LLNL-CONF-750270

LAWRENCE LIVERMORE NATIONAL LABORATORY

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April 26, 2018

International Conference on Negative CO2 Emissions
Göteborg, Sweden
May 22, 2018 through May 24, 2018

Making Negative Emissions Economically Feasible: The View from California

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Abstract Obtaining carbon dioxide atmospheric removals on the gigaton scale imagined by current discussions requires immediate attention not just to the technologies, but also to the economic and business conditions required to make those technologies viable. One of the most important issues is to make profitable businesses now, so that technologies demonstrated today can begin to reap the benefits of learning-by-doing and grow at realistic rates to meet the future demand. The U.S. State of California is likely to be fertile ground for the growth of these businesses because of existing beneficial policies and circumstances. The key example of such a California policy is the Low Carbon Fuel Standard (LCFS), which has been an effective approach for gradually reducing the carbon footprint of transportation fuels. Under the LCFS, transportation fuels sold in California are assigned a lifecycle carbon intensity. Sales of fuels with a carbon intensity above an annually declining limit incur a deficit that must be offset by purchasing credits generated from the sale of alternative fuels with a carbon intensity below the standard. Over the past year, this value per ton of emissions reductions has traded at about \$100/tCO_2 (ranging from \$80 to \$140). The governing regulations for the LCFS are in the process of being revised so that Carbon Capture and Storage (CCS) and direct air capture may be included as a means of reducing fuels' carbon footprint. If approved, the emissions reduction resulting from use of CCS will reduce the fuel carbon intensity. Reduction of the carbon intensity below zero would be valued as any other reduction, thus creating the first substantial payment system for negative emissions.

1 Introduction

Negative emissions on the scale of billions of tons of CO_2 will require industries on the scale larger than today's oil or grain industries, which move on the order of one to two billion tons of product per year. Many business models will have to be tried and optimized in order to succeed at this scale. With the world's government and environmental systems primarily (and properly) focused on reducing today's emissions, a major challenge for the developers of negative emissions technologies is the issue of how to create successful businesses that can examine many different technologies and commercial approaches, finding and growing the successful ones to the scale of today's largest enterprises. Early success in negative emissions

technology is likely to be predicated on finding the right business case, rather than the optimal technology.

2 The California Low Carbon Fuel Standard (LCFS)

The State of California controls the carbon intensity (CO_2 emitted per MJ of energy) for liquid transportation fuels. This is done by means of a Low Carbon Fuel Standard, which requires anyone producing or selling a fuel to meet the current year's standard for carbon intensity, or in the event that their fuel does not meet that standard, purchase credits from another seller who has an excess available from selling fuel that is below the current standard. The LCFS has several interesting aspects designed to increase technology adaptation. First, it is technology neutral: it does not specify how the carbon intensity is to be reduced, and is broadly acceptant of the use of biofuels, increase in production efficiency, using renewable energy for production and refining, and switching electrified or hydrogen powered vehicles. Second, the standard decreases every year by roughly 1%, forcing the adoption of new approaches and technology in order to remain in compliance.

The California LCFS has been a remarkably effective policy. After surviving a serious court challenge that resulted in a two-year hiatus from 2013-2015 with the standard frozen at a 1% reduction, the standard now stands at -3.5% from the original baseline of 98 grams CO_2 per MJ of energy. In the period from 2011 to 2015, the mandated reductions amounted to 9.2 million tons of CO_2 (equivalent), but the actual compliance far exceeded that, totaling 16.8 million tons.[1] (The excess 7.4 million tons of credits are saved for future use). By the end of 2017 the bank of excess credits stood at about 9.5 million tons.[2] Fuel sellers buy credits on an open market, and the price fluctuates depending on availability and apparently on expectations of future needs. The credits are priced in terms of tons of CO_2 avoided, based on calculations for specific fuel pathways. During the protracted legal battle of 2013-2015 prices fell as low as \$20, and briefly this year rose as high as \$140. The system is designed to operate in the vicinity of \$125/ton.

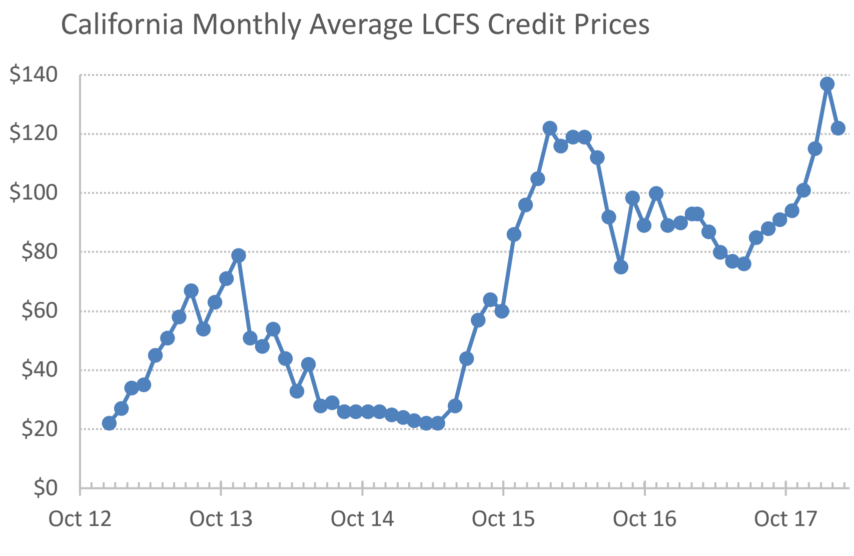

Figure 1: Average California LCFS credit prices, from the California Air Board.[2]

The LCFS has been proposed[3] to be extended to year 2030, with an increased carbon intensity goal of -20% (Figure 2).

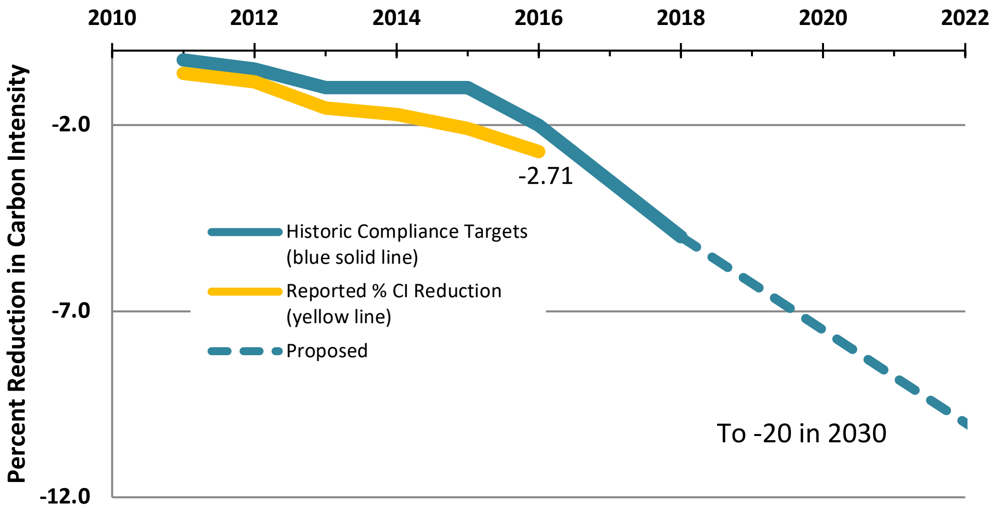

Figure 2: Composite carbon intensity reduction for gasoline and diesel.[2]

The proposed changes in the LCFS also include new ways to participate. These are so-called fuel pathways, or approved ways to reduce the carbon intensity. The LCFS rules outline general guidelines for these pathways, and then each producer with a new proposed approach must have their pathway approved for both technical and accounting details. In the new proposal, carbon capture and storage may be used to reduce the carbon intensity. In addition, direct air capture is proposed as a kind of post-emissions carbon intensity control.

It is important to note that the LCFS applies to fuels sold in California but is *not* restricted to any geography of fuel origin. Assuming that the CCS and air capture amendments are approved as proposed,[4] they will also not be geographically limited. This is particularly interesting for air capture, which can be operated at an optimal location for capture and storage.

Obtaining credits under the LCFS is a rigorous process, and if the CCS protocol is approved, it will add significant complexity in the form of storage assurance and monitoring costs. Among the costlier aspects of the draft protocol is the need for construction of new wells built to very high standards, and a provision for 100 years of monitoring. These restrictions are not in general based on the climate potential of the stored CO_2, but rather the accounting rigor required to ensure that the large up-front payment made for storing the CO_2 is reflected in long-term assured storage.

3 Opportunities for Negative Emissions

The technology-neutral format of the California LCFS contributes to a broad range of contributing approaches.[2] One of the most valuable aspects is that the seller's ultimate carbon intensity is the average of the carbon intensity of all the fuels produced or sold by that entity. This means that a small amount of very now carbon intensity fuel has a large impact. Today's standard is a 3.5% reduction, and many fuels such as hydrogenated soybean oil have carbon intensities in the range of 20-30 grams CO_2/MJ. Mixing a small amount of those into fossil

diesel at nearly 100 grams CO_2/MJ has a high leverage effect, and as such is highly valued (this is why the LCFS is measured in terms of tons of CO_2 avoided). Improving your process or feedstock is directly reflected in your bottom line, and if you are able to drive your process to actual negative emissions, it continues to be valued in a linear fashion. To our knowledge LCFS systems are the only climate mitigation scheme that currently has this trait.

The earliest opportunity for negative emissions associated with the California LCFS is for ethanol refineries. Capturing the CO_2 from fermentation and distillation can significantly reduce the carbon footprint of his production. Sanchez *et al.*[5] evaluate the opportunity this presents in the central United States and find that costs should be very low for capture and pipeline transport to appropriate underground storage sites. More than 30 million tons could be managed, including pipeline construction, at a credit of $60/ton. If the new California LCFS CCS protocol is approved, it is expected to generate an immediate push to create these capture and storage facilities. In conjunction with the new '45Q' storage tax credit in the United States which provides a $50 tax credit for geologically stored CO_2, ethanol producers will be highly incented to undertake CO_2 storage activities.

Sanchez et al.[5] evaluated whether these ethanol refineries can actually achieve negative emissions, even with a biologically-derived feedstock. Based on the work of McCoy[6] who calculated that the use of CCS on average corn ethanol plants can reduce the carbon footprint of the ethanol by 32 grams CO_2/MJ, they estimate that US plants can produce ethanol with a footprint of 25 grams CO_2/MJ. While this is dramatically smaller than conventional fossil gasoline at 98 grams CO_2/MJ, it is still not formally *negative.* The principal contributors to the remaining emissions are indirect land use change and agricultural practice such as fertilizer and fossil fuel use.

Our assessment of most current fuel production schemes is that it will be difficult to drive them to truly negative emissions values because of indirect land use change. To the extent that this can be reduced by increasing efficiency, utilizing waste materials such as manure, or using biofuel precursors that are not grown on land used for agriculture, there is an opportunity for true negative emissions. In California the most important examples of this are the use of compressed natural gas derived from dairy manure fermentation, and the creation of bio oil from forestry wastes and clearing for fire control. Both generate a fuel that is close to zero carbon intensity, but nearly half of the carbon that enters both processes escapes as CO_2. Capturing and storing this CO_2 provides a dramatic opportunity for true negative emissions, but the infrastructure and processes required to do this are not yet established. In the case of pyrolysis, a secondary product is biochar, which if used in a way that has a long lifetime, can provide significant reduction in ultimate carbon intensity.

4 Negative Emissions Through Forest Waste Auto-thermal Pyrolysis

The 'well-to-wheel' life cycle carbon intensity of fuels produced using pyrolysis pathways has been investigated in at least three studies.[7-9] These studies have considered both a range of different cellulosic feedstocks, including wood (pine, poplar, mixed residues), corn stover, and switchgrass, and integrated system configurations. Six out the total 12 fuel pathways in these studies consider wood as a feedstock: the carbon intensity of diesel fuel produced via these

pathways is estimated to be between zero and 54 gCO_2-eq/MJ. Notably, four of the six pathways estimate a carbon intensity less than the California Air Resources Board reference baseline for renewable diesel (39 gCO_2-eq/MJ).

Autothermal pyrolysis improves the carbon footprint of the process by removing fossil fuel as a heating source. Air is bled into the process to combust a small amount of the biomass, providing the necessary heat. Iowa State University[10] has developed this technique and will be demonstrating it in California, in partnership with LLNL, in the summer of 2019, treating 1000 tons of forest waste and producing 40,000 gallons of bio oil and 200 tons of biochar. We expect that the resulting carbon intensity from the fuel produced using autothermal pyrolysis of forestry residues will be towards the low end of the range presented in the literature for four reasons.

1. In our demonstration project, the feedstock (i.e., wood residues) is a waste from processing of wood into building products. Thus, in an attributional lifecycle assessment (LCA) framework, the environmental burdens associated with harvesting and transport of the wood would be allocated to the building products, rather than the waste. This would, for example, reduce the fuel carbon intensity by at least 50%, to between 9 gCO_2-eq/MJ and 20 gCO_2-eq/MJ, in the three pathways considered by Meyer et al.[9] Of course, should autothermal pyrolysis be widely successful, and the demand for forestry residues exceed the current California supply (i.e. approximately 2 million BDT per year), environmental burdens associated with harvesting and transport of wood may need to be allocated between the resulting wood products and fuel.
2. By its nature, ISU's autothermal process does not require additional heat input in the form of natural gas during normal operations, which is often required in traditional pyrolysis processes. Moreover, in the demonstration project, we will use electricity produced from on-site wood-fired power plant. Meyer et al.[9] and Han et al.[7] both show that natural gas and electricity consumption are substantial contributors to the carbon intensity of fuels produced from pyrolysis pathways. Thus, eliminating use of natural gas and using electricity with a near-zero carbon footprint will further reduce the carbon intensity of the resulting fuels.
3. The commercial autothermal process could produce low-CI ethanol (or, potentially, butanol) as a co-product, which may further reduce the carbon intensity of the diesel (or gasoline) products via allocation of the environmental burdens of the process to the co-products. Moreover, in the commercial implementation it may also be feasible to produce bio-gas from AD of wastewater streams. Use of this bio-gas, either as fuel for on-site electricity generation, as vehicle fuel could also benefit the carbon intensity of the diesel or gasoline products.
4. Pyrolysis processes, including ISU's autothermal pyrolysis process, generate a carbon-rich biochar. As there are no other fuel inputs to the autothermal process in normal operation, the carbon in this char comes directly from the wood and, thus, the atmosphere. Biochar has been shown to be very stable and to have beneficial effects on the soil, and when used as a soil amendment (or otherwise landfilled) would sequester the atmospheric carbon.[11] Han et al.[7] estimate that, even if 20% of the sequestered carbon returns to the atmosphere over a 100-year period, the associated fuel would have

a carbon intensity of zero (or lower). We intend to explore markets for use of biochar that would result in sequestration as part of our project.

Finally, we note that the California Air Board has approved two fuel pathways for renewable diesel produced from forest residues via pyrolysis and co-processing of bio-oil, which have carbon intensity values of 22 and 26. While these pathways employ a different pyrolysis technology, they both include transportation of the bio-oil by rail or truck over 2,800 mi, which would add substantially to the fuel CI.

In summary, we believe that there is strong potential – supported by the lifecycle assessments conducted to date and approved fuel pathways – for fuels produced from co-processing of autothermal pyrolysis bio-oil to have a carbon intensity far less than the California Air Board reference baseline for renewable diesel and even to have a near-zero CI. Future capture of CO_2 from processes such as this could produce substantial negative emissions. It is likely that further amendment of the accounting standards will be required to obtain this benefit, however, because the current CCS standard does not account for biochar-type storage of carbon.

5 Future LCFS-Incented Negative Emissions

As currently proposed, the new California LCFS standards provide an opportunity for significant carbon emissions reduction, paid at a price significantly above most CCS costs today. This can create new businesses that are profitable, and which can continue to increase the value of their products by reducing their carbon intensity below zero. Direct air capture has the potential to benefit significantly from this proposed standard, as the carbon intensity of most of the currently proposed schemes should be significantly negative when evaluated by formal life cycle analysis. We expect the new California standards to create a worldwide market for negative emissions that will be sufficient to create a number of new businesses in this field.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.
Lawrence Livermore National Security, LLC. LLNL-CONF-750270.

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