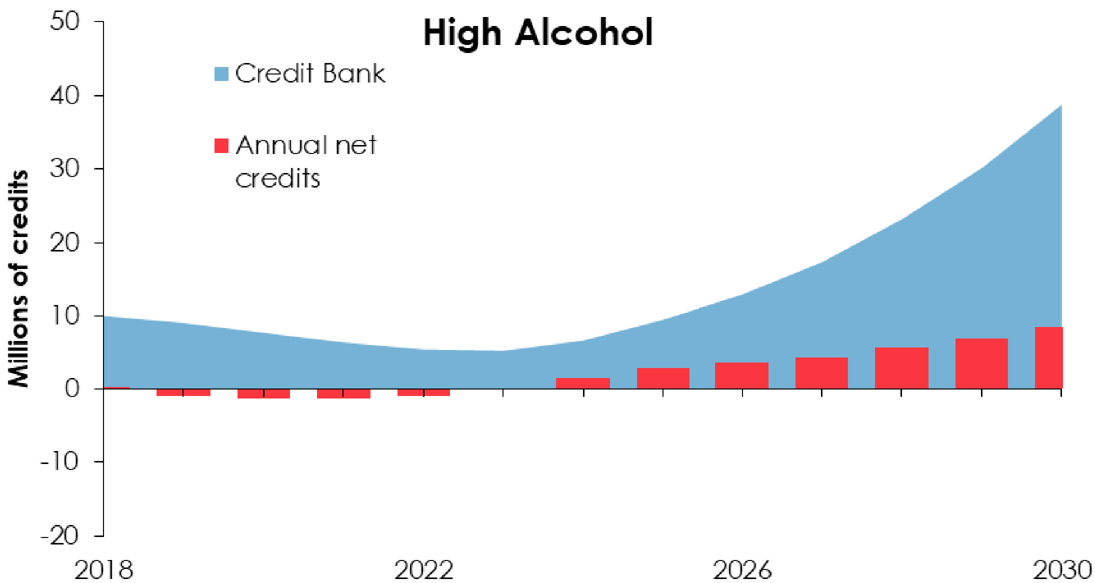

Figure 14 **Credit bank evolution for *High Alcohol* under draft compliance schedule**

Table 8 **Overview of results for *High Alcohol* scenario**

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.8	5.8	13.1
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.6	0.8
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.7	9.2
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.3	2.3	4.9
Additional credits from ethanol over steady progress (million tCO_2e)	0.2	1.6	2.8
Annual credit generation (million tCO_2e)	16.7	27.8	38.7
Banked credits at year end (million tCO_2e)	8.3	10.4	37.5
% CI reduction	**7.1%**	**14.9%**	**24.0%**

Cellulosic Breakthrough

In this scenario, all assumptions are the same as in the *Steady Progress* scenario, except that the roll out of cellulosic biofuel production is accelerated within the advanced biofuel deployment model detailed in (Malins et al., 2015). This acceleration is applied to both the cellulosic ethanol industry and the cellulosic drop-in fuels industry. By 2030, California consumes 500 million gallons of cellulosic ethanol and 300 gallons of cellulosic renewable diesel, jet and gasoline. The 2030 supply of cellulosic ethanol matches the supply of starch based ethanol. This represents a dramatic increase in cellulosic fuel supply, but the required growth rate remains modest compared, for instance, to the growth rates that would have been required from 2009 to 2022 to meet the original cellulosic fuel obligation under the Renewable Fuel Standard.

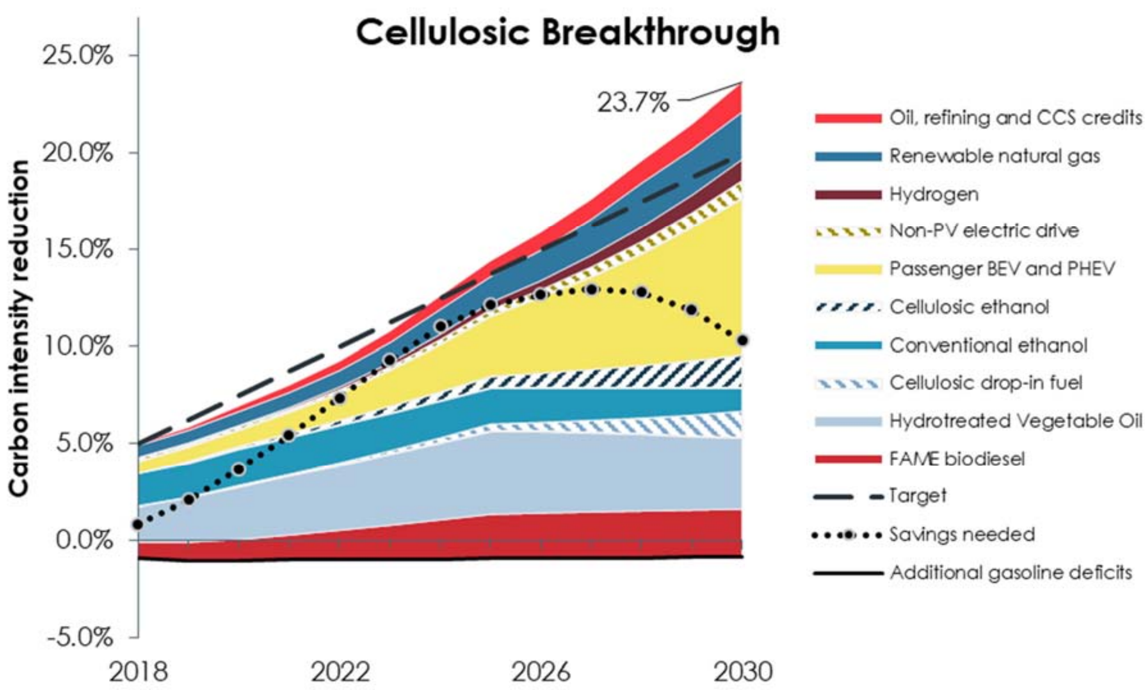

Figure 15 Carbon intensity reductions delivered in the *Cellulosic Breakthrough* scenario

As in the accelerated EV deployment scenarios, significant credit surpluses only start to appear at the back half of the 2020s (Figure 16), but by 2030 a bank of 28 million credits has developed (Table 9). In 2030, a 23.7 %carbon intensity reduction is delivered.

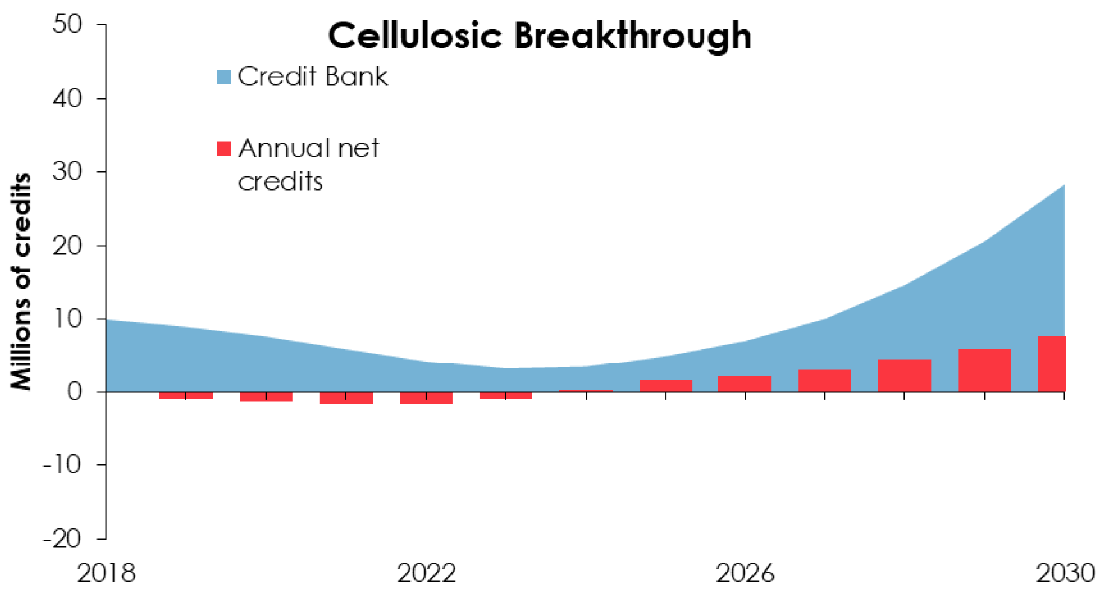

Figure 16 **Credit bank evolution for *Cellulosic Breakthrough* under draft compliance schedule**

Table 9 **Overview of results for *Cellulosic Breakthrough* scenario**

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.8	5.8	13.1
Credit generation by cellulosic biofuels (million tCO_2e)	0.4	1.8	4.9
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.7	9.2
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.1	2.5	5.2
Additional credits from cellulosic biofuel over steady progress (million tCO_2e)	0.2	1.2	4.0
Annual credit generation (million tCO_2e)	16.4	27.5	39.6
Banked credits at year end (million tCO_2e)	7.6	5.0	28.3
% CI reduction	7.0%	14.4%	23.7%

Clean Refineries

In this scenario, additional progress is assumed in the deployment of CCS at both ethanol and hydrogen production units associated with petroleum refineries from 2022 onwards, and also increased use of green hydrogen at petroleum refineries, compared to *Steady Progress.* Whereas in Steady Progress CCS is deployed only to California ethanol refineries, in Clean Refineries it is deployed for all starch ethanol consumed in California, doubling the rate of credit generation compared to *Steady Progress.*

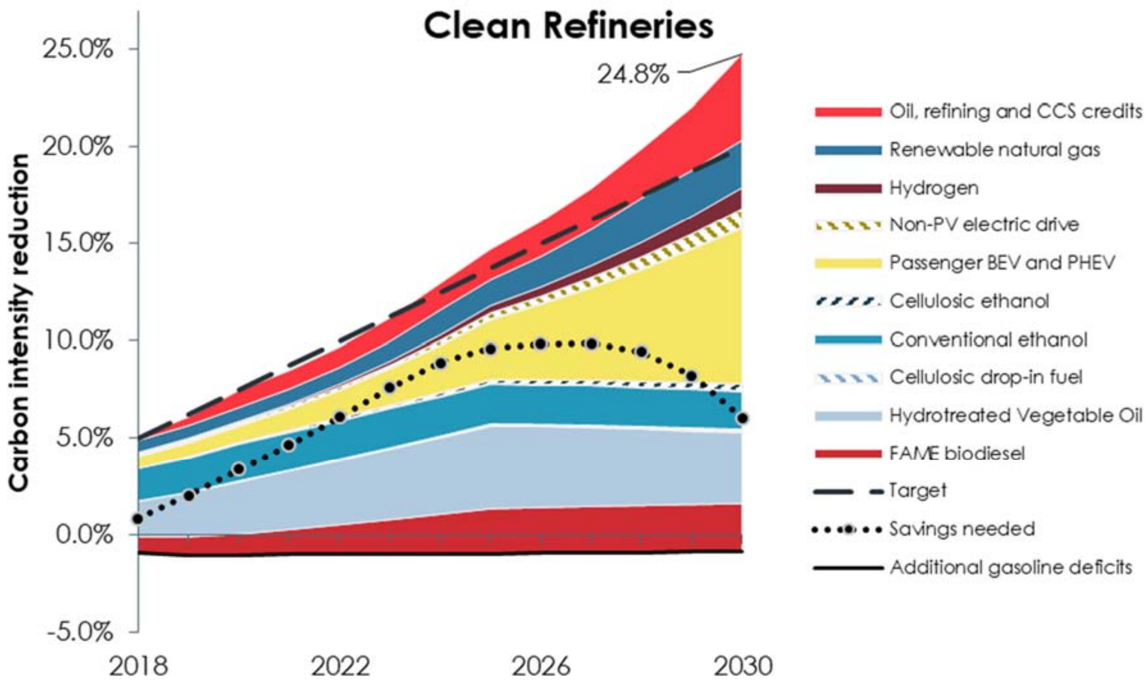

Figure 17 Carbon intensity reductions delivered in the *Clean Refineries* scenario

In this scenario, CCS is also deployed for steam methane reforming (SMR) units in Northern California, with an assumption of 60% CO_2 sequestration, delivering an additional 3.3 million tonnes a year of emissions reductions by 2030. Refinery use of renewable hydrogen is also increased, delivering 1.9 million tonnes of savings a year by 2030, reflecting the 'high' scenario from Stillwater Associates (2018). These additional greenhouse gas emissions reductions can be seen in the increased contribution from 'oil, refining and CCS credits' in Figure 17[17].

As detailed in Figure 17, by 2030 a 24.8% carbon intensity reduction is achieved. Annual credit surpluses start to grow from 2024 onward, resulting in significant credit banking when credit generation is compared to the draft compliance schedule (Figure 18), reaching 40 million tonnes of credits by 2030 (Table 10).

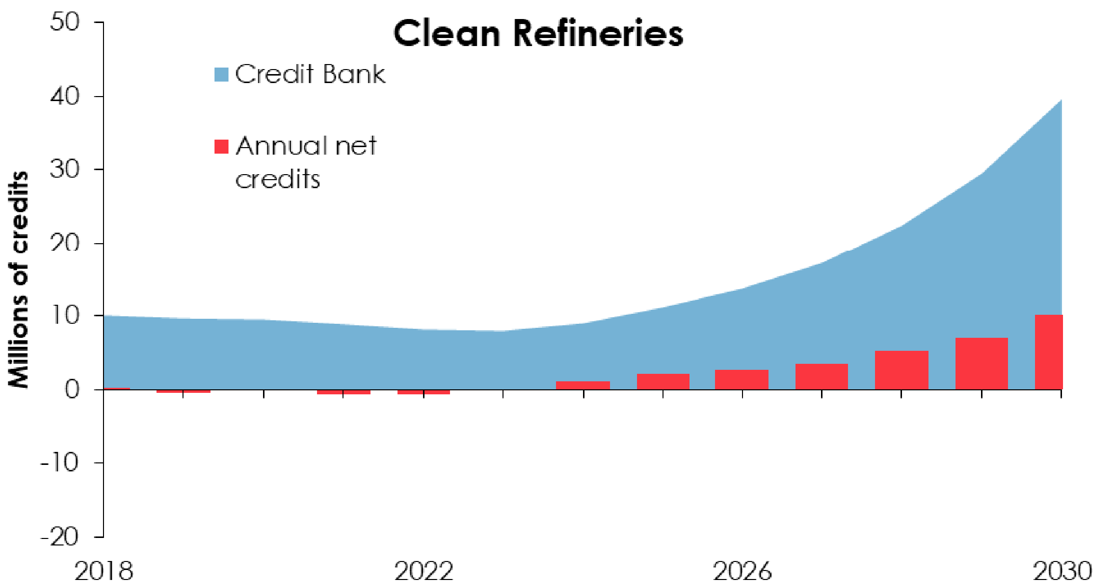

Figure 18 Credit bank evolution for *Clean Refineries* under draft compliance schedule

[17] Remembering that the savings delivered by CCS at ethanol plants are included in the 'oil, refining and CCS credits' category on the figure rather than in the 'conventional ethanol' category.

Table 10 Overview of results for *Clean Refineries* scenario

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.8	5.8	13.1
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.6	0.8
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.7	9.2
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	2.4	4.2	11.3
Additional credits from CCS over steady progress (million tCO_2e)	0.0	0.5	4.9
Annual credit generation (million tCO_2e)	17.6	28.2	42.5
Banked credits at year end (million tCO_2e)	9.5	11.2	39.6
% CI reduction	**7.5%**	**14.7%**	**24.8%**

Sensitivity scenarios – risks to rate of credit generation

In the previous section, five scenarios were presented in which accelerated rate of technology deployment (passenger or heavy duty ZEVs, increased ethanol blending, cellulosic biofuels and refinery emissions reduction) allowed for increase generation of LCFS credits. These positive outcomes resulted in carbon intensity reductions of 23.8-25.2% in 2030, and between 38 and 64 million tonnes of emissions reduction delivered above what is required by the draft compliance schedule.

In this section, in contrast, three cases are presented in which performance would be weaker than that detailed in *Steady Progress.* Firstly, a scenario is presented in which the rate of deployment of key technologies is slower than detailed in the *Steady Progress* scenario. Secondly, a case is considered in which reductions in passenger vehicle VMT proceed more slowly than anticipated in the main modeling, resulting in increased generation of deficits. Finally, a case is presented in which the credit generation performance of liquid diesel fuel substitutes (biodiesel and HVO) is reduced by the inclusion of an indicative term for indirect emissions in the lifecycle carbon intensity values.

Delayed Progress

In this scenario, deployment of key credit generation options is slow compared to the rates assumed in the *Steady Progress* case. Volumes of cellulosic biofuel production remain low, with only 19 million gallons of cellulosic ethanol and 62 million gallons of drop-in cellulosic fuels supplied by 2030. Simultaneously, the deployment of electric vehicles falls short of the Governor's target of 5 million, achieving only the Scoping Plan target of 4.2 million by 2030. In other regards, this scenario matches the *Steady Progress* scenario.

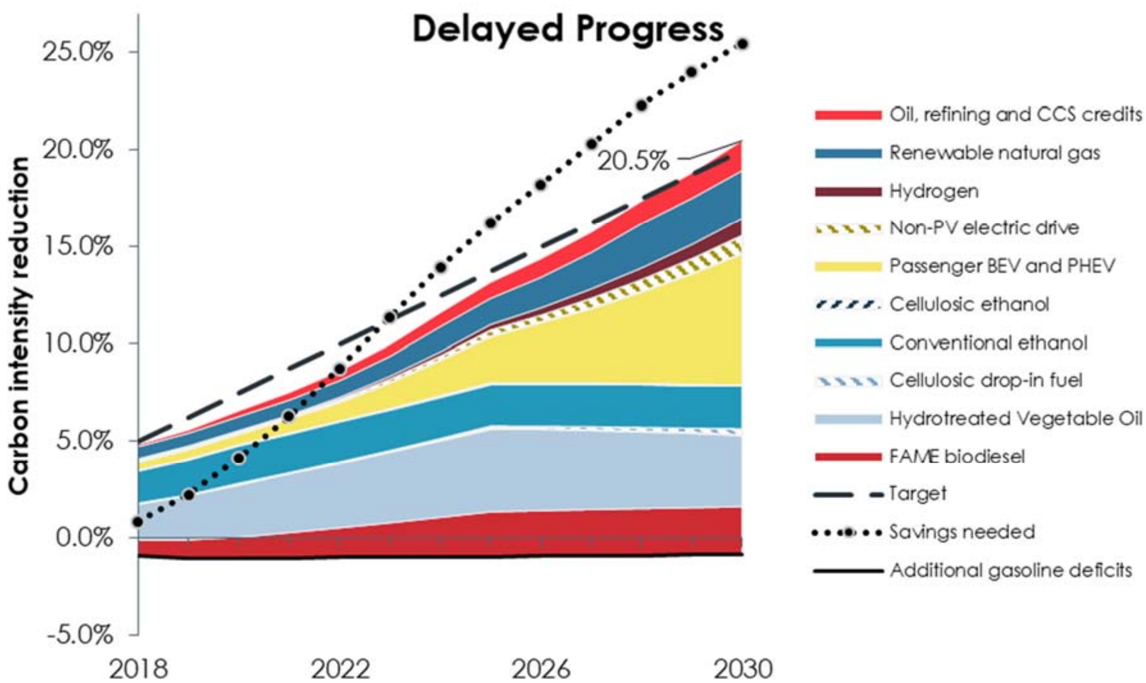

Figure 19 Carbon savings generated in the *Delayed Progress* scenario

The reduced deployment of these technologies means that, unlike in the *Steady Progress* scenario, annual deficits are generated every year until 2030, at which point the program starts generating net credits again as ZEV deployment accelerates. As shown in Figure 20, this results in a complete draw down of the credit bank by 2023, and the creation of a persistent deficit during the late 2020s, reaching about 11 million tonnes. Despite the deficits in intermediate years, the proposed 20% carbon intensity reduction target for 2030 is slightly exceeded, with a 20.5% reduction being delivered.

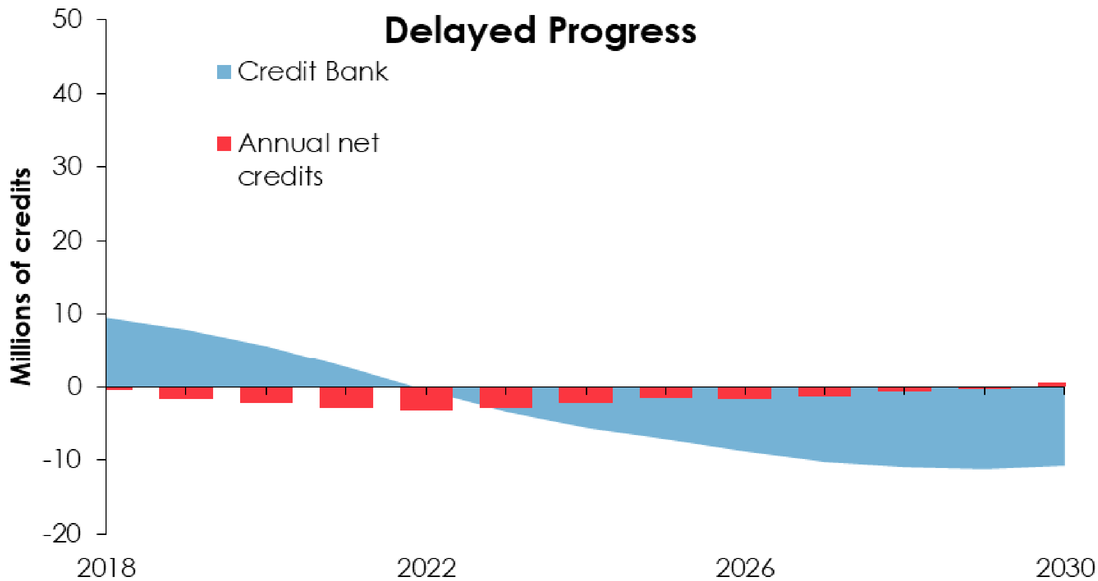

Figure 20 Credit bank evolution for *Delayed Progress* under draft compliance schedule

It is worth noting that because the *Delayed Progress* scenario is identical to the *Steady Progress* case except on cellulosic biofuel and ZEV deployment, it shares the slight reduction in the supply of HVO renewable diesel and jet after 2025 that is included in *Steady Progress*. Given a tighter credit market, this is one of the credit generation pathways that might be expected to respond in reality with increased fuel supply.

Table 11 Overview of results in the *Delayed Progress* scenario

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.2	4.4	10.9
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.3	0.6
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.7	9.2
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.1	2.5	5.2
Reduction in credit generation compared to steady progress (million tCO_2e)	-0.7	-1.6	-2.5
Annual credit generation (million tCO_2e)	15.6	25.0	33.9
Banked credits at year end (million tCO_2e)	5.6	-7.1	-10.7
% CI reduction	6.6%	13.2%	20.5%

Higher VMT

This scenario is identical to the *Steady Progress* scenario, except that a more modest reduction in vehicle miles travelled is assumed for passenger vehicles (3.5% instead of 6.9% from 2015 to 2030), resulting in higher overall demand for transportation energy. By 2030, this results in 1.6 million additional deficits being generated by fossil fuel use than in *Steady Progress* (Table 12).

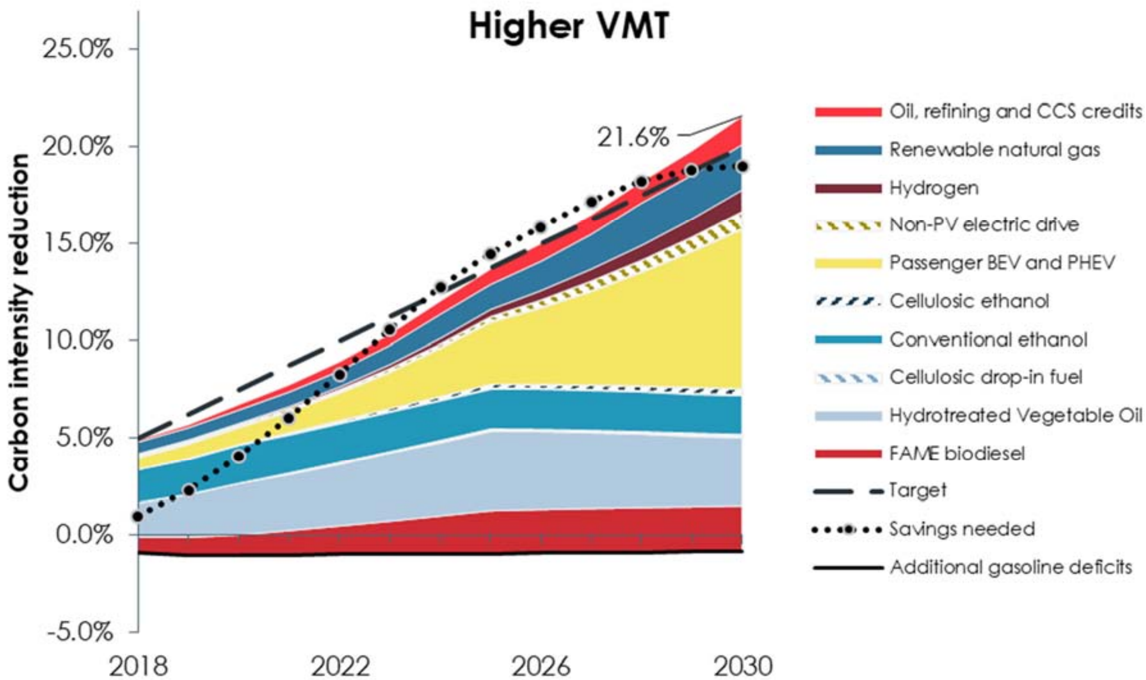

Figure 21 Carbon savings delivered in the scenario with a lower rate of VMT reduction

The higher rate of deficit generation results in a lower overall carbon intensity reduction in 2030 than is achieved in *Steady Progress* (21.6% rather than 21.9%, Figure 21). It also results in an increased rate of credit bank draw-down in the early 2020s, and a slight credit bank deficit from 2024 to 2027. The credit bank eventually grows back to 6 million in 2030 (Table 12).

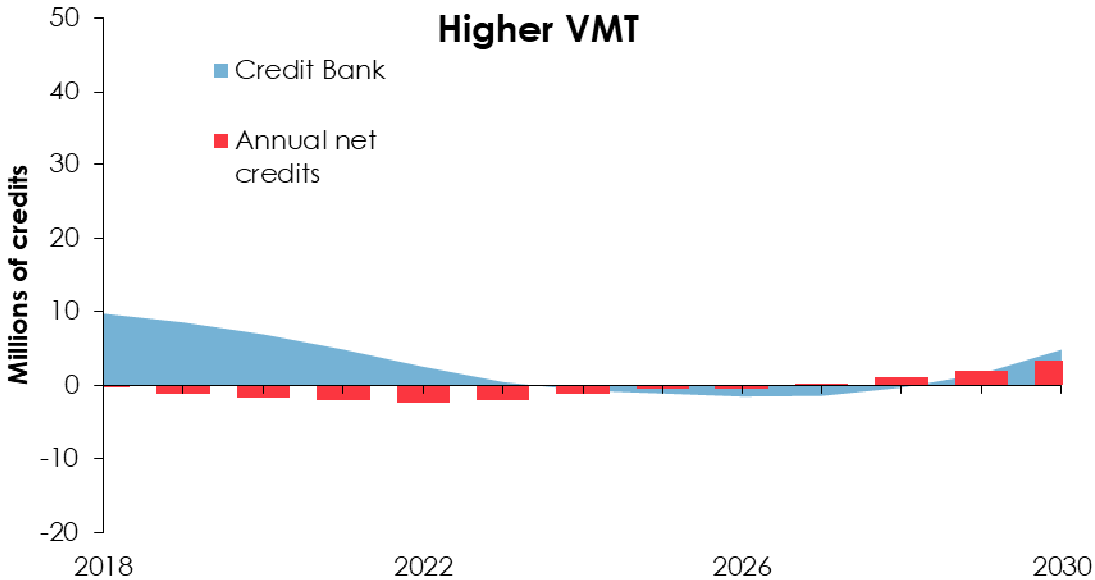

Figure 22 Credit bank evolution for *Higher VMT* under draft compliance schedule

Table 12 Overview of results for *Higher VMT* scenario

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.9	6.1	14.0
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.6	0.8
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	11.7	9.2
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.1	2.5	5.2
Additional deficits due to higher VMT (million tCO_2e)	0.7	1.2	1.6
Annual credit generation (million tCO_2e)	16.5	27.1	37.5
Banked credits at year end (million tCO_2e)	6.4	-2.1	5.9
% CI reduction	6.7%	13.7%	21.6%

Indirect emissions attributed to by-product and residual lipids

As discussed above, the current convention under the LCFS is to assume that using by-product or residual lipids such as animal fats and used cooking oils as biofuel feedstock is not associated with any indirect emissions. Given, however, that these are resources that are generally fully utilized in the economy already, for instance as animal feed ingredients, this assumption is likely an over-simplification that results in some indirect emissions effects being excluded from the lifecycle greenhouse gas emissions values for such biofuels. This scenario therefore considers the impact on credit generation of attributing an indicative level of indirect emissions to these lipid feedstocks.

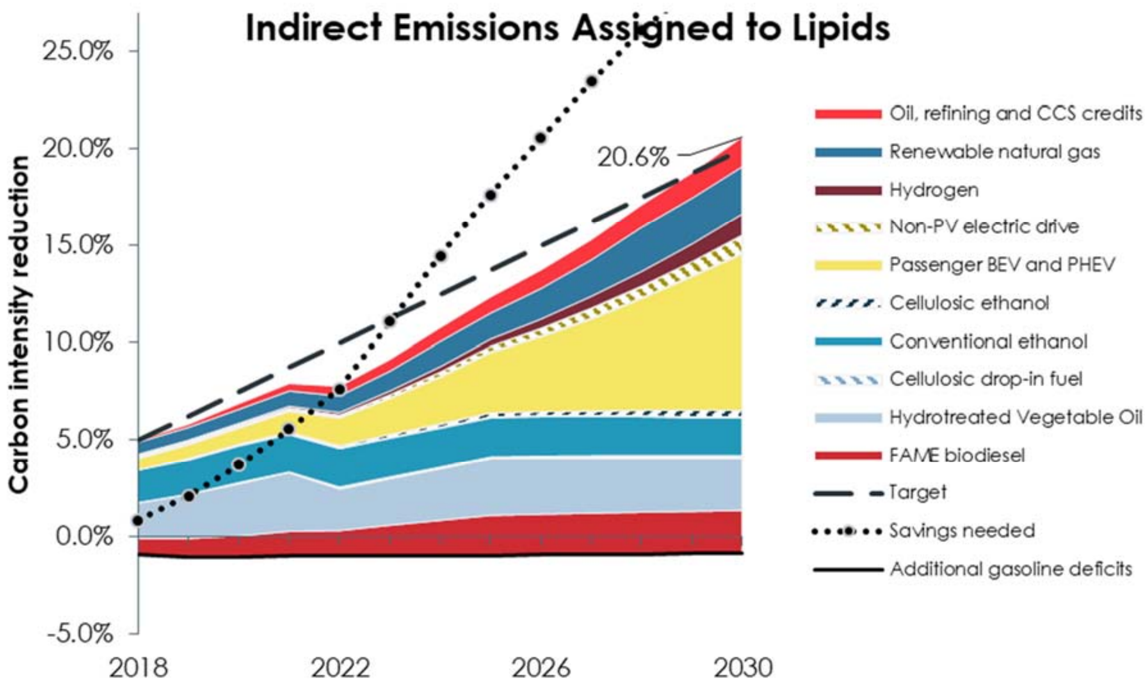

Figure 23 Carbon intensity reduction scenario with indirect emissions factors applied to used cooking oils and animal fats

The scenario is identical to the *Steady Progress* scenario, except that it is assumed that additional indirect emissions are attributed to used cooking oil and animal fat based biodiesels, to reflect the need to replace these materials in existing uses and to make the treatment of these feedstocks more comparable to that of crop-based feedstocks that have ILUC factors assigned to them. As discussed above, there is limited analytical work available attempting to quantify these indirect impacts ion the U.S. market. As a proxy for actual assessed indirect emissions values, the ILUC emissions of soy biodiesel are assigned to fuels from used cooking oil and from animal fats. This provides an illustration of the potential consequences for LCFS compliance of a change in the accounting regime for these oils. In recognition of the fact that it would take time for analysis to be undertaken of the indirect emissions associated with these fuels, and that it would also take time for any proposed regulatory change to be adopted, it is assumed in the modeling that these additional emissions are not counted until the year 2022 onward. This is evident in Figure 23 where a year on year reduction in total credit generation can be seen between 2021 and 2022.

As one might expect, reducing the credit generation per gallon of these biofuels results in lower credit generation than is seen in the *Steady Progress* case. When the supply of LCFS credits in this scenario is compared to the draft compliance schedule, deficits are generated each year up to 2029 (Figure 24), resulting in the spend-down of the credit bank and eventually in a 21 million tonne net deficit in 2030 (Table 13), although by this time the growth in credit generation through other compliance options has returned the program to annual net credits, with a 20.6% carbon intensity reduction delivered, ahead of the compliance schedule for the year. Just as it is important to recognize that in the real world the large supply of deficits in the more optimistic scenarios could result in low credit prices, it is important to recognize here that the tightness of the credit market would increase prices, and could well result in additional savings being delivered through the supply of other fuels.

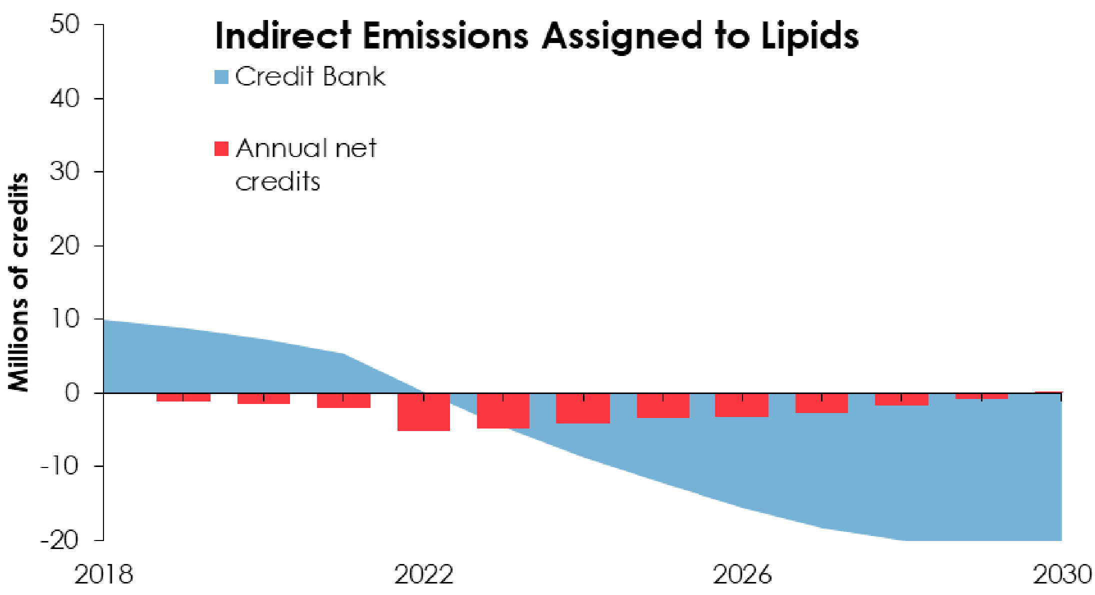

Figure 24 **Credit bank evolution for case with indirect emission assigned to lipids under draft compliance schedule**

Table 13 Overview of results for scenario with indirect emission assigned to lipids

	2020	2025	2030
Credit generation by light duty ZEVs (million tCO_2e)	1.8	5.8	13.1
Credit generation by cellulosic biofuels (million tCO_2e)	0.2	0.6	0.8
Credit generation by HVO and biodiesel (million tCO_2e)	8.0	8.1	6.6
Credit generation by renewable natural gas (million tCO_2e)	1.4	2.4	4.2
Credit generation by oil extraction and refining, CCS and other electrification (million tCO_2e)	1.1	2.5	5.2
Reduction in diesel substitute credits compared to steady progress (million tCO_2e)	0.0	3.6	2.7
Annual credit generation (million tCO_2e)	16.3	23.0	33.8
Banked credits at year end (million tCO_2e)	7.3	-12.3	-20.6
% CI reduction	6.9%	12.3%	20.6%

Discussion

The Low Carbon Fuel Standard is a vital plank of California's climate change mitigation efforts, delivering significant reductions in the global warming impact of California's transportation sector. In setting compliance requirements for the next phase of the program up to 2030 the ARB must balance the desire to deliver ambitious rates of decarbonization with the need to set targets that are affordable and achievable.

The Preliminary Draft Proposed Regulation Order for the next phase of the LCFS (California Air Resources Board, 2018b) includes a compliance schedule that would require 20% carbon intensity reductions from California transportation energy by 2030. The draft illustrative compliance scenarios for the LCFS in 2030 that have been released by the ARB (California Air Resources Board, 2017c, 2018a) include scenarios for delivering savings of between 10 and 25% by that time. Meeting the suggested 20% target would require ongoing evolution of California's transportation energy supply, through both electrification of road vehicles and continued expanded use of low carbon fuels. While delivering such a reduction in carbon intensity is not a trivial task, the scenarios presented in this report show that more ambitious targets than those proposed by ARB could be achieved; given reasonable rates of development of low carbon fuel technologies and the appropriate regulatory support, larger carbon emissions reductions could be achieved than would be required under the proposed compliance schedule. The *Steady Progress* scenario presented here shows a pathway to 22% CI reduction by 2030, while the High Performance case and the optimistic sensitivity cases indicate that with the right support targets as high as 25% could be deliverable in the 2030 timeframe.

The *Steady Progress* scenario assumes development of alternative and renewable fuel supplies that are generally based on moderate projections from existing literature and targets. Achieving the fuel supply modeled in this scenario would allow the draft compliance schedule to be comfortably met, with significant banked credits to spare. The credit generation potentials from each compliance option should not be taken for granted, but the utilization rates assumed in the *Steady Progress case* do not assume that any single pathway achieves at the higher end of its potential range. Given that some credit generation options, notably electric vehicles, can be expected to increase non-linearly especially coming up to 2030, the analysis suggests that it could be appropriate to toughen the compliance schedule between 2026 and 2030 to ensure that the LCFS credit price remains effective in driving new investments and pulling new low carbon transportation energy into the market.

Several scenarios are presented as sensitivity cases to illustrate the effects of credit generation from particularly significant pathways at the higher ends of their likely range. Performance at the higher end of plausible ranges for passenger ZEV's, heavy-duty vehicle electrification, cellulosic biofuels, ethanol utilization or CCS could support 2030 carbon intensity reduction targets in the 23-25% range. Near-term policy decisions could help determine the performance of these pathways, as well as the technical and regulatory feasibility of the high-alcohol scenario. California has considerable agency create the regulatory context that will help determine whether these more optimistic credit generation scenarios actually occur.

Three additional scenarios were modeled as sensitivity cases to test the implications for the LCFS program of under-performance of one or more pathways. The scenarios with higher VMT, with indirect emissions assigned to lipids, and with slower development of the electric vehicle market and cellulosic biofuels industries tested significant under-performance in aspects of significance, but the reduction in delivered carbon saving in 2030 in all cases was one and a half percentage points or less compared to the *Steady Progress* scenario. In any case, in the event of under-performance in any of these aspects, or in others, there are several possible counteracting factors: under-performance of any pathway would tend to result in higher LCFS credit prices, bringing more supply of other credit generation options on-line through market effects; CARB or other policy-makers could increase supply of other credits through complementary policies; and additional credits could come from pathways not modeled in this research (see "Credit Generation Opportunities Not Modeled").

The draft compliance schedule that has been proposed for the period from 2019 to 2030 starts with a slight reduction of targets for 2019 and 2020 compared to the current levels. The modeling undertaken for this report suggests that the ARB has made a reasonable decision in suggesting a slight relaxation of the rate of growth of targets, allowing compliance to be achieved over the coming years without expecting the existing credit bank to be fully exhausted.

At the other end of the regulatory period, the target of 20% proposed for 2030 is already slightly higher than the target outlined in initial illustrative compliance scenario assessment; this higher level of aspiration is supported by the outcomes of the modeling presented herein. While the modest increase in aspiration for 2030 is welcome, the modeling also suggests that the fully linear increases in the compliance schedule from 2023 to 2030 may not adequately reflect the non-linearity that can be expected in growth of supply of some categories of compliance credits, especially towards the end of the coming decade. In particular, as electric vehicles become a larger part of the vehicle pool, electricity consumption for transportation will increase rapidly. Coupled with reducing carbon intensity in the grid electricity mix, this growth will generate very significant numbers of LCFS credits. Perhaps harder to predict is the rate of development of CCS technology. Even the *Clean Refineries* case presented here includes only a modest roll out of CCS technology for relatively easy to capture CO_2 streams at ethanol and petroleum refineries. A breakthrough on CCS costs could make very large emissions reductions achievable at prices well below recent LCFS credit prices; emissions reductions that would inevitably accelerate during the 2020s as the technology is demonstrated.

In all of the scenarios presented here, compliance against the proposed targets becomes easier (or over-compliance increases) as the program approaches 2030. Without adjustment to the compliance schedule, this would drive significant credit banking; but it may also result in such a reduction of LCFS credit prices that supply would drop off, undermining the very businesses that will have facilitated success in the program. It would therefore be appropriate for the ARB to consider setting a more stringent trajectory in the years from 2025 to 2030, to ensure that the LCFS continues to represent a strong driver for progress in the context of increasing credit supply.

Part of the elegance of the LCFS is that it allows a range of decarbonization options to be supported alongside each other on their carbon intensity reduction merits. It would be pointless to pretend that it is possible to accurately predict the full array of low carbon fuels that will be available to California in 2030, and therefore the scenarios presented in this report are just that – scenarios rather than predictions. The decision as to the appropriate level for future LCFS targets is necessarily not a purely technical one, but also a political one. It is our hope that the scenarios presented here may inform the ARB's decision making in this regard, and help demonstrate that targets moderately more ambitious than the 20% for 2030 suggested in the Preliminary Draft Proposed Regulation Order would be reasonable.

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Annex A Updates to modelling framework

A.1 Scaling to California

Malins et al. (2015) is based on results from the VISION 2014 model for the whole of the United States. In order to provide results relevant to the Pacific region, the VISION 2014 outputs were scaled down by the fraction of VMT driven there. In this study, the gasoline and diesel markets have been scaled separately, based on reported consumption of gasoline type and diesel type fuels in California (California Air Resources Board, 2017c).

A.2 Compliance curves

For visualization of results, the compound regional compliance curves developed for Malins et al. (2015) have been replaced by the illustrative compliance curve to 2030 from California Air Resources Board (2018b). The number of banked credits in 2016 is set to 10 million, also based on California Air Resources Board (2017c).

A.3 VMT

The ARB draft illustrative compliance scenarios show significantly lower 2030 total fuel demand than was output by the VISION 2014 model based on default VMT assumptions. As explained in the body of the report, a 6.9% reduction in passenger vehicle VMT has been assumed in the baseline, making the model slightly more conservative on overall reductions in California transportation energy consumption than California Air Resources Board (2017c).

A.4 VISION 2017

The data in the VISION worksheets *Population-GDP data*, *Util Mix, Auto-LT data* and *LV VMT data* have been updated to VISION 2017.

A.5 Additional compliance options

A range of refinery related additional credit generation options that have been added to LCFS since the publication of Malins et al. (2015) have been added to the model. Credits for refinery investment and green hydrogen use are as detailed in the body of the report. Credit generation by innovative crude production and by low energy use refineries are based on the Project/LD/High ZEV/20% scenario in California Air Resources Board(2018a).

A.6 Natural gas vehicles

The VISION 2014 data for natural gas consumption in transportation results in an underestimation of natural gas consumption in the California market. The NG vehicle sales shares for 2010 and 2020 have been calibrated to deliver NG consumption results matching reported California data for 2010 and California Air Resources Board (2017c) for 2020.

A.7 First generation biofuel blends

The initial blends of ethanol and biodiesel have been calibrated to reported fuel volumes. For 2016, the biodiesel blend is 4.25% and the ethanol blend 10.26%. Given progress in resolving NOx emissions issues associated with higher biodiesel blends, the average biodiesel blend in the model is allowed to reach 7.4% by 2020 and 15% by 2030.

A.8 HVO supply

The initial supply of HVO to California has been updated to match reported volumes (California Air Resources Board, 2017c).

A.9 Cellulosic biofuel supply

The list of anticipated facilities from Malins et al. (2015) has been replaced in recognition of delays and cancellations in the intervening period. Cellulosic ethanol projects are based on data reported by Ethanol Producer Magazine[18], while data about pyrolysis and FT plants has been updated on a project by project basis.

A.10 Carbon intensity of biofuels

In general, the carbon intensities used in Malins et al. (2015) are considered to remain reasonable and have been reused.

For the case of renewable natural gas, the average carbon intensity has been adjusted to reflect the potential for increased supply of dairy gas with a large associated emissions credit. Dairy gas supply and landfill gas carbon intensity assumptions are taken from California Air Resources Board (2017c).

For the case of sugarcane ethanol, Malins et al. (2015) assumed used an approved pathway including an electricity cogeneration credit to set the starting carbon intensity. The ARB illustrative compliance scenarios assume a starting sugarcane ethanol carbon intensity that excludes that credit, and therefore a higher starting carbon intensity of 45 gCO_2e/MJ has been adopted for this report. As in the previous study, this carbon intensity is modeled as falling to 24 gCO_2e/MJ over time.

A.11 Carbon intensity of fossil fuels

The carbon intensity of fossil fuels has been updated to reflect values in California Air Resources Board (2018b).

A.12 Passenger electric drive vehicles

It is assumed that 20% of the EV fleet is in category ‘A’ (range around 100 miles) and 80% in category B (range around 200 miles), and that 20% of the PHEV fleet is in category A (able to run 10 miles on battery) and 80% in category B (able to run 40 miles on battery).

18 http://www.ethanolproducer.com/plants/listplants/US/Operational/Cellulosic

A.13 Medium and heavy duty electric drive vehicles

The VISION 2014 model does not include representation of medium and heavy duty electric vehicles. An increasing fleet of these vehicles has been modeled outside the VISIO framework by assuming that MD/HD electric vehicles displace an amount of diesel consumption proportionate to the number of vehicles in the medium and heavy duty categories respectively, as detailed in the body of the report. In order to be conservative, it has been assumed that each MD/HD vehicle displaces only 90% of the energy used for a conventional drive vehicle.

Annex B California Clean Medium/Heavy-Duty Vehicle Stock in 2030: Feasible Optimistic Scenario

This additional analysis was performed by and is included by kind permission of Ryan Schuchard of CALSTART.

	Current (est.)		Feasible Optimistic Scenario by 2030			
	NGV[19]	ZEV[20]	NGV	ZEV	Hybrid[21]	Notes[22]
All MD (Class 2B-6)	1,000	300	75,000	36,700	nil	Figures taken from CARB's Scoping Plan ("Vision Cleaner Technologies and Fuels scenario" in Appendix D – p. 16). Note that ZEV adoption highest in class 2B and last mile delivery trucks. Figures could arguably be higher if they incorporated ZE truck rule (15% of 2B-8 purchases ZE by 2030) or Jan 2018 Executive Order E-48-18, which sets target to deploy 5M ZEVs by 2030.[23]

[19] Natural Gas Vehicles. Assume 90%+ of fuel use is RNG.

[20] Zero-Emission Vehicles including battery electric and fuel cell vehicles

[21] Hybrid includes electric hybrid vehicles, plug-in hybrid electric vehicles (PHEV) that allow for some zero-emission range, and extended range (XR) vehicles that have series electric drive with power generator to allow longer range driving

[22] CARB scenarios taken from CARB Scoping Plan, Appendix D. Note that CARB assumes 4.2M electric LDVs in addition to MHDVs here.

[23] For reference, the minimum number of ZE class 2B-7 trucks required by ZE truck rule (15% of purchases ZE by 2030) corresponds to around 27,000 ZE trucks, based on 1.3M vehicles in class 2B-3 fleet and 386,300 in class 4-7 fleet, assuming 11 year vehicle life. Truck rule presentation: https://www.arb.ca.gov/msprog/actruck/mtg/170830arbpresentation.pdf. Also, the shuttle rule requires 100% of purchases ZE by 2030. Shuttle rule presentation: https://www.arb.ca.gov/msprog/asb/workgroup/dec4presentation.pdf.

HD Transit	4,000	150+	2,000	8,000	500	ZEV number based on proposed Innovative Clean Transit Rule (ICTR; ZE purchase requirement phasing from 25% for large fleets in 2020 to 100% for all fleets in 2029). Total pop is around 11,000. Assume most of remainder is NG, based on NGV Roadmap, p. 10 (5000 by 2030), developed prior to ICTR.
HD Refuse	2,000	Pilots	6,400	500	nil	Total pop is 11,000. HD refuse NG from NGV Roadmap, p. 10 (6400 by 2030). HD refuse EV is a rough estimate. Assumes some takeoff but limited size (5% of market)
HD Hostler	nil	Demos	nil	2,500	nil	Total pop is ~5,000. HD hostler EV extrapolated from CALSTART CTM (1000 by 2025)
HD Drayage	2,000	Demos	5,000	7,000	500	Total pop is ~20,000. HD drayage NG from NGV Roadmap, p. 10 (4077 at POLB by 2030). See also CALHEAT. HD EV figures from CTM (5000 by 2025)
HD Delivery	100	Demos	3,000	75000	nil	Total pop is ~75,000. NG 2030 figures from NGV Roadmap, p. 10. 2030 EV figures extrapolated from CALSTART CTM (1500 by 2025) and assume 1,000 in annual sales starting by early 2020s.
HD Regional Haul	~4000	Demos	3,000	7,500	nil	NG 2030 figures from NGV Roadmap, p. 10. HD 2030 figures assume 1,000 in annual sales starting by early 2020s.
HD Line Haul	~4,000	nil	41,000	2,000	500	Total pop is 175,000. NG 2030 figures from NGV Roadmap, p. 10. ZEV growth potential has big unknowns. 50 ZEVs in 2019 with 20% CAGR would equate to ~2400 cumulative sales by 2030, or 2,000 purchased after 2023 which would all contribute to 2030 vehicle stock, assuming 7-year vehicle life.

B.1 Discussion

The 2030 figures are intended to illustrate on-road vehicle stock that can reasonably be expected in California by 2030 assuming implementation of major clean vehicle regulations that are currently being proposed, including the Innovative Clean Transit Rule (ZE purchase requirement phasing from 25% for large fleets in 2020 to 100% for all fleets in 2029) ZE shuttle rule (ZE purchase requirement of 100% of by 2030) and clean truck rule (ZE manufacturer requirement of 15% of class 2B-8).

The above is not a projection, but rather, a scenario for an optimistic but plausible number of clean vehicle deployments. Critical variables that will affect actual vehicle deployments include (1) Battery costs, weight, charging speeds, and lifespan, (2) Adoption of autonomous and TNC driving tech, (3) Fuel prices, (4), Availability of R&D and incentive funding, (5) Availability of fueling and charging infrastructure, and (6) Supporting laws and regulations.

For simplicity, we assume that between now and 2030, the total number of vehicle stock and fuel use will remain relatively constant (for the latter condition, an increase in both VMT and fuel economy cancel each other out).

Although NGVs and ZEVs are broken into separate categories, we can assume for a high-deployment scenario that 80-100% of NGVs use renewable fuel, and hence for the purposes of modeling, the two categories have similar CI profiles.

Additional ZEV deployments that could be expected include forklifts (193,000 by 2030 for in-between case), airport GSE (5,000), truck stop electrification (2,000), and TRUs (67,000).[24]

B.2 Additional References:

CALSTART (2015) CALHEAT

CALSTART (2014) NGV Roadmap

ICF TEA Study (2014)

CARB (2017). Proposed Fiscal Year 2017-18 Funding Plan for Clean Transportation Incentives

[24] ICF, 2014.

Annex C Detailed credit generation in *Steady Progress* and *High Performance* scenarios

Table 14 Credits generated (million tonnes) by low carbon fuel pathways considered in the *Steady Progress* scenario

Fuel	2020	2025	2030
Starch Ethanol	2.6	2.0	1.5
Sugar Ethanol	1.0	1.1	0.9
Cellulosic Ethanol	0.1	0.4	0.6
Renewable Gasoline	0.0	0.0	0.1
Hydrogen for LDVs	0.1	0.6	1.4
Electricity for LDVs	1.8	5.8	13.1
CARBOB Deficits	-14.8	-21.8	-25.9
Biodiesel	2.3	4.1	3.7
Renewable Diesel	5.8	7.8	5.7
Renewable NG	1.4	2.4	4.2
Electricity for HDV	0.0	0.3	1.6
Electricity for Rail/Forklift/etc.	0.4	0.3	0.3
Diesel Deficits	-2.9	-4.3	-6.6
Cellulosic diesel	0.0	0.1	0.2
Refinery CCS and Investment Credits	0.1	0.3	0.8
Refinery Renewable Hydrogen	0.2	0.5	0.8
Innovative Crude Credits	0.3	0.9	1.0
LC/LEU Refinery	0.2	0.2	0.2
Ethanol CCS	0.0	0.0	0.6

Table 15 Credits generated (million tonnes) by low carbon fuel pathways considered in the *High Performance* scenario

Fuel	2020	2025	2030
Starch Ethanol	2.6	1.8	0.9
Sugar Ethanol	1.0	1.0	0.6
Cellulosic Ethanol	0.3	1.1	2.7
Renewable Gasoline	0.0	0.0	0.4
Hydrogen for LDVs	0.1	0.7	1.9
Electricity for LDVs	1.8	6.5	15.5
CARBOB Deficits	-14.9	-21.9	-25.8
Biodiesel	2.1	3.7	3.3
Renewable Diesel	5.8	8.0	6.7
Renewable NG	2.2	3.5	5.4
Electricity for HDV	0.0	0.3	1.6
Electricity for Rail/Forklift/etc.	0.4	0.3	0.3
Diesel Deficits	-2.8	-3.7	-5.3
Cellulosic diesel	0.0	0.3	1.2
Refinery CCS and Investment Credits	0.1	0.4	2.1
Refinery Renewable Hydrogen	1.6	1.6	1.9
Innovative Crude Credits	0.3	0.9	1.0
LC/LEU Refinery	0.2	0.2	0.2
Ethanol CCS	0.0	0.0	0.6