NextSTEPS White Paper:

Three Routes Forward for Biofuels: Incremental, Transitional, and Leapfrog

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Please note: the views and conclusions drawn in this report are those of the scientists writing the report.

Sustainable Transportation Energy Pathways Program (NextSTEPS)

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Abstract

Large quantities of low carbon fuels will likely be needed to meet the world's increasing levels of travel and need to achieve climate change goals. For example, electricity and hydrogen appear to be potentially attractive fuels for light duty vehicles, but these energy carriers may not be suitable for aviation, shipping or long haul trucking. Biofuels made from non-food sources such as agricultural, municipal, and forest waste, high yielding cellulosic crops, and algae are potentially important low-carbon liquid fuel options. Despite billions of dollars invested over the last decade in these advanced biofuels, the jump from labs and small demonstrations to commercial-scale operations is proceeding slowly. Progress is being made, however, at many existing commercial biorefineries to incrementally lower the carbon intensity of fuels; these facilities are improving efficiencies and adding new process fuels, as well as expanding into small scale cellulosic production using existing infrastructure and feedstock supply logistics.

This white paper characterizes the complex landscape of biofuels into three routes: (1) an **Incremental** route in which progress happens at existing biorefineries, (2) a **Transitional** route in which "bolt-on" equipment leverages existing production facilities to process small amounts of cellulosic material, gaining experience; and (3) a **Leapfrog** route that focuses on major technological breakthroughs in cellulosic and algae-based pathways at new, stand-alone biorefineries.

There is a tradeoff between investment risk today and carbon emissions reductions in the future. We examine how the industry is developing over time in terms of technologies and finances. Since 2007, investments in the Leapfrog route have averaged $1.9 billion per year from federal, private equity, and corporate backers. Incremental and Transitional routes, on the other hand, have been supported through biofuel tax credits and low carbon transport fuel policies. We discuss how, to date, California's Low Carbon Fuel Standard (LCFS) and the U.S. Renewable Fuel Standard (RFS) have tended to support the Incremental route. We conclude that the Incremental and Transitional routes will likely achieve the greatest near-term CO_2e reductions but that the Leapfrog route is ultimately needed to achieve deep, long-term reductions. Federal and state policies must continue to evolve to create an environment that ensures large-scale, low-carbon, advanced solutions are implemented.

Executive Summary

Biofuels[1] present great promise but also great challenges. Enthusiasm was high in 2006 when President George W. Bush promoted biofuels in his State of the Union speech to enhance energy independence and reduce greenhouse gases (White House, 2006). Achieving those goals seemed straightforward: boost corn ethanol, then transition to non-food (cellulosic or algal) materials. This plan received strong support from the agricultural industry, energy security advocates, and farm belt communities. Some environmentalists expressed concerns, but overall optimism was high.

Skepticism slowly spread in the following years. Corn ethanol production was energy-intensive (Farrell et al., 2006), consumed large amounts of land, raised food prices (Fresco, 2009), and indirectly increased greenhouse gas emissions (GHG) by diverting land to corn production (Fargione et al., 2008; Searchinger et al., 2008). With increasing quantities of U.S. corn production being diverted to ethanol production, reaching 40 percent in 2009 (USDA 2014), the debate over the magnitude of these impacts among stakeholder groups and researchers soon spilled over into the mass media and Congress. Skepticism was even stronger in Europe, aggravated by increasing use of fuels made from palm oil produced from the rainforests of Southeast Asia.

When the U.S. Congress codified the Bush goals into law in 2007 in the RFS, it established a mandate of 15 billion gallons of corn ethanol by 2015.[2] This was accompanied by a delayed but rapidly expanding target for cellulosic fuels reaching 16 billion gallons per year by 2022, [3] plus an additional one billion gallons for biodiesel from algae, waste oils, and oil seed crops. Corn ethanol was expected to create the conditions for cellulosic (and algal) biofuels to leapfrog forward—providing even greater energy and GHG benefits. However, the jump from demonstration to commercial stage has so far proven difficult for cellulosic (and algal) biofuel companies. In 2013, the production of starch and oil-crop-based fuels

[1] The term "biofuels" can encompass any energy derived from biomass, which is organic material derived from living or recently living organisms. In this paper, biofuels refers mainly to liquid fuels derived from biomass, used for transport purposes.

[2] This includes 15 billion gallons from the Renewable Fuel category that was expected to be met largely by corn ethanol, and a nominal 1 billion gallons from the Biomass-Based Diesel category that was expected to be met with primarily with soy biodiesel.

[3] Legislated cellulosic targets were dramatically lowered annually for 2010-2013 due to lack of commercial production, but future targets remain in place. Current mandates allow corn starch ethanol up to 15 billion gallons in 2015, and hold at that level until 2022. We return to this topic later in the paper.

topped 14 billion gallons while less than one *million* of cellulosic biofuels were produced. The mandated level for 2013 had been one *billion* gallons. To date, even smaller volumes of algae-based fuels have been produced. Given the slow development of commercial-scale cellulosic and algal biofuels, this paper examines the future of biofuels by characterizing three distinct routes forward:

Incremental Route … *progress happens at existing biorefineries by improving the existing production system:* There has been considerable innovation at existing biorefineries that produce corn ethanol and biodiesel.[4] Most notable are new technology processes to extract corn oil from the ethanol co-product stream for sale as biodiesel and animal feed—now integrated into about 80 percent of U.S. corn ethanol plants. Additionally, some biorefineries are switching their plant's process fuel to lower-carbon sources (e.g. from natural gas to landfill gas),[5] while others are lowering the energy use of their plant by switching from dry to wet distiller grain co-production.[6] Still others are improving the starch-to-ethanol yield through the use of corn strains that are genetically optimized for ethanol production.[7] The feedstock mix for biodiesel production has shifted toward corn oil and waste greases, which have lower rated carbon intensities.

Transitional Route … *firms gain experience with cellulosic feedstocks while using existing infrastructure and supply chain logistics to the largest extent possible:* A number of other biofuel technologies are emerging that facilitate a transition to large-scale cellulosic production. "Bolt-on" systems refer to equipment added onto existing biorefineries that allow processing of cellulosic material alongside corn or sugarcane sugar streams; bolt-ons are either physically bolted onto the existing system or added as adjoining facilities that share some infrastructure with the existing system. Currently, three types of feedstocks are being tested in bolt-ons:

- Corn kernel fiber (a physical bolt-on that shares most corn ethanol plant facilities);
- Bagasse (already processed at sugarcane ethanol plants to produce electricity, but requires some additional process vessels for ethanol conversion);
- Corn stover (like bagasse, except not as yet collected and brought to a central location).

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[4] The reporting requirements from California's LCFS provide the research community a first-hand view of decisions at existing biorefineries.

[5] POET's 105 MGY Chancellor, South Dakota plant began supplementing natural gas use with landfill gas in 2009.

[6] This switch reduces the energy required for drying the distiller's grain.

[7] Glacial Lakes Ethanol uses a corn variety "Enogen" which has been genetically engineered to boost ethanol output and reduce energy costs and water use.

Bolt-ons are transitional in that they generate additional demand to help establish larger markets for the enzymes needed to break down cellulosic material while also giving fuel producers experience using the enzymes as well as cellulosic material, including the logistics of collecting and preparing the feedstock for conversion. Some efforts also are helping increase the general knowledge base for handling and converting cellulosic biomass. In addition, biochemical firms have also begun converting cellulosics to industrial chemicals,[8] thus helping establish enzyme markets. Finally, other companies are also boosting the knowledge base about cellulosic material, turning it into intermediates used for heat and electricity.[9]

Leapfrog Route … ***cellulosic and algae investments to produce ethanol or drop-in gasoline or diesel replacement fuels are made at new, stand-alone biorefineries:*** Currently, about fifty firms are pursuing commercial-scale cellulosic and algae plants in the U.S. These associated facilities are at various stages of development, including at least six with partially or fully completed commercial-scale plants. However, output from the completed plants typically remains far below plant capacities due to financial and technical problems discussed below. As the next biorefineries come online this year (e.g. POET and Abengoa) as well as others in Europe, we will have a better picture of the current viability of commercial-scale cellulosic and algae biofuel.

The three biofuel routes introduced in this paper lay the foundation for an in-depth analysis of the tradeoffs between different investment and policy strategies—in terms of carbon emissions reductions and level of investment risk (Figure ES-1). Relative to the Transitional or Leapfrog route, Incremental improvements typically have lower financial risk, shorter payback periods, lower capital requirements, and higher probabilities of successful implementation. Therefore, as U.S. biofuel policies become increasingly stringent, these improvements appear to be the "lowest hanging fruit" for producers. However, the Incremental route is likely limited in its GHG reduction potential both by the thermodynamic potential of existing biorefineries and the fact that expanded use of conventional biofuel feedstocks includes the risk of higher emissions from land use change.[10]

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[8] Annelotech and BioAmber report using cellulosic material to produce industrial chemicals.
[9] Ensyn is working with Talko to turn cellulosic wood waste into pyrolysis oil for electricity generation.
[10] Corn ethanol production under the RFS is capped at 15 billion gallons. There is greater scope for production for export. There is some scope for additional soy biodiesel production, either for export or under the RFS; amounts depend on how the U.S. Environmental Protection Agency (EPA) implements the rule.

On the opposite end of the risk spectrum is Leapfrogging to large scale cellulosic facilities. Leapfrog technologies are expected to have low carbon intensities compared to corn ethanol, due to the high yields of dedicated energy crops, *as long as* they are grown on land not under pressure for other use. Leapfrog technologies also can unlock important resources – like organic fractions of municipal waste – that have no land use risk and few alternative uses. However, Leapfrog technologies may remain costly and challenging to move to maturity – with costs dropping slowly from the first plant to "nth plant" – and may be seen to waste public money if relatively little new technology advancements and benefits are achieved on a year-by-year basis. Below we present data on historical funding of Leapfrog technologies from venture capitalists,[11] federal programs,[12] and oil companies. Since 2009, these funding sources have averaged $1.9 billion per year. Modeling presented in this study suggests that in a world with low to moderate gasoline prices, Leapfrog technologies might never reach cost parity with petroleum fuels. Leapfrog technologies could also have additional environmental costs, such as those related to land competition, absent policies that mitigate against these.

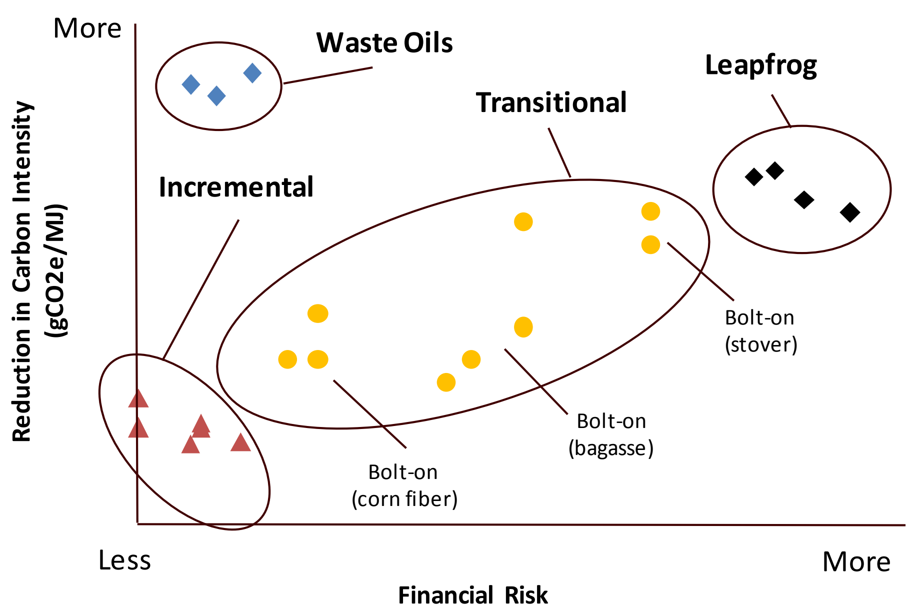


Figure ES-1: Conceptual plot showing trade-off between potential reduction in carbon intensity values and financial risk of project.

Between the Incremental and Leapfrog routes lie Transitional technologies, typically "bolt-on" units. Our research suggests that bolt-ons could increase ethanol yield per acre of corn by 5 percent for corn fiber

[11] Information from 40 Leapfrog firms.
[12] Includes funding from USDA, DOE, NSF, Air Force, Army, Navy, and the American Reconstruction and Recovery Act.

and up to 30 percent for stover.[13] This means the Transitional route is limited in its maximum potential GHG benefit, because total corn acreage in the U.S. is not expected to greatly expand in the future and would cause greater land-use impacts if it did expand. Ensuring that agricultural residue is sustainably harvested (enough left in place to meet production needs) also limits supply. If every corn ethanol plant in the U.S. added fiber and stover bolt-ons, this route would offer approximately 3.5 billion additional gallons of cellulosic biofuel. However, its much bigger benefit could lie in aiding a transition to large-scale cellulosic biofuel production.

In this paper, we analyze the GHG reduction potential for the three routes. Using a large dataset with information about individual planned or existing biorefineries in the U.S., we construct a supply-side model that generates potential production volumes and compares the three routes to reference fuels on rated greenhouse gas emissions. We estimate that the Incremental route might result in biorefineries with lifecycle GHG emissions about 30 percent lower than gasoline, Transitional biorefineries with 20 percent lower emissions, and Leapfrog refineries with 80 percent lower emissions.

Combining these assessments of GHG emission reduction rates with assumptions about technology deployment rates results in estimates of potential emission reductions based on an energy-constant comparison with a reference fuel as captured in carbon intensity ratings, presented in ES-2. The two graphics indicate that a strongly implemented Incremental route could improve the GHG ratings performance of a far larger biofuel production volume in the next 10 to 15 years than the Transitional or Leapfrog routes. This leads to greater potential GHG benefits in early years, but gains flatten out as eventually nearly all incremental biofuels are fully improved. In contrast, with steady growth, potential aggregate GHG reductions associated with an aggressive Leapfrog route could surpass the Incremental route by 2025 and eventually be much larger.[14]

[13] There is also fibrous material in soybeans which could potentially be used for cellulosic biofuel production; however, this is not a current focus of R&D efforts and is not discussed here.

[14] Nominal GHG reductions calculated using ratings can differ from achieved reductions because of unconsidered market effects from the additional biofuel production or errors in CI ratings.

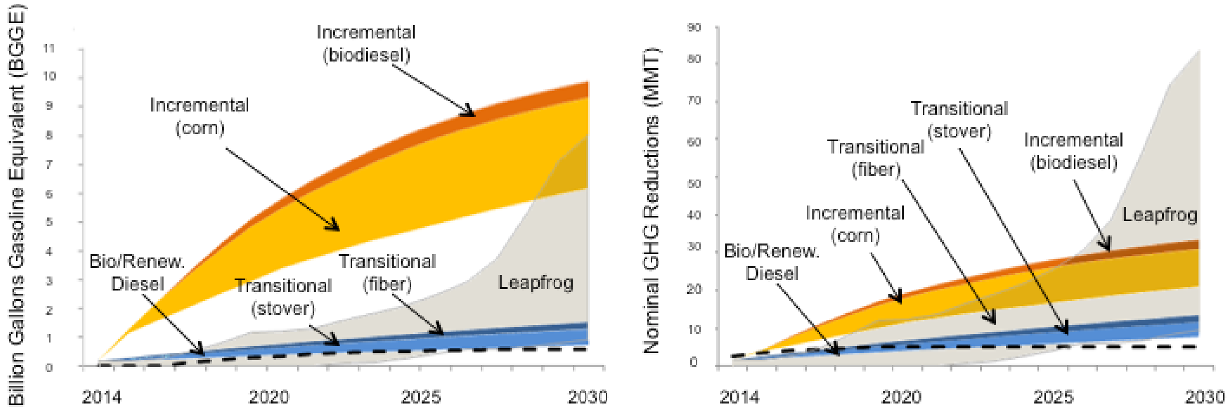


Figure ES-2. U.S. maximum fuel production if specified route is aggressively pursued (left), and associated GHG reductions (right). Fuel quantities grow over time as biorefineries are improved (Incremental), bolt-ons are built (Transitional), or stand-alone facilities are built (Leapfrog). Figures set '0' production/GHG reductions at 2014 levels, and track potential improvements relative to existing processes at current biorefineries (Incremental) or a fossil fuel comparator (Transitional and Leapfrog). Dashed line refers to the contribution from domestically-produced biodiesel or renewable diesel from waste oil, animal fats, and corn oil. See Fig. 12 for full methodology behind figure.

Ultimately, assessing the full potential for GHG reductions from biofuels requires a comprehensive analysis that incorporates complex topics with which the research community continues to grapple, such as emissions from land use change (Nassar et al. 2011; Khanna and Crago 2012; Witcover et al., 2013), soil carbon (Murphy and Kendall, 2013), fertilizers (Cherubini et al., 2009), and petroleum market rebound effects (Rajagopal and Plevin, 2012). While work to more comprehensively analyze emissions from particular fuel pathways has begun (Soimakallio 2014), such an analysis lies beyond the scope of this paper. Instead, in discussing CO_2e emissions reductions potential, this paper makes qualitative arguments about the likely scope of reduction. For calculations,

Box ES-1: Use of Carbon Intensity Estimates in Policy

Life cycle assessments (LCAs) of biofuels typically start by summing effects of inputs and outputs of an individual biorefinery or fuel production system to estimate the environmental impact of one unit of fuel. When used in policy, the estimate is often used to derive the environmental standing of one fuel compared to another. This assumes a one-to-one substitution between the fuels, which in reality is not usually the case. More fundamentally, the LCAs truncate the system boundary to the production system and ignore potential additional environmental impacts. Policy has recognized that assessment of emissions from a vastly expanded biofuel industry needs to account for land-use changes beyond the biofuel supply chain through global market effects. Plevin, Delucchi, and Creutzig (2013) discuss the inappropriate use of currently available LCA methodologies as an assessment of environmental impact. This paper acknowledges those concerns while focusing on a narrower topic, the rated carbon intensities (CIs) of current and potential future biofuels.

the paper uses carbon intensity ratings from the two main U.S. biofuel policies today – the U.S. RFS and California's LCFS – as well as some literature values, which when compared are indicative of notional, order-of-magnitude emissions reductions potentially available through these routes. Achieving such reductions would require separate evaluation tools and, likely, additional policy. See Box ES-1 for more discussion on the use of estimated carbon intensity values in policy to estimate climate impacts. **The aim of this paper is to illuminate the trade-offs among routes and their associated technologies in order to better highlight the policy and other strategies needed to set and achieve realistic goals for biofuel's contribution to a low-carbon transport future.**

Policymakers should recognize the important distinctions between these three routes for biofuels and how specific policy formulations may incentivize one route over the others. So far, policies like California's LCFS have tended to incentivize the Incremental and Transitional approaches, with a direct link to process efficiency improvements and CO_2e reduction efforts in many existing biorefineries around the country. As these policies become more stringent in future years, requiring deeper carbon intensity reductions, biofuel companies could increasingly be incentivized towards Leapfrog routes. The stringency level – or, exactly how deep a carbon intensity reduction – at which this would occur, however, is an open question.

We conclude that no route examined here guarantees long-term success, particularly from an overall CO_2e reduction perspective, and that all three should be pursued. While the Incremental route – and to a lesser extent the Transitional route – show considerable potential for near-term greenhouse gas reductions as captured by CI ratings methods, the U.S. will likely need large-scale use of Leapfrog technologies to achieve deeper GHG reductions. Considerations related to indirect effects, such as from land-use change, must also be taken into account in a more robust fashion. If a long-term goal is to expand the share of biofuels in aviation, marine transport, and heavy duty vehicles, then drop-in (diesel/kerosene replacement) biofuel pathways will be needed, and their development from ethanol or via other routes deserves a greater and more specific policy focus.

To move toward a large-scale, sustainable biofuel future by 2030 and beyond will require continued technology development, but also more experience using those technologies at a modest (less risky) scale, and a policy environment ensuring that scale-up to large, low-carbon, advanced fuel facilities are eventually achieved.

1. Introduction

1.a. The Need for Low Carbon Biofuels

A clear finding from economic modeling of future energy systems is that substantial quantities of low carbon biofuels will likely be needed if the goal is to reduce GHG emissions and reduce climate change (GEA, 2012; IEA, 2012). Biofuels may be the key enabling technology in certain sectors like transportation which are inherently difficult to decarbonize. In particular, long-haul trucking, aviation, rail, and marine transport currently have very few low carbon fuel alternatives. Fossil fuels are too high in carbon intensity (CI). Batteries are likely too heavy for the needed travel distances. Hydrogen may be an option, but suffers from low volumetric energy density and currently lacks the infrastructure and large-scale production volumes for low carbon intensity hydrogen.

The International Energy Agency (IEA, 2012) projects that approximately 25 percent of global transportation energy in 2050, or nearly 250 billion gallons (gasoline equivalent), must come from advanced, low carbon biofuels (or other, as yet unknown low-carbon technologies), as part of a strategy to limit climate change to a two-degree Celsius change in global mean temperature in the next century. The Global Energy Assessment estimates that we may expand biomass production for bioenergy from 45 exajoules (EJ) in 2005 to 80-140 EJ in 2050, including “extensive use of agricultural residues and second-generation bioenergy” (Nakicencovic et al., 2012, p. 10). Biofuels play an important role in low carbon projections in the U.S. and California.[15] Given these projections, how can we achieve large volumes of low carbon biofuels produced with minimum disruption to food systems and other environmental services?

In most analyses, the answer lies in cellulosic or algae-based biofuels; however, efforts at commercial-scale production of these fuels have yet to succeed. At the same time, existing commercial biorefineries

[15] The Annual Energy Outlook, Reference Case (2013) suggests 4.3 quads of bioliquids will be consumed in 2040 (16 percent of transportation energy), without any assumed carbon price. In California, using models that project state-level energy consumption, biofuels provide up to 40 percent of transportation energy in 2050 in scenarios that reach 80 percent reduction in GHGs by 2050. In these models, biofuel potential ranges from 3.3-15.5 billion gallons of gasoline equivalent in 2050 (Morrison et al., 2014).

continue to improve efficiencies and add the ability to process small streams of cellulosic material, thereby lowering the carbon intensity of their fuel output.

This study attempts to elucidate the situation through a systematic examination of three basic routes to GHG reductions via biofuels production:

1) an **Incremental** route in which progress happens at existing biorefineries, by improving the existing production system;
2) a **Transitional** route in which firms gain experience with cellulosics without building expensive, new stand-alone biorefineries, and
3) a **Leapfrog** route which focuses on major technological breakthroughs in cellulosic and algae-based pathways at new, stand-alone biorefineries.

This discussion illuminates the tradeoff between the level of investment risk today and carbon emissions reductions that are possible in the future. We examine how the industry is developing over time in terms of technologies and finances. We also discuss how the two main biofuel policies in the U.S. – the U.S. Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS) – have thus far largely supported the Incremental route. We conclude that the Incremental route can likely provide the greatest near-term CO_2e emission reductions, but that the Transitional route provides a foundation for learning about cellulosics and potentially enables the Leapfrog route, which is needed to achieve deep, long-term reductions. This study fits into the broader literature about the tradeoffs between pursuing easy, near-term technologies versus more substantial, higher risk breakthroughs.

1.b. Definition of Incremental, Transitional, and Leapfrog Approaches

Table 1 below defines Leapfrog, Transitional, and Incremental approaches across several dimensions. Others make similar distinctions between biofuel strategies with classifications like "First Generation versus Second Generation," "Advanced versus Conventional," and "Greenfield versus Brownfield" development. Our classification more closely links a given biofuel strategy with policy, carbon reduction, and investment risk.

Table 1. Definitions of three routes

Dimension	Incremental	Transitional	Leapfrog
Capital Requirement	Small	Moderate	Large
Risk to Capital	Small risk of failure	Moderate risk of failure	High risk of failure
Payback on Investment	<2 years	~2-10 years	>10 years
Carbon Intensity Reduction from Petroleum Reference	Small reductions	Expected to be 50 percent or greater. Only small quantities available.	Expected to be 50percent or greater
Actors	Established biofuel producers (e.g. corn ethanol, soy biodiesel, etc.)	Established biofuel producers (e.g. corn ethanol, soy biodiesel, etc.), biochemical firms, petroleum refiners	Start-ups, established biofuel producers, Fortune 500 companies
Technology Status	The vast majority of technologies used in biorefineries are currently available and proven at scale	Bolt-ons proven at demonstration scale; some commercial-scale projects underway	Facility depends on technologies that are unproven at scale
Primary Conversion Technologies	Fermentation + distillation (FD), Transesterification (TE)	Enzymatic hydrolysis + fermentation (EHF), Pyrolysis to bio-oil	Enzymatic hydrolysis + fermentation (EHF), Pyrolysis + hydrotreating, Hydrotreating of algae oil, Gasification
Examples of Firms	Pacific Ethanol, Little Sioux Corn Processors (corn ethanol), Minnesota Soybean Processors (biodiesel)	POET-DSM (corn stover), Quad County Processors (corn fiber)	KiOR, Mascoma, Ineos, DuPont, BP Biofuels, Abengoa Bioenergy

1.c. Summary of Incremental Developments

Incremental improvements made at existing biorefineries aim to incrementally lower energy use and cost, and potentially emissions as well. Examples include improvements made to feedstock harvest and transportation, feedstock loading, conversion efficiency, and distribution at corn ethanol or soy biodiesel plants.

Perhaps the richest dataset on incremental changes to existing conventional biorefineries comes from the ARB (2014) website, which lists different production pathways at individual biorefineries recorded under the LCFS policy (discussed in Section 3). From these documents, we see a large-scale movement towards more efficient and lower carbon-intensive plants in the U.S. and Brazil. In total, the biorefineries that have applied for new or modified pathways in the LCFS produce approximately 5.5

billion gallons of fuel per year, not all of which ends up in California. Table 2 gives examples of Incrementalism at conventional corn biorefineries, with (self-reported) reductions in carbon emissions. While these reductions need to be independently vetted and displacement effects analyzed, the advantages of this route are that (1) the existing fuel supply is large (over 14.5 billion gallons in 2013) and therefore the potential carbon reductions are also large, and (2) these improvements often add value to a producer, beyond carbon reductions.

Table 2: Examples of self-reported reductions in carbon intensity by biorefineries under the Low Carbon Fuel Standard (ARB, 2014)

Innovation	Example
Improve pre-treatment technology	POET uses Raw Starch Hydrolysis instead of dry grind process. Reduces CI value by 6.0 gCO_2e/MJ compared to a dry grind process.
Improve starch removal	Edeniq's "Cellunator" mixes and mills corn slurry to improve starch extraction. Reportedly improves ethanol yield by 2-4 percent over traditional technology.
Improve co-product production	Green Plains Holdings shifted to 54percent/56percent dry/wet distiller's grain (DDGS) from 10percent/90percent dry/wet distiller's grain, reducing plant carbon intensity (value not reported). Additionally, POET reports ~10 gCO_2e/MJ improvement when shifting from 100 percent dry to 100 percent wet distiller's grain. As noted in POET (2011), there is a tradeoff between ethanol yield and DDGS yield.
Shift towards higher carbon co-products (potentially displacing greater amounts of carbon)	Nearly 80 percent of all corn ethanol plants in the U.S. now produce corn oil as a co-product. Converting the corn oil to biodiesel then displaces diesel or other biodiesels in the market. POET shifted to generating combined heat and power (CHP) instead of using grid electricity for process heat and saved 3.7 gCO_2e/MJ.
Improved feedstock	Glacial Lakes of Watertown, South Dakota uses a corn variety called Enogen, which reduces the carbon intensity of corn ethanol production by a (self-reported) 11.5 gCO_2e/MJ.
Change process fuel to lower carbon energy resource	POET shifted from using natural gas to landfill gas as process fuel resulting in a reported ~4 gCO_2e/MJ improvement over natural gas. Other biorefineries are switching to using stover or lignin for co-generation.
Improve energy efficiency of biorefinery	Several plants have improved the energy efficiency of their production processes (e.g. Louis Dreyfus Elk Horn Valley). ICM reports new plants can get carbon intensity as low as 18,000 BTU/gal of ethanol.
Switch/blend feedstocks	Several conventional ethanol producers now blend some sorghum into input streams.
Reduce electricity use in biorefinery	Louis Dreyfus Elk Horn Valley reduced the electricity-use-per-gallon produced and improved their production efficiency. Together, these improvements resulted in ~9 gCO_2/MJ reduction.
Cold Starch Fermentation	Guardian Energy (corn ethanol producer) reports improved plant efficiency with cold starch fermentation.

Improve fiber separation technology	ICM estimates that an ICM-designed conversion process results in ~9 gCO_2e/MJ improvement in CI (ICM, 2013)

Improvements are also occurring in the biodiesel production system. Pradhan et al. (2010) describe improvements to oil-crop farming, crop transport, and processing and estimate that the energy input to biodiesel production (on a lifecycle basis) declined 42 percent between 1998 and 2006. LCFS documentation suggests that 21 biodiesel biorefineries in the U.S. that use soy or canola oil have made process improvements in recent years that reduced the carbon intensity of their fuel by at least 5 grams of CO_2e/MJ. Because the overall supply of oil crops and waste oils is much lower than ethanol feedstocks (2.4 billion gallons versus 15 billion gallons), improvements to the biodiesel and renewable diesel production system will likely have a lower magnitude of potential impact than improving the ethanol production system.

1.d. Summary of Leapfrog Developments

The Leapfrog category includes cellulosic and algae based biofuels produced at stand-alone plants. Because these technologies are not proven at scale, there is a chance the fuels will continue to be much more expensive than conventional routes or that they will fail to live up to the promised environmental performance. Additionally, the approach entails a large risk of failed investment as clearly demonstrated by multitudes of start-ups in the past decade. (We count at least 22 bankrupt firms and dozens of other firms which have pivoted out of cellulosic biofuels.)

The U.S. federal government is the largest single supporter of the leapfrog route and invests through: small-business loans, biorefinery grants, Advanced Research Projects Agency-Energy (ARPA-E) grants, U.S. Department of Agriculture (USDA) feedstock improvement grants, and the Department of Defense advanced biofuel program. Private equity funders like Kleiner Perkins Caufield & Byers and Khosla Ventures are also active funders of the Leapfrog approach and tend to focus on small, start-up Leapfrog firms. A third source of funding for the Leapfrog approach is from large, capital-intensive corporations like oil companies or chemical manufacturers. Firms like Shell, British Petroleum, and DuPont have the advantages of deep pockets to disperse the risk of failed investments and global operations to utilize low cost feedstocks and labor markets. They also tend to be technically sophisticated with a strong understanding about liquid fuel conversion processes and complex, global supply chains. However, for the corporate Leapfrog funders, biofuels offer a much lower profit margin than the products that fall in their core expertise (e.g. gasoline) and several have scaled back biofuel investment in the last three years.

We identified 66 firms worldwide that have built, are building, or plan to build cellulosic or algae biorefineries. Of these, 53 were based in the United States and 13 were foreign. Other Leapfrog firms have stayed alive simply through continuous fund raising or through switching to higher value, non-energy bioproducts. Figure 1 below gives the historical evolution of leapfrog biofuel companies in the U.S., disaggregated by conversion technology. This figure only includes U.S. firms that have announced plans to build or currently are building Leapfrog biorefineries. Of the various conversion technologies, biochemical conversion using enzymatic hydrolysis and fermentation is the preferred technology of the greatest number of firms.

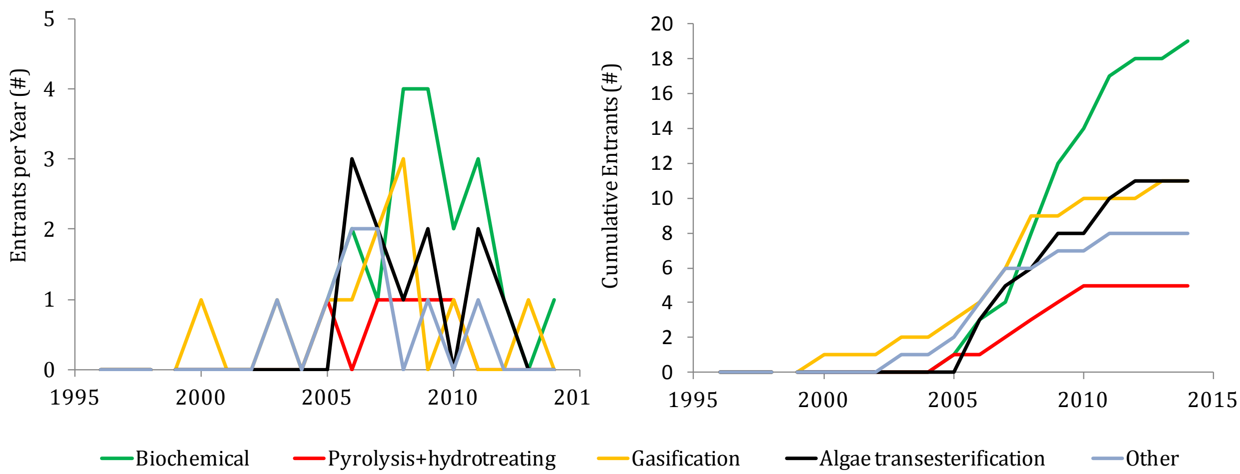


Fig. 1. Annual (left) and Cumulative (right) number of firms entering U.S. Leapfrog market, by conversion technology. Figure only shows firms that have announced intentions to build or are building commercial scale facilities.

1.e. Summary of Transitional Technologies

Technologies that utilize small quantities of cellulosic material are potentially a bridge to the Leapfrog route. These technologies give producers much-needed experience with handling and converting cellulosics, and potentially help establish market connections for cellulosic feedstocks. Three examples of products from Transitional Technologies are: ethanol from bolt-on plants (including additions within or adjacent to existing plants), industrial chemicals, and pyrolysis oil used in petroleum refining. Of these, bolt-ons are the focus in this paper.

Bolt-ons are typically smaller scale and have a lower investment risk than stand-alone cellulosic and algal biorefineries. These plants benefit from shared supply-chains, distribution networks, and capital costs with shared or adjacent conventional biorefineries. Figure 2 demonstrates the configuration of the POET-DSM corn stover facility set to open in the summer of 2014.

Fig. 2. Bolt-on facility under construction by POET-DSM in Emmetsburg, IA. Conventional corn ethanol plant on left and cellulosic stover plant on right.

Currently, three types of bolt-on facilities are under development: corn fiber, sugarcane bagasse, and corn stover. Bolt-ons using corn fiber have the smallest investment risk because the additional equipment is small compared to the conventional plant. Edeniq and ICM claim their corn fiber conversion technologies increase yield by 3-5 percent above conventional corn ethanol.

Bolt-on facilities that use bagasse are also being developed. They require larger processing units, fewer shared facilities, and higher investment risk than corn fiber conversion, but benefit from the fact that bagasse is already collected and stored at sugarcane plants. Thus, unlike for corn stover, a new collection process is not needed. Bagasse bolt-on units are expected to increase yield by as much as 25 percent. For the bolt-on plants considered here, the largest investment risk is corn stover. The POET-DSM plant in Emmetsburg, Iowa set to open in the summer of 2014, has a separate corn stover biorefinery adjacent to the existing corn ethanol plant. The plant is considered a bolt-on because it shares entry roads and grid connections as well as ethanol processing. We estimate that stover processing can increase yields at corn ethanol plants by 30 percent.[16] Table 2 below lists announced and under-construction bolt-on facilities.

[16] This estimate is based on a maximum 38 percent retention rate of stover in the field (Muth, 2012), 56 lbs. per bushel, 15.5 percent moisture content, and 70 gallons per ton of stover yield.

Table 2. Bolt-on additions that enable processing of cellulosic material

Firm	Location	Feedstock	Facility Type	Capacity of Bolt-on Facility (MGY)
Edeniq	Visalia, CA	Corn stover	Demo	3
Front Range Energy	Windsor, CO	Corn fiber	Commercial	0.5
Flint Hills Resources	Fairbank, IA	Corn fiber	Commercial	~5
GranBio	Alagoas Brazil	Bagasse	Commercial	22
ICM	St. Joseph, MO	Corn fiber	Pilot	TBD
POET-DSM	Emmetsburg, IA	Corn stover	Commercial	25
Quad County Corn Processors	Galva, IA	Corn fiber	Commercial	2
Raizen	Piracicaba, Brazil	Bagasse	Demo	11
Usina Vale	Sao Paulo, Brazil	Bagasse	Demo	0.2
Usina Santa Maria	Brazil	Bagasse	Commercial	3

Several other firms could reasonably be placed in Transitional Technologies. Some firms like Midori Renewables, Vertimass LLC, ICM, Edeniq, Gevo, BP, Inbicon, and DuPont develop and license bolt-on technology to existing biorefineries. Others are developing conversion technologies that might lower costs in the future. Ensyn and Talko Industries are building a fast pyrolysis plant in Alberta, Canada, which will be used to power Talko's sawmill. Ensyn has another project with an oil company in which they are blending small amounts of pyrolysis oil from cellulose in crude oil prior to refining into petroleum products, thereby lowering the carbon intensity of the petroleum production.

1.f. Investment Risk versus GHG Reduction

The three routes for biofuels operate on a spectrum of potential carbon intensity (CI) reduction and financial risk (Figure 3).[17] In the bottom-left corner of this spectrum are the low risk, low GHG reduction investments corresponding to Incrementalism. Some incremental investments are fully on the y-axis because they entail little-to-no financial risk (e.g. switching from dry distiller's grain to wet distiller's grain). In the upper-right corner are high-risk, high-reduction investments corresponding to Leapfrog. The relatively low carbon intensity reductions obtainable from the Incremental route are due primarily to thermodynamic potentials given existing processes. The relative carbon intensity benefits from the Transitional routes (bolt-on cellulosic) rely on the lower carbon intensity from high-yielding cellulosic residues combined with the shared infrastructure. The larger carbon intensity benefits from Leapfrog

[17] Here, financial risk relates to both the magnitude of the investment needed to carry out a project and the certainty that the investment will become profitable when complete.

also rely on a lower carbon intensity from high-yielding dedicated energy crops, cultivated so as to minimize emissions from land-use change. The sustainable use of residues for Transitional routes and minimized land competition for Leapfrog routes would both likely require some policy intervention.

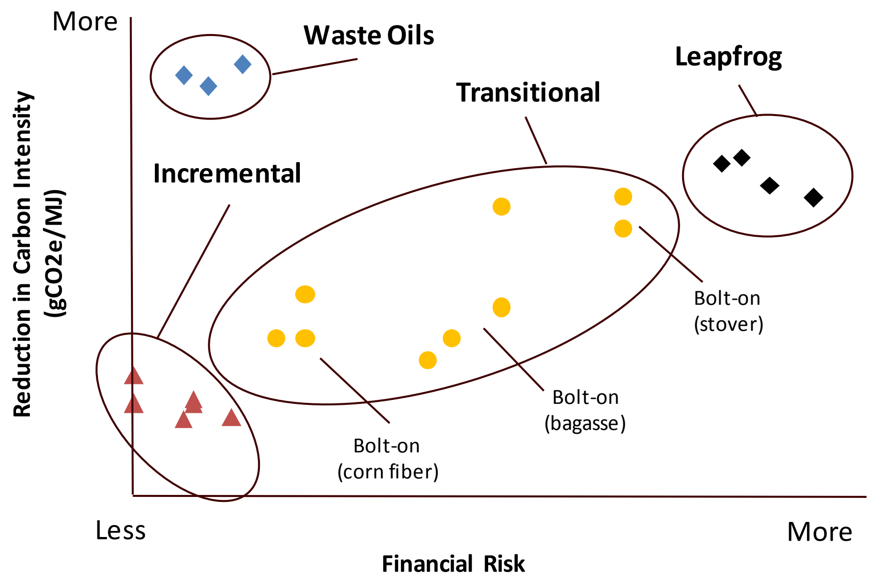


Figure 3. Spectrum of carbon intensity versus financial risk showing low risk for Incremental, Transitional, and Leapfrog routes.

Others have noted substantial flaws in our current LCA accounting system when used for policy (Plevin et al., 2013, see Box ES-1 for discussion). DeCicco (2011, 2013) echoes the concerns of others about carbon accounting policy (Searchinger et al. 2009), by highlighting a specific shortcoming of biofuel LCAs: that they treat biogenic carbon as "free." In other words, the LCAs implicitly assume that the carbon released at the time of combustion is equal to that sequestered during the growing process. DeCicco argues for expanding the LCA framework to include all land (DeCicco 2013), and accounting for carbon uptake explicitly where feedstock is grown, and instituting measures to ensure that carbon sequestered by feedstock is additional from the perspective of the biosphere, that is, would not have happened without the biofuel (DeCicco 2011). Others have begun to apply a more comprehensive analysis for specific fuel pathways, to examine potential conclusions in light of the considerable uncertainty (Soimakallio 2014). Policy and measurement issues associated with whether and how to track land-based carbon are under ongoing debate and discussion in research and policy arenas. **We do not deal with these concerns directly, but focus on how LCA is currently being used in policy and note the need for further policy steps and monitoring to track additional carbon sequestered (or not emitted) due to use of biogenic carbon sources.**

Regardless of how deeply flawed our current LCA accounting system is, we can be assured that improving the existing production system (i.e. Incremental Route) is preferable from an emissions perspective to not improving it. However, future research should examine whether this is the best allocation of resources. .

2. Costs and Financing

2.a. Costs and financing of Incremental and Transitional approaches

Understanding the cost and financing of the Incremental approach requires understanding the outlook of existing biofuel firm owners. They seek opportunities for near-term cost savings and efficiency gains. Typical Incremental improvements cost producers between several thousand dollars and tens of millions of dollars. According to a senior manager at ICM, biofuel producers will typically only pursue Incremental improvements if they entail payback of less than two years.

Transitional technologies entail greater risk and longer pay-back periods. In most cases, the development of bolt-on facilities has been spearheaded by large, multi-plant producers who can afford to take a longer perspective on investments. Bolt-on facilities cost anywhere from $5.7 million for the two-million gallons per-year of corn fiber ethanol additional capacity at the Quad County Corn Processor plant, to $100 million at Raizen's 11 -million gallon per-year bolt-on bagasse plant in Brazil.

2.b. Costs and financing of Leapfrog approach

Past estimates of the cost of production for Leapfrog biofuel routes often assume a mature technology. Technology maturity implies the technology works as expected (replicating lab or demo-scale performance) and no additional costs or delays arise operating at scale. Even models that include technological learning over time start with an assumption that the current technology can be proven at scale. This is a good way to project the long-term potential of a technology, but for two reasons is inadequate for implementing policies that are designed to pull new technologies into the market: It does not account for failures and it sets unreasonable expectations for the first generation of the technology both of which can undermine policy's realization.

NextSTEPS researchers are attempting to understand how much each technology and feedstock pathway is likely to contribute to United States biofuel production. Parker (2012) uses a spatially-explicit biorefinery siting model that estimates an aggregate biofuel supply curve (Figure 4). This estimate provides a feasible outcome for a future where cellulosic biofuels are proven and reliable technologies.

The process of proving and scaling the technologies to this level requires multiple generations of technologies and likely will include many failures.

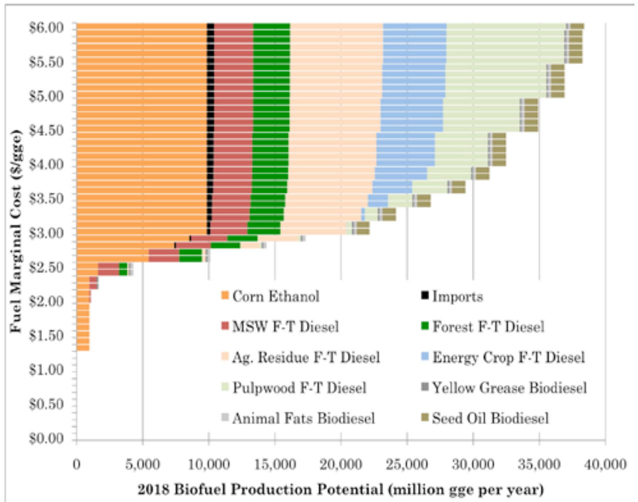


Figure 4. Biofuel production potential for baseline scenario by fuel pathway (Parker, 2012)

In their initial years, biorefineries that use a Leapfrog approach will cost significantly more than current estimates for three reasons. First-of-a-kind biorefineries will be at a smaller scale than is expected in a mature market. These facilities are risky investments and will face capital constraints that limit their size until their performance is proven. First-of-a-kind plants have historically been more expensive to build than is suggested by a design study (RAND, 1981). They have also been slow to achieve their expected operating capacity, in some cases taking years instead of months to ramp up to full capacity (RAND, 1981). Accounting for these last two factors, Annex et al. (2010) have estimated that first-of-a-kind biorefineries would have a cost of production 25-300 percent higher than the general cost estimate assumption for mature technologies. These problems are faced by all innovative, new facilities, not just biorefineries. In the long run, learning and technological improvements can lead to technologies that exceed the performance of the nth plant estimates. But the realistic path to get there is what we are interested in here.

There has been relatively little empirical study of first–of-a-kind plants, with a tendency to rely on the RAND 30 year-old study for insights. The paths of existing cellulosic biorefineries getting to market have been in-line with what would be predicted by the RAND study. KiOR's biorefinery operated at 17 percent of capacity in its second six months of operation, which is slightly below the expected performance for a first-of-a-kind facility with KiOR's characteristics. The capital expenditure for KiOR's Columbus biorefinery was close to mature technology estimates. But the facility required additional investment in order to achieve the expected performance. Figure 5 compares the anticipated and actual capital expenditures for cellulosic ethanol and pyrolysis-based drop-in biofuels.

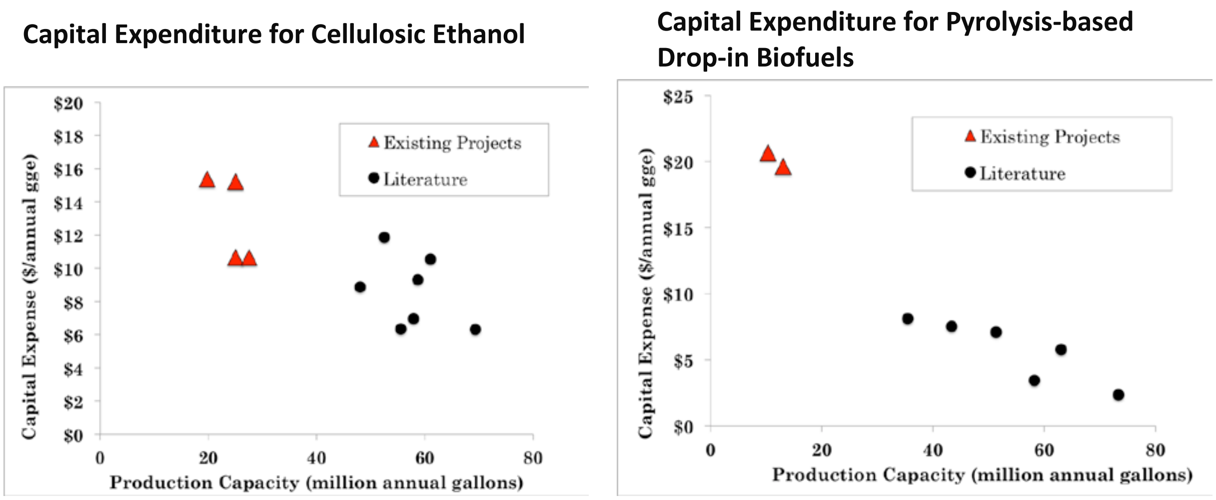


Figure 5: Comparison of capital expenditure projected in literature and announced facilities[18].

Research at UC Davis models the transition from first generation biorefinery to nth generation (mature technology). This analysis considers uncertainty in capital cost of early biorefineries, their performance in initial years, learning rates, rate of knowledge dissemination in the industry, the number of biofuels technologies brought through the transition, the speed of deployment and the price of oil—in order to estimate the size and length of subsidy required to bring cellulosic biofuels into a cost-competitive state with petroleum fuels starting from the first commercial-scale cellulosic biorefinery. We rely on our previous mature technology analysis of advanced biofuels (shown in Figure 4) to ground the analysis in the resource constraints and to maintain an estimate that is feasible given spatial resource availability (Parker, 2012).

Figure 6 shows the industry cash flow for cellulosic biofuels in one of the scenarios generated. After the first commercial scale facility (millions of gallons of fuel produced) is built, the industry starts with several years of negative cash flow as it makes its way through the so-called "valley of death." This is

[18] Existing projects for cellulosic ethanol include DuPont, POET, Abengoa and Beta Renewables. The pyrolysis-based biofuels projects are KiOR. Cellulosic ethanol literature represented here are design reports from NREL: Humbird *et al* (2011), Wooley *et al* (1999), Aden (2008), Aden *et al* (2002) and Dutta *et al* (2011). The pyrolysis-based biofuel literature represented here are Brown *et al* (2013), Wright *et al* (2010) and Zhang *et al* (2013).

followed by the eventual positive cash flows. The "buy-down cost" is the sum required to make the industry whole through this process (the minimum of the cumulative cash flow).

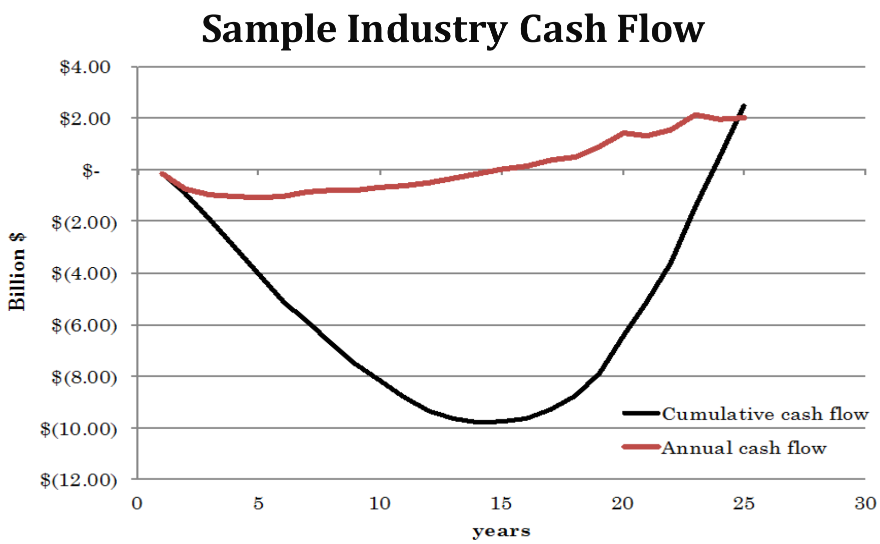


Figure 6: An illustrative[19] simulation of cash flow for Leapfrog technology development. The initial biorefineries require a subsidy to compete with petroleum fuels but technology improvements from experience and learning eventually brings costs to a competitive level.

Under certain conditions, such as low oil prices, cost competitive biofuels are never achieved. For scenarios that do achieve parity, buy-down costs are between $2 and $70 billion over perhaps two decades. For perspective, U.S. consumers spent $469 billion on motor gasoline in 2013 and are projected to spend nearly $10 trillion through 2035.[20] The high end of the subsidy required represents an increase of approximately $0.02/ gallons of gasoline equivalent (gge) to all transportation fuels over the duration of the transition. We also find that the first 10 biorefineries are never profitable without a subsidy, even under optimistic assumptions. Additionally, our analysis shows that positive annual cash flows are reached between 6-26 years after construction of the first plant. It takes another 5 to 20 years for the cumulative cash flow to become positive (i.e., break even for the industry). For policy purposes, the relevant metrics are how much of a subsidy for this industry must be generated and for how long. The industry would be self-sustaining with a total subsidy equal to the buy-down cost and lasting to the point of positive annual cash flows. These metrics are presented in Figure 7 below for the scenarios that

[19] The example here assumes the first biorefinery cost twice the expected investment from literature (~$20/gge annual capacity) and has a 40% capacity factor in the first year that improves to fully operational in 3 years; capacity is ramped up at the same rate as historical corn ethanol growth; learning reduces costs with a progress ratio of 0.85 (costs are reduced by 15% for every doubling of capacity).

[20] Average motor gasoline price = $3.51; total consumption 134 billion gallons (EIA, 2014)

lead to cost competitive biofuels. The subsidy here does not need to take the form of direct government payments but could come through the existing mechanisms of Renewable Information Numbers (RINs) and LCFS credits (see discussion, next section). These estimates are for needed production subsidies and do not include the research and development funding that has already been spent and will continue to be needed. Existing loan guarantees to cellulosic biorefineries and feedstock guarantees (through the Biomass Crop Assistance Program) count toward fulfilling the estimated subsidy.

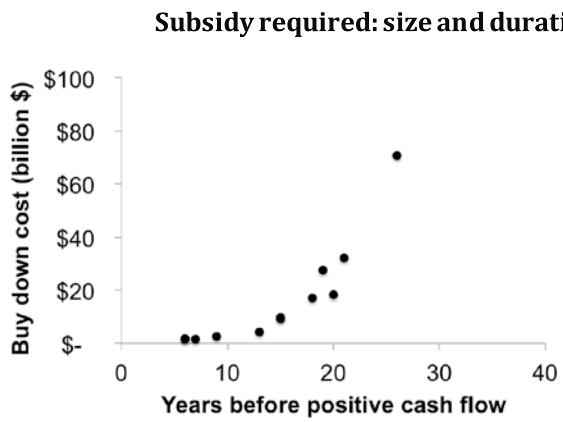


Figure 7: Buy down cost ($billions) and required policy duration in various scenarios

As mentioned in the introduction, the funding for the Leapfrog route comes from one of three main sources: government grants/loans, private equity, and large Fortune 500 companies (with implications for taxpayers and/or consumers). We examined the U.S. federal spending on biofuels from 2009 to 2012. In total, the federal government spent $3.3 billion in this period on grants and loans for research, development and deployment of biofuels (Figure 8). This includes money from the American Recovery and Reinvestment Act (ARRA) of 2009.

From our analysis, the vast majority of this spending went to the Leapfrog approach. Only the $840 million from the Department of Treasury went to conventional biofuel producers in the form of tax credits. The rest of the funding went to research and development activities at universities or supported small biorefinery construction. Another interesting development in recent years is the interest by the Department of Defense (DOD) in advanced biofuels. In particular the Air Force and to a lesser-extent, the Navy, are developing drop-in biofuels for aircraft and ships. The DOD has stated it is “feedstock agnostic,” meaning they have made investments in a wide range of feedstocks from algae to wood waste to energy crops. In total, $3.3 billion were spent on developing Leapfrog technologies between

2009 and 2012 including $862, $1,198, $156, and $1,120 million for basic science, R&D, demonstration, and development, respectively.

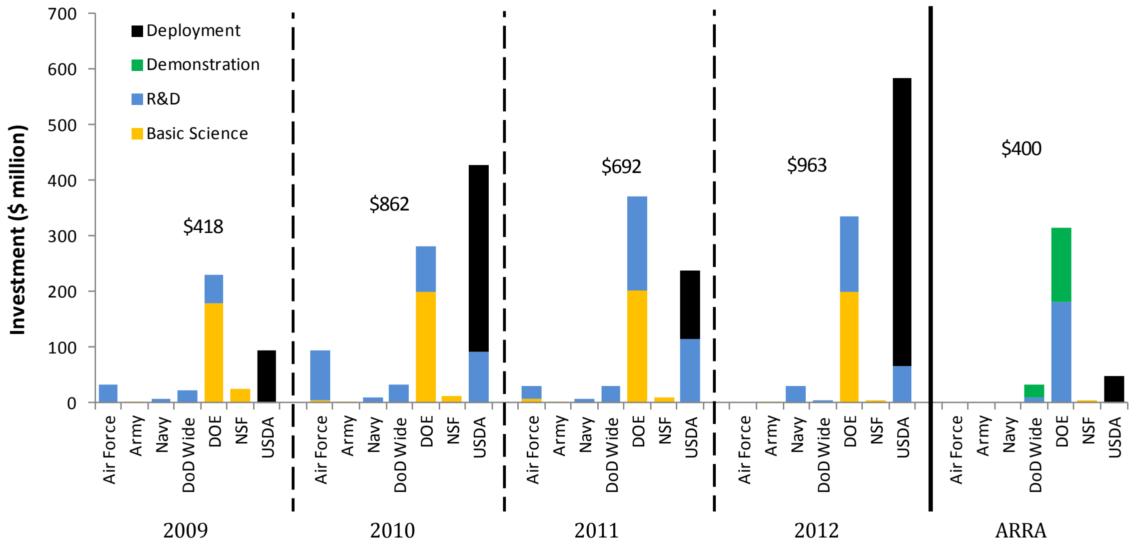


Figure 8: Federal government investment into Leapfrog biofuels development, 2009-2012. Total investment in year given at top of each column. Source: http://energyinnovation.us

Other national and state governments also fund the development of biofuels, but not to the same total level as US. For example, the National Development Bank of Brazil provided approximately $1 billion Brazilian dollars between 2011 and 2014 for the financing of innovation in the Brazilian ethanol industry.

The second pot of funding for the Leapfrog route comes from private equity investors like venture capitalists, angel investors, and private individuals. Figure 9 illustrates the trend in private equity investment between 2006 and 2012, including federal ARRA funds. Private equity funding for biofuels during this period averaged $368 million per year.

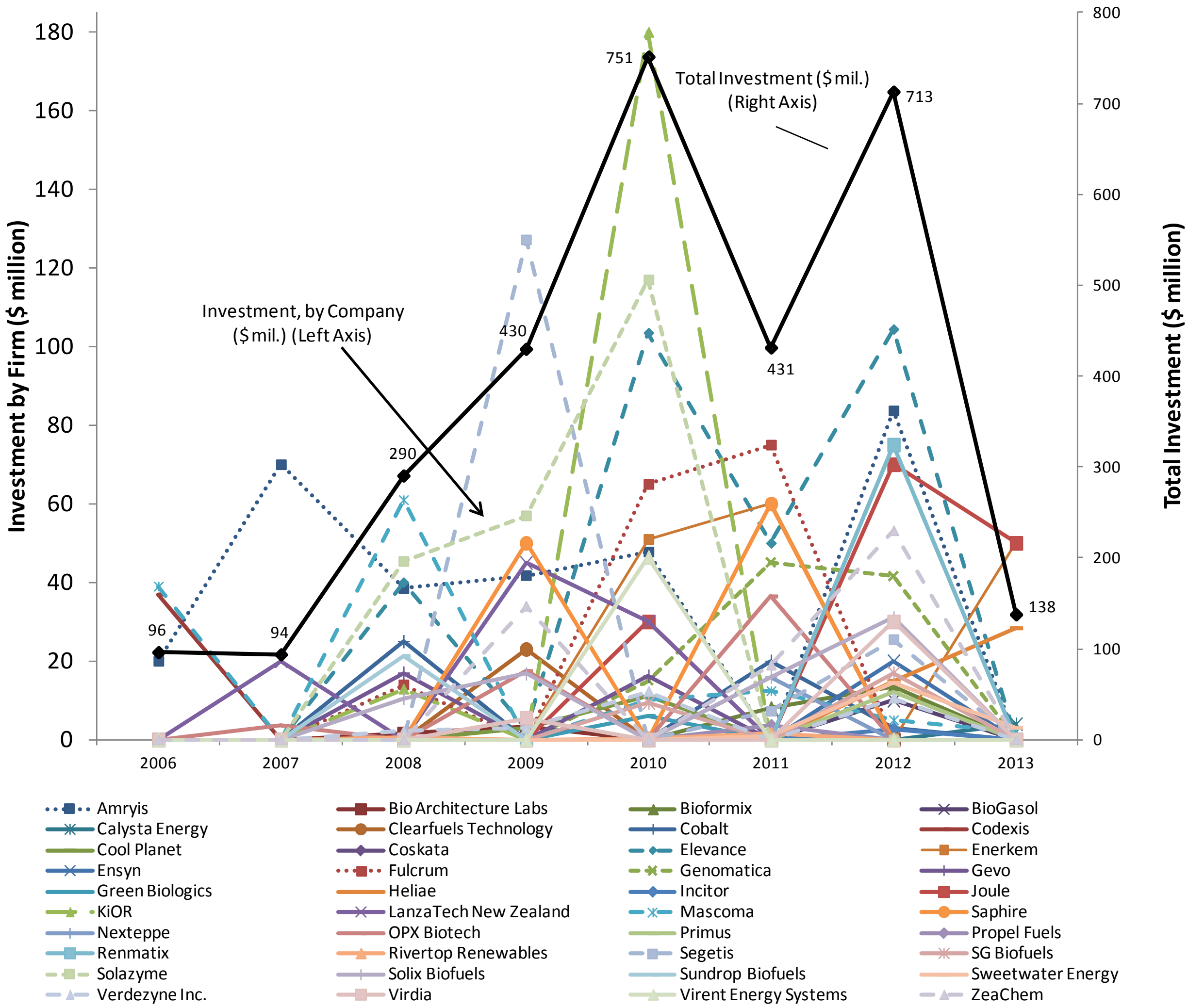


Figure 9: Private equity investment in biofuels, 2006-2013. Note: not all advanced biofuel companies are shown in figure. Some, like POET-DSM and DuPont, do not rely on private equity for funding. Source: privco.com

A final funding source for the Leapfrog route comes from large, capital intensive companies like oil producers and chemical manufacturers like Valero and DuPont. Although these companies made some investments in late 2000s and early 2010s, many recently reduced or eliminated funding into biofuels. In the summer of 2013, two companies – British Petroleum (BP) and Royal Dutch Shell – substantially scaled back biofuel investments, saying technology to produce fuel from cellulosic material would not be economical until at least 2020. Table 5 summarizes the total profits and biofuel activities from a number of large companies.

Table 5. Investments into Leapfrog biotechnologies from Fortune 500 companies

	Revenue in 2013 (billions)	Profit in 2013 (billions)	Main Activities in biofuels
British Petroleum	$396	$24	$500 million over 10 years in Energy Biosciences Institute; owns three sugarcane ethanol mills in Brazil. Working with DuPont and AB Sugar to build $500 million commercial-scale ethanol plant in UK at BP refinery. Owner of 1.4 MGY cellulosic demonstration plant in Louisiana purchased from cellulosic producer Verenium. Funder of Butamax, firm with plans to make butanol in MN, USA. Past partnerships include $135 million to support cellulosic startup Verenium (2010 acquisition), investments in Martek Biosciences for new sugar-to-diesel route, Qteros, Mendel Biotechnology
Royal Dutch Shell	$451	$16	Joint venture with Cosan for sugarcane ethanol production in Brazil (2 billion liters per year capacity); past investments in Codexis, Virent Energy Systems, HR Biopetroleum.
ExxonMobil	$438	$34	$100 million invested in Synthetic Genomics algal biofuels producer, claim to be investing another $600 million over next 10 years in same technology.
Valero	$125	$2	Pulled out of $232 million investment in Mascoma's wood to ethanol plant in Michigan. Past investments in VeraSun, Renew Energy, Terrabon, Qteros, ZeaChem, Solix.
Chevron	$220	$21	Investments in LS9, Mascoma, Weyerhauser, Solazyme, Codexia, Galveston Bay Biodiesel
DuPont	$35	$4	Operator of largest cellulosic ethanol plant (planned to open in summer 2014) of 30 MGY.

Large companies typically have longer planning horizons than small, venture-funded startups. They have the advantage of continuing funding a project even when there are problems or delays. At present, there is not a durable market signal to make the case for a large shift of investment into biofuels by these companies. Their profit margins are simply too large in their core businesses.

For example, in October 2013, BP scrapped four-year-old plans for a $300 million cellulosic ethanol project in Florida; and in April, 2013 Shell canceled plans with Iogen Corporation for a commercial-scale plant in Canada. Chevron shelved plans back in 2010 after examining 100 different feedstocks, while ExxonMobil spent $100 million over four years on algae only to cancel the program. DuPont is one company that, according to the EPA, could start producing substantial quantities of cellulosic biofuels in the next year.

3. Policy Landscape

A central purpose of this study is to gain a better understanding about how and why our current biofuel policies are supporting the three approaches. In the previous section, we looked at government loans and grants to biofuel development. Here, we examine the two main policies in the U.S.: California's Low Carbon Fuel Standard (LCFS) and the U.S. Renewable Fuel Standard (RFS).

3.a. Low Carbon Fuel Standard

California's LCFS requires a 10 percent reduction in carbon intensity (grams of CO_2e per megajoule (MJ) of fuel) in the state's transportation fuels between 2010 and 2020. This reduction applies to all transportation fuel providers who must either reduce the average intensity of their own fuel portfolio or purchase credits from other compliant providers.[21] More specifically, the carbon intensity reduction cap for the gasoline pool (gasoline and its substitutes) slowly declines from 98 to 96 gCO_2e/MJ between 2010 and 2014 then speeds up to eventually achieve 89 gCO_2e/MJ in 2020. LCFS credit prices ranged from $12/ton of CO_2e (September 2012) to over $80/ton of CO_2e (November 2013), and dropped to around $20/ton in April 2014, translating to potential gains of 2-14c/gallon of corn ethanol or 18-85c/gallon of waste-based renewable diesel (Yeh and Witcover 2014).

The LCFS has a number of elements that encourage the Incremental and Transitional approaches, at least through 2014. Court challenges to the legislation have caused uncertainty about the LCFS policy, which remains in force but with a delayed compliance schedule.[22] Absent policy certainty, the back-loaded compliance schedule and capacity to bank LCFS credits incentivizes fuel providers to make relatively easy, small adjustments to their fuel mix to meet or over comply with the modest carbon reduction requirements in early years rather than invest in large, more expensive carbon reduction measures that may be needed in later years of the program. At the same time, the LCFS is set up so that producers can realize financial benefits from low-cost CI reductions, because each gram of CO_2e per MJ in the CI rating has a real, associated dollar value. A fuel provider that lowers the carbon intensity of an existing pathway by more than 5 grams of CO_2e per MJ can apply for a modified pathway, and reap the

[21] Fuels determined to already meet 10 percent reduction requirements (electricity, hydrogen, natural gas) need not register under the program, but can opt in to generate credits.

[22] 2020 target of 10% CI reduction remains unchanged.

monetary benefit of the lower CI. New processes for existing feedstock/fuel combinations or new combinations may apply for eligibility under a new pathway, with no minimum CI reduction threshold.

A final element that aligns the LCFS with the Incremental approach is the ratio of the financial incentive from the LCFS to the financial requirement of CI reductions. An executive at the engineering firm ICM[23] pointed out that conventional biorefiners typically pursue a project if it has less than a two-year pay off period. Thus, these biorefiners can look to generate revenue from the LCFS by making a series of small and manageable changes to their plants. Undoubtedly, a financial signal exists for Leapfrog companies, but it seems currently too small and uncertain to motivate a large capital risk.

At the moment, biofuel producers have an array of options for reducing the rated CI of their production systems. [24] Figure 10 shows the range of CI values set as defaults in the LCFS by ARB (green bands), for new and modified pathways submitted by the private sector (blue bands), and for biofuel pathways in use (orange bands) as of April 2014. The new and modified pathway CIs, and CIs associated with each biofuel production facility are self-reported by providers and subsequently examined by ARB staff (the new/modified pathway CIs are subject to approval by ARB at periodic board hearings). Ethanol from feedstocks other than corn alone has CI ratings that range from 22 to about 100 gCO_2e/MJ.[25] The improvements seen in new pathways include CI declines due to on-site adjustments that may cause fewer problematic market effects (Plevin 2010).

[23] ICM provides engineering and planning support for approximately 50 percent of U.S. biorefineries.

[24] We discuss CI ratings for policy, as opposed to carbon impacts of fuels, which requires a more comprehensive analysis—see discussion in Executive Summary.

[25] Feedstocks in the grain mix category include mixes of corn and sorghum, or corn, sorghum and wheat slurry. Feedstocks in the grain/oth category include ethanol from sorghum, molasses, and waste beverage. The 22 gCO_2e/MJ is for sugarcane molasses ethanol, obtained by treating molasses as a waste from sugarcane processing.

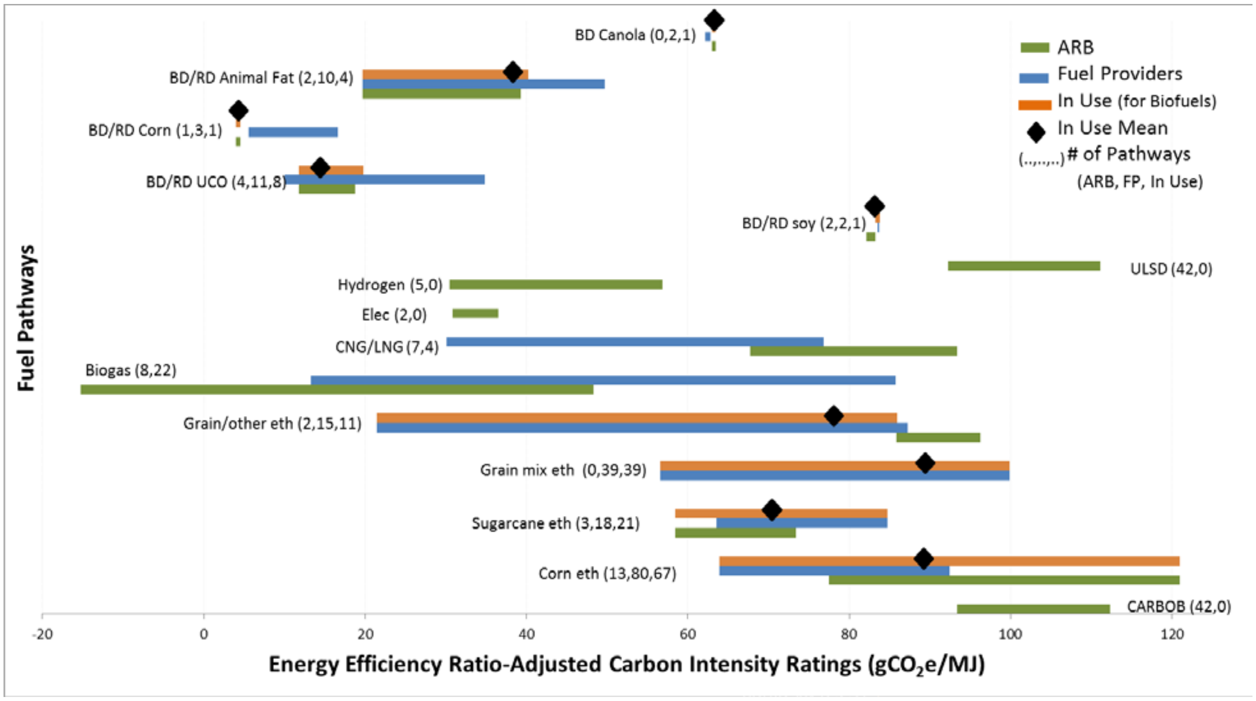


Figure 10. Summary statistics (ranges and averages) of carbon intensities for fuels under California's LCFS, by feedstock, April 2014. The green bands are the ranges of default values set by ARB. The blue bands represent ranges for new and modified pathways submitted by fuel providers. The orange bands indicate CI ranges for biofuel pathways in use (black diamond is the mean for used biofuel pathways, unweighted by volume).

Because many biofuel providers only send a portion of their fuel to California, only that portion of their fuel mix will garner an associated value based on rated CI. A larger regional or national LCFS could change the calculus for providers making Incremental (or even Leapfrog) changes. The size of the financial incentive varies, depending on the LCFS credit price. Further research is needed to examine if the LCFS is actually driving fuel providers to make improvements at their plants.

Ultimately, near-term reductions to CO_2e ratings may make Incremental changes (and to a lesser extent the Transitional route)more attractive to biofuel producers, and Incremental improvements at existing facilities may have a lower potential to cause fuel swapping and leakage than added production. While the LCFS could eventually provide an incentive for Leapfrog technologies if credit prices are sufficiently high for a long enough time, policy uncertainty undermines this signal. So far no cellulosic ethanol produced in the U.S. has been shipped to California. The reason for this is unclear, but getting an LCFS pathway approved and certified may be too much of a burden for companies attempting to prove a technology at scale with limited resources.[26]

[26] They may also have established an initial market outlet (outside California), as part of the investment strategy.

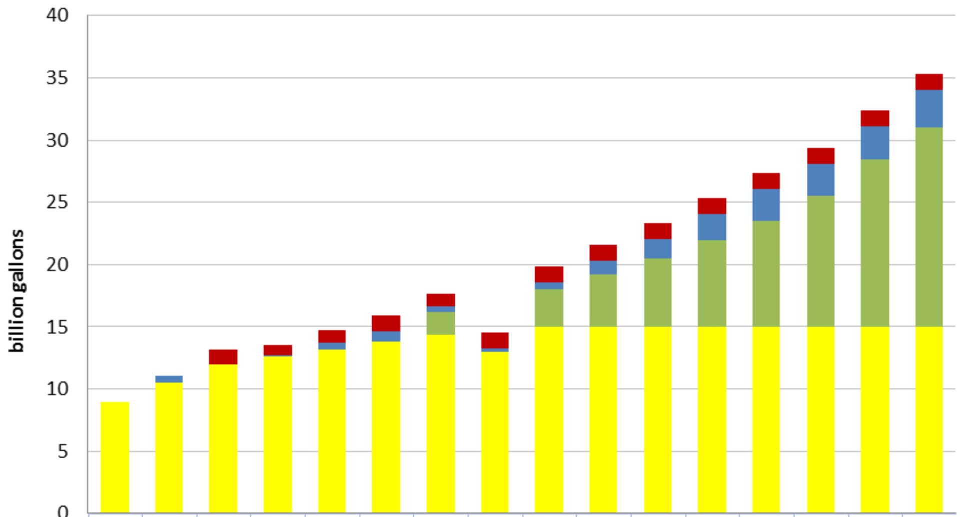
3.b. Renewable Fuel Standard

The Renewable Fuel Standard (RFS) requires U.S. renewable transport fuel providers to supply at least 36 billion gallons of renewable fuels by 2022 – up from 9 billion gallons in 2009 – through a series of annual volume mandates. Unlike the LCFS, the RFS mandates fuels in specific categories, each with a minimum threshold for lifecycle percentage CI reduction[27]: renewable fuels (20 percent); advanced fuels (50 percent); biomass-based diesel (50 percent); and cellulosic fuels (60percent). The mandates for the categories nest: the overall mandate consists of renewable fuels; some renewable fuels are advanced; and advanced fuels include biomass-based diesel and cellulosic fuels. Like the LCFS, compliance is based on a market mechanism: tradable compliance credit (RINs) for each submandate that track fuel volumes, and are separated from biofuels (for trade or compliance) as they enter the transport market (e.g., upon blending). Regulatory language allows downward annual adjustment to the cellulosic mandate if commercialization lags initial expectations, and optional decreases in the advanced fuel mandate in line with the cellulosic adjustment. Providers can purchase “waivers” at a price tied to the prior year’s gasoline price to make up the difference between actual cellulosic production and that year’s adjusted cellulosic mandate. But unlike cellulosic fuel, the waiver does not count toward the advanced fuel mandate.

Figure 11 summarizes the RFS annual schedule of mandates – as implemented through 2013, the original level, proposed adjustments for 2014, and as legislated from 2015 through 2022.[28] The stacked columns illustrate the nested mandate structure.

[27] Compared to gasoline or diesel in 2005.

[28] The legislation sets a floor of 1 billion gallons for the biomass-based diesel mandate; this graph assumes the mandate will remain at the level proposed for 2014.



Mandates (% CI reduction)	2008	2009	2010	2011	2012	2013	2014 orig	2014 prop	2015	2016	2017	2018	2019	2020	2021	2022
biomass-based diesel (50%)	0	0	1.15	0.8	1	1.28	1	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
addit'l advanced (50%)		0.6	0	0.15	0.5	0.816	0.5	0.263	0.58	1.08	1.58	2.08	2.58	2.58	2.58	3.08
cellulosic (60%)	0	0	0	0	0	0.014	1.75	0.017	3	4.25	5.5	7	8.5	10.5	13.5	16
addit'l renewables (20%)	9	10.5	12	12.6	13.2	13.8	14.4	13.01	15	15	15	15	15	15	15	15

Figure 11. Renewable Fuel Standard volumetric mandates, billion gallons (ethanol equivalent, except actual gallons for biomass-based diesel).

The RFS has elements that appear to incentivize the Leapfrog approach: it requires increasing volumes of non-conventional fuels (advanced fuel, cellulosic submandates), it bins fuels into discrete categories with large reductions needed to get from one bin to the next, it provides a premium for cellulosic fuels (the size of the cellulosic waiver),[29] and it guarantees a market for cellulosics once they appear. However, the advanced fuel submandate can be met using existing technologies (e.g. biodiesels from transesterification), and fuel providers can only cash in on the cellulosic market if they actually produce fuel. So far, the financial hurdle of the pre-startup phase has been too great for almost all firms entering the advanced fuel market, other than biodiesel and renewable diesel using vegetable oil feedstocks and waste.

Additionally, although the cellulosic waiver price provides a premium for cellulosic fuels, it also effectively caps the financial incentive for cellulosic fuels. The waiver price dropped from $1.56/gallon

[29] Because waivers are applied only to the cellulosic mandate, whereas actual cellulosic volumes are applied to *both* cellulosic and advanced fuel mandates, an obligated party who buys a cellulosic waiver must still pay a cost to meet the advanced fuel mandate. That means the parties should be willing to pay up to the combined price of the waiver and the advanced fuel mandate for cellulosic fuels.

in 2010 to the $0.42/gallon in effect starting in 2013, tracking a decline in gasoline prices. A legal challenge resulted in the retrospective zeroing out of cellulosic mandates from 2010 to 2012, undermining the waiver's reliability as an incentive.[30] A more fundamental challenge to the RFS policy is currently under way, due to concern about the ethanol "blendwall" of 10 percent per volume in gasoline, the prevalent standard. Renewable mandates going forward imply a need to break through the blendwall by ramping up use of higher ethanol blends requiring changes at the pump, in vehicle types, and fuel delivery infrastructure, or to go around the blendwall with drop-in fuels that use existing infrastructure. The 2014 proposal, which adjusts the overall renewable mandate downward, has sparked controversy and speculation of more court challenges ahead. This calls into question the reliability of all mandate levels and increases policy uncertainty since adjustments are made yearly.

The RFS may actually favor some Incremental routes. The U.S. EPA analyzed a process change for dry mill grain sorghum ethanol – namely, substituting natural gas with biogas (and up to 0.15kWh of electricity supplied from off-site) – that moved the fuel from a 32 percent CI reduction (and eligibility towards the renewable mandate) to a 52 percent CI reduction ("advanced fuel" rating). However, the principal effect of the large CI bins and higher mandates is to encourage existing, commercialized biofuels rated as eligible to be scaled up in volume to meet mandates. Finally, the cellulosic waiver "premium" discussed above may be high enough to provide some incentive for bolt-on Transitional cellulosic innovation.

[30] The court found that the revised mandate was set higher than current expectations about cellulosic fuel supply, and that incentivizing fuel production in this way was inappropriate.

4. GHG Reduction Potential

This section presents an analysis and discussion on the potential for Incremental, Transitional, and Leapfrog approaches to reduce GHGs. To make these estimates, we utilize policy-based carbon intensities to represent notional, order-of-magnitude differences in potential across the three routes. Figure 12 shows the estimated fuel production and CO_2e reduction for three strategies relative to a reference fuel.[31] For the Incremental improvements, we separated corn ethanol facilities and biodiesel facilities. Similarly, for the Transitional approach, we separated corn stover and corn fiber. Here, fuel production is the quantity of fuel to which a given strategy is applied.[32] Assumptions are stated below the figure.

Under our assumptions, the Leapfrog approach appears to have the greatest potential for CO_2e reduction, particularly in later years; however in the near-term, the Incremental approach will likely lead to greater GHG reductions. As currently conceived in the U.S., the Transitional approach, only applies to existing corn ethanol plants for stover and corn fiber. Due to the moderate investment risk of bolt-on facilities, we assume their deployment is slower than Incremental improvements. This results in the GHG benefits from bolt-ons being the lowest of the three routes by 2030.

Given the most optimistic assumptions about the growth of Leapfrog technologies, the cross-over point at which the Leapfrog route could have greater GHG benefits will not occur until at least 2020, if cellulosic and algae biofuels reach about 2.0 billion gallons. By 2030, the highest possible CO_2e reduction in the U.S. from the three routes is 84 million metric tons of CO_2e per year (MMT/yr) from Leapfrog technologies, 39 MMT/yr from Incremental technologies, and 13 MMT/yr from Transitional technologies. For perspective, in 2012, U.S. GHG emissions were 6,502 MMT/yr for the entire economy and 1,735 MMT/yr for the Transportation sector (EPA, 2014). Thus if all three of these approaches were aggressively pursued, by 2030, the combined reduction of transport CO_2e would be around 7 percent relative to today's emissions.

[31] For cellulosic fuels (bolt-ons and Leapfrog), the reference fuel is gasoline. For conventional fuels (Incremental (corn/soy)), the reference is corn ethanol and soy biodiesel. Reference fuels are determined by the most likely fuel to be replaced. The comparison against a reference fuel implies a one-to-one replacement between fuels, ignoring real world market effects (see Executive Summary for more discussion).

[32] For example, the Incremental (corn/soy) fuel production band is the volume of corn ethanol and soy biodiesel which realizes the CI reduction from the reference level of 98.3 gCO_2e/MJ to a new state of 70 gCO_2e/MJ, for existing facilities.

California is currently considering extending its LCFS past 2020, with a goal of reducing GHG emissions an additional 10 percent between 2020 and 2030. Our analysis suggests that such a target for the entire U.S. would be difficult to achieve with domestically produced biofuels alone. However, when combined with electrification of transportation, reductions in driving, improved fuel economy of light and heavy duty vehicles, and improvements to imported fuels, transportation emissions could be dramatically reduced.

Overall, the analysis suggests that Incremental improvements to existing biorefineries in the form of efficiency improvements and bolt-ons could lead to significant but not dramatic CO_2e reductions and, if pursued simultaneously, likely would have greater impact than the Leapfrog approach for at least the next 10 years. However, these reductions are limited by their marginal CI improvement potential and by the capacity of conventional crop and waste-based biofuel production in the U.S. An expansion of conventional crop biofuels would be needed to capture more gains from this approach, but the risk of adverse impacts increases with scale of production. Ultimately, achieving deep reductions in transportation fuels past 2030, and developing biofuels for the modes most likely to need large volumes (aviation, marine, long haul trucking) will require development of Leapfrog technologies.

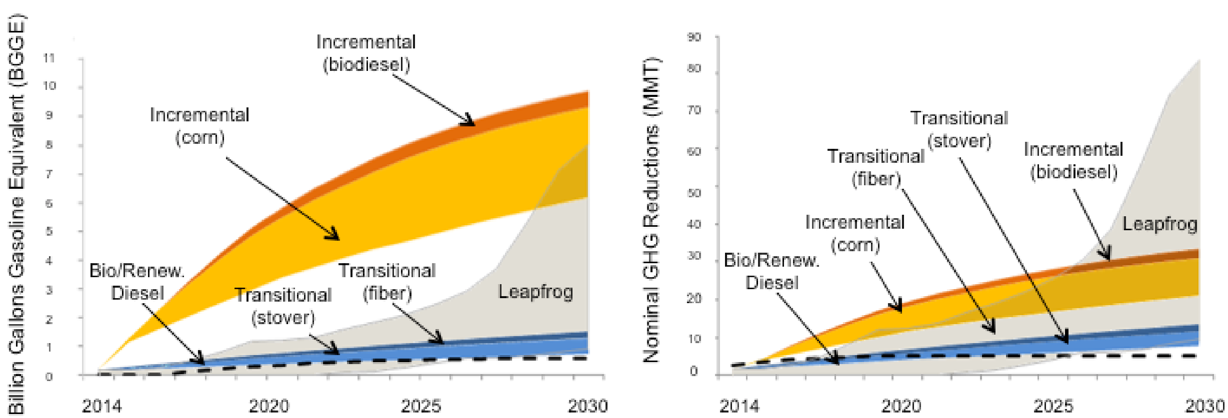


Fig. 12. Maximum fuel production available to specified route (left) and associated GHG reductions (right) in the U.S. Fuel quantities grow over time as biorefineries are improved (Incremental), bolt-ons are built (Transitional), or stand-alone facilities are built (Leapfrog). Figures show production/GHG reductions relative to 2014. Incremental (corn/soy) refers to efficiency improvements at existing biorefineries. Transitional (stover/fiber) refers to bolt-on additions to corn ethanol plants. Leapfrog refers to stand-alone cellulosic and algal facilities. Dashed line refers to the contribution from domestically-produced biodiesel or renewable diesel from waste oil, animal fats, and corn oil.

Assumptions: Incremental (corn/soy): upper bound assumes 10 percent of corn ethanol and soy biodiesel plants per year can make upgrades to reduce carbon intensity of plant from 98.4g/MJ and 83.25g/MJ to 70 g/MJ and 65 g/MJ for corn ethanol and soy biodiesel, respectively, starting in 2013. Volume projections from 2013 AEO High Oil Price case. Lower bound uses same assumptions except 5 percent of plants make upgrades each year and 2013 AEO Reference case projections are used. Transitional (stover/corn fiber): upper bound assumes stover conversion of 58 lbs. of stover per bushel, 70 gal/ton, 15.5 percent moisture content, 38 percent retention rate in field; corn fiber conversion achieves 5 percent yield increase per gallon of corn ethanol. Together, stover/fiber achieve 36 percent yield increase. Only 1.5-3.0 percent of plants make the upgrades each year. The CI reduction from 99 to 20 gCO_2e/MJ is achieved on added yield. Projections of ethanol use come from 2013 AEO High Oil Price case. Lower bound uses same assumptions except 2.5 percent of plants make upgrades per year and the 2013 AEO Reference case is used. Leapfrog: upper bound uses corn ethanol ramp-up in U.S. so that cellulosic volume in 2016 equals corn ethanol volume in 1999. The reference fuel is gasoline, CI 99 gCO_2e/MJ. New carbon intensity is 20 gCO_2e/MJ. Lower bound uses 50 percent ramp-up rate of upper bound and delays 5 years. Bio/Renewable diesel uses Gompertz curve which transitions from ~150 MGY today to maximum penetration 2.4 BGY. Bio/Renewable diesel is assumed to have CI of 55, 30, 18, and 20 gCO_2e/MJ for soy/canola, animal fats, waste grease, and corn oil, respectively, compared with a CI of 98 gCO_2e/MJ for the reference fuel (diesel).

As discussed in Section 1.f above, the use of LCA for policy is an ongoing arena of debate and research. Some have argued for additional comprehensive modeling (e.g., Plevin et al., 2013), while others advocate a move away from reliance on modeling (e.g., DeCicco 2011) and focus on mitigating (unmeasured) displacement effects (DeCicco 2011), or avoiding them all-together (DeCicco 2013); still others are trying to implement more streamlined versions of modeling uncertainty (selected parameters) (Soimakallio 2014). We do not deal with these concerns directly, but concentrate on how LCA is currently used in policy, while noting the need for additional research, policy steps, and monitoring to investigate how the *potential* for carbon reduction can be realized. We reiterate that improvements in emissions from existing production systems (e.g., efficiency gains in the Incremental Route) are preferable to no improvement, and that emissions from routes that rely on additional land use and displacement of gasoline are uncertain but hold great potential. Further research is needed on the trade-offs between investments in the various routes (e.g., potential for early GHG gains vs. delayed development of breakthrough technologies, potential positive spillovers in terms of knowledge base or market development from current to future biofuel technologies).

5. Conclusions

This study examines three paths forward for decarbonizing liquid biofuels: Incremental, Transitional, and Leapfrog. Since the LCFS and RFS policies were codified into law seven years ago, we have witnessed primarily incremental improvements in biofuel production. Recently, firms have begun developing Transitional technologies. As these policies become more stringent, the biofuel industry may eventually reach a tipping point in which Leapfrog technologies are needed.

If all three routes were pursued in an aggressive fashion we estimate a modest decline in transportation GHG emissions by 2030 relative to today's level. (This calculation relies on controversial carbon intensity values and accounting used in today's policies.) Of course, several other biofuel GHG reduction strategies are also being pursued around the world, such as bolt-on facilities in Brazil utilizing sugarcane bagasse and various renewable and biodiesel facilities utilizing non-food crops (e.g. jatropha) and algae.

In the near-term, we see Incremental improvements at existing corn ethanol and soy biodiesel plants or similar facilities using other feedstocks offering the greatest carbon reduction potential. However, if the goal is to achieve large GHG reductions from biofuels (e.g. > 20percent), then Leapfrog technologies appear very likely to be needed. Cultivating them at the scale required under conditions that do not erode their low-carbon status, especially given other demands on biomass, is a pressing challenge for the future.

An Incremental strategy has been especially attractive, given the slow development and commercialization of Leapfrog technology and the unpredictable current and future policy landscape. Precisely how far process improvements can go in terms of lowering CI at a relatively low cost is uncertain, and remains an empirical question. The Transitional technologies are attractive because of their potential to facilitate learning and development for future cellulosic biofuel production at a far lower investment and risk level than full-scale Leapfrog investments. But ultimately Leapfrog technologies should be attractive to any policy maker serious about deep GHG reductions in the transportation sector.

This paper focuses on innovations that are currently occurring in the marketplace. Most recent innovations produce ethanol, which is demand-constrained in the U.S. If a long-term goal is to expand the share of biofuels in aviation, marine transport, and heady duty vehicles, then drop-in biofuel pathways will be needed. As we discuss above, the Transitional innovations and most of the current Leapfrog innovations do not involve the use of drop-ins. From an energy planning perspective, we recommend greater specific policy focus be placed on developing drop-in biofuels.

We should also note that the discussion of Incremental, Transitional and Leapfrog routes applies to other energy technologies as well. Two examples include: (1) self-driving vehicles in which some firms are pursuing full automation (Leapfrog) while others are pursuing partial automation (Incremental/Transitional) and (2) vehicle CI in which some firms are pursuing breakthrough fuel technology (Leapfrog) while others are pursuing "lightweighting" (Incremental/Transitional).

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