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Three routes forward for biofuels: Incremental, leapfrog, and transitional

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HIGHLIGHTS

- Three technological pathways are compared that lower carbon intensity of biofuels.
- Incremental changes lead to faster greenhouse gas reductions.
- Leapfrog changes lead to greatest long-term potential.
- Two main biofuel policies (RFS and LCFS) are largely incremental in nature.
- Transitional biofuels offer medium-risk, medium reward pathway.

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ABSTRACT

This paper examines three technology routes for lowering the carbon intensity of biofuels: (1) a *leapfrog* route that focuses on major technological breakthroughs in lignocellulosic pathways at new, stand-alone biorefineries; (2) an *incremental* route in which improvements are made to existing U.S. corn ethanol and soybean biodiesel biorefineries; and (3) a *transitional* route in which biotechnology firms gain experience growing, handling, or chemically converting lignocellulosic biomass in a lower-risk fashion than leapfrog biorefineries by leveraging existing capital stock. We find the incremental route is likely to involve the largest production volumes and greenhouse gas benefits until at least the mid-2020s, but transitional and leapfrog biofuels together have far greater long-term potential. We estimate that the Renewable Fuel Standard, California's Low Carbon Fuel Standard, and federal tax credits provided an incentive of roughly $1.5–2.5 per gallon of leapfrog biofuel between 2012 and 2015, but that regulatory elements in these policies mostly incentivize lower-risk incremental investments. Adjustments in policy may be necessary to bring a greater focus on transitional technologies that provide targeted learning and cost reduction opportunities for leapfrog biofuels.

1. Introduction

1.1. Background

Long-term energy planning models suggest an important role for bioenergy in the coming decades (GEA, 2012; IEA, 2012). Krey and Clarke (2011) present output from 15 large-scale energy-economic and integrated assessment models and show that across 98 scenarios that maintain global CO_2 concentrations below 440 ppm, global liquid biofuel expands from about 0.6 exajoules (EJ) today to a median of 20 EJ in 2050 (with a range of 0–70 EJ across scenarios).[1] A prevailing assumption in climate mitigation scenarios is that the carbon intensity of biofuels decreases in the future (e.g., GEA, 2012). However, a feature lacking in the literature – and addressed in this paper – is a clear framework for understanding how such a transition might occur.

Since the mid-2000's, the U.S. federal government has taken an active role in promoting the development of large-scale, stand-alone lignocellulosic biorefineries – or *leapfrog* technology (i.e., transformative technology that provides a discrete leap forward in environmental benefits and available volumes such as biofuels from purpose-grown biomass and municipal solid waste (MSW)). Examples of federal involvement in leapfrogging include the Departments of Energy (DOE) and Agriculture (USDA) grants and loans program that seeks to build commercial-scale facilities and guarantee feedstock supply. Other federal monies supporting leapfrog biofuels include: the Department of Defense aviation and marine biofuel program, the Department of Treasury producer tax credits on blended volumes of lignocellulosic biofuel, and the

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[1] Searle and Malins (2014) find that, if food production and forestland are protected, the global potential for biofuels in 2050 is 10–20 EJ.

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National Science Foundation, DOE, and USDA research and development money to support basic science on feedstocks and lignocellulose to fuel conversion. Lastly, two prominent biofuel policies in the U.S. – the Renewable Fuel Standard (RFS) and California Low Carbon Fuel Standard (LCFS) – were codified, in part, to help spur the lignocellulosic industry.

Despite government and institutional investments in leapfrogging however, lignocellulosic biofuel producers have struggled to jump from lab/demonstration to commercial scale. In 2014, less than 1 million gallons of leapfrog lignocellulosic biofuel were produced, along with 17 million ethanol-equivalent gallons of biogas (EPA, 2015a) – far short of the originally mandated 2 billion gallons for the year. A recent projection estimates a maximum of 1.9 billion gallons of liquid lignocellulosic biofuel could be produced in the U.S. by 2022 (Morrison et al., 2014).

At the same time, several academic studies as well as facility-level government data suggest that conventional biofuel producers are *incrementally* improving feedstocks, supply chain efficiency, material handling, production process, and process heat supply (CARB, 2015; EPA, 2015b). Wang et al. (2011) review 35 studies and show a reduction between the 1970s and late 2000s in fossil input energy intensity per liter of ethanol produced: in dry milling plants, from 19.5 to 7.97 MJ, and in wet milling plants from 19.1 to 13.2 MJ per liter. They also find that the nitrogen, phosphorus, and potash fertilizer application intensity for corn decreased by 35 percent, 60 percent, and 50 percent, respectively, between 1970 and 2005. Liska et al. (2009) use four surveys of U.S. biorefineries to show that input energy per gallon of biofuel was decreased in newer biorefineries, concluding that improvements like the burning of lignin for process heat or the addition of an anaerobic digestion unit to a biorefinery moves corn starch ethanol towards the hypothetical estimates for lignocellulosic biofuels. Lastly, Cassman (1999) estimates that the quantity of nitrogen fertilizer per unit of corn harvested decreased by 36 percent between 1980 and 2000. For conventional biodiesel production systems, 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.

A third recent development in the U.S. biofuel industry is the rise of *transitional* technologies – those that give producers experience with growing, handling, and chemically converting lignocellulosic biomass to products. These technologies require lower financial investment than a large-scale, stand-alone leapfrog biorefinery by making use of existing capital stock (i.e. bolt-on facilities). The primary examples of transitional technologies discussed in this paper are corn stover to ethanol, sugarcane bagasse to ethanol, corn fiber to ethanol, and paper sludge to ethanol.[2]

The objective of this paper is to use these three routes – leapfrog, incremental, and transitional – to provide a clear narrative about options for moving towards low carbon-intensity biofuels. While other studies have examined one of the three routes individually, we broadly consider all three. We make the following contributions to the national biofuel dialogue: (1) we present a conceptual model that highlights the relationship between CO_2e reduction potential and firm-level financial risk for each of the three routes, (2) we estimate the maximum volumes and emission reduction potential of each of the three routes over the next 15 years, and (3) we provide a qualitative discussion that argues that elements in two major biofuel policies – the LCFS and RFS – have so far incentivized existing pathways as well as incremental investments. This paper draws on examples from the U.S. biofuel industry but many insights are applicable in other jurisdictions.

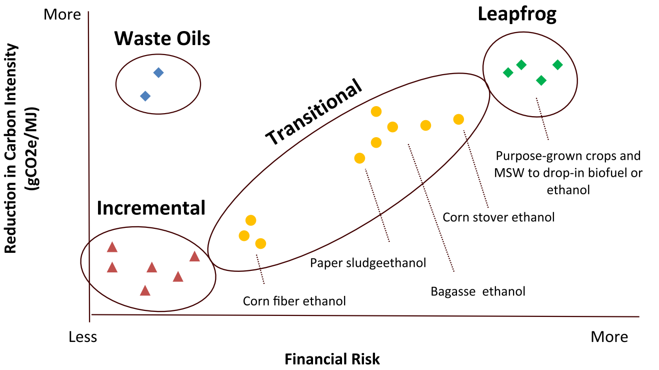

Fig. 1. Theoretical spectrum of carbon intensity reduction versus financial risk, showing increasing risk for incremental, transitional, and leapfrog routes.

1.2. *Theoretical background*

Before investing in new capital, potential biofuel producers weigh the net present value of the expected revenues and costs of a project, while incorporating the cost of risk (i.e. the risk premium). Tyner (2010) identifies five uncertainties that increase the risk of biofuel projects[3]: feedstock availability and costs, conversion efficiency and cost, future oil price, environmental impact of biofuels, and government policy. While these uncertainties potentially raise the risk for all three routes, newer biofuel technology and projects with larger scope or scale carry the highest risks (Miller et al., 2013).

In Fig. 1, we place the three routes on a conceptual map of financial risk to investors and nominal carbon intensity reductions (grams of CO_2e per MJ of fuel).[4] This stylized figure relates to the authors' view of current biotechnology based on the academic literature, industry publications, and interviews with biofuel engineering firms. We define financial risk as the likelihood of a negative return on an investment.[5]

In the bottom-left corner of this spectrum are low risk, low CO_2e-reduction investments corresponding to incrementalism. Some incremental investments are near the *y*-axis because they entail little financial risk. For example, a biofuel producer might switch to a new corn variety optimized for biofuel production. In the upper-right corner of the spectrum are high-risk investments corresponding to leapfrog technology. These technologies offer high CO_2e reduction mainly due to lower land-use impacts and fewer agricultural inputs relative to corn starch ethanol, as well as the burning of lignin for process heat. Lastly, the transitional route falls between leapfrog and incremental routes.

The figure depicts a number of individual transitional technologies, from lower-risk corn fiber ethanol to higher-risk corn stover ethanol. As noted above, greater scale of projects implies greater risk. On one hand, existing and planned corn fiber ethanol facilities are 0.5–2 million gallons per year (MGY), whereas large paper mills could produce roughly 20 MGY (although many are much smaller). At the high end, existing and planned stover and bagasse ethanol facilities are 20–40 MGY. Bagasse ethanol is

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[2] Sugar to farnesene is another example of a technology that could help pave the way for "drop-in" biofuels but is not discussed here. Currently production volumes are very limited for farnesene, most of which is used in specialty products like lubricants and perfumes.

[3] Tyner (2010) was specifically focusing on what we call leapfrog biofuels, but the risks are also present for incremental and transitional biofuels.

[4] "Nominal carbon intensity reductions" throughout this paper are those suggested by current policy, including land use effects.

[5] The figure conveys the risk and reward from a single, generic biofuel producer's perspective – therefore the counterfactual case is that the biofuel producer continues to produce unimproved biofuel.