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ANALYSIS

Comparison of supply and demand constraints on U.S. biofuel expansion

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ABSTRACT

This paper compares supply and demand constraints on the ramp-up of biofuels in the United States. Three recent supply-side developments are assessed: (1) build-out of commercial-scale cellulosic biorefineries, (2) incremental improvements to existing ethanol and biodiesel biorefineries, and (3) use of waste oils for renewable diesel and biodiesel. From a technical perspective, we estimate these developments could increase domestic biofuels production by up to 4.3, 2.3, and 1.3 billion gallons of gasoline equivalent (BGGE) by 2030, respectively. This corresponds to 3.7% of final energy in the U.S. transportation sector in 2013. On the demand side, the main technical constraints to biofuel growth involve the blend rate of ethanol with gasoline. Rapid removal of E85 and E15 vehicle and infrastructure barriers could generate room for an additional 13.0 BGGE of ethanol and 2.7 BGGE of biodiesel consumption by 2030. There is no demand constraint on drop-in biofuels. Both supply and demand constraints limit the expansion of biofuels, but demand constraints can likely be relaxed at a faster pace than supply constraints. Whether the further expansion of biofuels is socially, economically, or environmentally justifiable is not a research question examined here.

1. Introduction

Since the 1970s, the expansion of domestic biofuels has been a policy objective in the United States. This objective has been based, in part, on a broader goal to increase U.S. energy independence[1] [1]. Today, domestically produced biofuels account for 4.7% of final energy in the U.S. transportation sector,[2] or 4.9% of liquid fuels for transportation [2]. In the future, the contribution of U.S. biofuels to U.S. energy independence remains uncertain as concerns about the impact of biofuels on agricultural sustainability, criteria emissions, greenhouse gas emissions, and competition with food come to light. Additionally, given that the price of most biofuels has not been consistently lower on an energy basis than petroleum products in the last 20 years, a compelling economic incentive for a transition has been lacking, and the expansion of biofuels has been largely a policy-driven phenomenon.

Beyond these societal challenges for expanding the use of biofuels, there are number of other near-term technical constraints on how quickly the industry can ramp up. These include constraints on both the supply and demand side. The Energy Information Administration (EIA) hinted at a number of these constraints in its 2013 Annual Energy Outlook (Reference Case) when, between 2012 and 2013, it drastically lowered the projected volume of biofuels in the future (Fig. 1), citing "diminished flex-fuel vehicle penetration, a smaller motor gasoline pool for blending ethanol, and reduced production of cellulosic biofuels…" [3 p. 8].

The purpose of this paper is to examine the near-term technical supply and demand constraints in detail and to estimate how quickly

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[1] We use energy independence generically in this paper. The US increases its independence when it is less reliant on foreign sources of energy. This could mean both volume dependencies and price dependencies. For the purposes of our analysis, we focus on the potential contribution of U.S. production to energy independence, following existing U.S. policy objectives, as laid out in the Energy Independence and Security Act (EISA). An important consideration is that demand reduction (e.g., a reduction in aggregate miles traveled) can also lead to greater energy independence.

[2] Final energy is the same as delivered energy. This value includes ethanol, biodiesel, renewable diesel and gasoline, biobutanol, liquids from biomass and subtracts exported ethanol. Other options to diversify transport energy are available and are being pursued, such as fossil or renewable natural gas, electricity, and hydrogen. Discussion of these alternative fuel strategies lies beyond the scope of this paper.

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Glossary

- BGGE billion gallons of gasoline equivalent. Used to place liquid fuels with different energy contents into common volume metrics.
- Biodiesel a methyl ester fuel from oil feedstocks used as a substitute for conventional diesel fuel
- E10 typical transportation fuel for light-duty vehicles in the U.S. blended at up to 10% ethanol by volume. E10 accounts for the majority of gasoline sold in the U.S. and contains mostly gasoline.
- E15 ethanol–gasoline blends with up to 15% ethanol, by volume.
- E85 ethanol–gasoline blends with up to 83% ethanol, by volume, per ASTM D5798 (often erroneously thought to include up to 85% ethanol).
- Flexible fuel vehicles (FFVs) vehicles capable of running on E85 fuel or conventional E10 fuel.
- ICO inedible corn oil. ICO is a co-product from the majority of corn ethanol facilities.
- Renewable diesel a chemically-similar fuel as conventional diesel produced from hydro processing of oil feedstocks.

biofuels could feasibly ramp-up by 2030. Market conditions will ultimately determine if these become binding constraints or whether the market finds an equilibrium point below the constraints. We estimate the constraints over time using feasible technology turnover rates along with reasonable consumer adoption for the demand side and potential capacity expansion rates on the supply side. A side-by-side comparison of these constraints helps illuminate which (supply or demand) is more constraining in the near-term and where future policy should be directed.

An important supply-side constraint is that cellulosic biofuel companies have struggled to transition from lab and demonstration-scale to commercial scale projects. In 2013, less than one *million* gallons of cellulosic biofuels were produced in the U.S., while the original Renewable Fuel Standard (RFS) mandate called for one *billion* gallons in 2013.[3] However, at least 11 cellulosic firms have constructed or are in the midst of constructing commercial-scale biorefineries. Additionally, many corn starch biorefineries have purchased technologies and processes that increase the ethanol yield per input bushel of corn (i.e., incremental improvements). Biodiesel and renewable diesel from waste oil is also experiencing a surge.[4] For each development, we discuss 4both the maximum potential and the pre-2030 potential.

On the demand side, the key near-term technical constraint is the "blend wall" – a market saturation point above which no additional ethanol can be blended with gasoline due to federal blending requirements or vehicle warranty limits, driven by the different molecular structure of ethanol that necessitates separate delivery infrastructure for higher ethanol blends. Most gasoline sold in the U.S. is E10 (up to 10% ethanol and 90% or more gasoline, by volume) meaning the blend wall was effectively reached in 2013 when the U.S. consumed 13.7 billion gallons of ethanol and 133 billion gallons of gasoline [1]. This demand constraint could be overcome through a combination of: (1) increasing the number of flex-fuel vehicles (FFVs), (2) expanding the number of service stations that offer higher blends of ethanol fuel such as E15 and E85, (3) making ethanol considerably cheaper than gasoline, or (4) producing "drop-in" biofuels[5,6] that can be blended to any ratio with petroleum fuels. Biodiesel consumption faces some, but less serious demand constraints (discussed further below).

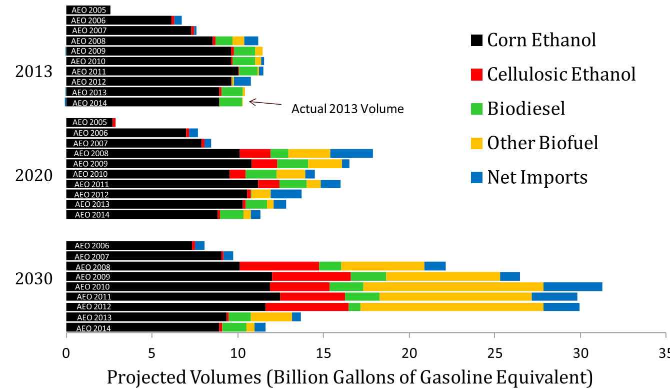

Fig. 1. Biofuel projections to 2030 from past Annual Energy Outlooks (Ref. Case) [2–12]. "Other" biofuel category refers to "green liquids," "liquids from biomass," and "renewable diesel" and includes drop-in fuels from cellulose, algae, and other non-corn feedstocks.

Section 2 discusses supply constraints. Section 3 discusses demand constraints. In Section 4, we compare the constraints over time. Finally, in Section 5 we conclude. Because of length requirements, the majority of the analysis is presented in the Supplementary information (S.I.) and in the Supplemental spreadsheet.

2. Supply constraints

In estimating supply constraints, an important distinction must be made between food crop-based biofuels and those derived from other (non-food) feedstocks. An assumption we make in our calculations is that no additional biorefineries will be constructed that use food crops as feedstocks (such as corn and soybean), due to concerns about food-fuel competition. U.S. corn ethanol already consumes around 40% of annual U.S. corn production[7] and construction of new corn ethanol biorefineries has plummeted since the decade between 2000 and 2010. Thus, our focus here is on identifying additional sources of domestically produced biofuels that do not compete directly with the food production system.[8]

2.1. Expansion of commercial-scale cellulosic biorefineries

At least two studies estimate the maximum nation-wide resource availability of cellulosic biomass using geographically detailed, feedstock-specific models [15,16]. DOE [15] suggests that up to 1.4 billion dry tons of cellulosic biomass could be available in the contiguous United States by 2030 for less than $60 per ton. This includes

3 The mandated target would have represented industry growth beyond what corn ethanol experienced, despite the pioneering nature of the cellulosic technologies. Foreseeing this possibility, the legislation instating the RFS allowed for downward waivers of the cellulosic mandate annually to match expected production, in the event that commercialization lagged.

4 Waste oil refers to animal fats, oils, and greases (FOG). More detail given below.

5 Almost all gasoline sold in the U.S. has 5–10% ethanol by volume. Most cars on the road can also run on up to 15% ethanol blends while flex-fuel vehicles can use up to 83% blends [13]. More is discussed below.

6 Drop-in biofuels are molecularly similar to petroleum-based fuels like gasoline and diesel. Thus, they do not require the same infrastructure and vehicle changes as other types of biofuel.

7 While 40% of corn acreage goes is used for ethanol production, the value could be reported as much lower if co-product production is considered (namely dried distillers grains and solubles, which can substitute for corn in animal feed). Mumm et al. [14] estimate that using this alternate method, 25% of today's corn crop goes to ethanol production.

8 Energy crops can be grown on marginal land, less suitable for food crops, but policy action may still be required to avoid displacing food crops.

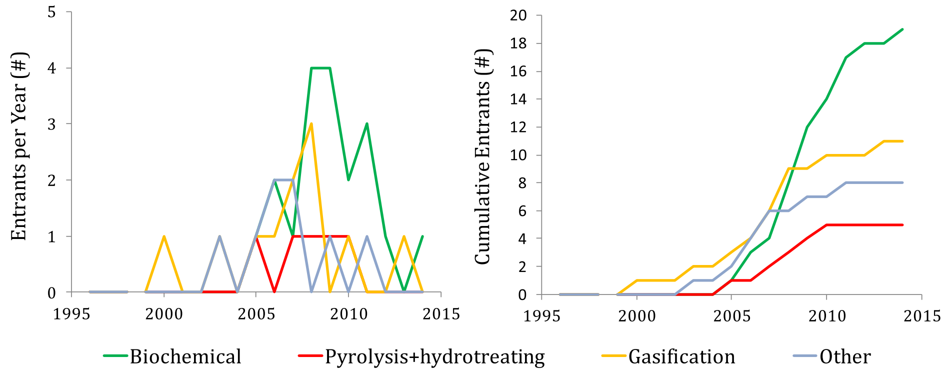

Fig. 2. Annual (left) and Cumulative (right) number of firms with planned or existing U.S. cellulosic biofuel production facilities, by conversion technology. Source: authors' database available in supplemental spreadsheet.

agriculture and forest residues, dedicated energy crops like switchgrass and poplar, and pulpwood from mills. In a similar estimate, Parker [16] finds that for $50–100 per dry ton, the U.S. has 80-801 million dry tons of agriculture and forest residue, energy crops, pulpwood, and municipal solid waste (MSW). Assuming a yield of 50–70 gallons of biofuel (gasoline-equivalent) per dry ton, these estimates reflect a vast long-term potential for cellulosic biofuels to contribute to energy independence, theoretically capable of producing around 50–100 BGGE per year, or about 25–50% of today's U.S. transportation energy. Debate continues as to how best to quantify supply potential in light of a variety of environmental concerns for each of the feedstocks [17].

There are numerous technical pathways to produce cellulosic biofuels and it is still unclear which, if any, will prove commercially viable. The three commercial-scale cellulosic biorefineries coming online in 2014 and early 2015 use corn stover as feedstock. Our own calculations (given in the S.I.) suggest that stover processing alone has a long-term potential to increase ethanol production in the U.S. by up to 3.0 billion gallons or 22% from today's level (i.e., assuming all sustainably-available stover is utilized after accounting for other uses). Two earlier completed commercial-scale biorefineries (Ineos and KiOR) used MSW and wood as feedstocks, respectively. While many biofuel firms have entered the market and announced ambitious long-term objectives, few are actively planning commercial-scale biorefineries. We identified 55 firms worldwide with announcements for planned or existing commercial-scale cellulosic or algae biorefineries. Of these, 42 are based in the U.S. and nearly all entered the biofuels market before 2011 (Fig. 2). Of conversion technologies in Fig. 2, the greatest number of firms undertake biochemical conversion using enzymatic hydrolysis.[9]

Our database suggests that only 11 firms in the U.S. have the potential to produce cellulosic biofuel at commercial-scale biorefineries before 2019.[10] Because first-of-a-kind plants have historically been slow to achieve their expected operating capacity [18], we assumed that biorefineries will begin at low production levels in their first year and ramp-up output by 20 percentage points per year until reaching full capacity. Furthermore, to reflect the higher risk for industry pioneers, we assumed 50% of completed commercial-scale biorefineries fail before producing any biofuel. Using expected biofuel production through 2018, we fit the points to an S-shaped Gompertz curve that levels out by mid-century at 16 BGGE. Gort and Klepper [19] review the introduction of 46 new products and show that the first phase of a new industry, in which the number of firms entering the market increases each year, has lasted as short as <1 year for fluorescent lamps to up to 50 years for artificial Christmas trees (with an average of 15 years across products). This inflection point for our S-curve for cellulosic firms occurs after 14 years, or in 2027. Our full methodology is explained in the S.I. and is based on Plevin et al. [20].

Of the three approaches to increase the supply of biofuels described in Sections 2.1, 2.2, and 2.3 of this paper, commercial-scale cellulosic facilities have the greatest long-term potential but also the highest near-term investment risk (see Fulton et al. [21]). Whether and when large-scale, profitable plants will be constructed in significant numbers remains an open question.

2.2. *Innovations at existing biorefineries*

Innovations at existing biorefineries could allow the total biofuels production capacity to expand without a commensurate expansion of cropped land.[11] Recent and potential innovations at existing corn ethanol plants include improvements in the milling process,[12] enzyme development, and genetically modified corn strains optimized for corn ethanol production.[13] The yield increases from these innovations vary by biorefinery. Our estimates suggest it is possible to increase the yield of corn ethanol and biodiesel by up to 25% above the yield of older biorefineries. Our data on the potential for these innovations come from a variety of sources including a literature review, discussions with biorefinery engineering firms, industry websites, and documentation from California's Low Carbon Fuel Standard (LCFS) policy, which has detailed information about process improvements at 148 domestic biorefineries [24].

Other innovations enable limited amounts of cellulosic material to be processed at existing corn ethanol facilities. Sometimes called "bolt-on" or "Gen 1.5" facilities, these biorefineries plan to utilize the corn fiber from the corn plant to supplement the sugar stream made from corn starch. ICM claims the use of its corn fiber technology increases ethanol yield by 2–3% per bushel [22] while Edeniq claims a 2–4% yield increase with its Cellunator technology [25].

Innovations are also occurring in the biodiesel production system. Pradhan et al. [26] described 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

[9] This figure does not track firms that exited from the market.

[10] While many companies are active in the cellulosic biofuel space, only 11 have made concrete financing plans and sought permitting for their plants. In the SI, we give evidence of these 11 plants moving towards commercialization.

[11] If and how the acreage for biocrops expands in the future is an open question. Policy concerns have been raised about undue expansion, because of the potential for unwanted consequences for food prices and GHG emissions.

[12] ICM claims its Selective Milling Technology (SMT) achieves 1.5–3.0% higher yields and higher corn oil recovery [22]. In both cases, the author/website does not specify a comparison technology (i.e., "compared to what?"), but our assumption is these are compared to ethanol batches in which the given technology is not used.

[13] In 2013 Syngenta began selling such a corn strain known as "Enogen" [23].

2006. LCFS documentation suggests that 21 biodiesel biorefineries in the U.S. that use soy or canola oil have made process improvements since 2007. A major recent development that is bolstering biodiesel production without further encroaching on food crops is the inedible corn oil (ICO) co-product, now produced at approximately 80% of corn ethanol plants.

Using simple assumptions about potential deployment rates of the above innovations (described in the S.I.), we estimate that by 2030, 0.4 BGGE per year of corn fiber ethanol and 2.0 BGGE per year of additional ethanol and biodiesel at existing plants could be produced. The degree to which agronomic advances (e.g., crop yield increases) could contribute to additional biofuels has been assessed elsewhere [27].

2.3. Expansion of waste oil-based fuels

Another emerging development is the construction of new facilities that produce biodiesel and renewable diesel from waste oils. While these fuels use different production pathways, they draw from the same feedstock pool: production byproduct oils like used cooking oil, tallow, and greases; ICO from corn ethanol biorefineries; and oil from crops such as soybean and rapeseed.[14] Biodiesel and renewable diesel have seen their combined U.S. production grow from near zero in 2000 to 1.60 billion gallons in 2013.[15] If we assume no additional expansion of cropland for oil crops in the U.S., then domestically-produced biodiesel and renewable diesel could expand by an additional 1.3 BGGE by 2030 (0.43 BGGE from ICO from ethanol plants and 0.84 BGGE from waste oils). The ICO estimate assumes 80% of corn ethanol plants generate ICO as a co-product. The waste oil estimate is from Parker [16]. These quantities are separate from innovations at biodiesel biorefineries described above. If the U.S. supplies this additional volume, then domestically produced biodiesel and renewable diesel from these sources could account for approximately 4% of 2013 U.S. road diesel fuel consumption, i.e., 2% of final energy in the U.S. transportation sector.[16] For some products commonly labeled as "waste oil," competing uses (animal fats in soap production, oleochemicals, and animal feed, for example), or validation difficulties (verifying no additional use of virgin oils to generate used cooking oil) could affect their further growth [29,30]. In the U.S., tallow used for biodiesel increased by 60% from 2011 to 2013, tightening supplies available for chemical and food uses; tallow exports dropped by almost 4% from 2012 to 2013 [31].

3. Demand constraints

A combination of federal blending requirements and auto manufacturer warranties creates near-term demand-side constraints. For biodiesel, about 75% of auto manufacturers permit their diesel engines to run on blends up to 20% by volume (i.e., 80% conventional diesel and 20% biodiesel) without a void of warranty [32]. Similarly, most heavy-duty truck engines can run on up to B20 blends. Since diesel sales in the U.S. in 2013 were 54.5 billion gallons and are expected to grow in the future [2], this implies an upper limit of biodiesel demand well-beyond the supply constraints discussed above. Even if most diesel sold in the U.S. stays at B5 blend levels (i.e., 5% biodiesel), there would be approximately 2.7 billion gallons of biodiesel demand, which is above the supply constraint. If, in a future year, vast quantities of cellulosic biomass or algae were used to produce oils for biodiesel feedstock, then it is possible biodiesel could be demand limited.

Ethanol consumption constraints appear to be more limiting than those on biodiesel consumption. Expansion of ethanol beyond today's levels is demand-limited due to three factors: (1) number of E85- and E15-capable vehicles, (2) E85 and E15 distribution systems, and (3) ethanol-to-gasoline price differential.

Others have examined one or more of these constraints in detail. Greene [33] constructed an econometric model of historical stations and vehicles that use E85. He concluded that meeting a 2017 goal of 26 million gallons of E85 sold in the U.S. (87 million gallons were sold in 2013) would require 30%–80% of service stations to offer E85 and 125–200 million vehicles to be FFVs. Babcock and Pouliot [34] estimated an E85 demand curve using historical data from Brazil and showed that if ethanol were priced 6% below gasoline price on an energy basis, that would lead to about one billion gallons of additional E85 sold. Salvo and Huse [35] also used a dataset from Brazil to show that consumers are relatively unresponsive to changes in the gasoline–ethanol price ratio. For example, they showed that roughly 20% of FFV drivers still choose gasoline over ethanol when gasoline is 20% more expensive than ethanol on a dollars per mile basis. Anderson [36] built an econometric model to show that a $0.10 per gallon price increase in ethanol relative to gasoline induces a 12–16% decrease in the volume of ethanol demanded. A substantial price differential may never exist without government action since the two fuels tend to rise and fall together [37].[17] A policy already in place – the RFS – has the potential to incentivize higher blend ethanols through its tradeable compliance credits (Renewable Identification Numbers, or RINs). If annual mandates are set so as to exceed the blend wall, higher RIN prices can create attractive incentives for investment in higher blend ethanol infrastructure, providing savings opportunities for oil companies facing RFS compliance costs [38].

Greater market share of FFVs and E15-capable vehicles requires a fleet turnover of existing vehicles. With an engine modification at the time of manufacturing, vehicles can be turned into FFVs at a cost of about $70–100 per vehicle [39]. As of 2012, only 5.1% of light-duty cars and trucks on the road were FFVs[18] [1]. For E15, although the EPA has permitted its use in all post-2001 vehicles, many automakers void the vehicle warranty if E15 is used. Exceptions are General Motors, Ford, and Porsche who permit E15 use in certain vehicles.[19] The void in warranty is due to automaker concerns about accelerated engine wear, failure of fuel systems, and false check engine lights.

Both E85 and E15 also incur a cost for added refueling infrastructure. For example, NREL [40] estimates that converting a service station to E85-capable incurs $100,000–$200,000 of equipment and permitting cost. Searle et al. [39] suggested that E10 refueling infrastructure could be used for E15, thereby lowering the cost and time it would take to transition to E15. Other institutional barriers include certification of converted fuel dispensers and fuel specifications (oxygen waiver) for higher blends. Only 2408 of the 114,223 service stations in the U.S. offer E85 [41,42] and only 59 currently offer E15 as a unique product, although this number is increasing [43]. Additionally, the ethanol infrastructure (i.e., pipelines, rail lines, etc.) must grow to transport fuels at levels commensurate with service station needs.

In recent years, drivers of FFVs have favored using gasoline over E85 because, on an energy basis, wholesale motor gasoline has averaged

[14] Oils can also be made from any cellulosic material through thermo-chemical conversion. However, the potential for cellulosic-based oil is the same as other cellulosic biofuel biorefineries and was assessed above.

[15] This includes 1339 million gallons of biodiesel production reported by EIA [2], and about 260 million gallons of domestic renewable diesel production (417 million gallons of renewable diesel reported by the EPA in the RFS [28] minus 157 million gallons of renewable diesel imports reported by EIA [2]).

[16] Other potential diesel substitutes include cellulosics and algae converted to oil.

[17] Some differential is justified, especially in lower ethanol blends: there, a higher value for ethanol than gasoline on a per energy basis is in part due to the octane and oxygen it contributes to the blend, whereas at blends as high as E85, ethanol's energy content to propel the vehicle (a substitute for gasoline) is the principal attribute [38].

[18] Includes fleet and private vehicles.

[19] 2001 or newer Porsche, 2012 or newer GM, 2013 or newer Ford models.

$2.64 per gallon while wholesale E85 has averaged $3.11 per gallon of gasoline equivalent. In addition, more than 40% of FFV drivers live more than 10 miles from the nearest E85 station [34]. E15 growth has been hampered by lack of clarity on liability issues for retailers dispensing the fuel, and lack of engine warranties covering E15 [44].

We consider the maximum FFV and post-2012 vehicle market shares between today and 2030 using a fleet turnover model described in the S.I. We estimate the additional E15 and E85 fuel sales that would result from this increased market share using a lagged regression model based on FFV and E85 use in Minnesota, USA from 2000 to 2013. We take a case of 25% FFV owners using E85 to be reflective of the feasible technical limit for E85 demand. This would require wholesale ethanol to sell at a discount of $0.40–$1 per gallon of gasoline equivalent compared to wholesale gasoline. We find that at reasonable[20] penetration rates of E15 and E85-capable vehicles, E15 and E85 could contribute another 2.9 BGGE and 10.3 BGGE by 2030, respectively. Alternatively, if both E15 and E85 strategies are pursued simultaneously, we estimate a maximum demand constraint in 2030 of 13.0 BGGE.

Other drop-in cellulosic biofuels (like bio-jet fuel, renewable gasoline, etc.) do not face the same demand constraints as ethanol. Renewable gasoline can be blended in the petroleum-based fuel without modifying vehicles, distribution systems, or refueling infrastructure. Drop-in fuels made from cellulosic and algae biomass could be a transformative technology because they can substitute for gasoline, diesel, jet fuel, or marine fuel. Drop-ins are a broad category of fuels created using a thermochemical route. Based on our assessment of the fuels market, 26 firms are currently pursuing drop-in biofuels.

4. Comparison of supply and demand constraints

Estimating potential rates of relaxation of the supply and demand constraints allows a side-by-side comparison of these constraints. An important consideration is that only ethanol has a near-term *demand* constraint, while all fuels have near-term supply constraints. In Fig. 3, we show our estimated maximum possible additional ethanol supply from cellulosic, corn fiber, and incremental improvements to existing ethanol biorefineries. We also show the highest potential demands given an aggressive roll-out of E85 and E15 refueling stations and FFVs. The methodology and assumptions behind this figure are given in the S.I.

We want to emphasize that Fig. 3 focuses on technical aspects of supply and demand expansion. The figure does not account for competing uses for feedstocks, competition within the fuels market, or the effect of prices and other economic factors on supply and demand. There is almost certainly not a one-to-one replacement of petroleum from this expansion because: (1) some additional petroleum will be needed in the production of the biofuels, (2) the market effect of expanded biofuel production depresses the price of oil, and (3) some new production could displace existing production's use in the U.S. market [45]. Still, it provides a rough guide as to the maximum potential increase in U.S.-based biofuel production and consumption to 2030.

Fig. 3 suggests a number of policy implications. First, if expanding ethanol use is a policy goal, then both supply and demand constraints deserve attention since both are limiting factors in the near-term. On the other hand, it appears E85 constraints can be relaxed at a faster pace than supply constraints. This is because (based on our calculations) the rate at which FFVs and E85 refueling stations can penetrate the market is faster than the supply of new ethanol can ramp-up if aggressive policy measures are taken. An additional implication is that an E15-only strategy appears to be more constraining than E85 or E85 + E15 strategies. It also appears to be more constraining than the fastest build-out of supply. Finally, if cellulosic production steers more toward drop-in fuels, the E15 demand strategy with some E85 may suffice to realize domestic use of domestic production potential.

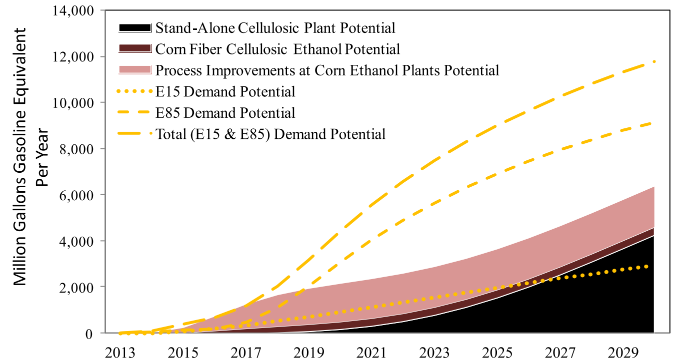

Fig. 3. Maximum potential supply (area) and demand (lines).

5. Conclusions

This paper projects how quickly domestically produced, non-food based biofuels could expand in the U.S. in the next 15 years from a technical standpoint. Additionally, we compare these maximum supply potentials to technical demand constraints. Overall, we find that by 2030, an additional 8.0 billion gallons of gasoline-equivalent biofuel supply is possible, 6.6 billion of which could be ethanol (Fig. 3). This amounts to an additional 3.7% of today's final energy in the U.S. transportation sector and is slightly less biofuel growth than projected by the EIA during the years 2008–2012 (Fig. 1). Market conditions will determine a biofuel supply-and-demand equilibrium within the technical constraints. Indeed, constraints on both the supply and demand side must be removed to achieve the potential, and it will likely take aggressive new policies to do so.

An important consideration for energy independence that is not empirically considered here is that imports of biofuels provide several advantages over importing oil. These include: (1) the number countries that can provide substantial biomass and biofuels to the U.S. is much higher than the number that can provide substantial volumes of fossil energy, and thus can reduce energy dependence on specific countries and regions, (2) given uncertainty in year-to-year weather conditions, supplying biofuels from more countries and regions of the world may increase energy security compared to a fully-domestic biofuel production system,[21] and (3) some imported biofuels may have better economic and environmental performance than domestic biofuels. For example, sugarcane ethanol from Brazil is rated lower in carbon intensity than corn ethanol from the U.S. under both the RFS and LCFS.

One limitation of this analysis is a lack of spatial data. As noted by others, the spatially disaggregated nature of biomass supplies [16] as well the as the spatial mismatch between FFVs and E85 stations [45] mean that the geographic layout of the biofuels industry should be considered in estimating biofuel supply and demand constraints. However, our analysis is meant as a "first cut," providing energy planners and stakeholders a side-by-side comparison of technical constraints. A second major limitation is that we do not incorporate market-mediated effects in our supply or demand estimates. Since the substitute of biofuels for petroleum is not a 1-to-1 ratio [45], an economic model is needed to determine system-wide impacts of expanding biofuels. Such an approach could hone estimates of technical potentials, as well as generate estimates of equilibrium outcomes.

[20] See discussion in S.I.

[21] Sugarcane ethanol imports rose markedly after the 2012 U.S. drought.

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Appendix A. Supplementary information

Supplementary information related to this article can be found online at http://dx.doi.org/10.1016/j.esr.2014.09.001.

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