

NextSTEPS White Paper:

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

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Please note: the analysis and statements presented in this paper are the sole responsibility of the authors.

Sustainable Transportation Energy Pathways Program (NextSTEPS)

NextSTEPS is a four-year (2011-2014) multidisciplinary research consortium, part of the Institute of Transportation Studies at the University of California, Davis. Our mission is to:

- Generate new insights and tools to understand the transitions to a sustainable transportation energy future for California, the US and the world (Research)
- Disseminate valued knowledge and tools to industry, government, the environmental NGO community, and the general public to enhance societal, investment, and policy decision making, (Outreach)
- Support the training of the next generation of transportation and energy leaders and experts. (Education)

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Executive Summary

Background

Biofuels¹ present great promise but also great challenges. Enthusiasm for biofuels 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). The path to achieving those goals seemed straightforward: boost the production of corn to make ethanol and then transition to non-food (cellulosic or algal) materials. This plan received fervent support from the agricultural industry, energy security advocates, and local communities throughout the farm belt. Some environmentalists expressed concerns, but overall support was high.

But over the next few years skepticism slowly spread. Not only was corn-ethanol production energy-intensive (Farrell et al., 2006), but it consumed large amounts of land; and, evidence suggested there were large potential greenhouse gas impacts of diverting land to corn production (Fargione et al., 2008; Searchinger et al., 2008). As corn-ethanol production ramped up in the 2000s and especially after 2006 – soon utilizing over 30% of U.S. corn production post-2007 and over 40% since 2009 (USDA 2014) – concerns mounted about competition with food and the effect on food prices (Fresco, 2009). Even stronger objections were heard in Europe regarding the overall sustainability of biofuels, aggravated in the European case by the ramp up of fuels made from vegetable oils and the associated, greater use of palm oil produced from the rainforests of Southeast Asia.

When the U.S. Congress codified the Bush goals into law in 2007 in the Renewable Fuel Standard (RFS), it established a mandate of 16 billion gallons of crop-based fuel production by 2015.² This was accompanied by a delayed but then rapidly expanding target for cellulosic fuels, reaching 16 billion gallons in 2022, surpassing a 15 billion gallon legislated limit for corn starch ethanol.³ The widespread belief was that corn ethanol would set the stage for cellulosic (and algal) biofuels to leapfrog forward,

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 which was expected to be met largely by corn ethanol, and a nominal 1 billion gallons from the Biomass-Based Diesel category which 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.

reducing the carbon intensity of the fuel pool in the U.S. However, the jump from demonstration to commercial stage has so far proven difficult for cellulosic (and algal) biofuel companies. In 2013, while over 14 billion gallons of starch and oil-crop-based fuels were produced, less than one million gallons of cellulosic biofuels were produced, far short of the mandated level of one *billion* gallons. The EPA foresees a maximum of 30 million gallons of production in 2014 (EPA, 2013). To date, even smaller volumes of algae-based fuels have been produced.

Since the mid-2000s, considerable innovation has occurred at existing biorefineries that produce corn ethanol and biodiesel. For example, the extraction of corn oil now occurs at about 80% of U.S. corn ethanol plants. Additionally, some biorefineries are swapping their plant's process fuel (e.g. from natural gas to landfill gas), thereby lowering the greenhouse gas intensity of their products.⁴ Others are lowering the energy use of their plant by switching from dry to wet distiller grain co-production.⁵ Still others are improving the starch to ethanol yield through the use of corn strains that are genetically optimized for ethanol production.⁶ The feedstock mix for biodiesel production has shifted toward corn oil and waste greases, which have lower rated carbon intensities.

A number of biofuel technologies are also emerging that may help enable 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 on 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),
- and corn stover (like bagasse, except not as yet collected and brought to a central location).

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 in their plants. At the same time, they gain experience with handling cellulosic material, including the logistics of collecting and preparing the feedstock for conversion. Some efforts also are

⁴ Poet's 105 MGY Chancellor, SD plant began supplementing natural gas use with landfill gas in 2009.

⁵ This switch reduces the energy required for drying the distiller's grain.

⁶ Glacial Lakes Ethanol uses a corn variety "Enogen" which has been genetically engineered to boost ethanol output and reduce energy costs and water use.

helping increase the general knowledge base for handling and converting cellulosic biomass. In addition, biochemical firms have also begun converting cellulose to industrial chemicals,⁷ thus helping establish enzyme markets. Finally, other companies are gaining experience with cellulosic material, turning it into intermediates which are used for heat and electricity.⁸

Another emerging development is the growth of biodiesel or renewable diesel.⁹ These fuels (mainly biodiesel) have seen their combined U.S. production grow from 2 million gallons in 2000 to about 1.6 billion gallons in 2013.¹⁰ Waste oils are an attractive feedstock for biodiesel and renewable diesel because they have little to no land-use impact and few alternative uses outside of transportation fuel. However, the domestic supply of waste oils in the U.S. is limited. A resource assessment by Parker (2013) suggests a maximum annual potential of 1.2 billion gallons of fuel from waste oil, animal fat, and used cooking grease. Competing uses for some of these products (animal fats in soap production, for example) could affect their supply and environmental impact. U.S. plant-based vegetable oils in the form of soy, canola, and corn oil can provide an additional 1.2 billion gallons based on current production levels for a total of 2.4 billion gallons.¹¹ While this production could be expanded, doing so would typically involve greater land-use impacts. This combined volume of biodiesel and renewable diesel amounts to approximately 6% of 2013 U.S. road diesel fuel consumption, i.e. 2% of total U.S. petroleum consumption.¹²

Objectives of this White Paper

Against this backdrop, a range of energy models project a substantial future need for low-carbon liquid biofuels for specific transportation sectors (marine, aviation, perhaps heavy-duty) to meet long-term climate goals (IEA 2012, GEA 2012). Given the slow development of commercial scale cellulosic and algal biofuels, what is the role of incremental and transitional technologies in future greenhouse gas

⁷ Anelotech and BioAmber report using cellulosic material to produce industrial chemicals.

⁸ Ensyn is working with Talko to turn cellulosic wood waste into pyrolysis oil for electricity generation.

⁹ The term “biodiesel” typically refers to a methyl ester whereas “renewable diesel” typically is chemically similar to conventional diesel and is considered a drop-in diesel replacement fuel.

¹⁰ 1,339 million gallons of biodiesel production reported by EIA (2014), and about 260 million gallons of domestic renewable diesel production (417 million gallons of renewable diesel reported in the RFS, less 157 million gallons of renewable diesel imports reported by EIA).

¹¹ For comparison, in 2013, biodiesel and renewable diesel combined to produce volumes of nearly 2 billion gallons.

¹² Cellulosics and algae could be converted to oil as diesel substitutes as well, but we consider this to fall under the Leapfrog route.

reductions? Will these developments eventually lead the way to an expanded cellulosic and/or algal biofuels industry? What role does policy play in incentivizing one route versus the others? This paper examines these questions through the lens of three distinct routes forward for biofuels:

- 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 cellulose while using existing infrastructure and supply chain logistics to the largest extent possible, and
- 3) a **Leapfrog** route that develops cellulosic or algae pathways to produce ethanol or drop-in gasoline or diesel replacement fuels at new, stand-alone biorefineries.

The paper discusses the potential for CO₂e emissions reductions from these routes, issues associated with their commercialization, funding that has already been spent on their development, and the implications of policies such as the U.S. Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS) on their potential future contributions.

Ultimately, assessing potential greenhouse gas emission reductions from biofuels requires a comprehensive analysis that

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

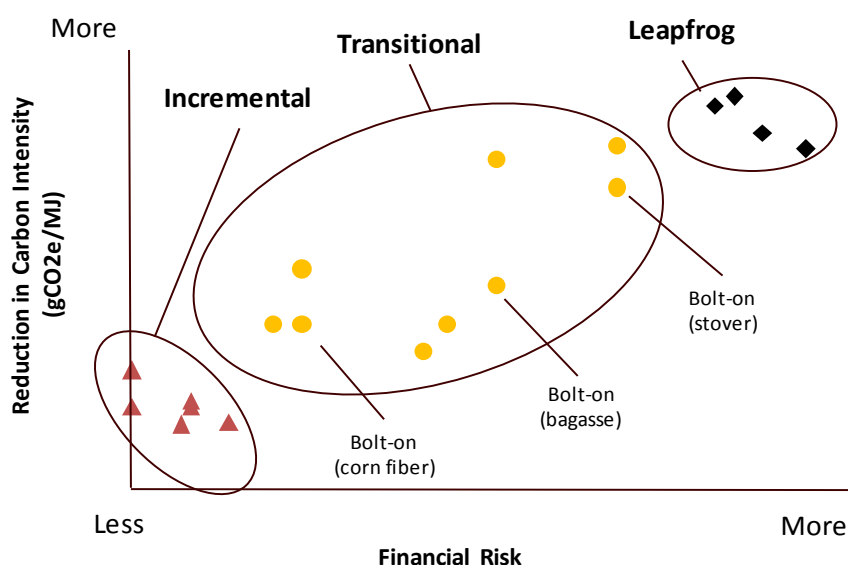
Life cycle assessments (LCAs) of biofuels typically start by summing effects of inputs and outputs of an individual biorefinery or fuel production system to estimate the environmental impact of one unit of fuel. When used in policy, the estimate is often used to derive environmental standing of one fuel compared to another. This assumes a one-to-one substitution between the fuels, which in reality is usually not the case. More fundamentally, the LCAs truncate the system boundary to the production system and ignore potential environmental impacts beyond. Policy has recognized that assessment of emissions from a vastly expanded biofuel industry needs to account for land-use changes prompted beyond the biofuel supply chain through global market effects. Plevin, Delucchi, and Cruetz (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.

incorporates 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). Such an analysis lies beyond the scope of this paper. Instead, in discussing CO₂e emissions reductions potential, this paper makes qualitative arguments about the likely scope of reduction. In calculations, the paper uses carbon intensity ratings from the two main U.S. biofuel policies today – the U.S.'s RFS and California's LCFS – as well as some literature values, that 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 estimated carbon intensity values' use 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 contribution to a low-carbon transport future.**

Characterizing alternative pathways

The three-pronged paradigm introduced in this paper lays the foundation for an in-depth discussion about tradeoffs between the routes of biofuel development in terms of scope for carbon emissions reductions and level of investment risk from biofuels (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



ES-1. Spectrum of carbon intensity versus financial risk showing low risk for Incremental, Transitional, and Leapfrog routes.

biofuel feedstocks includes the risk of higher emissions from land use change.¹³

On the opposite end of the risk spectrum is Leapfrogging. 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. The leapfrog technologies can also unlock some significant resources, like organic fractions of municipal waste, which have no land use risk and a few alternative uses. However there is a risk that Leapfrog technologies will remain costly to move to maturity – from the first plant to “nth plant” costs – and, in the end, will be a waste of public money. Below we present data on historical funding of Leapfrog technologies from venture capitalists,¹⁴ federal programs,¹⁵ and oil companies. Since 2009, these funding sources have averaged over \$1 billion per year. Modeling presented in this study suggests that in a world with low to moderate gasoline prices, there is a chance Leapfrog technologies never reach cost parity with petroleum fuels. There is also a risk that Leapfrog technologies have additional environmental costs, absent policies that would mitigate against these (e.g., limiting the extent of land competition).

Between the Incremental and Leapfrog routes lay transitional technologies. Our research suggests that bolt-ons could increase ethanol yield per acre of corn by 5% and 30% for corn fiber and stover, respectively.¹⁶ This means the Transitional route is limited in its maximum GHG benefit, because the 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.

Which route offers the largest reduction in GHG emissions? 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. Figure ES-2 shows the assumptions about rated carbon intensities for each

¹³ 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 EPA implements the rule.

¹⁴ Information from 40 leapfrog firms.

¹⁵ Includes funding from USDA, DOE, NSF, Air Force, Army, Navy, and American Reconstruction and Recovery Act.

¹⁶ 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.

path relative to a reference fuel (existing biofuels where we envision process improvements, and gasoline for additional production towards cellulosic mandates), and gives examples of technology shifts and associated reductions in rated carbon intensity for each of the three routes.

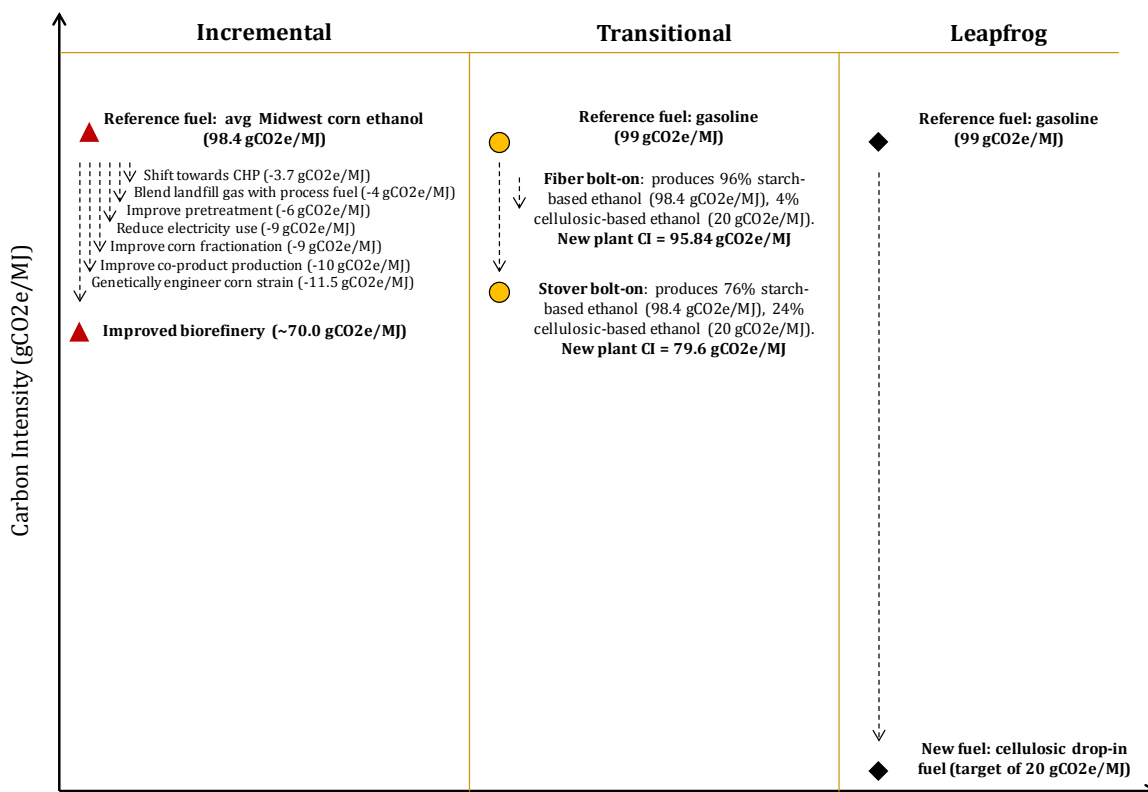


Figure ES-2. Examples of carbon intensity (CI) reduction strategies occurring in each of the three routes. All calculations shown at the biorefinery level. Incremental strategy CI reductions are examples from reductions self-reported under California's LCFS policy and are not necessarily additive. Transitional strategy CI values are based on personal interviews (Rivers, 2014; Griffith, 2014). Leapfrog CI value is based on average attributional LCA literature value.

Combining the information in ES-2 with assumptions about deployment rates of these technologies allows us to estimate the potential production of these fuels in the future (ES-3, Left) and how their potential rated GHG emissions compare to those of reference fuels between today and 2030 (ES-3, Right). The figures show that a strongly implemented Incremental route could lead to far larger production of improved biofuels in the next ten to fifteen years among gasoline and diesel substitute fuels than the Transitional or Leapfrog routes, but by about 2025 the GHG benefits of an aggressive Leapfrog path could be greater under these assumptions.

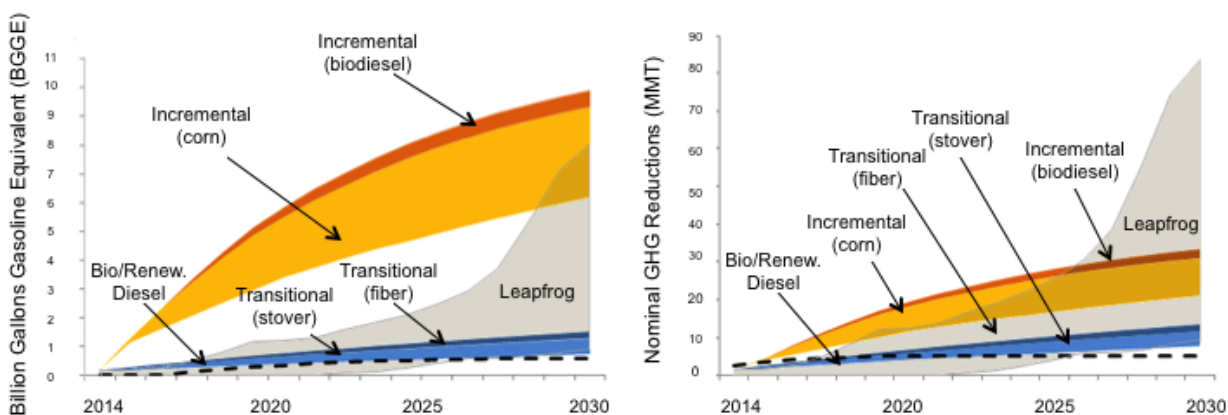


Figure ES-3. Maximum fuel production if specified route is aggressively pursued (left) and associated GHG reductions (right) in U.S. Fuel quantities grow over time as biorefineries are improved (Incremental), bolt-ons are built (Transitional), or stand-alone facilities are built (Leapfrog). Figures set '0' production/GHG reductions at 2014 levels. Dashed line refers to the contribution from domestically-produced biodiesel or renewable diesel from waste oil, animal fats, corn oil, and vegetable oil. Assumed growth rates: Incremental = 5-10% of biorefineries per year achieve lower carbon intensity (70 gCO₂e/MJ); Transitional = 1.5-3.0% of biorefineries add stover & fiber bolt-ons per year; Leapfrog = corn ethanol expansion from 1999-2014; Bio/Renew. Diesel = Gompertz curve, max penetration 2.4 BGY.

Based on the assumptions used here, the crossover point (where Leapfrog systems provide more direct CO₂e reduction than Incremental) occurs when cellulosic and algae biofuels reach about 2.0 billion gallons. By 2030, the high range of plausible CO₂e reductions in the U.S. from the three routes compared to reference fuels is 84 million metric tons of CO₂e per year (MMT/yr) from Leapfrog technologies, 33 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, using our assumptions, if all three of these routes were aggressively pursued, the combined reduction of transport CO₂e would be around 7% relative to today's U.S. transportation emissions, by 2030.

A number of limitations to our analysis are worth noting. The focus of this paper is on liquid biofuels, but these fuels operate in a larger bioenergy and biochemical marketplace; technologies like anaerobic digestion-to-biogas and biomass-to-electricity are not directly discussed here but will likely compete for feedstocks. The role of bioenergy with carbon capture and storage or co-processing biomass with coal or natural gas, potentially crucial technologies for enabling deeper GHG reductions pathways (GEA, 2012), also is not discussed. This paper does not directly address the ethanol blend limits (i.e. "blend wall"). Rather, our projections of biofuel production represent what is realistically possible by 2030 in the absence of blend requirements. As already discussed, the carbon intensity ratings do not reflect actual

climate impacts, and our one-to-one comparison with reference fuels leaves out important displacement effects. Lastly, the paper’s focus is on U.S. biofuel production. However, the concepts outlined could have relevance for biofuels production in other countries; indeed, improving agricultural systems and biofuel production efficiency in other countries might be more cost effective and have a greater magnitude of environmental benefit than doing so in the U.S. Finally, a key uncertainty and important question for policy is the potential total future demand for biofuels and the resulting scale of production that would occur in the U.S. and around the world, relative to available feedstocks and volumes of biofuels that could be produced sustainably, with low net GHG emissions, and what policies are required to reach those potentials. These volume-related issues are described somewhat in the first section of the paper but are not directly considered in this analysis.

Conclusions and Recommendations

The paper explores a range of issues around these three distinct types of biofuel strategies, or “routes” (Incremental, Transitional, and Leapfrog), including investment requirements and the levels of funding from governments and the private sector that these strategies have already received. To date, investments in incremental improvements have yielded higher returns than the other two approaches in terms of total reductions in direct carbon intensity. After almost \$8 billion invested in Leapfrog approaches since 2009, there has been very little production, and as a result, very little reduction in direct carbon intensity (Figure ES-4). This does not mean that RD&D funding for Leapfrog has been wasted, but it does mean that it has not reached its goals. It may be valuable to reassess how research dollars are allocated across these three approaches, paying more attention particularly to transitional strategies that may help bring down the cost – and risk – of Leapfrog approaches.

	Total (millions)	Per year (millions)	Source
Federal	\$3,335	\$833	http://energyinnovation.us/
Venture Capital	\$2,325	\$581	www.privco.com
Energy Companies	~\$2,000	\$500	Company websites

Figure ES-4: RD&D funding for Leapfrog technology biofuels, 2009-2012, by source. See Figures 8-10 in body of document for further details.

Policymakers should recognize the important distinctions between the routes 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 CO₂e 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 – exactly how deep a carbon intensity reduction – at which this would occur, however, is an open question.

A 2030 target for CI reductions should be linked to policy formulations that acknowledge limits to the incremental and transitional approaches and that help to reduce the risks associated with leapfrog – namely, large scale, risky investments in advanced technologies. Ideally, the progress on incremental and transitional technologies can create the knowledge base to help reduce risks to the Leapfrog strategy.

We conclude that no route examined here guarantees long-term success, particularly from an overall CO₂e reduction perspective, and that all three should be pursued. While the Incremental route – and to a lesser extent the Transitional route – shows considerable potential for near-term, direct greenhouse gas reductions, the U.S. will likely need large-scale use of Leapfrog (or some similar low-carbon liquid fuel solution) technologies to achieve deeper GHG reductions. Considerations related to indirect effects must also be taken into account in a deeper, more robust fashion.

To move toward a large-scale, sustainable biofuel future in 2030 and beyond will require continued technology development, but also a policy environment that ensures large-scale, low-carbon, advanced solutions are implemented.

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% 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 from IIASA estimates that we may expand biomass production for bioenergy from 45 EJ in 2005 to 80-140 EJ in 2050, including “extensive use of agricultural residues and second-generation bioenergy” (Nakicenovic et al., 2012, p. 10). Biofuels play an equally important role in low carbon projections in the U.S. and California.¹⁷ 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 be successful. At the same time, existing commercial biorefineries continue to improve efficiencies and add the ability to process small streams of cellulosic material, thereby lowering the carbon intensity of their fuel output.

¹⁷ The Annual Energy Outlook, Reference Case (2013) suggests 4.3 quads of bioliquids will be consumed in 2040 (16% of transportation energy), without any assumed carbon price. In California, using models that project state-level energy consumption, biofuels provide up to 40% of transportation energy in 2050 in scenarios that reach 80% 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).

This study attempts to elucidate the situation through a systematic examination of three basic routes to greenhouse gas (GHG) reductions in 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.

From this discussion emerges a 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.’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 CO₂e 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 in a 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	Small reductions	Expected to be 50% or greater. Only small	Expected to be 50% or greater

Petroleum Reference		quantities available.	
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. 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 CARB (2014) website, which lists different production pathways at individual biorefineries recorded under the Low Carbon Fuel Standard (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 (CARB, 2014)

Innovation	Example
Improve pre-treatment technology	Poet uses Raw Starch Hydrolysis instead of dry grind process. Reduces CI value by 6.0 gCO ₂ e/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% over traditional technology.
Improve co-product production	Green Plains Holdings shifted to 54%/56% dry/wet distiller's grain (DDGS) from 10%/90% dry/wet distiller's grain, reducing plant carbon intensity (value not reported). Additionally, Poet reports ~10 gCO ₂ e/MJ improvement when shifting from 100% dry to 100% 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% 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 ₂ e/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 ₂ e/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 ₂ e/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 ₂ e/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% 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 CO₂e/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 “startups” 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, ARPA-E grants, USDA feedstock improvement grants, and the Department of Defense advanced biofuel program. Private equity funders like Kleiner Perkins and Vinod Khosla 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 or currently are building Leapfrog biorefineries. Of the various conversion technologies, biochemical conversion using enzymatic hydrolysis and fermentation has the greatest number of firms.

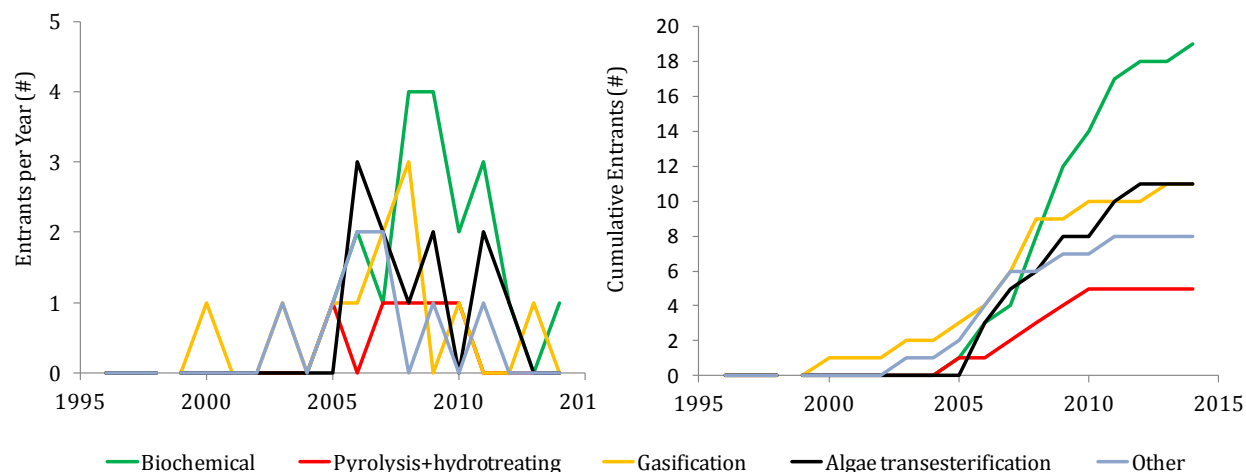


Fig. 1. Annual (left) and Cumulative (right) number of firms entering U.S. Leapfrog market, by conversion technology. Figure only shows firms that have announced intentions to build or are building commercial scale facilities.

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 cellulose, 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% 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%. The largest investment risk among bolt-on plants considered here is for 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%.¹⁸ Table 2 below lists announced and under construction bolt-on facilities.

¹⁸ This estimate is based on a maximum 38% retention rate of stover in the field (Muth, 2012), 58? (56) lbs per bushel, 15.5% 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	Vasalia, 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 technology which 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 reduction and financial risk (Figure 3).¹⁹ 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

¹⁹ 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.

residues combined with the shared infrastructure. The larger carbon intensity benefits from Leapfrog 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.

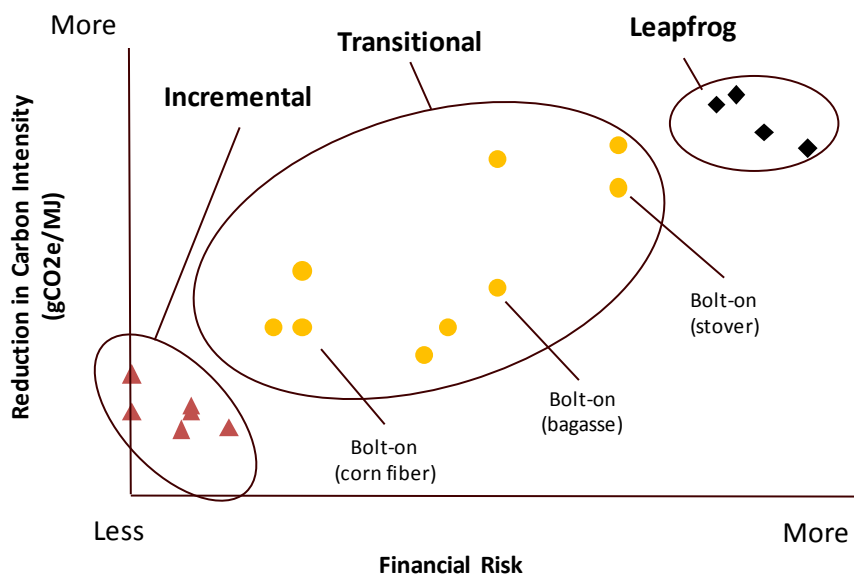


Figure 3. Spectrum of carbon intensity versus financial risk showing low risk for Incremental, Transitional, and Leapfrog routes.

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 owners of existing biofuel firms. 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 less than two years for a payback.

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 2.0 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 is incomplete in analyzing policies that are designed to pull new technologies into the market for two reasons. It does not account for failures and it sets unreasonable expectations for the first generation of the technology, which can undermine a policy.

NextSTEPS researchers attempt 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 state requires multiple generations of technologies and will likely include many failures.

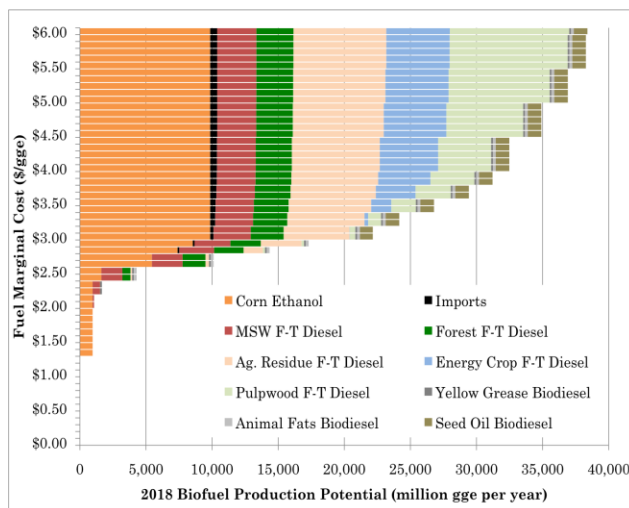


Figure 4. Biofuel production potential for baseline scenario by fuel pathway (Parker, 2013)

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 cost of production 25-300% higher than the cost estimated using the mature technology assumption. 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 path to get there is what we are interested in here.

There has been relatively little empirical study of first-of-a-kind plants (e.g. there is a tendency to rely on the RAND 30 year-old study for insights). The paths of existing cellulosic biorefineries to market have been in-line with what would be predicted by the RAND study. KiOR's biorefinery operated at 17% of capacity in its 2nd 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 requires 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.

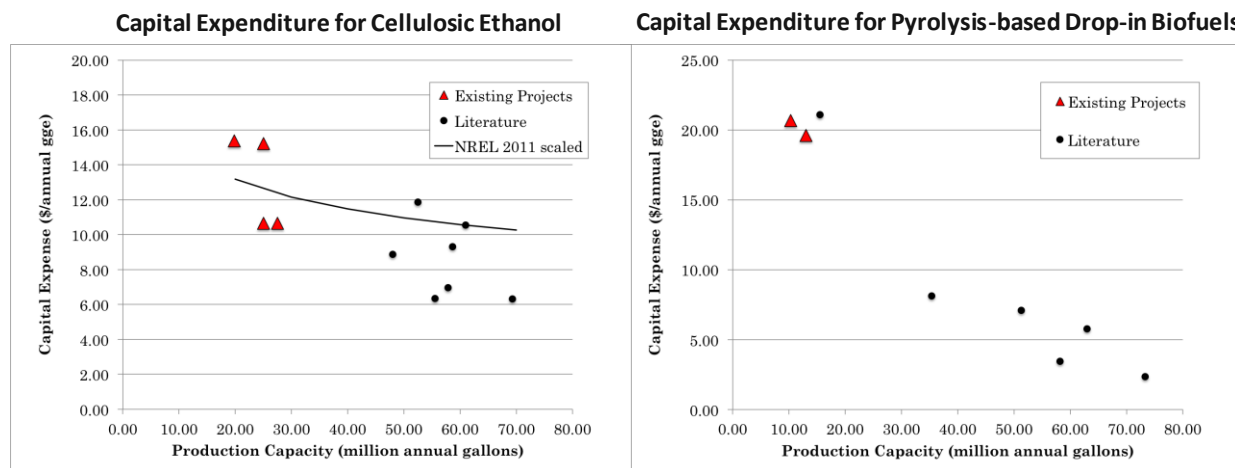


Figure 5: Comparison of capital expenditure projected in literature and announced facilities

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 to estimate the size and length of subsidy required to bring biofuels into a cost-competitive state with petroleum fuels. 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, 2013).

Figure 6 shows the industry cash flow for cellulosic biofuels in one of the scenarios generated. The industry starts with several years of negative cash flow as it makes its way through the so-called “valley of death.” This is 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).

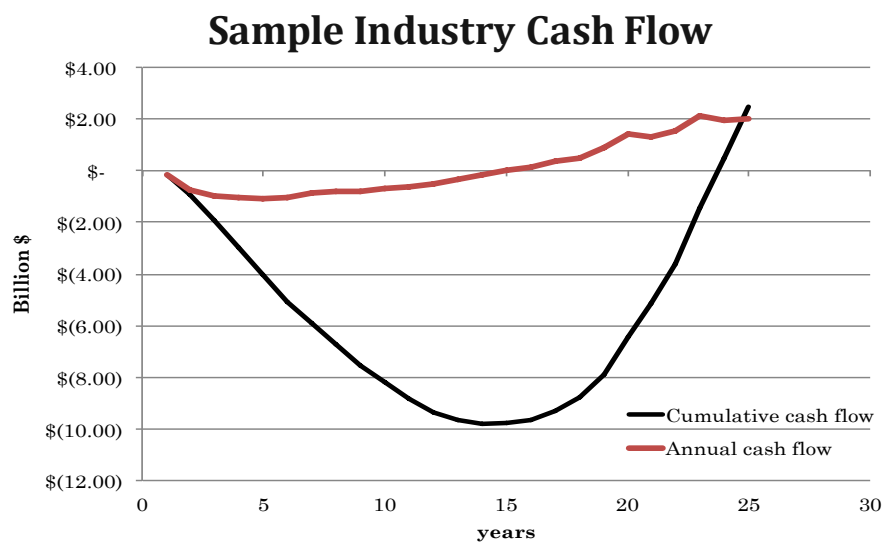


Figure 6: Comparison of capital expenditure projected in literature and announced facilities

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/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 1st plant. It takes another 5 to 20 years for the cumulative cash flow to become positive (breakeven for the industry). For policy 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 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 RINs and LCFS credits (see discussion, next Section).

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

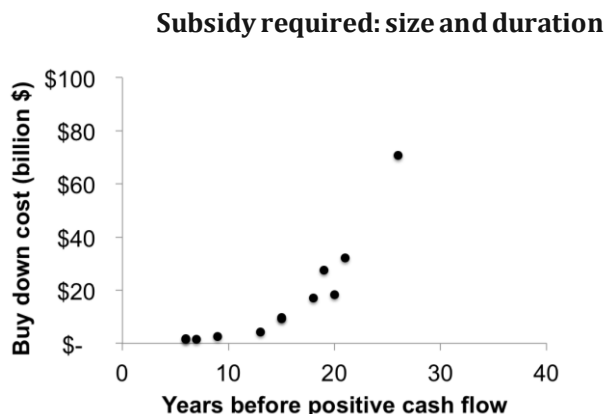


Figure 7: Buy down cost (\$billions) and required policy duration in various scenarios

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 \$4.4 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, is 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.

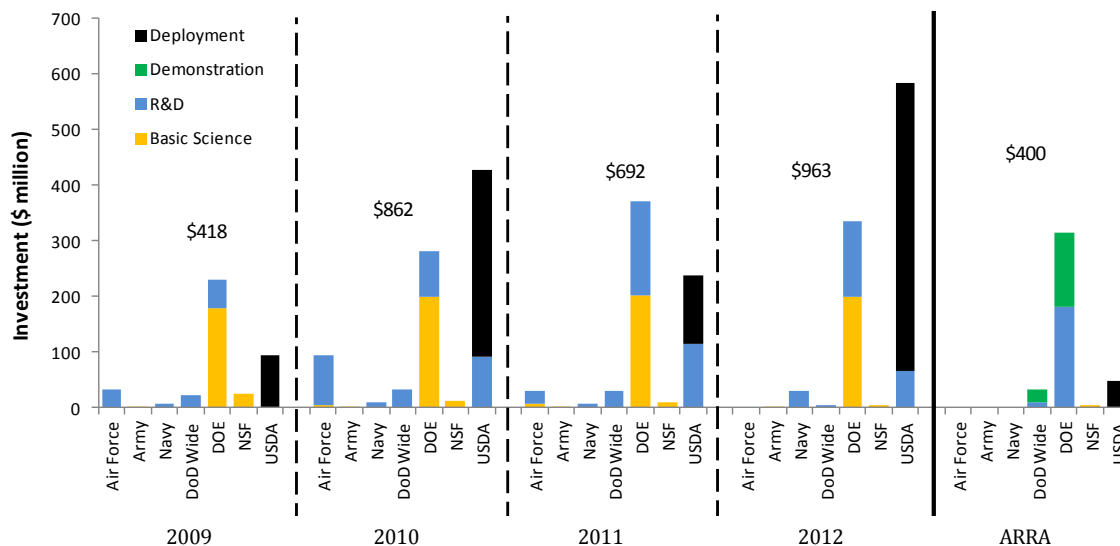


Figure 8: Federal government investment into Leapfrog biofuels development, 2009-2012. Total investment in year given at top of each column. Source: <http://energyinnovation.us>

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 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 below gives the trend in private equity investment between 2006 and 2012, including the American Reinvestment and Recovery Act funds. Private equity funding for biofuels during this period averaged \$368 million per year.

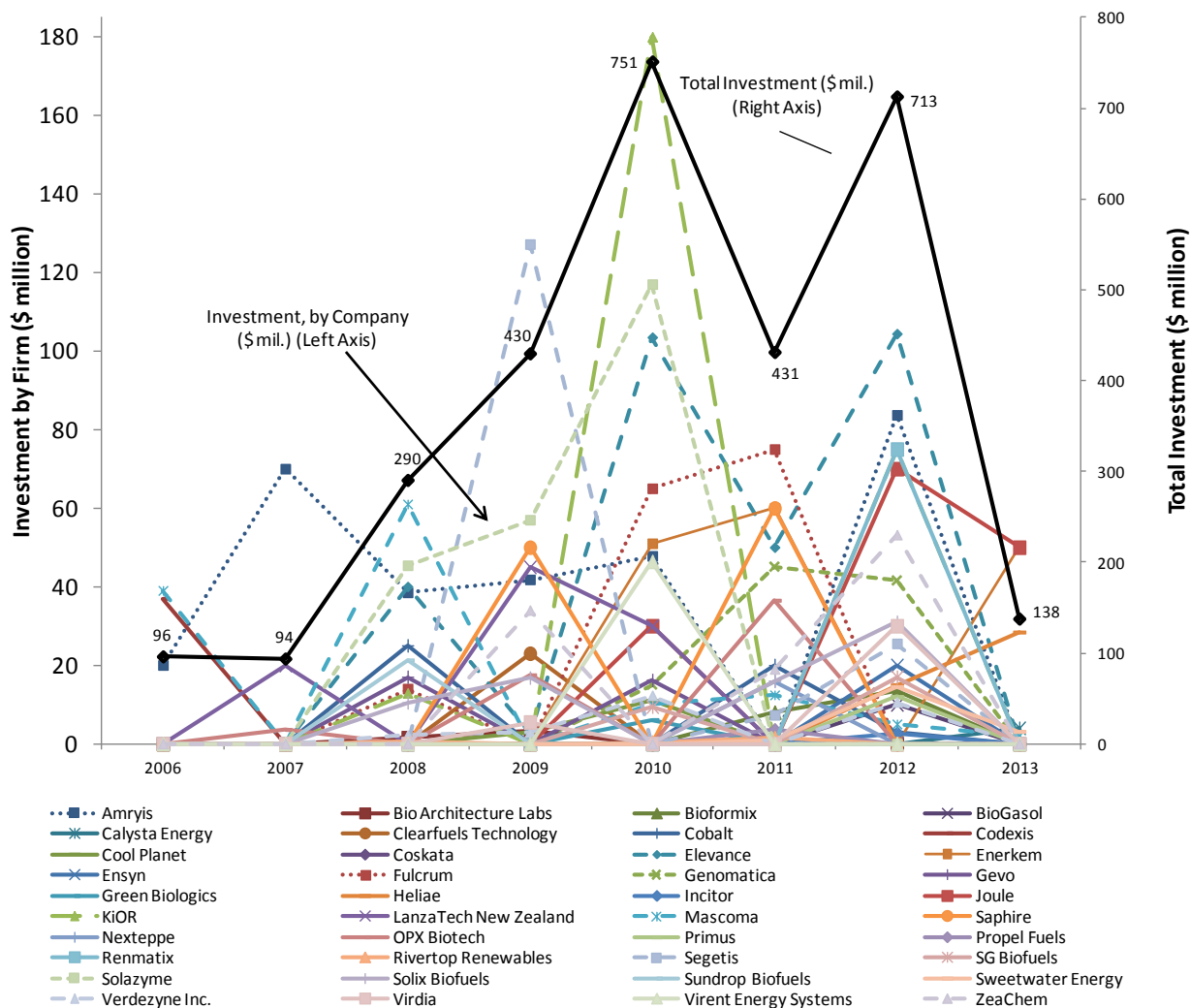


Figure 9: Private equity investment in biofuels, 2006-2013. Note: not all advanced biofuel companies are shown in figure. Some, like Poet-DSM and DuPont, do not rely on private equity for funding. Source: privco.com

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 – 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. 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 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, Weyerhaeuser, 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 4-year-old plans for a \$300 million cellulosic ethanol project in Florida and in April, 2013 Shell canceled plans with Iogen Corp. for a commercial-scale plant in Canada. Chevron shelved plans back in 2010 after examining 100 different feedstocks, while Exxon 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 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.: the Low Carbon Fuel Standard (LCFS) and Renewable Fuel Standard (RFS).

3.a. Low Carbon Fuel Standard

California's LCFS requires a 10% reduction in carbon intensity (grams of CO₂e per 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 gCO₂e/MJ between 2010 and 2014 then speeds up to eventually achieve 89 gCO₂e/MJ in 2020. LCFS credit prices ranged from \$12/ton of CO₂e (September 2012) to over \$80/ton of CO₂e (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. Policy uncertainty around the legislation stemming from court challenges may discourage expensive investments to achieve deep carbon reductions, only required in later years of the policy (even though the policy has remained in force throughout). The backloaded compliance schedule and capacity to bank LCFS credits also incentives 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. The LCFS is also set up so that producers can realize financial benefits from low-cost carbon reductions. The LCFS operates on a continuous spectrum of fuel carbon intensity. Each gram of CO₂e per MJ has a real, associated dollar value. If a fuel provider can reduce the carbon intensity of an existing pathway by more than 5 grams of CO₂e per MJ, they can apply for a modified pathway,

²¹ Fuels determined to already meet 10% reduction requirements (electricity, hydrogen, NG) need not register under the program, but can opt in to generate credits.

and ultimately save or make more money. New processes for existing feedstock/fuel combinations or new combinations can apply for a new pathway, with no minimum carbon 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 carbon reductions. An executive at the engineering firm ICM²² 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 may currently be too small and uncertain to motivate a large capital risk.

At the moment, biofuel producers have an array of options for reducing the rated carbon intensity of their production systems. Figure 10 below shows the range of carbon intensity values set as defaults in the LCFS by CARB (green bands) and as assessed for new and modified pathways (blue lines). These new and modified pathways are self-reported for each biorefinery (or other fuel production facility), and subsequently examined by CARB staff (and subject to approval by CARB at periodic board hearings). As is evident, the non-corn ethanol band ratings span from 22 to 95 gCO₂e/MJ.²³ Obviously, not every plant could achieve 22 gCO₂e/MJ (waste molasses from sugarcane) but this low value serves as an example of what might be possible. It is also important to reiterate that CI ratings of a given plant are different from the global carbon effects from an expanded biofuel industry, due to uncertainties in measurement, regulatory resource constraints, and market-related impacts not counted in the rating (e.g., rebound effects in fuel markets mean a gallon of biofuels probably ends up displacing less than a gallon of gasoline, not the one-for-one assumed in the ratings system) (see discussion in Executive Summary). Still, the decline in CI due to on-site adjustments without sizeable effects on production levels may cause fewer market effects (Plevin 2010).

²² ICM provides engineering and planning support for approximately 50% of U.S. biorefineries.

²³ Feedstocks in the band include grain mixes (corn, sorghum, wheat slurry), sorghum alone, and molasses.

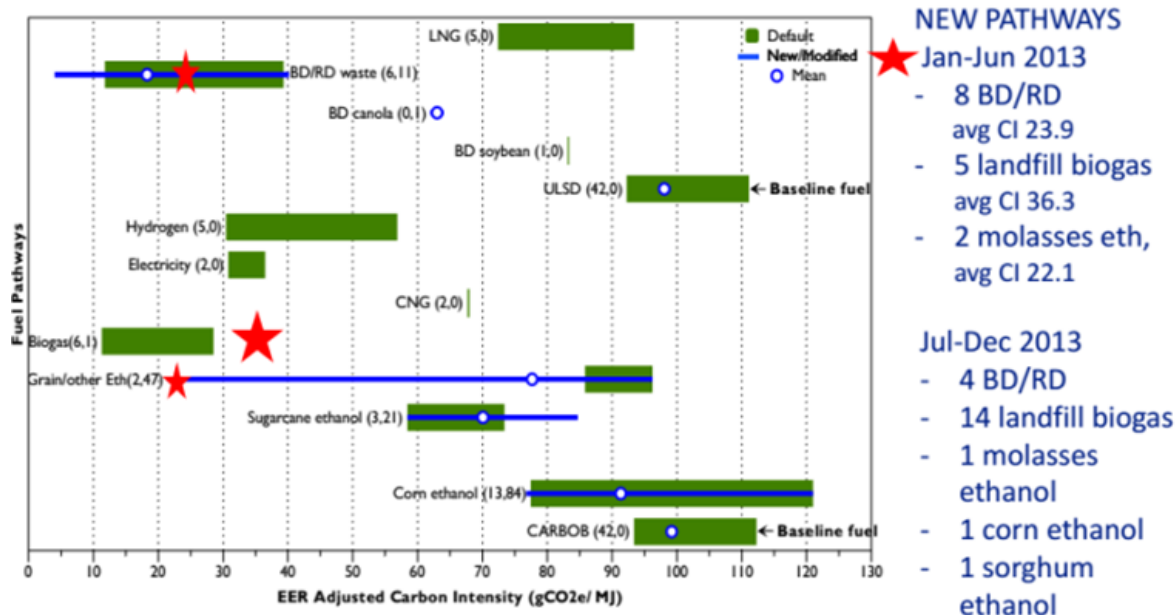


Figure 10. Summary statistics (ranges and averages) of carbon intensities for fuels under California's LCFS, by feedstock. The green bands are the ranges of default values. The blue lines are for biofuels in use, and include new and modified pathways. The red stars are averages for pathways added in the first half of 2013.

An important note is that many biofuel providers only send a portion of their fuel to California. This means that only a portion of most fuel providers' fuel mix will garner an associated value based on carbon intensity. A larger regional or national LCFS could change the calculus in how providers are incentivized towards making incremental (or even leapfrog) changes. Further research is needed to examine if the LCFS is actually driving fuel providers to make improvements at their plants.

Ultimately, incremental changes (and to a lesser extent the Transitional route) are attractive because they offer biofuel producers near-term reductions to CO₂e ratings. Additionally, incremental improvements at existing facilities may lead to less fuel swapping and leakage. While the LCFS could eventually provide an incentive for Leapfrog technologies with credit prices high enough for long enough, 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. However, the burden of getting an LCFS pathway approved and certified is likely not the top priority for companies attempting to prove a technology at scale with limited resources.²⁴

²⁴ 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 US renewable transport fuel providers to supply at least 36 billion gallons by 2022 – up from 9 billion gallons in 2009 – through a series of annual volume mandates. Unlike the LCFS, the RFS credits fuels that belong to specific categories, each with its own minimum threshold for lifecycle percentage carbon intensity reduction²⁵: renewable fuels (20%); advanced fuels (50%); biomass-based diesel (50%); and cellulosic fuels (60%). Each fuel category has its own mandate, but 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 market-based: Renewable Identification Numbers (RINs) are used to track fuel volumes by submandate. RIN credits are separated from biofuels as they enter the transport market (upon blending), and can be traded to meet compliance. The regulation has a provision allowing downward annual adjustments to the cellulosic mandate if commercialization lags initial expectations. Providers can purchase cellulosic “waivers” at a price tied to the prior year’s gasoline price to make up the difference between actual production and the adjusted mandates.

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

²⁵ Compared to gasoline or diesel in 2005.

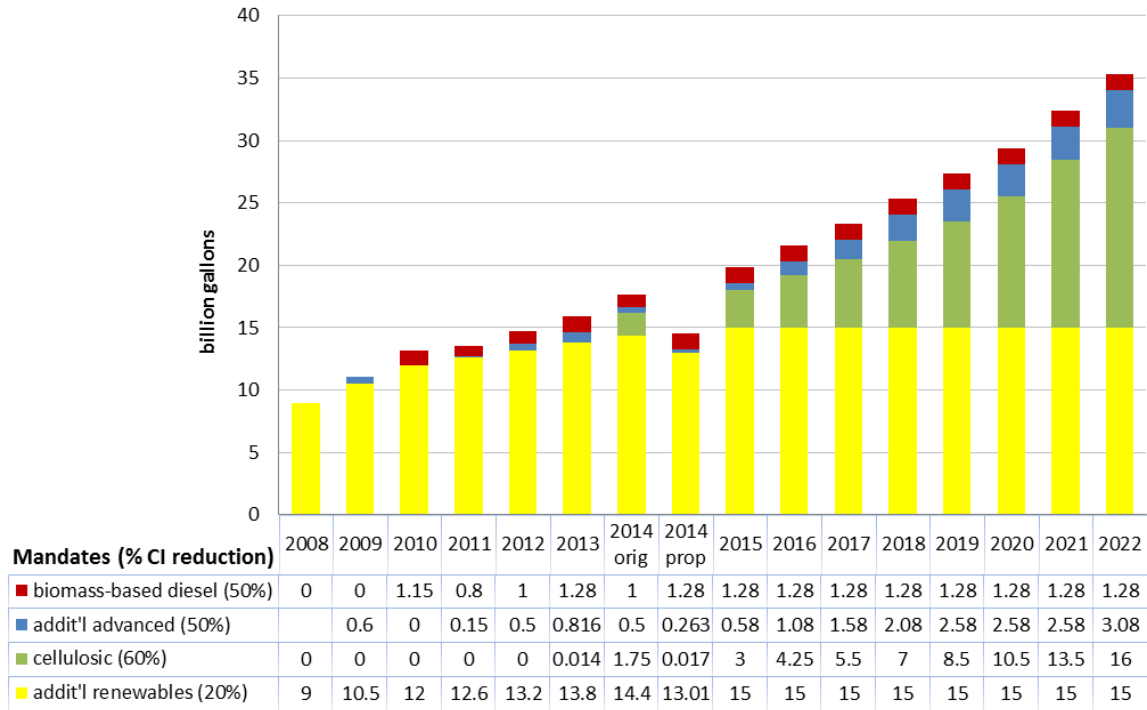


Figure 11. Renewable Fuel Standard volumetric mandates

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, and it promises a guaranteed 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 beyond biodiesel and renewable diesel using vegetable oil feedstocks and waste. Others have also noted that RFS lacks incentives for breakthrough technologies.

Additionally, the cellulosic waiver price effectively caps the financial incentive to cellulosic fuels.²⁶ The waiver price has been dropping (from \$1.56/gallon in 2010 to the \$0.42/gallon in effect starting in 2013), tracking a decline in gasoline prices. And a legal challenge resulted in retrospective zeroing out of

²⁶ More precisely, it caps a premium for cellulosic over the value of other advanced fuels. This is because waivers are applied only to the cellulosic mandate, whereas actual cellulosic volumes are applied to *both* cellulosic and advanced mandates. That means that an obligated party who buys a cellulosic waiver, must still pay the cost of meeting the advanced mandate.

cellulosic mandates from 2010 to 2012, undermining the waiver's reliability as an incentive.²⁷ A more fundamental challenge to the RFS policy is currently under way, due to concern about the ethanol "blendwall" of 10% per volume in gasoline, the prevalent standard. Renewable mandates going forward imply a need to break through or go around the blendwall by ramping up use of higher ethanol blends that require changes at the pump or in vehicle types or 'drop-in' fuels that use existing infrastructure. A proposal to adjust the overall renewable mandate downward in 2014 has sparked controversy and speculation of more court challenges ahead. This calls into question the reliability of all mandate levels and increases the policy uncertainty as adjustments are made yearly.

The RFS may actually favor some Incremental routes. The EPA's analysis suggests 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) –moves the fuel from a 32% CI reduction (and eligibility towards the renewable mandate) to a 52% CI reduction ("advanced fuel" rating). However, the principal effect of the large CI bins and higher mandates is to scale up volumes of existing, commercialized biofuels that are rated as eligible. Finally, the cellulosic waiver "premium" discussed above may be high enough to provide some incentive for "bolt on" Transitional cellulosic innovation.

²⁷ 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, using policy-based carbon intensities to represent notional, order-of-magnitude differences in potential across approaches. Figure 12 shows the estimated fuel production and CO₂e reduction for three strategies relative to a reference fuel.²⁸ For the incremental improvements we separated corn ethanol facilities and biodiesel facilities. Similarly, for Transitional approach, we separated corn stover and corn fiber. Here, fuel production is the quantity of fuel to which a given strategy is applied.²⁹ Assumptions are stated below the figure.

Under our assumptions, the Leapfrog approach appears to have the greatest potential for CO₂e reduction, in particular in later years; however in the near-term the Incremental approach will likely lead to greater GHG reductions. The Transitional approach, as currently conceived in the U.S., 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 CO₂e reduction in the U.S. from the three routes is 84 million metric tons of CO₂e 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, the combined reduction of transport CO₂e would be around 7% relative to today's emissions, by 2030.

²⁸ 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, so ignores real world market effects (see Executive Summary for more discussion).

²⁹ For example, the Incremental(corn/soy) fuel production band is the volume of corn ethanol and soy biodiesel which realizes the carbon intensity reduction from the reference level of 98.3 gCO₂e/MJ to a new state of 70 gCO₂e/MJ, for existing facilities.

California is currently considering extending its LCFS past 2020, with a goal of reducing GHG emissions an additional 10% 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, and improved fuel economy of light and heavy duty vehicles, and improvements to imported fuels, transportation emissions could be drastically 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 CO₂e reductions and, if pursued simultaneously, would likely 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.

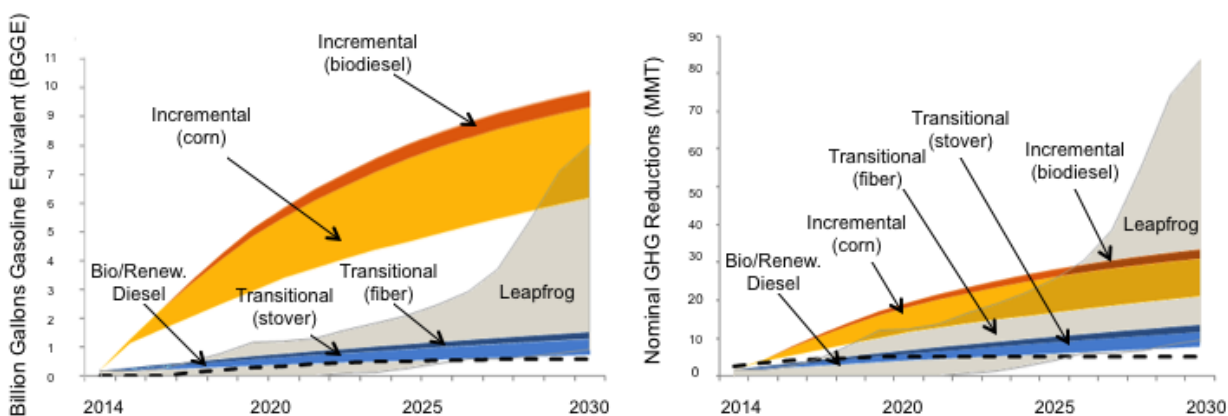


Fig. 12. Maximum fuel production available to specified route (left) and associated GHG reductions (right) in U.S. Fuel quantities grow over time as biorefineries are improved (Incremental), bolt-ons are built (Transitional), or stand-alone facilities are built (Leapfrog). Figures show production/GHG 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 cellulosics and algal facilities. Dashed line refers to the contribution from domestically-produced biodiesel or renewable diesel from waste oil, animal fats, corn oil, and vegetable oil.

Assumptions: Incremental (corn/soy): upper bound assumes 10% 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. Lower bound uses same except 5% of plants make upgrades per year and 2013 AEO reference case projections used. Transitional (stover/corn fiber): upper bound assumes stover conversion of 58 lbs of stover per bushel, 70 gal/ton, 15.5% moisture content, 38% retention rate in field; corn fiber conversion achieves 5% yield increase per gallon of corn ethanol. Together, stover/fiber achieve 36% yield increase. Only

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1.5-3.0% of plants make upgrades per year to lower carbon intensity of new fuel stream. Thus, 36% yield increase and reduction from 98 to 20 gCO₂e/MJ is achieved on added yield. Projections of ethanol use from 2013 AEO High Oil Price case. Lower bound is same except 2.5% of plants make upgrades per year. 2013 AEO Reference case 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, 99 gCO₂e/MJ. New carbon intensity is 20 gCO₂e/MJ. Lower bound uses 50% ramp-up rate of upper bound and delays 5 years. Bio/Renew. Diesel uses Gompertz curve which transitions from ~150 MGY today to max penetration 2.4 BGY.

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. Of course, several other biofuel GHG reduction strategies are also being pursued around the world, such as bolt-on facilities that use sugarcane bagasse in Brazil or renewable and biodiesel from dedicated 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. > 20%), 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, and given other demands on biomass, is a pressing challenge moving ahead.

An Incremental strategy has been especially attractive while the development and commercialization of leapfrog technology has been slow, and while current and future policy directions remain uncertain. 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 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.

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

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