BIODIESEL FOR THE 21^{ST} CENTURY RENEWABLE ENERGY ECONOMY

John J. Perona[*]

Synopsis: Liquid fuels from renewable biomass can make an important contribution to decreasing the use of fossil petroleum and hence limiting the amount of global warming. Transforming this aspiration into a large-scale practical reality requires confronting many challenges, including the environmental impacts of harvesting or cultivating the biomass resource, the supply of water and energy to expanded biomass industries, development and scale-up of industrial processes for extracting and refining market-ready biofuel at competitive costs, and certainly not least, administrative and political roadblocks to making the necessary difficult choices. In the United States, the biofuels landscape is dominated by corn-derived ethanol, which is blended into gasoline under the Clean Air Act's Renewable Fuel Standard (RFS). Mandates also exist for "advanced" biofuels, especially ethanol from cellulosic biomass and biodiesel presently derived from soybeans and other oil-rich plants. In this article, analysis of commercial biofuels production in the context of the overall renewable energy challenge first demonstrates that none of the developed sources is likely capable of substantially replacing fossil petroleum in the United States' economy. Further, the demand for ethanol blending will decrease in coming decades owing to increased fuel efficiency standards and the advent of all-electric cars. Notwithstanding these difficulties, the RFS and other state and federal programs should continue to play an important role in accelerating development of renewable biodiesel industries, including from new, pre-commercial sources such as photosynthetic microalgae, to enable the eventual replacement of petroleum diesel in commercial applications not susceptible to electrification. The high energy density of biodiesel, its ability to function as a "drop-in" fuel in diesel engines, and its superior capacity as a feedstock for chemicals and commodities synthesis all recommend that future policies should strongly emphasize biodiesel development over ethanol. Specific attention to producing biodiesel from algae is also warranted because of the potential to interface this technology with both carbon dioxide capture and wastewater treatment, allowing "algaculture" to play a key role in long-term environmental sustainability in the United States.

---

[*] John Perona holds degrees in chemical engineering, biochemistry, and law. He is Professor of Environmental Biochemistry at Portland State University, Adjunct Professor of Biochemistry and Molecular Biology at Oregon Health and Science University, and a recent recipient of the LL.M. in Environmental and Natural Resources Law from the Northwestern College of Law, Lewis & Clark University. His research interests include synthetic biology, the biochemistry of sulfur trafficking in environmentally important microbes, and the interface of law and science applied to energy systems and climate change. Thanks to Lewis & Clark Professors Dan Rohlf and Melissa Powers for critical comments on this article.

I. INTRODUCTION

The first years of the twenty-first century have witnessed remarkably rapid growth in the production and consumption of renewable energy. This expansion has occurred in the United States and worldwide, and is most evident in the changing mix of fuels used to generate electricity. The use of renewables in power generation grew to nearly 3% of global production in 2015, with average annual growth rates of over 15% in the past ten years.[1] In the United States, wind and solar generation facilities contributed 4.55% and 0.67%, respectively, of the total electricity produced in 2015, with each industry poised for further rapid expansion.[2] Although most recent growth has been at the expense of coal, the levelized costs of electricity generation for both wind and solar PV have now reached parity with natural gas when tax credits are factored into the estimates.[3] These data offer a compelling portrait of an electrical energy sector in the midst of a rapid and accelerating transition.

Change is arriving more slowly, however, in the transportation and industrial portions of the U.S. and global economies, as shown by the continued dominance

---

[1] *Renewable Energy – 2015 in Review*, BP GLOBAL, http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy.html (last visited Feb. 27, 2017).

[2] *How much US electricity is generated from renewable energy?* U.S. ENERGY INFO. ADMIN., http://www.eia.gov/energy_in_brief/article/renewable_electricity.cfm (last updated Mar. 27, 2016).

[3] *Levelized costs and levelized avoided cost of new generation resources in the Annual Energy Outlook 2016*, U.S. ENERGY INFO. ADMIN. (Aug. 2016), http://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

of petroleum as the world's most abundant energy source.[4] Oil contributed just 1% of U.S. electricity generation in 2015,[5] but in 2014 it was responsible for 92% of energy consumption in transportation and 38% in industry; together, these two demand sectors account for nearly 50% of all U.S. consumption.[6] In contrast, renewables, including biofuels, contributed just 5% of the total energy used by the U.S. transportation sector in 2014.[7]

The much slower gains made by renewables in the transportation and industrial sectors reflect substantial practical barriers associated with producing liquid fuels from biomass at competitive costs.[8] In the United States, gasoline accounts for about 80% of liquid petroleum use, while the remaining 20% consists of diesel.[9] These two fuels serve separate markets: gasoline powers the light vehicle fleet, while diesel is used for heavy vehicles, air transportation, and many industrial applications.[10] The roles of renewable biofuels in these markets are also very different. Ethanol produced primarily from corn is used almost universally in the United States as a 10% blend with gasoline.[11] The industry's fortunes therefore rise and fall with the amount of gasoline consumption in light vehicles, making them highly susceptible to the advent of electric cars. In contrast, biodiesel produced from soybeans and other oil-rich crops has potential to fully replace petroleum diesel.[12] Further, it will likely remain important in a future renewable energy economy because its applications require very high energy densities and are consequently difficult to replace with electric batteries.[13] Biodiesel can also replace petroleum diesel in the production of plastics, chemicals, and many other commodities.[14]

Significant environmental and economic considerations justify expanding the production and use of biodiesel in the United States. Atmospheric carbon dioxide (CO_2) levels from fossil fuel combustion surpassed 400 parts per million (400

---

[4] In 2015 oil accounted for 32.9% of global energy consumption. BP Statistical Review of World Energy, June 2016. http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf.

[5] U.S. ENERGY INFO. ADMIN., *supra* note 2.

[6] *U.S. Primary Energy Consumption by Source and Sector 2015,* U.S. ENERGY INFO. ADMIN., https://www.eia.gov/energyexplained/ (last visited Feb. 27, 2017).

[7] *Id*.

[8] VACLAV SMIL, ENERGY MYTHS AND REALITIES: BRINGING SCIENCE TO THE ENERGY POLICY DEBATE 98-115 (2010); *See also infra* Part II.

[9] *Oil: Crude and Petroleum Products, U.S. ENERGY INFO. ADMIN.,* http://www.eia.gov/energyexplained/index.cfm?page=oil_use (last updated Nov. 28, 2016) [herinafter *Oil: Crude and Petroleum Products*].

[10] *Id.*

[11] SMIL, *supra* note 8.

[12] *Infra* Parts II and IV.

[13] Martin Hepperle, *Electric Flight – Potential and Limitations*, GERMAN AEROSPACE CTR. (Jan. 2013), https://www.researchgate.net/publication/234739098_MP-AVT-209-09.

[14] For an overview of biofuels uses, *see generally Bioenergy Technologies Office*, DEP'T OF ENERGY, http://www.energy.gov/eere/bioenergy/bioenergy-technologies-office (last visited Feb. 27, 2017).

ppm) in 2015,[15] generating severe and escalating human impacts.[16] Continued CO_2 accumulation reflects the challenge of formulating effective international climate agreements,[17] while also overcoming entrenched interests in the present energy system and the risks and expenses of developing alternative sources.[18] The rapid growth of renewables is remarkable, yet still insufficient to limit global temperature increases to below 2°C, as agreed in recent negotiations.[19] Decreases in fossil fuel CO_2 emissions of approximately 5% per year to 2050 are now likely required to stay below 2°C warming, assuming that accelerated development of renewable energy resources can begin almost immediately.[20] The scale of the task is well outside historical precedent for any energy transition,[21] yet the quality of Earth's future environment now almost certainly depends on the rapid and effective mobilization of a renewable energy economy.[22]

Expanded production of renewable energy is consistent with rapid economic growth. Global CO_2 emissions remained constant in 2014 and 2015 while global GDP increased by over 3% each year.[23] In the United States, a recent study shows that over thirty states have also significantly decoupled economic growth from

---

[15] *See, e.g.*, *Carbon Cycle Science*, NOAA EARTH SYS. RES. LAB., www.esrl.noaa.gov (last visited Feb. 28, 2017); *Carbon Dioxide Measurements,* SCRIPPS INSTITUTION OCEANOGRAPHY, www.scrippsco2.ucsd.edu (last visited Feb. 28, 2017) (supporting CO_2 atmospheric accumulation data); *see also* GLOBAL CARBON PROJECT, https://www.esrl.noaa.gov/research/themes/carbon/ (last visited Feb. 28, 2017) (showing emissions data and global carbon budgets).

[16] *See generally* CLIMATE CHANGE 2014: IMPACTS, ADAPTATION, AND VULNERABILITY: PART A: GLOBAL AND SECTORAL ASPECTS, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE WORKING GR. II (C.B. Field et al. eds., Cambridge University Press 2014).

[17] A key issue is the "free rider" problem: costs to reduce emissions are high for any country participating in international climate negotiations, but benefits of the reduction are distributed to all nations through the atmospheric commons. William Nordhaus, *Climate Clubs: Overcoming Free-riding in International Climate Policy*, 105 AM. ECON. REV. 4 (Apr. 2015).

[18] P.J. Loftus et al., *A Critical Review of Global Decarbonization Scenarios: What do They Tell Us About Feasibility?*, 6 WIREs CLIMATE CHANGE 93 (Jan./Feb. 2015).

[19] The consensus was reached at the sixteenth Conference of the Parties (COP16) to the United Nations Framework Convention on Climate Change (UNFCCC). The temperature increase from 1880 to 2014 is about 0.9°C. UNFCCC, DECISIONS ADOPTED BY THE CONFERENCE OF THE PARTIES, DECISION 1/CP.16, section I, ¶ 4 (Mar. 15, 2011).

[20] To meet the 2°C target, CO_2 emissions from fossil fuels and industrial processes should decrease from 36 $GtCO_2$/yr for 2013 to approximately 10 $GtCO_2$/yr by 2050 (1 Gt (gigaton) equals 10^{15} grams (g)). M.R. Raupach et al., *Sharing a Quota on Cumulative Carbon Emissions*, 4 NATURE CLIMATE CHANGE 873, 877 (Sept. 21, 2014). For a primer on carbon arithmetic, *see generally* David Archer, *The Global Carbon Cycle*, PRINCETON U. PRESS (2010).

[21] SMIL, *supra* note 8.

[22] The only alternative to emissions reductions is geoengineering: the ongoing management of Earth's climate by reflecting solar radiation and/or removing CO_2 from the atmosphere. The U.S. National Academy of Sciences has recently released two comprehensive analyses on the prospects for these approaches. For a lay summary, *see generally* NAT'L RES. COUNCIL NAT'L ACADS., CLIMATE INTERVENTION: CARBON DIOXIDE REMOVAL AND RELIABLE SEQUESTRATION (2015); NAT'L RES. COUNCIL OF THE NAT'L ACADS., CLIMATE INTERVENTION: REFLECTING SUNLIGHT TO COOL EARTH (2015).

[23] *Global Energy-related Emissions of Carbon Dioxide Stalled in 2014,* INT'L ENERGY AGENCY (Mar. 13, 2015), https://www.iea.org/newsroom/news/2015/march/global-energy-related-emissions-of-carbon-dioxide-stalled-in-2014.html; *see also Decoupling of Global Emissions and Economic Growth Confirmed,* INT'L ENERGY AGENCY (Mar. 16, 2016), https://www.iea.org/newsroom/news/2016/march/decoupling-of-global-emissions-and-economic-growth-confirmed.html.

increased CO_2 emissions, again demonstrating that the rise of the renewable energy industry can have positive economic ramifications.[24] The replacement of coal with natural gas and renewables for electricity generation has played a major role in U.S. and global decoupling, suggesting that a similar replacement of petroleum diesel with biodiesel may also have positive consequences if aggressively pursued.[25] Biodiesel produced from domestic sources will also contribute to further reducing the reliance of the United States on petroleum imports.[26]

Here I advocate for aggressive state and federal policies to shift the source of diesel fuels from fossil petroleum deposits to biodiesel extracted from plants and algae (see Box 1 for a summary of recommendations).

Box 1 – Summary of Recommendations

- Eliminate the bias in favor of cellulosic ethanol in the federal RFS2 program, and increase applicable volume mandates for biomass-based diesel. This will provide a better signal for long-term investors, so that growth of the biodiesel industry is incentivized by larger guaranteed markets for the fuel. Additionally, Congress and EPA should foresee the substantial decreases in gasoline fuel use for light vehicles by the mid-to-late twenty-first century, and take steps to reduce applicable ethanol blending volumes in RFS2 (or a new standard) in parallel with these decreases.
- Couple increases in the biodiesel mandates in RFS2 with new incentives to drive technological improvements in the capacity of all diesel engines to operate efficiently with fuels containing high levels of biodiesel, or neat biodiesel (B100). Such incentives should include funding for consortia of private industry, national laboratory, and/or public or private universities to investigate fuel properties and engine performance. Production tax credits for diesel engine manufacturers that incorporate new biodiesel-friendly design characteristics are another possibility.
- The $1 per gallon biodiesel and renewable diesel blenders tax credit, presently set to expire on January 1, 2017, should be renewed for at least a five year period. The present credit was in effect for only two years. The longer time period will reduce investor uncertainty, and is justified given the low volumes of biodiesel presently produced and the expected time needed to expand supply from soybeans and other crops, and to accelerate commercial development from new sources.

---

[24] Devashree Saha & Mark Muro, *Growth, Carbon and Trump: State Progress and Drift on Economic Growth and Emissions "Decoupling,"* BROOKINGS INST. (Dec. 8, 2016), https://www.brookings.edu/research/growth-carbon-and-trump-state-progress-and-drift-on-economic-growth-and-emissions-decoupling/#fullreport.

[25] *Id.*

[26] U.S. petroleum imports have declined by a third since peaking in 2005. The United States presently imports 24% of the petroleum it uses. *Oil: Crude and Petroleum Products,* U.S. ENERGY INFO. ADMIN., https://www.eia.gov/energyexplained/index.cfm?page=oil_imports (last updated Nov. 28, 2016) [herinafter *Oil: Crude and Petroleum Products*].

- DOE and USDA fund substantial amounts of biofuels research through the BETO, Sun Grant and BRDI programs, but much of this is directed to the exploration of new sources for cellulosic ethanol and the development and improvement of ethanol production from these sources. Funding in these programs should be substantially redirected to biodiesel applications. Efforts to develop scalable biodiesel production from new plant crops would also be a more valuable use of funds.
- State programs to promote biodiesel production and algaculture can provide significant impetus for these industries, and their expansion is encouraged. Many states would do well to follow the model for public-private partnerships provided by Arizona's broadly based AzCATI program, which has effectively leveraged funding from a wide variety of sources. Such programs provide centers of expertise to attract private investment and encourage entrepreneurship in the field. Targeted federal funding assistance for such initiatives could be provided to Gulf Coast states that are well-situated to develop the industry because of their access to required resources. Another mechanism for states to attract investment is establishment of LCFS programs that follow the successful California model.
- The EPA, USDA or equivalent state agencies should promote efforts to better quantify the extent to which existing sources of agricultural and municipal wastewaters can meet the demands of a commercial algaculture sector for water, phosphorus and nitrogen. Much more work to characterize the infrastructure requirements for channeling wastewaters, brackish groundwaters, or saline waters to algaculture facilities is also warranted. These efforts could bear fruit for large-scale pollution control regardless of whether algae ultimately become a significant source of biodiesel.
- Expand the eligibility of algae-based products for federal agricultural support programs, so that non-food uses of algae-based products are also included.

These policy proposals are consistent with international climate negotiations: at the Twenty-First Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), every nation agreed to develop a "deep decarbonization" strategy for reducing its CO_2 emissions.[27] The scenarios typically include portfolios of renewable energy technologies, removal of CO_2 from fossil fuel combustion products, and improvements in energy efficiency,

---

[27] *See* WORKING PAPER: KEY ELEMENTS FOR SUCCESS ON CLIMATE CHANGE MITIGATION AT COP21 IN PARIS, SUSTAINABLE DEV. SOLUTIONS NETWORK (2015), http://unsdsn.org/resources/publications/key-elements-for-success-on-climate-change-mitigation-at-cop21-in-paris/. The Deep Decarbonization Pathways Project (DDPP) was formed under the auspices of the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI). *See generally* JAMES H. WILLIAMS ET AL., SUSTAINABLE DEV. SOLUTIONS NETWORK, PATHWAYS TO DEEP DECARBONIZATION IN THE UNITED STATES (2014), http://unsdsn.org/resources/publications/pathways-to-deep-decarbonization-2014-report/ (last visited Sept. 20, 2014).

among other approaches.[28] The preliminary U.S. plan (the U.S. DDPP report) describes four scenarios to stay within the 2°C limit, all of which include the use of renewable biomass as a feedstock to provide pipeline gas, liquid transportation fuels, or both.[29] All U.S. scenarios also include rapid expansion of solar and wind energy infrastructures and implementation of carbon capture and storage (CCS) to trap and bury CO_2 from power plant emissions.[30]

Section II offers a concise, quantitative analysis of the present U.S. biofuels landscape, demonstrating the need for new biofuels sources and development policies. The industry has been dominated by the production of ethanol from corn, with development driven mainly by federal mandates for blending with gasoline that originated with political pressure from agricultural interests.[31] However, limits to arable land and intrinsic energy inefficiencies certainly preclude corn ethanol from a significant role in the new energy economy.[32] The new cellulosic ethanol resource derived from dedicated energy crops, agricultural residues, or unharvested timber has been highly touted, but has so far been severely limited by technical difficulties in developing production facilities at industrial scale, while also facing concerns regarding the environmental impacts of harvesting.[33] Perhaps most critically, the entire ethanol industry faces severe, if not insurmountable, challenges associated with decreased consumer demand from higher vehicle fuel efficiencies and the advent of electric cars.[34] In contrast, biodiesel has much more growth potential than ethanol because of its higher intrinsic energy content, and its capacity to substitute directly for petroleum diesel in the distinct heavy industry and transportation sectors.[35] So far, however, biodiesel has been derived almost entirely from food crops, primarily soybeans. Like corn ethanol, biodiesel development has thus also been limited by the availability of arable land.[36]

Section III explains the potential and challenges of using single-celled algae as a source of biodiesel that is not constrained by limits to arable land.[37] Although

---

[28] For a detailed comparative assessment of scenarios, *see, e.g.*, Leon Clarke et al., *Technology and U.S. Emissions Reductions Goals: Results of the EMF 24 Modeling Exercise*, 35 Energy L.J. 9 (2014). For a critical view highlighting the limitations in these models, see *supra* note 4 (analyzing seventeen global decarbonization scenarios using four different general approaches to model low-carbon scenarios, and concluding that much more detailed treatment of the key constraints on energy systems transformations is needed for these studies to provide reliable guides to policymaking).

[29] Williams et al., *supra* note 27.

[30] *Id*.

[31] Smil, *supra* note 8, at 98.

[32] *Id.* at 102.

[33] Kevin Bullis, *The Cellulosic Ethanol Industry Faces Big Challenges*, MIT Tech. Rev. (Aug. 12, 2013), https://www.technologyreview.com/s/517816/the-cellulosic-ethanol-industry-faces-big-challenges/.

[34] Melissa Powers, *Lessons from U.S. Biofuels Policy: The Renewable Fuel Standard's Rocky Ride*, L. & Pol'y Biofuels (Yves Le Bouthillier et al. eds., 2016).

[35] Alternative Fuels Data Center – Fuels Properties Comparison., Dep't Energy (Oct. 29, 2014), http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf.

[36] The United States Energy Information Administration (EIA) publishes data on biodiesel production. *See Biodiesel is made from vegetable oils and animal fats*, https://www.eia.gov/energyexplained/index.cfm/data/index.cfm?page=biofuel_biodiesel_home (last visited April 9, 2017).

[37] *John Ferrell & Valerie Sarisky-Reed*, Off. Energy Efficiency & Renewable Energy, National Algal Biofuels Technology Roadmap (May 2010), http://www1.eere.energy.gov/bioenergy/pdfs/algal_biofuels_roadmap.pdf.

algal biofuels are presently at the pre-commercial stage,[38] focused policy attention is warranted now because of the urgency of the renewable energy transition, the shortcomings of all other biofuel sources, and the potential of algae to offer subsidiary benefits. For example, the present requirement for externally supplied CO_2 to grow algae at high yields may help drive CCS technology by providing a market for the CO_2 emissions collected from coal and natural gas-fired power plants.[39] Further, because algae can grow on wastewater and saline water inputs, the new industry may also offer substantial benefits in pollution control, especially for agricultural waste from industrial-scale farming and animal production operations.[40] This also diminishes the need for freshwater resources to support "algaculture" operations.

Section IV provides an analysis and recommendations for how law and policymakers can best incentivize the development of the biodiesel industry. All biodiesel technologies would benefit from a much-needed substantial increase in funding for basic energy sciences by a number of federal agencies, and from an increase in targeted public-private partnerships that could be initiated with joint federal and state support. This section also describes how the renewable fuels standard in the Clean Air Act might be reconfigured to better promote the growth of biodiesel.[41] A recently issued Environmental Protection Agency (EPA) rule that resets the mandated volumes for renewable fuel production may offer an opportunity to reimagine this program in a manner that signals federal support and recognition for the biodiesel industry.[42] State low carbon fuel standard programs also provide important mechanisms to drive biodiesel industry development.[43] Finally, this section highlights which law and policy proposals may be particularly useful to foster development of the algaculture industry. State-level policies are likely to be of particular value in this endeavor, given that the technology is most likely to prosper in particular regions of the country that are able to provide the necessary resources in the form of adequate sunlight, carbon dioxide and nutrients.

II. BIOFUELS FOR RENEWABLE ENERGY IN THE UNITED STATES

The United States consumes about seven billion barrels (nearly 300 billion gallons) of liquid petroleum each year.[44] Much of this is used for transportation, although significant quantities are also employed in industry and as feedstocks to

---

[38] NAT'L RES. COUNCIL, SUSTAINABLE DEVELOPMENT OF ALGAL BIOFUELS IN THE UNITED STATES (2012), http://www.nap.edu/catalog/13437/sustainable-development-of-algal-biofuels-in-the-united-states.

[39] FERRELL & SARISKY-REED, *supra* note 37, at 80.

[40] *Id.* at 83-86.

[41] *Renewable Fuel Standard Program,* ENVTL. PROT. AGENCY, https://www.epa.gov/renewable-fuel-standard-program/program-overview-renewable-fuel-standard-program (last visited Mar. 1, 2017).

[42] James Rubin, *As EPA Sets 2017 Renewable Fuel Volumes, Future is Unclear*, LAW 360 (Dec. 7, 2016), https://www.law360.com/articles/870346/as-epa-sets-2017-renewable-fuel-volumes-future-is-unclear.

[43] *Low Carbon Fuel Standard,* CTR. FOR CLIMATE & ENERGY SOLUTIONS, https://www.c2es.org/us-states-regions/policy-maps/low-carbon-fuel-standard (last visited Mar. 1, 2017).

[44] For U.S. petroleum demand statistics, see the Energy Information Administration (EIA) website operated by the U.S. DOE. *Frequently Asked Questions: How Much Oil is Consumed in the United States?*, U.S. ENERGY INFO. ADMIN. (last updated Mar. 17, 2016), http://www.eia.gov/tools/faqs/faq.cfm?id=33&t=6.

synthesize plastics, fine chemicals, and other commodities.[45] Together, these uses make petroleum the largest contributor to CO_2 emissions in the energy sector.[46] However, energy-economy models such as those presented in the U.S. Deep Decarbonization Pathways Project (DDPP) report suggest that much less than 300 billion gallons of liquid biofuel may be needed as the energy transition develops, because electrification of light-vehicle transportation should reduce demand significantly.[47] Several U.S. DDPP scenarios that meet the 2°C limit project that liquid biofuels in 2050 might need to contribute just 20% of the present petroleum demand, if both wind and solar power are aggressively developed and the technology for onboard vehicle storage of electric energy (batteries) continues to improve.[48] A target production amount of 60 billion gallons per year in the United States thus offers a reasonable benchmark to evaluate the potential of biofuels resources to meet climate goals. 60 billion gallons also corresponds to the amount of petroleum diesel fuel that is presently consumed in the United States.[49] As explained below, however, none of the commercially developed resources can currently deliver anywhere near this quantity of fuel.[50]

A. Corn and Cellulosic Ethanol

The predominant liquid biofuel in the United States today is corn ethanol.[51] Corn is the "first generation" biofuel, thanks to the considerable head start it received from an array of Congressional subsidies and tax credits.[52] In addition to subsidies for growing corn itself, these policies included an excise tax credit for certain ethanol blends, setting of bioethanol production targets,[53] and imposition of a stiff tariff on import of Brazilian ethanol made from sugar cane.[54] There is little doubt that the U.S. corn ethanol industry would not be operating at anywhere

---

[45] *Frequently Asked Questions: How Much Oil is Used to Make Plastic?*, U.S. Energy Info. Admin. (last updated Apr. 25, 2016), http://www.eia.gov/tools/faqs/faq.cfm?id=34&t=6.

[46] U.S. Energy-Related Carbon Dioxide Emissions: 2015, U.S. Energy Info. Admin. (Mar. 16, 2017), https://www.eia.gov/environment/emissions/carbon/ [herinafter U.S. Energy-Related Carbon].

[47] For the United States, the 2°C upper limit approximately translates to an 80% reduction in greenhouse gas emissions by 2050, compared to a 1990 benchmark. Details on how biofuels contribute to the new energy economy under distinct scenarios that each satisfy this condition are found in Williams et al., *supra* note 27.

[48] For U.S. liquid biofuels demand projections in 2050, *Id.* at 62.

[49] *Oil: Crude and Petroleum Products*, *supra* note 9.

[50] It is conceivable that biomass will not be used at all for transportation and industry in the renewable energy economy, if renewably generated electricity and its applications in these sectors can achieve full market penetration, and/or if a comprehensive hydrogen economy develops in which the main energy currency is hydrogen gas (H_2) produced by renewable electricity. However, even if these alternatives are achieved, biomass will still be required because there is no other source of non-fossil fuel energy-rich carbon for production of plastics, chemicals and other commodities.

[51] Melissa Powers, *King Corn: Will the Renewable Fuel Standard Eventually End Corn Ethanol's Reign?*, 11 Vt. J. Envtl. L. 667, 679-80 (2010).

[52] John A. Sautter et al., *Construction of a Fools' Paradise: Ethanol Subsidies in America*, Sustainable Dev. L. & Pol'y 26, 26 (2007).

[53] Mandates for ethanol blending and bioethanol production targets are part of the Renewable Fuel Standard (RFS). Energy Policy Act of 2005, Pub. L. No. 109-58, 119 Stat. 594. *See also infra*, Part IV.A.1.

[54] Congress eliminated the ethanol import tariff and the tax credit to blenders of ethanol effective January 1, 2012, after corn ethanol production plateaued and the industry had become self-sustaining. Robert Pear, *After Three Decades, Tax Credit for Ethanol Expires*, N.Y. Times, Jan. 1, 2012.

near its present output of 14.8 billion gallons per year had these subsidies not been in place.[55] However, whether corn ethanol can or should provide future demand depends on several factors that must be considered with respect to any liquid biofuel: (1) does the energy yield substantially exceed the energy invested in the production process; (2) can the requirements for other resource inputs (land, water, and nutrients) be met on the scale demanded by "deep decarbonization;" and (3) are there other factors—environmental, economic or social—that mitigate against the adoption of the technology?

Corn ethanol fares badly with respect to all these factors. First, energy return on energy invested (EREI) is estimated in the range of 0.77 to 1.67 (that is, negative to marginally positive), in part because ethanol contains only 65% of the heating value of petroleum,[56] and corn can only be efficiently grown by adding copious amounts of fossil-fuel based fertilizers.[57] Yields of corn ethanol in the United States have increased at a slower rate since 2011,[58] likely reflecting the fact that about 40% of the harvested crop is already dedicated to ethanol production.[59] Although some continued increases in corn crop yields from existing land are certainly possible,[60] arable land for agricultural production in the United States decreased by about 7% between 1990 and 2012 due to residential and industrial developments to meet population growth.[61] In addition to the greenhouse gas emissions associated with fertilizer production, corn ethanol also generates additional negative externalities in the forms of higher food costs[62] and environmental degradation from greater pollution of surface waters from the crop runoff.[63]

---

[55] 14.8 billion gallons of ethanol were produced in the United States in 2015. *US Ethanol Exports Exceed 800 Million Gallons for Second Year in a Row,* U.S. ENERGY INFO. ADMIN. (Mar. 10, 2016), http://www.eia.gov/todayinenergy/detail.php?id=25312.

[56] The 65% factor means that corn ethanol delivers just 8.5 billion barrels of petroleum-equivalent fuel per year in the United States. This amounts to only 3% of the energy derived from petroleum liquids.

[57] SMIL, *supra* note 8, at 102. The EREI for ethanol derived from sugar cane is five to ten-fold higher than for corn ethanol. However, sugar cane can only be cultivated in tropical climates. This industry is productive and profitable in Brazil, and unquestionably makes a significant contribution to reducing greenhouse gas emissions in the transportation sector of that economy. Unfortunately, overpopulation and other demands on land use suggest that there are few other tropical countries where this success is likely to be replicated, and other analyses indicate that Brazil's capacity to export ethanol probably cannot make a significant dent in global petroleum use. *Id.* at 104-105.

[58] *Abundant 2013 Corn Harvest Boosts Ethanol Production,* U.S. ENERGY INFO. ADMIN. (Dec. 13, 2013), http://www.eia.gov/todayinenergy/detail.cfm?id=14171.

[59] Gerard Wynn, *U.S. Use of Corn for Ethanol is High but Hyped*, REUTERS (Aug. 8, 2012), http://www.reuters.com/article/2012/08/08/column-wynn-ethanol-corn-idUSL6E8J65JU20120808.

[60] Increases in corn crop yields must also serve the larger populations expected for the United States in 2050 and beyond. DOUG GURIAN-SHERMAN, UNION CONCERNED SCIENTISTS, FAILURE TO YIELD: EVALUATING THE PERFORMANCE OF GENETICALLY ENGINEERED CROPS 1-2 (Apr. 2009), http://www.ucsusa.org/sites/default/files/legacy/assets/documents/food_and_agriculture/failure-to-yield.pdf.

[61] AG 101, ENVTL. PROT. AGENCY (last visited April 9, 2017), https://www.epa.gov/sites/production/files/2015-07/documents/ag_101_agriculture_us_epa_0.pdf .

[62] Food & Agric. Org. of the U.N. [FAO], *High-Level Conference on World Food Security: The Challenges of Climate Change & Bioenergy, Soaring Food Prices: Facts, Perspectives, Impacts, and Actions Required*, ¶ 18, U.N. Doc. HLC/08/INF/1 (June 3-5, 2008).

[63] Perhaps the most prominent example of environmental degradation from agricultural runoff is the hypoxic zone ("dead zone") in Northern parts of the Gulf of Mexico. *Hypoxia 101*, ENVTL. PROT. AGENCY, https://www.epa.gov/ms-htf/hypoxia-101 (last visited Mar. 1, 2017).

Without question, ethanol from cellulosic sources, a "second generation" biofuel, avoids many of these difficulties.[64] It can be derived from crop residues, wood residues, forest thinnings, and even industrial and other wastes, none of which depend on the further consumption of arable land.[65] Therefore, cellulosic ethanol does not directly compete with food crops for land, solving several of the major societal and environmental problems presented by corn ethanol. Cellulosic ethanol also received a substantial boost from U.S. policies—the revised renewable fuel standard (RFS2) incorporated in the 2007 Energy Independence and Security Act (EISA) contains a specific carve-out that mandates production of at least 5.5 billion gallons by 2017.[66] Further, since many cellulosic energy crops grow with reduced or no fertilizer inputs compared to corn, depending on the feedstock the EREI can be substantially improved as compared with corn ethanol.[67]

However, the cellulosic ethanol industry has faced unanticipated technical challenges in developing to industrial scale. Six commercial cellulosic ethanol plants began operation in the United States and Canada in 2014, clearly signaling that the technology has passed a significant milestone. Nonetheless, in that year EPA reported that the total U.S. production of cellulosic ethanol was just 33 million gallons,[68] while the combined final capacity of the six new plants is about 100 million gallons, far short of the RFS2 mandate and over 100-fold below annual corn ethanol production levels.[69] One key technical challenge is efficient extraction of the resilient cellulose fibers from surrounding plant material.[70] Additionally, the industry faces significant difficulties in raising sufficient investment capital to build facilities that could reach production levels similar to corn ethanol plants.[71]

Despite these challenges, the abundance and wide variety of cellulosic biomass feedstocks suggest that cellulosic ethanol may plausibly be able to replace

---

[64] The U.S. ethanol industry heralds the potential of cellulosic sources as "enormous" and describes 2014 as the year "the dream [that] became a reality." *See, e.g.*, *Advanced and Cellulosic Ethanol,* RENEWABLE FUELS ASS'N, http://www.ethanolrfa.org/issues/advanced-and-cellulosic-ethanol/.

[65] *Alternative Fuels Data Center: Cellulosic Ethanol Feedstocks*, U.S. DEP'T OF ENERGY (last updated Mar. 16, 2017), http://www.afdc.energy.gov/fuels/ethanol_feedstocks.html.

[66] 42 U.S.C. § 7545(o)(2)(B)(i)(III) (2009). *See also infra*, section IV.B.1 for analysis of a recent proposed revision to RFS2 by the EPA necessitated by the failure of the cellulosic ethanol industry to generate anywhere near the mandated product volume.

[67] Anil Baral et al., *Assessing Resource Intensity and Renewability of Cellulosic Ethanol Technologies Using Eco-LCA*, 46 ENVTL. SCI. & TECH. 2436 (2012).

[68] *Final Renewable Fuel Standards for 2014, 2015 and 2016, and the Biomass-Based Diesel Volume for 2017, Renewable Fuel Standard Program,* ENVTL. PROT. AGENCY (last updated Oct. 18, 2016), https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2014-2015-and-2016-and-biomass-based.

[69] The 100 million gallon estimate is derived from posted information on the websites for each of the six companies: Quad County (IA), Poet (IA), Albengoa (KS), Dupont Nevada (IA), Ineos (FL) and Enerkem (Alberta, Canada). The 33 million gallon production in 2014 represents 0.25% of the amount produced from corn.

[70] SMIL, *supra* note 8, at 107-113. Dislodging the cellulose from surrounding material is essential before the fermentation process to produce ethanol can begin.

[71] Large corn ethanol plants can produce 100 million gallons or more per year. Bullis, *supra* note 33.

corn ethanol in its present role in providing a 10% blend with gasoline, thus realizing significant environmental benefits.[72] The six new cellulosic ethanol plants use the residual crop residue from corn and wheat cultivation (corn stover and wheat straw, respectively), or municipal solid waste (MSW) as feedstocks. All of these resources exist in substantial amounts. With respect to crop residues, quantities that may be removed are limited by the need to maintain soil moisture and prevent erosion.[73] Nonetheless, it has been estimated that sustainable harvesting of stover from the U.S. corn crop could yield about 9 billion gallons of ethanol per year.[74] Estimates for MSW-based cellulosic ethanol plants yield a similar value for the potential size of that resource.[75] Together, these estimates exceed the present annual production of corn ethanol.

The variety and abundance of U.S. biomass resource potentially useful as a cellulosic ethanol source is also emphasized in the Billion Ton Study Update by the Department of Energy (DOE), which projects a harvesting potential of over 1 billion tons of biomass from forest and agricultural sources on non-federal lands in the continental United States by the mid-twenty-first century.[76] If fully exploited for ethanol production, this excess biomass could supply over 100 billion gallons of ethanol per year, far in excess of present demand.[77] Several scenarios in the U.S. DDPP report project that some of this biomass could instead be gasified and used to provide a renewable source of pipeline gas to replace fossil fuel methane.[78] The improved energy balance and better resource base for cellulosic ethanol are among the key arguments made by the ethanol industry in favor of expanding supply.[79]

These arguments in favor of cellulosic ethanol, however, appear unlikely to overcome other market and social factors that mitigate against the expansion of the technology. It is crucial to appreciate that, regardless of its source, consumer demand for ethanol-blended gasoline in the United States is declining due to altered driving habits, increasing fuel efficiency mandates, and, most importantly,

---

[72] The analysis in this paragraph considers the technical possibilities only. Replacement of corn ethanol with cellulosic ethanol would also require Congressional action to reformulate RFS2. *See generally infra*, Section IV.

[73] Humberto Blanco-Canqui et al., *Soil Hydraulic Properties Influenced by Corn Stover Removal from No-till Corn in Ohio*, 92 SOIL & TILLAGE RES. 144, 145 (2007).

[74] SMIL, *supra* note 8, at 107-113.

[75] *Id*.

[76] 2016 U.S. BILLION-TON UPDATE: ADVANCING DOMESTIC RESOURCES FOR A THRIVING BIOECONOMY 1, U.S. DEP'T OF ENERGY 265-66 (July 2016), https://energy.gov/eere/bioenergy/2016-billion-ton-report (updating an original DOE analysis from 2005. Since then, the work has been the subject of little public debate, even though such a massive undertaking would clearly implicate the interests of environmental groups and other stakeholders on state and private land in many parts of the country.).

[77] Ethanol yields are estimated at about 100 gallons per dry ton of forestry, agricultural and waste biomass resources. *Id.* at 18-20. Dry, woody agricultural and forest residues (cellulosic biomass) is a source of ethanol by fermentation. Very little biodiesel is produced from dry source materials of this kind. *See, e.g.*, *Monthly Biodiesel Production Report*, U.S. ENERGY INFO. ADMIN. (Feb. 28, 2017), http://www.eia.gov/biofuels/biodiesel/production (showing a detailed list of biodiesel production inputs); *See also infra*, Section II.B.

[78] WILLIAMS ET AL., *supra* note 27, at 14.

[79] *RFA 2016 Two Page Issue Briefs, Current Issues, Policy,* RENEWABLE FUELS ASS'N, http://ethanolrfa.org/policy/issues/rfa-2016-two-page-issue-briefs/ (last visited Mar. 4, 2017) (providing issue briefs and other advocacy from the Renewable Fuels Association, a leading U.S. proponent of ethanol industry expansion).

the advent of electric cars, which are predicted to reach 35% of new car sales by 2040 as costs for the batteries fall.[80] In the relatively short term, ethanol production volumes may expand if existing regulatory barriers to the spread of E15 are overcome and if consumers and automakers can be fully persuaded that this higher ethanol blend is compatible with gasoline engines without causing damage.[81] However, blending of ethanol with gasoline at fractions above 15% is unlikely in the United States because of required modifications to engine design in new vehicles, costs of retrofitting the existing fleet, and the need for dedicated pumps to dispense the fuel.[82] Moreover, while some aspects of performance might improve from the boost in oxygen content provided by the higher ethanol fraction, these vehicles would perform less efficiently because of the low energy density of ethanol compared to gasoline. This feature may be unattractive to many consumers and is certainly inconsistent with higher mileage standards that are also mandated by EPA.[83] The 15% limit is known as the "blend wall" for ethanol production.[84] It is not an intrinsic technological limitation: E85 engines are widespread in Brazil, where ethanol is efficiently produced from sugar cane.[85] Rather, the blend wall reflects the severe difficulties in reorganizing the U.S. automotive market to accommodate higher percentage ethanol blends. Regardless of short-term growth opportunities, the ultimate reality check for the U.S. ethanol industry is that its fortunes rise and fall with the fate of the gasoline-powered internal combustion engine in light vehicles. Yet the rapid growth of renewable electricity generation and the recent technological advances in battery production now offer a clear and environmentally much friendlier alternative. As others have noted, the future of ethanol does not look bright.[86]

B. Biodiesel from Food Crops

Ethanol, whatever its source material, is not the only biofuel. The alternative choice is biodiesel—a blend of energy-rich hydrocarbon compounds that is chemically similar to the diesel fraction refined from crude oil, and that is presently derived almost entirely from animal or vegetable oils. Biodiesel is a general term for these substances, but the EPA recognizes the existence of two distinct types of the fuel that arise from differences at the final stage of processing of the raw plant

---

[80] *Electric Vehicles to be 35% of New Car Sales by 2040*, BLOOMBERG NEW ENERGY FIN. (FEB. 26, 2016), https://about.bnef.com/blog/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040.

[81] *E15 Market Update: Boosting consumer choice,* RENEWABLE FUELS ASS'N (2016), http://ethanolrfa.org/wp-content/uploads/2017/03/E15-Market-Update_RFA.pdf.

[82] *Cellulosic Ethanol*, CTR. FOR CLIMATE & ENERGY SOLS., http://www.c2es.org/technology/fact-sheet/CellulosicEthanol (last visited Mar. 4, 2017).

[83] *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends Report Overview*, ENVTL. PROT. AGENCY (last updated Nov. 16, 2016), https://www3.epa.gov/fueleconomy/regulations.htm.

[84] Robert Rapier, *Refiners Hit "Blend Wall" With Ethanol: Now What?*, CHRISTIAN SCI. MONITOR (Mar. 22, 2013), http://www.csmonitor.com/Environment/Energy-Voices/2013/0322/Refiners-hit-blend-wall-with-ethanol.-Now-what.

[85] Sautter et al., *supra* note 52.

[86] Mark Peplow, *Cellulosic Ethanol Fights for Life*, NATURE (Mar. 11, 2014), http://www.nature.com/news/cellulosic-ethanol-fights-for-life-1.14856.

material.[87] The first type, which (unfortunately) is also termed "biodiesel" or "FAME" (fatty acid methyl ester), is produced by combining the purified plant hydrocarbon product with methanol via a reaction known as transesterification. The second general type of biodiesel is termed "renewable diesel;" it is produced by subjecting the purified plant hydrocarbon product to a process of hydrogenation rather than transesterification. Both types of biodiesel are registered with the EPA as fuels and fuel additives, and both can be blended with petroleum diesel fuels, with 5% (B5) and 20% blends (B20) most common.[88] Both types of biodiesel can also be used in their 100% "neat" form (B100).[89] EPA lumps these two types of biodiesel into a single broad category termed "biomass-based diesel." Like cellulosic ethanol, biomass-based diesel also was granted a specific carve-out in RFS2.[90] In 2013, the U.S. biodiesel industry produced nearly 1.8 billion gallons of its product, far more than cellulosic ethanol and exceeding requirements under RFS2.[91] Nearly two-thirds of this was produced from soybeans grown on arable farmland, with the remainder generated from corn oil, palm oil, canola oil, and animal fats.[92]

Biodiesel has at least three significant advantages over ethanol. First, it has an intrinsically high energy content that is nearly identical to crude oil and low-sulfur petroleum diesel fuel, and is about 50% higher than ethanol.[93] Second, because its chemical structure is similar to major components found in crude oil, it is also useful as a feedstock to produce commodities such as petrochemicals, plastics, and other fossil fuel products, with only minor modifications required in industrial-scale syntheses. Ethanol, while possessing added value in production of certain plastics,[94] is a much smaller molecule and thus is much less useful as a versatile synthetic feedstock. Finally, biodiesel approximates a "drop-in fuel" that can be directly substituted for petroleum diesel in diesel engines, or, depending on its source, can be readily refined to do so. About 20% of U.S. crude oil, about 60 billion gallons per year, is refined and used as diesel fuel at present, with about

---

[87] 42 U.S.C. § 7545(b). In terms of chemical composition, a principal distinction between diesel and gasoline fuels is that all diesel fuels, regardless of source, possess longer chain hydrocarbons and about 10-15% greater energy content. Petroleum diesel and biodiesel resemble each other and are substantially different from gasoline, accounting for why specific engine designs are required to burn each type of fuel. RENEWABLE DIESEL FUELS 1-2, DISEL FORUM, http://www.dieselforum.org/files/dmfile/renewablefuelsfactsheet_01.30.13.pdf (last visited Mar. 4, 2017).

[88] *Biodiesel Blends, Alternative Fuels Data Center,* DEP'T OF ENERGY (last updated Mar. 30, 2016), http://www.afdc.energy.gov/fuels/biodiesel_blends.html.

[89] *Id.*

[90] 42 U.S.C. §§ 17001-17386 (2007). *See also infra*, Section IV.B.1.

[91] *Production Statistics,* BIODIESEL.ORG, http://www.biodiesel.org/production/production-statistics (last visited Mar. 4, 2017) (1.8 billion gallons represents about 3% of the petroleum diesel consumption in the United States in 2013).

[92] *Table 3. U.S. Inputs to Biodiesel Production*, U.S. ENERGY INFO. ADMIN., http://www.eia.gov/biofuels/biodiesel/production/table3.pdf (last visited Mar. 4, 2017).

[93] *Fuel Property Comparison*, DEP'T OF ENERGY (Oct. 29, 2014), http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf.

[94] Erin Voegele, *Feeding the Chemical Market*, ETHANOL PRODUCER MAG. (Mar. 5, 2012), http://www.ethanolproducer.com/articles/8617/ feeding-the-chemical-market (discussing how fermentation from biomass sources can be used as a platform to generate ethylene, which in turn is polymerized to polyethylene, an important industrial plastic).

three-quarters of this amount employed in transportation, especially for larger vehicles.[95] This portion of present-day petroleum use would be most easily substituted by biodiesel if suitable sources can be found. Further penetration of biodiesel into the larger consumer transportation market would require conversion from gasoline to diesel engines. This is an unlikely scenario given the advent of electric cars.[96]

Unfortunately, the amount of biodiesel that can be produced from soybeans and other crops is limited in the same way as the production of ethanol from corn: ultimately, only so much arable farmland can be converted from food to energy production.[97] However, comparisons of ethanol and biodiesel production from corn and soybeans in the United States, respectively, do show that soybean biodiesel yields EREI values substantially higher than corn ethanol.[98] This arises from more efficient processing of the plant material and lower requirements for inputs such as phosphorus, nitrogen, and pesticides. Given the advantages of biodiesel described above, transitioning arable land acreage dedicated to energy crops from corn to soybeans would have substantial short-term benefits, especially if decreased corn ethanol production were offset with cellulosic ethanol as needed.

C. Perspectives

The present state of the U.S. biofuels industry does not inspire tremendous confidence about its future. As described above, the overwhelming dominance of corn ethanol fostered by existing federal policies is highly detrimental from an energy and environmental standpoint. Although the tardy emergence of a cellulosic biofuels industry can be viewed positively, its success very likely depends on the broad acceptance of E15 blends and/or concomitant decreases in corn ethanol production. Meanwhile, demand for ethanol blended in gasoline will likely continue to fall because of higher mileage standards and, more importantly, breakthroughs in renewable electricity generation and electric car batteries. This ultimately limits the growth of all ethanol industries. Biodiesel, conversely, suffers from few of ethanol's difficulties and is very well-suited as a drop-in substitute for petroleum diesel. Importantly, the uses for biodiesel in the transportation and industry sectors are precisely in those applications that are least susceptible to electrification. This is a strong argument for accelerating biodiesel development, as it

---

[95] *Use of Oil*, U.S. ENERGY INFO. ADMIN. (last updated Nov. 28, 2016), http://www.eia.gov/energyexplained/index.cfm?page=oil_use.

[96] *See generally supra* Section II.A

[97] Jason Hill et al., *Environmental, Economic and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels,* 103 PROC. NAT'L ACAD. SCIS. 11206, 11209 (2006). Canola oil is the primary source for biodiesel in Europe, with production volumes comparable to that of soybean-based biodiesel in the United States. *See* Iris van Duren et al., *Where to Produce Rapeseed Biodiesel and Why? Mapping European Rapeseed Energy Efficiency*, 74 RENEWABLE ENERGY 49, 49-59 (2015). Extremely unfavorable energy conversion efficiencies of animal products as biodiesel sources certainly render any such uses infeasible except for small specialty markets. SMIL, *supra* note 8, at 113.

[98] U.S. ENERGY-RELATED CARBON, *supra* note 46.

is unclear what other technology to replace petroleum diesel may ultimately become available.[99] The main physical impediment to the spread of biodiesel is the availability of land to cultivate the food crop sources of the fuel. Because of this, substantial attention has been devoted to uncovering sources for biodiesel that do not depend on dedicating limited and valuable arable land. By far the most promising such source identified so far is microalgae. The next section describes the nascent state of "algaculture" in the United States with attention to both its great potential and the considerable technological challenges associated with its development from the present pre-commercial stage. Section IV then considers what policies at the federal, state and local levels might be most beneficial to promote the biodiesel industry generally, and algaculture in particular. Substantial incentives are needed to accelerate the development of algae as a source of biodiesel, because of the very high costs associated with establishing a new large-scale industry that can meet a substantial fraction of U.S. demand.

III. THE POTENTIAL OF ALGAE AS A SOURCE OF BIODIESEL

A. General Features of Algaculture

Algae are a source of biodiesel that may hold the greatest promise to replace petroleum as a liquid fuel on a large scale.[100] Like plants, algae grow by the same process that generated fossil fuels over Earth's past history: they use sunlight to convert atmospheric CO_2 into a source of chemical energy.[101] The algae encompass a broad array of organisms, even including some large seaweeds, but the only subgroup likely to be useful for producing large volumes of biodiesel are the "microalgae"—microorganisms that, like bacteria, consist of just one cell. Although it may seem remarkable that small, single cells could generate large amounts of liquid fuels, microalgae can be grown to high densities in either large open ponds or closed "photobioreactors" (PBRs).[102] Like all cells, the algae possess membranes that separate their watery interiors from the outside environment. These membranes provide the concentrated source of oil that ultimately yields biodiesel.[103]

All methods for generating biodiesel from microalgae—the "algaculture" process—require the same basic steps. Cells must first be cultivated at very large

---

[99] Perhaps the best alternative to biodiesel for heavy industry and transportation would be the development of a hydrogen economy in which hydrogen fuel is generated in fuel cells run with renewable electricity. Whether this nascent technology can ultimately become commercially scalable is uncertain. *See, e.g.*, Marc Rosen & Seama Koohi-Fayegh, *The Prospects for Hydrogen as an Energy Carrier: An Overview of Hydrogen Energy and Hydrogen Energy Systems*, 1 ENERGY, ECOLOGY, & ENV'T 10, 26 (2016).

[100] FERRELL & SARISKY-REED, *supra* note 37.

[101] For a comprehensive source of general information about algae, see the on-line resources of the Society for General Microbiology. *Algae, About Microbiology,* MICROBIOLOGY ONLINE, http://microbiologyonline.org/about-microbiology/introducing-microbes/algae (last visited Mar. 4, 2017).

[102] FERRELL & SARISKY-REED, *supra* note 37, at 29.

[103] Lipids refer to the oily small molecules primarily concentrated in the membranes of all cells. Harvested algae cells can contain over 50% lipid by dry weight, making them superior feedstocks for biodiesel production. *See, e.g.*, *Algal Oil Yields*, OILGAE.COM, http://www.oilgae.com/algae/oil/yield/yield.html (last visited Mar. 4, 2017) (providing detailed information about the algae fuels industry).

scales in a liquid culture, and provided with necessary water and nutrients to enable growth to high densities.[104] Performing the cultivation step in large ponds that are open to the atmosphere is advantageous because capital investment, operating costs and energy demands are lower than for closed PBRs. Today, typical production ponds are constructed of earth materials with plastic liners, and measure 50-100 meters per side with depths of 15-70 centimeters.[105] However, these open ponds are susceptible to invasion by other microorganisms and larger species, and must be carefully managed to maintain dominance of the desired algae in the culture.[106] Demand for water is high because much is unavoidably lost through evaporation.

PBRs are closed transparent vessels with large surface to volume ratios, designed to optimize light harvesting by photosynthetic algae. At present, a large facility of this kind occupies a land area roughly 100 meters square, similar to that of a large open pond, and contains an enclosed volume of 700 cubic meters.[107] The capital construction costs and operational energy demands of PBRs are high, but this is compensated by greater productivities of cells in a given volume than is possible in open ponds. The stability of the operation over time is also improved as there is no susceptibility to predation or open exposure to the environment. Demands for both land and water use are lower than for open ponds.[108]

After cultivation to high cell densities, the next steps in the algae biodiesel pathway involve harvesting of the cells, followed by extraction and separation of the oils. Cells can be separated from the aqueous suspension by a variety of processes, including filtration and centrifugation.[109] This step is energy intensive. Next, the oil is extracted from cells using a solvent that can be largely recovered and reused. After solvent removal, the derived lipid is subjected to a final reaction to yield the biodiesel product.[110] Over sixty distinct production pathways for the cell separation, oil extraction, and final conversion steps have been proposed.[111]

---

[104] Many hundreds of distinct microalgae species are known, although research thus far has focused on just a small subset of these. Strains for commercial development are chosen for their photosynthetic efficiencies, lipid content and profiles, capacity for genetic modification, and hardiness to changes in temperature, salinity and other environmental conditions. NAT'L RES. COUNCIL, *supra* note 38, at 27-41.

[105] *Id.* at 42-45.

[106] Michael Hannon et al., *Biofuels from Algae: Challenges and Potential,* 1 BIOFUELS 763, 763-84 (2010).

[107] NAT'L RES. COUNCIL, *supra* note 38, at 45-50.

[108] *Id.* at 50-53.

[109] Centrifugation, a common technique in biochemical research, involves using the force of gravity induced by rapid spinning to concentrate suspended cells at the bottom of a harvesting container, after which the supernatant liquid can be disposed of or recycled. *Id.* at 59.

[110] The extracted lipids may be reacted with methanol in a transesterification process to yield the fatty acid methyl ester, or FAME product. Alternatively, the lipids can be subjected to a reaction known as hydroprocessing to yield a product that more closely resembles a petroleum-based diesel fuel. The latter approach is more energy-intensive but yields a product that may perform better as a "drop-in" fuel interchangeable with petroleum. If extracted lipids are subjected to a process known as cracking, smaller fuel molecules that are components of gasoline can be produced. *Id.* at 60; *see also* Yan Luo et al., *The Thermal Cracking of Soybean/canola Oils and Their Methyl Esters,* 91 FUEL PROCESSING TECH. 613, 614 (2010).

[111] Dongyan Mu et al., *Life Cycle Environmental Impacts of Wastewater-based Algal Biofuels*, 48 ENVTL. SCI. & TECH. 11696, 11696-704 (2014); NAT'L RES COUNCIL, *supra* note 38, at 2.

The "algaculture" industry is still in its nascent stages, but it has already attracted hundreds of millions of dollars in funding from the DOE and the Department of Agriculture (USDA).[112,113] Dozens of private ventures have been initiated,[114] and the field now boasts an annual conference that brings together professionals from industry, academia, and government.[115] As a sign of the growing promise of the field, some fuel industry giants are establishing partnerships with small algae-focused firms to invest in the technology. Two of the most prominent among these have been formed between ExxonMobil and Synthetic Genomics, Inc. (SGI), and between Phillips 66 and Sapphire Energy.[116] In addition to the prospects for replacing significant fractions of U.S. petroleum, private and government interests are also motivated by markets for valuable coproducts that can be derived from the biodiesel processing pathways.[117] A distinct, novel approach to produce coproducts exploits the capacity of some algae to secrete these compounds into the culture medium inside PBRs, enabling recovery without the need for cell harvesting and extraction steps.[118] The economic viability of the industry in the short term, while development of biodiesel production at large scale is ongoing, is also assisted by the ability of algae to serve as a source of ethanol when grown under particular conditions.[119]

Developing algaculture from its present pilot-scale level to a full-fledged commercial enterprise is expected to be both technically challenging and expensive. In the following sections, I review current thinking about the physical resource requirements for this endeavor: sufficient sunlight, dedicated land, water supply, and nutrients such as phosphorus, nitrogen, and CO_2. These projections, of course, are necessarily speculative given the pre-commercial state of the enterprise. One insight is that Southern states are the preferred venues for industrial development, although no particular state or region emerges as a clear best choice.

---

[112] Jim Lane, *DOE Launches $25 Million Funding Opp to Overcome Two Key Barriers for Algal Biofuels*, BIOFUELS DIG. (Sept. 30, 2016), http://www.biofuelsdigest.com/bdigest/2014/09/30/doe-launches-25m-funding-opp-to-overcome-two-key-barriers-for-algae-biofuels (announcing recent funding for algal biofuels). In 2010, under the American Recovery and Reinvestment act (ARRA), DOE granted $78 million for algae biofuels development to two large consortia, each including government laboratories, university laboratories, and private firms. *US DOE Funding Algae-, Biomass-based Biofuels Research Consortia*, DIESELNET.COM (Jan. 14, 2010), https://www.dieselnet.com/news/2010/01doe2.php.

[113] *USDA-Biorefinery Assistance Program*, DEP'T ENERGY, http://energy.gov/savings/usda-biorefinery-assistance-program (last visited Mar. 4, 2017).

[114] *2015 Algae Industry Survey: Full Speed Ahead*, ALGAE BIOMASS ORG. (Mar. 11, 2015), http://algaebiomass.org/blog/8611/2015-algae-industry-survey-full-speed-ahead/. The ABO is a non-profit organization whose mission is to promote the development of viable commercial markets for renewable and sustainable commodities derived from algae.

[115] *About the Summit,* ALGAE BIOMASS ORG., http://www.algaebiomasssummit.org/?page=AboutSummit (last visited Mar. 4, 2017) (providing a description of the 2017 conference in Salt Lake City, Utah).

[116] Jim Lane, *The 10 Hottest Trends in Algae*, BIOFUELS DIG. (Feb. 25, 2014), http://www.biofuelsdigest.com/bdigest/2014/02/25/the-10-hottest-trends-in-algae/.

[117] Coproducts include animal feed supplements, nutrient supplements, and feedstocks for synthesis of chemicals and plastics that are presently obtained from petroleum. NAT'L RES. COUNCIL, *supra* note 38, at 61-64.

[118] Dan E. Robertson et al., *A New Dawn for Industrial Photosynthesis*, 107 PHOTOSYNTHESIS RES. 269 (2011).

[119] ALGAE BIOMASS ORG., *supra* note 114.

This opens the field for healthy competition among states to create favorable policies for attracting algaculture enterprises.[120] Among the required resources, the delivery of sufficient quantities of nutrients, especially CO_2, is expected to be the most challenging, and very large scale development sufficient to replace a significant fraction of fossil petroleum will likely require development of new genetically engineered strains capable of more efficient nutrient utilization.

B. Land Requirements

The scale of algae biofuels production is still small, and no commercial facilities are yet in operation. Although detailed information regarding development at private firms is often not available, a prominent project that has received large amounts of federal funding is Sapphire Energy's Green Crude Farm biorefinery located outside of Columbus, New Mexico.[121] This project operates open pond cultivation on 100 nonarable acres of land, and expects to produce 1 million gallons per year of finished fuel product with greenhouse gas reductions of 60-70% compared to crude oil.[122]

Sapphire Energy's predicted yield for its 100-acre farm, a detailed computational life-cycle analysis of open ponds versus PBRs at the three to six-acre scale,[123] and a survey of published experimental literature at small scales of hundreds to thousands of liters,[124] provide the best current basis to estimate the nonarable land requirements of a future U.S. algaculture industry. The Sapphire Energy projection is for finished yields of 10,000 gallons per acre generated in one year in its open ponds, about eight-fold higher than found in the comparative six-acre study.[125] However, the Sapphire estimate is less than two-fold above the upper end of reported yields for open ponds operating at much smaller scales.[126] If reliable, these data suggest that Sapphire has realized considerable efficiencies in its scaleup operations. Comparable larger scale production data for algae growth in PBRs are not available, but comparison of the computational analysis with the experimental smaller scale studies shows that it predicts a biomass yield at about

---

[120] *See generally infra*, Section IV.

[121] *Algae Farm*, SAPPHIRE ENERGY, http://www.sapphireenergy.com/locations/green-crude-farm.html (last visited Mar. 4, 2017).

[122] *Id*. Sapphire Energy has recently moved to diversify its product line in light of low crude oil prices and possibly other factors, but it is reported that algae-based biofuels remain an important part of the company's future. Bruce V. Bigelow, *Algal Biofuel Icon Sapphire Energy Moves to Diversify Product Line*, XCONOMY (Feb. 3, 2015), http://www.xconomy.com/san-diego/2015/02/03/algal-biofuel-icon-sapphire-energy-moves-to-diversify-product-line.

[123] Orlando Jorquera et al., *Comparative Energy Life-cycle Analyses of Microalgal Biomass Production in Open Ponds and Photobioreactors,* 101 BIORESOURCE TECH. 1406 (2010).

[124] NAT'L RES. COUNCIL, *supra* note 38, at 42-53 (compiling data from Paul Chen et al., *Review of the Biological and Engineering Aspects of Algae to Fuels Approach*, 2 INT'L J. AGRIC. & BIOLOGICAL ENG'G 1 (2009); and C.U. Ugwu et al., *Photobioreactors for Mass Cultivation of Algae,* 99 BIORESOURCE TECH. 4021 (2008)).

[125] SAPPHIRE ENERGY, *supra* note 121.

[126] Yields for small open pond studies were compiled and tabulated in grams of dry weight per liter per day. *Oil: Crude and Petroleum Products*, *supra* note 26, at 52. These values were linearly scaled with the data provided in the six-acre computational study reported. Jorquera, *supra* note 123. This assumes the same efficiencies of finished biofuel production. Author's calculation.

the midpoint of the latter estimates. This midpoint corresponds to about one-third the yield of Sapphire's projection for its 100-acre open pond project.[127]

Extrapolation of these findings to large scale industrial cultivation at scales commensurate with the 60 billion gallons of petroleum diesel annually consumed in the United States are clearly very uncertain at this time. However, it is not unreasonable to suggest that improvements in many parts of the operation, including strain selection and engineering, optimization of engineering designs in ponds and photobioreactors, and extraction processes should be realizable as experience accumulates during progressive scaleup. As a conservative estimate, I use the data at the midpoint of the experimental studies of PBRs, which predicts about 3,200 gallons of oil product generated per acre in a year.[128] Producing 60 billion gallons of petroleum, or 20% of current consumption, then requires about 19 million acres of dedicated, nonarable land. For comparison, corn is presently grown on 92 million acres of arable land in the United States,[129] and about 40% of the crop is used for ethanol production. Therefore, algae biodiesel production of 60 billion gallons per year by 2050 may be possible with a *nonarable* land footprint less than that presently used to generate 15 billion gallons per year of corn ethanol. A comprehensive analysis of U.S. land potentially usable for open pond algaculture, which excluded economically valuable territory for agriculture and other uses, and all land located on a slope greater than 1%, suggested that 5.5% of the lower forty-eight states (about 106 million acres) could be suitable.[130] Thus, land availability should not significantly constrain the development of algaculture. The important bottom line is that the amount of energy-rich fuel produced per acre of dedicated land is much higher for algaculture than for other biofuels.[131] Further, the absence of an arability requirement suggests that the land could be acquired from private, state or federal holdings at relatively low cost.

C. Siting Algaculture: Light, Water and Nutrients

In addition to land, a number of other key requirements must be met to enable the commercial development of algaculture, and these will in large measure determine where the new facilities should be located, as well as what law and policy-makers should focus on in devising strategies to promote growth of the industry. First, since the energy for growth of microalgae is provided by sunlight, it is clearly preferable to locate algaculture sites in regions of the United States where this resource is most abundant. Algae biomass yields are predicted to be up to

---

[127] FERRELL & SARISKY-REED, *supra* note 37; ALGAE BIOMASS ORG., *supra* note 114; SAPPHIRE ENERGY, *supra* note 121.

[128] Author's calculation, based on benchmarks from the computational study reported in JORQUERA, *supra* note 123.

[129] *Overview of Corn and Other Feed Grains*, U.S. DEP'T OF AGRIC. ECON. RES. SERV. (last updated Mar. 23, 2017), https://www.ers.usda.gov/topics/crops/corn/.

[130] Mark S. Wigmosta et al., *National Algae Biofuel Production Potential and Resource Demand*, 47 WATER RES. RES. 4 (Apr. 13, 2011).

[131] *Oil: Crude and Petroleum Products*, *supra* note 36, at 123; SUSTAINABLE DEV. SOLUTIONS NETWORK, *supra* note 27, at 3.

50% higher in southern states stretching across the continent, with some preference for the desert southwest region where the number of cloudy days is lower.[132] Higher temperatures found in the U.S. South and Southwest generally promote better growth of microalgae as well, although the absence of evaporative cooling in closed PBRs may lead to higher energy costs or water requirements to keep temperature from increasing too much in these locations.[133] In general, sunlight and temperature are the key geographic variables that determine what fraction of the year an algaculture facility can maintain economically viable operations.[134]

The next key resource is water. An important advantage is that algae can be grown with either wastewater or salt water as feedstocks. This is fortunate, because freshwater consumption is substantially decreased, while wastewaters provide necessary nutrients—particularly the nitrogen and phosphorus that are major pollutants in agricultural runoff.[135] Nonfreshwater sources include wastewater (agricultural, industrial, and municipal sources), brackish groundwater, produced water from oil, gas and coalbed methane wells, and coastal marine water.[136] According to one recent comprehensive study, it is likely that running open pond algaculture operations primarily with one or more of these water sources will be essential, because demands for production of 10-50 billion gallons of biodiesel could consume on the order of 100% of the available freshwater in several regions of the country.[137] Open ponds demand substantially more make-up water than PBRs, because evaporative losses cause sharp decreases in growth yield when concentrations of dissolved solids and nutrients exceed certain thresholds.[138] Estimates for water requirements from PBR operations are much lower, but projections for the actual amounts needed vary widely, depending in part on how much circulating water is needed for cooling (which in turn depends on ambient temperature and reactor configuration).[139]

Clearly, the extent to which either open pond or PBR algaculture operations may burden water supplies depends on the fraction of the total water needed that can be provided by nonfreshwater sources, and the extent to which water in the growth medium can be recycled to replenish ponds or PBRs after cells are harvested. However, even when algaculture is conducted in PBRs, significant freshwater will still be required to make up the volumes and to provide cooling.[140] All

---

[132] Wigmosta et al., *supra* note 130, at 11.

[133] FERRELL & SARISKY-REED, *supra* note 37, at 29.

[134] *Id.* at 77.

[135] *Id.* at 83.

[136] Ron Pate et al., *Resource Demand Implications for US Algae Biofuels Production Scaleup*, 88 APPLIED ENERGY 3377, 3377, 3386 (2011).

[137] *Id.* at 3381-83.

[138] SUSTAINABLE DEV. SOLUTIONS NETWORK, *supra*, note 27, at 101. The amount of water needed for open pond operations can be mitigated if the pond water is partly recycled after the algae are harvested. Jia Yang et al., *Life-Cycle Analysis on Biodiesel Production from Microalgae: Water Footprint and Nutrients Balance*, 102 BIORESOURCE TECH. 159, 159-60, 164 (2011).

[139] One study projected needs for freshwater for PBRs in the range of 30-63 liters per liter of biodiesel. In contrast, the range reported for open ponds is 22-3,600 liters of water per liter of biodiesel. Sapphire Energy projects a need for 906 liters of fresh water per liter of "green crude." SUSTAINABLE DEV. SOLUTIONS NETWORK, *supra* note 27, at 105-106.

[140] FERRELL & SARISKY-REED, *supra* note 37, at 77.

such make-up water will represent a consumptive use. While genetically engineering algae for increased tolerance to salinity may ultimately enable decreased water consumption,[141] the new operations will, of course, also need to acquire water rights. This is likely to be more challenging in arid Western states that operate under prior appropriations law,[142] where water rights to many major rivers are already fully allocated.[143] However, all states functioning under riparian rights, prior appropriations, or mixed regulatory systems have developed administrative permit systems and procedures for reallocation of water rights.[144] Water markets are also developing as a forum for efficient reallocation of supplies,[145] and may be especially effective as a counterweight to traditional prior appropriations systems that incentivize retaining existing uses to avoid forfeiting rights, even where other uses are arguably much more beneficial. This is an area where forward-looking states that desire to benefit from algaculture can effectively position themselves as preferred venues.

Algaculture facilities also require nutrient inputs, especially nitrogen, phosphorus and carbon dioxide. Nitrogen and phosphorus are major components of wastewater streams, particularly from agriculture.[146] Hence, the use of such water runoff in algaculture has substantial benefits in mitigating the need for both freshwater and nutrient additions to the ponds and PBRs, while lessening the eutrophication of surface waters from largely unregulated, nonpoint agricultural sources.[147] Nutrients can also be derived from the wastewater collected in the sludge drying process in wastewater treatment plants (the *centrate*), which is a particularly concentrated source.[148] Indeed, algae have been used for some time in wastewater treatment, where they have been effective in removing not just nitrogen and phosphorus, but also persistent organic pollutants such as antibiotics,[149] as well as toxic heavy metals.[150]

The amounts of nitrogen and phosphorus required for algaculture are large, and it is very unlikely that demands of large-scale production can be satisfied using available stocks, in competition with other industries that also require these resources.[151] Hence, the use of nitrogen and phosphorus-laden wastewaters, and recycling of these nutrients in the algaculture facilities, are likely to both be required. These considerations become even more important when it is recognized that the

---

[141] *See generally infra*, Section IV.A, for a discussion of algae-based geoengineering.

[142] BARTON H. THOMPSON, JR. ET AL., LEGAL CONTROL OF WATER RESOURCES 168-73 (6th ed. 2013).

[143] For example, waters in twelve of the fifteen major river systems in Texas are fully allocated. Andrew K. Jacoby, *Water Pressure: The Eightieth Texas Legislature Attempts to Protect Instream Flows of Rivers and Streams, and Freshwater Inflows to Bays and Estuaries*, 20 TUL. ENVTL. L. J. 381, 383 (2007).

[144] THOMPSON, *supra* note 142, at 136, 305.

[145] Robert Glennon, *Water Scarcity, Marketing, and Privatization*, 83 TEX. L. REV. 1873, 1884 (2005).

[146] NAT'L RES. COUNCIL, *supra* note 38, at 110-115.

[147] FERRELL & SARISKY-REED, *supra* note 37, at 79.

[148] Mu et al., *supra* note 111, at 11697.

[149] James B. Houser et al., *Wastewater Remediation Using Algae Grown on a Substrate for Biomass and Biofuel Production*, 5 J. ENVTL. PROT. 895, 896 (2014).

[150] Edward W. Wilde & John R. Benemann, *Bioremoval of Heavy Metals by the Use of Microalgae*, 11 BIOTECHNOLOGY ADVANCES 781 (1993).

[151] Pate et al., *supra* note 136, at 3384-85.

abundant fertilizer used in agriculture is ultimately derived from atmospheric nitrogen with the use of massive amounts of fossil fuel energy,[152] and that the availability of phosphorus in source rocks may also become limiting.[153] One attractive possibility for recycling algaculture nutrients involves anaerobic digestion of leftover biomass after the oils have been extracted, which has the co-benefit of generating methane (natural gas) that can be burned to support the energy requirements of the facility.[154]

Further research is required to quantify levels of required nitrogen and phosphorus inputs with respect to the availability of these nutrients in agricultural and wastewater effluents, to enable more accurate estimation of the extent to which other external supplementation will also be required. It is nearly certain, however, that both nutrient and water requirements will provide strong constraints on the siting of algaculture facilities. Runoff from agriculture is more concentrated in the East and Midwest; warmth and sunlight requirements then suggest the Southeast and South central parts of the United States as preferred regions. Expertise in fossil fuel refining in that region should be readily adaptable to the new industry.[155] Business-friendly state policies in Texas further suggest that state as a preferred location, while the very small proportion of publicly owned land may also facilitate development by lowering regulatory costs.[156] These considerations may outweigh the Southwest's advantage in sunlight—particularly since the development of solar thermal power generation—another likely component of the renewable energy economy—also requires substantial water resources and is best-suited to that part of the country.[157]

Meeting algaculture's requirements for nonarable land, sunlight, water, nitrogen, and phosphorus will present substantial challenges, but none of these appear insurmountable. By contrast, the need for externally supplied CO_2 does appear daunting at the present time. The need arises because the enzymes that catalyze CO_2 uptake from the atmosphere do not function efficiently enough to enable the rapid cell growth needed to achieve high fuel yields.[158] Hence, all operations are conducted either by externally adding more CO_2 into the airspace above the culture, or piping it into the liquid culture directly.[159] It has been suggested that as the algae biodiesel industry develops, the necessary CO_2 could be provided at larger scales from CCS operations at fossil fuel-fired power plants.[160]

---

[152] THOMAS G. SPIRO & WILLIAM M. STIGLIANI, CHEMISTRY OF THE ENVIRONMENT 361-68 (2nd ed. 2003).

[153] Renee Cho, *Phosphorus: Essential to Life – Are We Running Out?* EARTH INST. COLUM. U. (Apr. 1, 2013), http://blogs.ei.columbia.edu/2013/04/01/phosphorus-essential-to-life-are-we-running-out/.

[154] NAT'L RES. COUNCIL, *supra* note 38, at 115.

[155] Petroleum refining and algaculture are essentially each large scale engineering operations, and the later steps of algaculture involving processing of the oil product have substantial overlap with petroleum refining.

[156] *See generally Home*, TEXASWIDEOPENFORBUSINESS.COM, https://texaswideopenforbusiness.com (last visited Feb. 27, 2017).

[157] Cynthia L. Schwartz, *Concentrated Solar Thermal Power and the Value of Water for Electricity in* THE WATER-ENERGY NEXUS IN THE AMERICAN WEST 71-83 (D.S. Kenney & R. Wilkinson eds., 2011).

[158] *See* NAT'L RES. COUNCIL, *supra* note 38, at 112.

[159] *Id.*

[160] FERRELL & SARISKY-REED, *supra* note 37, at 80.

This is an appealing idea, since algaculture could provide a market to spur CCS development that is environmentally benign as compared to using the trapped CO_2 to enhance oil recovery from spent wells.[161] Using captured CO_2 for algaculture also avoids the alternative approach of geological sequestration, which carries significant risks.[162] Unfortunately, substantial obstacles stand in the way of realizing this proposal.

First, the amount of CO_2 that is potentially available from CCS sources in the United States may not be enough to meet the algae industry's needs at the 60 billion gallon annual scale necessary to replace petroleum diesel. A comprehensive study concluded that the best-case scenario utilizing CO_2 inputs from CCS operations in nineteen Southern states likely to host algaculture would require about half the CO_2 that is presently generated at fossil fuel power plants, to produce just 10 billion gallons of biodiesel per year.[163] Of course, this shortfall is compounded by the scaling down of fossil fuel-fired electricity generation that will occur as the renewable energy economy becomes more established.

Second, despite substantial investments, the establishment of CCS at fossil-fuel powered electricity generating facilities in the United States has substantially lagged expectations. Existing U.S. CCS operations include facilities that produce hydrogen gas, fertilizers and other chemicals, and that produce natural gas.[164] The world's first large-scale electric power sector CCS operation was established in 2014 in Canada, while the first two U.S. power plant operations are slated to begin operation at the end of 2016 or early part of 2017.[165] These facilities, located in Mississippi and Texas, are projected to capture 3.0 million and 1.4 million metric tons of CO_2 annually, respectively, for use in enhanced oil recovery.[166] The projects, while breaking significant ground, still represent a very small fraction of the total U.S. CO_2-equivalent emissions of 6.9 billion metric tons. The slow development of CCS in the United States suggests that the CO_2 requirements for algaculture may not be met.

Third, while EPA has issued a final rule establishing that post-combustion partial CCS is the best system of emissions reduction (BSER) for newly constructed fossil fuel-fired electricity generating units that burn pulverized coal,[167] it has eliminated CCS as BSER from the final rule governing CO_2 emissions limits from existing sources, as described in the Clean Power Plan.[168] CCS is also not

---

[161] *See generally* NAT'L ENERGY TECH. LAB., CARBON DIOXIDE ENHANCED OIL RECOVERY: UNTAPPED DOMESTIC ENERGY SUPPLY AND LONG TERM CARBON STORAGE SOLUTION (2010), https://www.netl.doe.gov/file%20library/research/oil-gas/small_CO2_EOR_Primer.pdf.

[162] NAT'L RES. COUNCIL, CLIMATE INTERVENTION: CARBON DIOXIDE REMOVAL AND RELIABLE SEQUESTRATION 75-82 (2015), https://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration.

[163] Pate et al., *supra* note 136, at 3384.

[164] *Large Scale CCS Projects*, GLOBAL CCS INST., https://www.globalccsinstitute.com/projects/large-scale-ccs-projects (last visited Mar. 22, 2017).

[165] *Id.*

[166] *Id.*

[167] 80 Fed. Reg. § 64510 (2015).

[168] 80 Fed. Reg. § 64662 (2015).

recommended as the BSER for CO_2 emissions reductions from either new or existing natural gas-fired electricity generating plants.[169] These developments represent a substantial lost opportunity for CCS technology, particularly since the recent sharp pullback in coal company investments (together with several high-profile bankruptcies) suggests that few new coal-fired plants will be built in the near future—or perhaps anytime.[170]

Even if CCS technology were to be greatly accelerated in the United States, the nascent algaculture industry would still be faced with the need to locate its facilities near CO_2 emissions sources to minimize transport costs.[171] Further, the algal production facility would need to be of sufficient size to make the transaction competitive with CO_2 use for enhanced oil recovery, and would need to coordinate its operations with power plants given that active CO_2 absorption by algae occurs only during daylight.[172] Fortunately, the Southern U.S. is rich in both agricultural runoff and in power plants to provide CO_2.[173]

Taken together, these considerations indicate that CO_2 supply is a significant challenge in developing algaculture. However, if necessary investments in local and regional pipeline infrastructure can be made, limitations in total CO_2 availability should not be an impediment to achieving commercialization at smaller scales. In the longer term, genetic engineering of algae cells to enhance their CO_2 uptake capacity has potential to diminish or eliminate the need for added CO_2.[174] Broad-based metabolic engineering of algae also can enhance oil yields and make more efficient use of nutrients. These goals imply a need for substantial investment in basic research into algal biology. We turn next to this and other approaches for accelerating the growth of algaculture and of the biodiesel industry more generally.

IV. ENABLING GROWTH OF THE BIODIESEL INDUSTRY

A. Renewable Fuel Standards

Both federal and state governments have been active in promoting the transition from fossil fuels to renewable biofuels. Standards are set directly as mandated volumes of particular renewable fuels for blending with fossil fuels (federal program), or as lowered greenhouse gas (GHG) emissions irrespective of the fuels chosen (California program). The federal program is focused primarily on ethanol, and is facing considerable challenges and calls for elimination. In contrast, the newer California law has performed above expectations in the first few years of its operation and has been especially effective in driving increased use of biodiesel. Both programs will be up for re-examination in the next five years as statutory timeframes expire. In this section I describe the basic structure of these

---

[169] *Id.* at § 64601.

[170] *See generally Arch Coal's Bankruptcy: More Gloom for The Industry*, CBSNEWS.COM (Jan. 11, 2016), http://www.cbsnews.com/news/arch-coals-bankruptcy-more-gloom-for-the-industry/.

[171] FERRELL & SARISKY-REED, *supra* note 37, at 80.

[172] *Id.*

[173] *Id.*

[174] *See generally infra*, Section IV.B.1, for a discussion of algae genetic engineering.

programs and the underlying concerns that have led the federal program to its present state of crisis, and I suggest that it should be restructured by Congress to better incentivize the growth of the biodiesel industry. At the state level, California's program provides a leading and effective model, and challenges are associated with the successful negotiation of the political processes to enact and then implement standards in diverse state environments.

1. The Federal Renewable Fuel Standard

The federal renewable fuel standard (RFS), adopted in the Energy Policy Act of 2005 (RFS1) and later revised in the Energy Information and Security Act (EISA) of 2007 (RFS2), establishes minimum volumes of renewable fuels that importers, refiners, and blenders (the "obligated parties") must add to petroleum (fossil) fuels for motor vehicles.[175] This creates a guaranteed market for renewable fuels and a hence a substantial incentive for development of the industry. RFS1 was primarily designed to enhance market demand for corn ethanol, and was very successful in spurring a dramatic increase in production from 2005 to 2014, when volumes reached 14 billion gallons per year.[176] RFS1 did not function as a technology-forcing law, since production of corn ethanol was already well-established at the time of its enactment.[177] Instead, by mandating continually increasing blending ratios with gasoline, RFS1 simply provided corn farmers with a new and lucrative guaranteed market for their product.

RFS1 contained provisions designed to spur the development of cellulosic ethanol and other biofuels, by assigning these fuels greater weight than corn ethanol in meeting the volume requirement.[178] However, the provisions were ineffective in overcoming the dominance of corn ethanol in the markets. RFS2, by contrast, goes much further by mandating that increasingly large amounts of "advanced biofuels" be included in the total volume of renewable fuels for blending with gasoline. In RFS2 biofuels are defined in four nested categories: (1) renewable fuel; (2) advanced biofuel; (3) cellulosic biofuel; and (4) biomass-based diesel.[179] *Renewable fuel* is a broad-based category that includes any fuel produced from renewable biomass, which encompasses crops and crop residues from agricultural land (including corn), among many other sources, including algae.[180] Lifecycle greenhouse gas (GHG) emissions for renewable fuels generally must be

---

[175] *See generally* Powers, *supra* note 51, for description and analysis of the RFS program up to 2010. RFS1 and RFS2 are codified within the Clean Air Act, at 42 U.S.C. § 7545. The RFS has been called "the single most important legal and regulatory regime affecting the commercialization of biofuels in the United States." Timothy Slating & Jay Kesan, *The Renewable Fuel Standard 3.0?: Moving Forward with the Federal Biofuel Mandate*, 20 N.Y.U. ENVTL. L. J. 374, 380 (2014).

[176] *See generally supra* Section II.A.

[177] About four billion gallons of corn ethanol was produced in the United States in 2005, when the federal RFS was first enacted. *U.S. Bioenergy Statistics*, U.S. DEP'T OF AGRIC. at Table 2 (last updated Mar. 7, 2017), http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx.

[178] This was accomplished by means of a credit trading system administered by EPA, by which alternative fuels were assigned equivalence values 2.5 times the value of corn ethanol. Powers, *supra* note 51, at 689.

[179] 42 U.S.C. § 7545(o)(2)(A)(i).

[180] 42 U.S.C. § 7545(o)(1)(I)(vi) (algae are specifically cited in the statute).

at least 20% below the petroleum baseline.[181] *Advanced biofuels* are a subset of renewable fuels and encompass any biofuel except corn ethanol, with lifecycle GHG emissions at least 50% below the petroleum baseline.[182] *Cellulosic biofuel* and *biomass-based diesel* are nested categories inside advanced biofuels, with lifecycle GHG emissions requirements set at 60% below and 50% below the petroleum baseline, respectively.[183] Biodiesel from algae would satisfy RFS2 criteria in three of the four categories, excepting only cellulosic biofuel,[184] presuming that lifecycle GHG emissions when commercially produced would satisfy the necessary criteria for advanced biofuels and biomass-based diesel.[185]

Despite the inherent limits in the U.S. ethanol market described above, the advanced biofuel mandates of RFS2 were initially greatly biased in favor of cellulosic ethanol, and gave much shorter shrift to biomass-based diesel. Applicable volumes of cellulosic biofuel increase incrementally from 0.1 billion gallons in 2010 to 16.0 billion gallons in 2022,[186] while biomass-based diesel increases from 0.5 billion gallons in 2009 to 1.0 billion gallons in 2012—after which volumes are set each year by regulation, considering the expected annual rate of future commercial production, and the impact of biomass-based diesel on the environment, U.S. energy security, U.S. infrastructure, cost of transportation fuel, and other factors including job creation, agricultural commodity prices, rural economic development, and food prices.[187] Thus, cellulosic ethanol targets were set far higher and over a much longer specified timeframe, even though biomass-based diesel

---

[181] 42 U.S.C. § 7545(o)(2)(A)(i). However, an exemption to the GHG emissions requirement exists for older corn ethanol production plants, which substantially limits the effectiveness of the law.

[182] 42 U.S.C. § 7545(o)(1)(B)(i).

[183] 42 U.S.C. §§ 7545(o)(1)(D) & (E).

[184] EPA has established a process for companies to petition for new fuel pathways to qualify for the RFS program, including specification of the feedstock, production process, and fuel type. This includes the lifecycle GHG analysis. Despite the many uncertainties associated with reaching the production scale required for commercialization, algae has already been approved by EPA as source material for generally applicable biomass-based diesel and advanced biofuel pathways. 40 C.F.R § 80.1426 (2010); *see also* Letter from Christopher Grundler, Director, Office of Transportation and Air Quality, to Paul Woods, Chief Executive Officer, Algenol Biofuels (Dec. 2, 2014), https://www.epa.gov/sites/production/files/2015-08/documents/algenol-determination-ltr-2014-12-4.pdf. New production pathways for algal biodiesel will necessitate new petitions by the private companies developing the processes. In June 2015, as part of its revisions to the RFS2 requirements, EPA issued a proposed regulation clarifying that only algae grown photosynthetically will qualify for RFS credits. Proposed Rule, *Renewable Fuel Standard Program: Standards for 2014, 2015 and 2016, and Bio-mass Based Diesel Volume for 2017*, 80 Fed. Reg. 33,100, at 33,107-08 (2015) (to be codified at 40 C.F.R. part 80).

[185] Full lifecycle computer-modeling based assessments of greenhouse gas (GHG) emissions and EREI for algae-to-energy systems have yielded widely varying results. *See generally* Alissa Kendall & Juhong Yuan, *Comparing Life Cycle Assessments of Different Biofuels Options*, 17 Current Op. Chem. Biology 439 (2013). However, at least one study shows that an algae biodiesel production stream design yields projected lifecycle GHG emissions that are lower than both petroleum and cellulosic ethanol benchmarks. Xiaowei Liu et al., *Pilot Scale Data Provide Enhanced Estimates of the Life Cycle Energy and Emissions Profile of Algae Biofuels Produced by Hydrothermal Liquefaction*, 148 Bioresource Tech. 163 (2013).

[186] 42 U.S.C. § 7545(o)(2)(B)(i)(III). Cellulosic biofuel must be derived from cellulosic plant sources, and could potentially include biodiesel in addition to ethanol. However, in practice it is not efficient to extract and refine biodiesel from cellulosic sources because they are not oil-rich substances. Hence, production in the cellulosic biofuel category consists almost entirely of ethanol derived from fermentation of the source material.

[187] 42 U.S.C. § 7545(o)(2)(B)(i)(IV)(ii).

was already in production when EISA was passed, while cellulosic biofuel was not.

The cellulosic biofuels industry produced no ethanol until 2014, and was thus unable to meet the statutory applicable volume requirements. This triggered a waiver mechanism within RFS2, by which the EPA administrator determines that domestic supply is inadequate and issues regulations resetting the applicable volumes to the amounts actually produced.[188] This avoids the possibility that refiners, blenders and importers may face fines for failing to use fuels that are unavailable.[189] RFS2 required obligated parties to purchase 18.15 billion gallons of total renewable fuel in 2014,[190] of which 1.75 billion gallons were specified as cellulosic biofuel.[191] However, the cellulosic ethanol industry produced just 33 million gallons in that year, less than 2% of the requirement.[192] Because this deficit was so large, it caused concomitant failures to meet the applicable volumes set for total renewable fuels and advanced biofuels as well. EPA thus undertook a comprehensive revision of RFS2 in which it considered revisions to the applicable volumes in all categories.[193] Ultimately, EPA issued a final rule effective February 2016 in which it reset cellulosic biofuel volumes for 2014-2016 at 33 million (the amount actually produced), 123 million and 230 million gallons, respectively.[194]

It is certain that U.S. cellulosic ethanol production cannot possibly reach anywhere near the statutory mandates of 5.5-16 billion gallons for 2017-2022. Therefore, unless Congress acts, EPA will be forced to issue successive regulations to repeatedly reset applicable volumes to production levels. This dynamic lays bare the flawed structure of the statute, which applies a purchasing mandate to fuel refiners, blenders, and importers—while the source of the renewable fuel itself is in the hands of different industries: those who grow and process the biomass source materials to yield the specified volumes for blending.[195] The present situation has triggered a general crisis of confidence in U.S. biofuels policy. Congress is threatening to repeal the program entirely,[196] an industry group has sued

---

[188] 42 U.S.C. § 7545(o)(7)(A)(ii) (describing the waiver).

[189] 40 C.F.R. § 80.1460(b).

[190] 42 U.S.C. § 7545(o)(2)(B)(i)(I).

[191] 42 U.S.C. § 7545(o)(2)(B)(i)(III).

[192] ENVTL. PROT. AGENCY, *supra* note 68. Production requirements for cellulosic biofuels were also not met in any year from 2010 to 2013.

[193] *See generally* 80 Fed. Reg. 33,100, at 33,107-08.

[194] Final Rule, *Renewable Fuel Standard Program: Standards for 2014, 2015, and 2016 and Biomass-Based Diesel Volume for 2017*, 80 Fed. Reg. 77,419, at 77,422 (2015) (to be codified at 40 C.F.R. pt. 80).

[195] Meredith Pressfield, *Cellulosic Biofuel: Dead on Arrival*?, 41 ECOLOGY L. Q. 461, 477-78 (2014). The flawed structure of RFS2 can be seen clearly by comparing it to the Clean Air Act's effective early mandate to reduce vehicle emissions by 90%, which spurred the development of the catalytic converter. In that case technology forcing worked because the obligated parties were the automakers directly responsible for and ultimately capable of developing the necessary new pollution control technology. David Gerard & Lester B. Lave, *Implementing Technology-Forcing Policies: The 1970 Clean Air Act Amendments and the Introduction of Advanced Automotive Emissions Controls in the United States*, 72 TECH. FORECASTING & SOC. CHANGE 761, 763 (2005).

[196] *Biofuels: Greenwire's Stecker Discusses Next Legal, Legislative Battles for RFS*, CUTTING EDGE (Dec. 4, 2015), http://www.eenews.net/tv/videos/2063/transcript.

to block implementation of the rule,[197] and EPA apparently lacks vision for what policies might follow RFS2 when it expires in 2022.[198] In the meantime, advanced biofuels companies, well aware that demand in the United States is unlikely to increase beyond what is already provided by corn ethanol, are looking abroad to find more fertile investment prospects.[199]

The demise of RFS2 threatens to cause great damage to the U.S. biodiesel industry, which, unlike ethanol, has every reason to expect a healthy demand for its product that should grow as the renewable energy economy becomes more established. As described above, biodiesel has very similar properties to petroleum diesel. Rather than functioning as a minor blended additive as EISA envisioned, biodiesel instead has potential to function in its pure state (B100) and thus to entirely replace the fossil fuel product.[200] Biodiesel therefore represents a genuine threat to the dominance of fossil fuels in the diesel-driven heavy industrial and transportation sectors of the U.S. economy.

A reformulated biofuels statute that more strongly emphasizes biodiesel should be an important priority in the federal regulatory framework of the new renewable energy economy.[201] EISA set the 2012 mandate for biomass-based biodiesel at one billion gallons,[202] and EPA then set an increase to 1.28 billion gallons for 2013.[203] In several new rules, EPA set targets of 1.63, 1.73, 1.90, 2.00, and 2.10 billion gallons for 2014-2018.[204] This consistently increasing mandate is certainly welcome movement towards a greater role for biodiesel, but it is very slow movement compared to what is needed to significantly replace petroleum diesel. In fact, the biodiesel industry has shown itself capable of exceeding these targets. In 2013 and 2014, the actual volumes of biomass-based diesel produced were about 1.59 billion and 1.97 billion gallons, respectively, above the specified applicable volumes.[205] In December 2014, the industry generated over 213 million gallons in just one month, suggesting that a production level of over 2.5 billion

---

[197] Mark Heller, *Industry Group Sues to Block Latest RFS Implementation*, Energy & Env’t News (Feb. 11, 2016), http://www.governorsbiofuelscoalition.org/?p=16197.

[198] Mark Heller, *EPA Has No Plans for a Post-RFS World*, Energy & Env’t News (Mar. 17, 2016), http://www.eenews.net/eedaily/stories/1060034163.

[199] *Biofuels: DSM’s Welsh talks company plans to shift investments to China*, OnPoint (Feb. 25, 2016), www.eenews.net/tv/videos/2099/transcript.

[200] *See generally infra*, Section II.B.

[201] Under EISA, the Administrator of the Energy Information Administration must provide the EPA Administrator with estimates of the volumes of transportation fuel, biomass-based diesel and cellulosic biofuel that are then used by EPA to determine renewable fuel obligations in successive years. These obligations terminate in 2021, suggesting that Congress must act by then if it wishes to continue the renewable biofuels program. 42 U.S.C. §§ 7545(o)(3)(A) & (B).

[202] 42 U.S.C. § 7545(o)(2)(B)(IV).

[203] 80 Fed. Reg. 33,100, at 33,106.

[204] *See generally* 80 Fed. Reg. 77,419 (for the final rule specifying 2014-2017 applicable volumes). The 2018 applicable volume for biomass-based diesel was published as a final rule in December, 2016. Final Rule, *Renewable Fuel Standard Program: Standards for 2017 and Biomass-Based Diesel Volume for 2018*, 81 Fed. Reg. 89,746 (2016) (to be codified at 40 C.F.R. pt. 80).

[205] *2013 Renewable Fuel Standard Data*, Envtl. Prot. Agency (last updated Feb. 10, 2017), https://www.epa.gov/fuels-registration-reporting-and-compliance-help/2013-renewable-fuel-standard-data; *2014 Renewable Fuel Standard Data*, Envtl. Prot. Agency (last updated Feb. 10, 2017), https://www.epa.gov/fuels-registration-reporting-and-compliance-help/2014-renewable-fuel-standard-data.

gallons per year is already within reach.[206] The National Biodiesel Board (NBB), in its response to the EPA proposed rule, describes even higher production capacities, tracking 232 domestic production facilities with an annual capacity of almost 3.4 billion gallons, and noting that eighty foreign facilities with a further capacity of 1.7 billion gallons are registered with EPA under RFS2.[207] Another comment to the EPA proposed rule suggested that feedstocks for biodiesel production are not limiting, and could support at least 8.5 billion gallons of biodiesel production per year by 2020.[208] The plausibility of this analysis is supported by the fact that biodiesel production is spread over all regions of the United States, reflecting the fact that, unlike corn used to produce ethanol, soybeans for biodiesel can be effectively grown in a wide range of climates.[209]

EPA cites a number of factors in support of its choice to propose only a modest increase in biomass-based diesel production volumes, including concerns about use of certain blends or neat biodiesel on engine warranties, cold-weather performance, and competition with other advanced biofuels in a presumed limited market for these fuels.[210] However, as noted in the NBB comments,[211] these considerations are largely inconsistent with the purpose of the RFS2 program to accelerate the penetration of renewable fuels into the market. Further, EPA focuses its analysis on the competition among renewable biofuels, rather than directly on the capacity of biomass-based biodiesel to replace petroleum diesel in the separate, 60 billion gallon diesel market.[212]

In a revised statute, Congress should set more aggressive applicable volumes for biomass-based diesel,[213] and should couple these new standards with other programs targeted to improving the capacity of diesel users to employ the biomass-derived products in place of petroleum diesel.[214] First, the $1 per gallon biodiesel

---

[206] *2013 Renewable Fuel Standard Data*, *supra* note 205; *2014 Renewable Fuel Standard Data*, *supra* note 205. The excess biodiesel production augments the volumes recorded in the Advanced Biofuels and Renewable Fuel categories.

[207] 42 U.S.C. § 7546 (Setting the standards for 2014, 2015, and 2016 and biomass-based diesel volume for 2017); 80 Fed. Reg. 33,100 (Comments by NBB, https://www.noticeandcomment.com/EPA-HQ-OAR-2015-0111-fdt-77425.aspx).

[208] *Id.*

[209] RANDY SCHNEPF, CONG. RESEARCH SERV., R41282, AGRICULTURE-BASED BIOFUELS: OVERVIEW AND EMERGING ISSUES 16-17 (2010).

[210] 80 Fed. Reg. 77,419, at 77,465.

[211] *Id.*

[212] The replacement of petroleum diesel with biodiesel is desirable because primary feedstocks for biodiesel are derived from surface biomass, and thus do not inject more carbon into the surface carbon cycle. 80 Fed. Reg. 77,419.

[213] In *American Petroleum Institute v. EPA*, 706 F.3d 474 (D.C. Cir. 2013), the court ruled that EPA must use a neutral methodology in setting targets rather than an approach in which the risk of overestimation is deliberately set to exceed the risk of underestimation. The court emphasized that its holding is specific to cellulosic biofuels, because this is the only fuel type for which Congress evinced a concern for the industry's ability to meet the applicable volume targets. This holding should not negatively impact EPA's ability to set aggressive future targets for biomass-based diesel, since the statutory waiver provision for this fuel type is triggered only by price spikes and contemplates at most a 15% reduction in applicable volumes. 42 U.S.C. 7545(o)(7)(E)(ii).

[214] Unlike cellulosic ethanol, where very significant technical hurdles prevented meeting of RFS2 targets, legally mandated increased demand for biodiesel would be effective within the current structure of RFS2 because there is no need for technology forcing. Driven by RFS1 and then RFS2, US ethanol production increased from

and renewable diesel blenders tax credit, presently set to expire on January 1, 2017, should be renewed for at least a five-year period to provide a strong signal to investors.[215] In addition, Congress should consider the use of tax incentives and subsidies targeted to diesel engine manufacturers for the purpose of promoting private sector research and innovation towards improving the capacity of the engines to tolerate high-fraction biodiesel blends, especially B100.[216] Another key technology-promoting option is for DOE and/or other federal agencies to fund academic and national laboratories, or university/industry consortia, for the specific purpose of discovering biodiesel blends and additives that improve diesel engine performance. These programs would distinguish between the unique properties of the two types of biodiesel produced by the distinct final-stage transesterification and hydrogenation reactions ("biodiesel" and "renewable diesel").[217] The intention of the programs would be to accelerate market penetration of both types of biodiesel by addressing present concerns about engine damage, cold weather performance, pollution control, and engine efficiency compared to petrodiesel.[218] Any success with such targeted programs should help hasten the transition from petroleum diesel to biomass-based diesel.

In reformulating the biofuels program, Congress and EPA should recognize that ethanol use in the United States will likely continue to decline as the passenger vehicle fleet becomes more fuel efficient and is increasingly converted to electric cars. This dynamic suggests that the U.S. biofuels agenda should be focused instead on programs that facilitate biodiesel penetration into targeted sectors of the economy that are heavy users of petroleum diesel, since these diesel applications are also much less amenable to electrification.[219] More industry experience with and acceptance of biodiesel and renewable diesel derived from soybeans and other crops should ultimately also help facilitate the introduction of biodiesel from non-plant sources such as algae. Adjustments in equipment design and operations that

---

under 4 billion gallons in 2005 to over 14 billion gallons in 2015, because the essential technology was already in place and only expansion was needed. Similarly, the technology of biodiesel production from soybeans and other crops is also mature and thus poised to substantially increase if the market is created in a revised RFS2. Technological hurdles with biodiesel reflect use of high-fraction blends in diesel engines, and can be addressed with other targeted programs, as described in the text.

[215] In summer 2016 the House and Senate proposed identical legislation to extend the credits through 2019, but there has been no action as of this writing (December, 2016). The present bill covers just a two-year period and was enacted at the end of 2015 to apply retroactively as of January 1, 2015. Biodiesel Tax Incentive Reform and Extension Act of 2016, S. 3188, 114th Cong. (2015); Ron Kotrba, *Biodiesel Blenders Tax Credit Passes US House, Senate*, BIODIESEL MAG. (Dec. 18, 2015), http://www.biodieselmagazine.com/articles/646582/biodiesel-blenders-tax-credit-passes-us-house-senate.

[216] High-fraction biodiesel blends are formulated from mixtures of biodiesel and petroleum diesel with higher percentage volume from biodiesel. B100 is pure biodiesel with no fossil petroleum diesel component. *See generally supra*, Section II.B.

[217] *See generally*, Section II.B; DEP'T ENERGY, *supra* note 88.

[218] Effects of variation in biodiesel fuel properties on engine performance are presently not well understood. James Pullen & Khizer Saeed, *Factors Affecting Biodiesel Engine Performance and Exhaust Emissions – Part I. Review*, 72 ENERGY 1 (2014). It is worth noting that a switch from petroleum diesel to biodiesel may also result in a decrease in particulate and carbon monoxide emissions owing to the oxygen content of the fatty acid alkyl esters that comprise most commercial biodiesel today. Leo d'Espaux et al., *Synthetic Biology for Microbial Production of Lipid-Based Biofuels*, 29 CURRENT OP. CHEM. BIOLOGY 58 (2015).

[219] Powers, *supra* note 34 (for further policy recommendations).

my be needed because of differences in biodiesel properties between algae and plant sources should be easier to make when end users already have experience in transitioning away from petrodiesel.

2. State Low Carbon Fuel Standard Initiatives

The replacement of petroleum diesel with biodiesel can also be hastened by implementing forward-looking policies at the state level. In the past few years, California has initiated a low carbon fuel standard (LCFS) program to reduce the carbon intensity of transportation fuels, which has considerable potential to facilitate the growth of biodiesel and to serve as a model for other states.[220] The California LCFS program was authorized by executive order in 2007, and mandates a stepwise 10% reduction in the greenhouse gas (GHG) emissions intensity of transportation fuels by 2020.[221] Under the LCFS, regulated providers or blenders of fuel must reduce average fuel carbon intensity, but there are no specified requirements for particular new fuel types that replace fossil sources. As implemented in California, the LCFS also allows for trading of emissions credits among regulated parties, and banking of credits for future use.[222] These policies allow for greater innovation and flexibility in meeting emissions targets.

The California LCFS was implemented under state law AB32, the Global Warming Solutions Act of 2006, by which the California Air Resources Board (CARB) was authorized to implement a cap-and-trade program to limit emissions of greenhouse gases.[223] Although the federal Clean Air Act generally preempts states from regulating motor vehicle emissions, California was granted an exemption to create its own programs so long as its standards are at least as protective of health and welfare as the federal requirements.[224] Other states can choose to follow either the federal or California standards, although they are not entitled to create entirely new programs of their own.[225] Thus, California's leadership on the LCFS program has potential to have national ramifications.

A consortium of parties representing corn ethanol and fossil fuel interests challenged CARB's regulations under AB32 in district court, asserting harm to their interests and claiming that the regulations violated the Dormant Commerce Clause and should be declared invalid because of conflict preemption with the

---

[220] *See generally Low Carbon Fuel Standard*, CTR. FOR CLIMATE & ENERGY SOLS., http://www.c2es.org/us-states-regions/policy-maps/low-carbon-fuel-standard (last visited Mar. 22, 2017). In March 2015, Oregon became the second state to implement an LCFS program. Washington and 11 Northeast states have also considered LCFS program adoption. Peter Lehner, *Big Win: Oregon Moves Ahead on Clean Fuel Standards, Building Momentum for West Coast Clean Fuel Corridor,* NAT'L RES. DEF. COUNCIL (Mar. 13, 2015), http://switchboard.nrdc.org/blogs/plehner/big_win_oregon_moves_ahead_on_.html.

[221] Exec. Order S-01-07 (Jan. 18, 2007) (Cal.), http://gov.ca.gov/news.php?id=5172. The executive order was issued in 2007 and began to be implemented by the California Air Resources Board (CARB) in 2011. The baseline year for determining compliance with the 10% reduction mandate was 2010. "Carbon intensity" means the mass of greenhouse gas emitted per unit of fuel energy. Emissions are calculated based on a full life cycle GHG analysis of the fuel's use, similar to the metric used for the federal RFS program.

[222] Sonia Yeh et al., *Status Review of California's Low Carbon Fuel Standard,* UC DAVIS INST. TRANSP. STUD. (Apr. 2015).

[223] CAL. HEALTH & SAFETY CODE § 38500-00 (West 2016).

[224] 42 U.S.C. §§ 7543(a) & (b).

[225] 42 U.S.C. § 7507.

federal RFS program.[226] The District Court ruled in favor of the plaintiffs and issued an injunction blocking CARB from moving forward to implement the program.[227] While declining to rule on the issue of RFS preemption, on appeal the Ninth Circuit reversed, holding that the LCFS does not violate the Dormant Commerce Clause's prohibition on extraterritorial regulation, and freeing the program for implementation.[228] Other legal challenges in the California state courts regarding compliance with the California Environmental Quality Act (CEQA) and Administrative Procedures Act were also favorably resolved,[229] and the corrections required have recently been implemented in updated regulations.[230]

In California, the LCFS is impacted by the simultaneous existence of the cap-and-trade program under AB32, which sets emissions limits for sectors throughout the state economy.[231] Beginning in 2015, GHG emissions from on-road transportation fuels came under the cap-and-trade program. Unlike cap and trade, however, LCFS is not limited to on-road emissions, but covers full lifetime combustion and non-combustion GHG emissions of all on-road transportation fuels in the program whether the emissions occur inside or outside the state.[232] Further, compliance credits are not traded between the two programs.[233] Nonetheless, because the programs overlap the effects on fuel prices may not be straightforward to separate. It has been suggested that the impact of LCFS and cap-and-trade on prices is likely to be additive, but this assumption may not hold when the credit/allowance prices under either or both programs are high.[234] The effects of the combined programs on fuel switching in California will be of substantial interest to monitor, and California's experience should serve as a guide to LCFS implementation in other states whether concomitant cap-and-trade or carbon tax programs are also operating or not. Oregon is the only other state to pass an LCFS so far, but the program there has been controversial, and its possible cancellation is being used as a bargaining chip for passage of other energy legislation in the state.[235] Most of the Northeast states considering an LCFS also participate in the

---

[226] Rocky Mountain Farmers Union v. Goldstene, 843 F. Supp. 2d 1042 (E.D. Cal., 2011). On the preemption issue, plaintiffs did not challenge California's waiver to implement its own fuel standards, but argued that the federal RFS already occupied the field.

[227] *Rocky Mountain Farmers Union*, 843 F. Supp. 2d at 1047.

[228] Rocky Mountain Farmers Union v. Corey, 730 F.3d 1070 (9th Cir. 2013).

[229] POET, L.L.C. v. Cal. Air Res. Bd., 218 Cal. App. 4th 681 (2013).

[230] *POET, L.L.C.*, 218 Cal. App. 4th. *Low Carbon Fuel Standard Program*, CAL. ENVTL. PROT. AGENCY (last updated Mar. 3, 2017), http://www.arb.ca.gov/fuels/lcfs/lcfs.htm. CARB readopted the program with revisions in September, 2015. Tony Barboza, *California Air Regulators Readopt Fuel Standard to Fight Climate Change*, L.A. TIMES (Sept. 25, 2015), http://www.latimes.com/science/la-me-0925-carbon-fuels-20150925-story.html. The changes were approved by the California Office of Administrative Law (OAL) in November 2015.

[231] Exec. Order S-01-07, *supra* note 221.

[232] Yeh et al., *supra* note 222, at 7-8.

[233] *Id.* at 7.

[234] *Id.* at 8.

[235] Matt Rosenberg, *Fuel Standard Gums Up Transpo Deal in Oregon; Washington Too?*, WASH. ST. WIRE (June 26, 2015), http://washingtonstatewire.com/blog/fuel-standard-gums-transpo-deal-oregon-washington/.

Northeast Greenhouse Gas Initiative (RGGI),[236] which is also a cap-and-trade program, so California's experience will be more directly relevant.

Although LCFS credits in California are generated when any less carbon intensive fuel is substituted for petroleum, from 2011 to 2014 87% of the credits were accounted for by biofuels.[237] Further, credits for ethanol decreased from 90% of the biofuels total in 2011 to 54% in 2014, while biodiesel increased from 9% to 42% during this three-year period.[238] This shift is presumably occurring because fuel-specific carbon intensities set by regulation, based on lifecycle GHG emissions, are more favorable for biodiesel than for ethanol.[239] Expected GHG reductions from transportation fuels by 2020 are over 20%, while increases in gasoline prices at the pump are predicted to be under fifteen cents per gallon.[240] Carbon intensities of transportation fuels also decreased by 15% from 2011 to 2014, and credits in substantial excess of the minimum requirements have been generated.[241] Given these successes, required carbon intensity reductions of 10% by 2020 appear quite conservative. It does not seem unreasonable to consider much greater transportation fuel carbon intensity reductions in future years, to bring about accelerated reductions of GHGs when the compliance schedule ends in 2020.

Based on these performance analyses, it appears clear that the California LCFS is meeting the goals set for its function by the 2007 Executive Order, and is making an important contribution to the goals set in the 2006 Global Warming Solutions Act. Interestingly, most of the increased biodiesel used in California to reduce carbon intensities is being imported from out of state.[242] Thus, the LCFS appears to be creating the conditions for a lucrative marketing opportunity for biodiesel in California. Ultimately, because the program is technology neutral, the actual technology forcing that it brings about will depend on the capacities of each renewable fuel subsector to generate increased volumes of its product at a competitive cost. Nonetheless, green investors throughout the United States with an eye on the development of biodiesel from either new and existing sources would do well to call for LCFS legislation. For biodiesel generation from algae, LCFS programs would be particularly beneficial in Texas and the Gulf Coast states, given their superior access to the nutrient resources needed.

---

[236] *See generally Regional Greenhouse Gas Initiative*, RGGI INC., www.rggi.org (last visited Mar. 23, 2017).

[237] Small percentages of the total credits were generated for compressed and liquefied natural gas, electricity, and biogas from anaerobic digesters. Yeh et al., *supra* note 222, at 2-3.

[238] *Id.* at 3.

[239] CAL. ENVTL. PROT. AGENCY, *supra* note 230 (detailing the process by which carbon intensities are set); OR. ST. DEP'T, http://www.deq.state.or.us/aq/cleanFuel/qa.htm (providing a simple graphic showing the Oregon approved carbon intensities, modeled after California's standards).

[240] CAL. AIR RES. BD., STAFF REPORT: INITIAL STATEMENT OF REASONS FOR RULEMAKING: PROPOSED READOPTION OF THE LOW CARBON FUEL STANDARD REGULATION, ES-18 – ES-20 (Jan. 2, 2015), http://www.arb.ca.gov/regact/2015/lcfs2015/lcfs15isor.pdf.

[241] Yeh et al., *supra* note 222, at 1.

[242] *Id.* at 6.

B. Biodiesel from Algae

The existence of federal and California renewable and low carbon fuel standards is beneficial to the development of algaculture for biodiesel, since these programs demonstrate interest on the part of legislatures to incentivize the biofuels industry generally. From the standpoint of attracting private investment, it is also valuable that both programs are structured to easily accommodate algal biodiesel as a creditable fuel source. Of course, at the present pre-commercial stage, algaculture cannot directly benefit from either program. If federal, state and local governments desire to promote algal biodiesel for a role in the new renewable energy economy, they must instead offer programs that function as bridges to more rapid commercialization. These programs include supporting basic and applied research, fostering partnerships among government, private industry and universities, and better accommodating algaculture within existing programs that support U.S. agriculture.

These government supports will be worthwhile even if the algal biodiesel industry fails to reach commercialization, because algae has substantial potential to provide many other environmental and consumer benefits. Presently, algae is the source material for a variety of human nutritional supplements, for animal feed, and for pharmaceuticals used in cancer treatment.[243] Production of these commodities is crucial to the commercial success of private ventures in the algae field, as it maintains profitability while efforts to develop and scale up biodiesel production are undertaken. Algae are also very effective at wastewater treatment because they can take up a wide range of pollutants.[244] Other technologies are also promoted by this process. For example, Algae Enterprises, Inc. uses its algae wastewater treatment plant to generate large quantities of algal biomass, from which it generates biogas by anaerobic digestion. In turn, the biogas fuels electrical power generation.[245] For these reasons, federal and state subsidies and incentives for promoting algaculture are arguably strongly in the public interest. Moreover, many of the programs described below are also useful to promote new and existing biodiesel sources among food crops in addition to algae.

1. Basic Research Initiatives and Synthetic Biology

A variety of federal and state programs, together with private initiatives, provide the funding for research on algae.[246] The most directed federal initiative is the recently renamed Advanced Algal Systems Research and Development Program sponsored by the Bioenergy Technologies Office (BETO) at the DOE.[247] BETO's program funds long-term applied research and development (R&D) to

---

[243] Emily M. Trentacoste et al., *The Place for Algae in Agriculture: Policies for Algal Biomass Production*, 123 PHOTOSYNTHESIS RES. 305, 305-06 (2015).

[244] FERRELL & SARISKY-REED, *supra* note 37, at 83-86.

[245] *Wastewater Treatment: Advanced Algae Bioremediation System*, ALGAE ENTERS., http://www.algaeenterprises.com/wastewater-treatment (last visited Mar. 22, 2017).

[246] *See generally* OILGAE, www.oilgae.com (last visited Mar. 23, 2017); Lane, *supra* note 112; DEP'T ENERGY, *supra* note 113; ALGAE BIOMASS ORG., *supra* note 114.

[247] *Bioenergy Technologies Office: Multi-Year Program Plan*, DEP'T ENERGY (Mar. 2016), http://energy.gov/sites/prod/files/2016/07/f33/mypp_march2016.pdf.

increase yields and lower costs of algal biofuels,[248] with a goal of producing five billion gallons of algal biodiesel per year by 2030.[249] An interim goal is production of 5,000 gallons of biodiesel per acre by 2022,[250] a yield that could already suffice to meet constraints of land availability at large scale.[251] To accomplish these objectives, BETO sponsors work in production of algal biodiesel (including analysis of required resources, development of cultivation systems, and characterization of the biomass), methods for oil extraction from cells, scaleup, and integration into biorefineries.[252] Given the still-early development of the technology, algal biodiesel is presently much more expensive to produce than gasoline from fossil petroleum. To meet this challenge, BETO also funds work to meet a third goal of reducing the cost of algal biofuel to less than $3 per gallon of gasoline equivalent by 2030.[253] This price would be competitive, since a minimal profitable fuel selling price of $3 per gallon of gasoline-equivalent is necessary to compete in a market where the cost of a barrel of petroleum is $75-90.[254] However, federal or state subsidies or other programs are likely necessary to enable commercialization sooner, or if the $3 per gallon cost goal takes longer to reach.[255]

BETO's algae programs are funded at $30 million for 2016, within a total BETO budget of $225 million.[256] Some other parts of BETO's bioenergy technologies portfolio, such as the "Biochemical Conversion" and "Analysis and Sustainability" programs, fund cross-cutting bioenergy research that at least indirectly benefits the Algae program.[257] However, this level of federal support is inadequate to meet the challenges of transforming algae from a promising nascent technology to a full-scale commercial operation that significantly cuts into the dominance of fossil petrodiesel. For comparison, the cumulative global investment in CCS, another nascent industry for the renewable energy economy, has been $12 billion over a timeframe of several decades, with an additional $22 billion available soon from countries associated with the Organization for Economic Cooperation and Development (OECD).[258] This level of commitment has generated sufficient resources to overcome the many hurdles to commercialization—after decades of effort, the first CCS facility with full CO_2 capture, at a coal-fired power plant in Canada, finally opened in 2014.[259] Even this level of investment in the required

---

[248] *Id.* at 2-38.

[249] *Id.* at 2-42. Five billion gallons per year may be a reasonable interim goal towards an ultimate 60 billion gallon target in 2050, if most of the scale-up issues are solved by then.

[250] *Id.* at 2-43.

[251] *See generally supra* Section III.B.

[252] DEP'T ENERGY, *supra* note 247.

[253] *Id.* at 2-43.

[254] *Bioenergy Technologies Office: Multi-Year Program Plan*, DEP'T ENERGY (Mar. 2015), http://www.energy.gov/sites/prod/files/2015/03/f20/mypp_beto_march2015.pdf.

[255] *See generally infra*, Section IV.B.3.

[256] FY 2017 CONGRESSIONAL BUDGET REQUEST, DEP'T ENERGY (2016), https://energy.gov/sites/prod/files/2016/02/f29/FY2017BudgetVolume3_2.pdf.

[257] *Id.* at 19, 24.

[258] INT'L ENERGY AGENCY, TRACKING CLEAN ENERGY PROGRESS 2016, at 30-32 (2016), https://www.iea.org/etp/tracking2016/.

[259] *Id.*

basic and applied research still leaves the penetration of CCS technology well below benchmarks established for keeping global temperature rise below the 2°C limit.[260] Given the many technical challenges of algaculture, it is unreasonable to expect that the low level of public investment so far offered could suffice. Most algaculture research centers are located in the United States,[261] which, given its land resources and technical capacity, likely must lead any global effort.

One reason why funding for algae research has been limited is that BETO takes a broad approach to stimulate growth of renewable energy and, within that wide field, a similarly expansive approach to bioenergy in particular. Another example of such broadly based funding is the Biomass Research and Development Initiative (BRDI), a joint program of the DOE with the USDA.[262] DOE and USDA presently focus their funding on feedstocks development, biofuels and biobased products development, and biofuels development analysis.[263] While research on algae of course fits this description, so does much other work—in 2011, for example, this program funded, among other areas, work to convert paper mill byproducts into useful commodities, to enhance yield of fuels from switchgrass (a cellulosic ethanol source), and to convert biomass to a mixture of alcohols and organic acids for downstream refining.[264] In fact, a section of the BRDI singles out the development of cellulosic biomass technologies for special attention.[265] Other federal programs that actively fund basic bioenergy research also paint with a broad brush, including the Department of Defense (DOD),[266] the distinctive Advanced Research Projects Agency (ARPA-E) initiative at DOE,[267] and the Sun Grant Initiative, a national network of land-grant universities and national laboratories jointly funded by DOE, USDA and the Department of Transportation (DOT).[268]

---

[260] *Id*.

[261] Trentacoste et al., *supra* note 243, at 313.

[262] The legislative intention behind the interagency BRDI is to reduce reliance on imported oil. 7 U.S.C. § 8108 (2014).

[263] 7 U.S.C. § 8108(e)(3).

[264] Press Release, U.S. Dep't Agric., USDA and DOE Award Biomass Research and Development Grants to Reduce America's Reliance on Imported Oil (May 5, 2011), http://nifa.usda.gov/press-release/usda-and-doe-award-biomass-research-and-development-grants-reduce-americas-reliance.

[265] 7 U.S.C. § 8108(e)(3)(B)(i). The bias in favor of cellulosic ethanol over biodiesel is of course also evident in the Renewable Fuel Standard program RFS2 administered by the EPA. *See generally supra*, Section IV.A.1.

[266] Both the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA) fund research programs in synthetic biology that are relevant to development of algal biofuels. Further, under the Defense Production Act, DOD enters into specific contracts with private companies to construct and commission biorefineries to produce drop-in biofuels for military and private sector transportation needs. In 2014, three contracts collectively valued at $45 million were awarded to produce biofuel from woody biomass, municipal solid waste, and (unfortunately) animal waste fats. Anna Simet, *DOD Awards 3 Biofuels Contracts Under Defense Production Act*, BIODIESEL MAG. (Sept. 19, 2014), http://www.biodieselmagazine.com/articles/183799/dod-awards-3-biofuel-contracts-under-defense-production-act.

[267] The goal of ARPA-E is to advance high potential, high impact energy technologies that are not yet ready for private sector investment. The 2015 budget for ARPA-E is $280 million. *See generally* FY 2015 CONGRESSIONAL BUDGET, ADVANCED RES. PROJECTS AGENCY (2014).

[268] *See generally SunGrant Initiative: About Sun Grant*, U. TENN., https://ag.tennessee.edu/sungrantinitiative/Pages/default.aspx (last visited Mar. 23, 2017). There are five regional centers located at land grant universities in five regions of the country. The intention is to further the establishment of a biobased economy and

Some of the funding directed to algaculture also involves efforts not directly related to biodiesel production; for example, programs directed toward using algae for producing useful commodity chemicals, for ethanol production, and for wastewater remediation.[269]

Given budgetary restrictions,[270] directing more federal (and state) research funding to algal biodiesel development will require recognizing the costs of the broad approach taken to funding bioenergy research. Clearly, funding for programs that seek to develop algae and other biomass feedstocks for chemicals and commodities synthesis, and to employ algae for wastewater treatment, serve distinct goals and should be maintained. However, the substantial intrinsic advantages of biodiesel over ethanol, and the ethanol blend wall, strongly argue for a shift in research dollars toward programs that are more likely to lead to the development of commercial-scale biodiesel fuels,[271] and away from cellulosic ethanol.[272] Given the still pre-commercial of the algae biofuels enterprise, funding to develop alternate biodiesel sources, such as various oilseed crops, should also be accelerated. Although these other sources require much more land than algae, and inevitably generate competition between fuel and food use, these may be necessary compromises if the nutrient supply and other challenges associated with algaculture scaleup are ultimately not solved.

State and federal funding agencies, especially DOE and USDA, should more fully recognize that the most difficult problems in algal biodiesel development are the supply of CO_2, nitrogen and phosphorus nutrients.[273] Basic research can contribute to solving these problems by better understanding and then deliberately engineering the intrinsic biochemistry of the microalgae to improve fuel yields while lowering required nutrient inputs. This is the new field of synthetic biology, which has transformed the application of genetic engineering techniques to microorganisms, enabling wholesale redesign of biological functions.[274] This applied

---

to revive rural communities through biobased development. The regional centers also award and administer grants to laboratories at other universities. Total funding is $75 million per year from 2008 to 2018, but only a small fraction of this is directed to work on algae. 7 U.S.C. § 8114.

[269] *See generally supra*, Section III.

[270] Eduardo Porter, *Innovation Sputters in Battle Against Climate Change*, N.Y. TIMES (July 21, 2015), https://www.nytimes.com/2015/07/22/business/energy-environment/innovation-to-stanch-climate-change-sputters.html?_r=0. Combined funding for all technology research, development and demonstration, and basic energy sciences at DOE has been constant at about five billion dollars per year since 2010.

[271] A good resource for biodiesel feedstocks is in the eXtension learning environment set up by the US land grant universities. *Oilseed Crops for Biodiesel Production*, EXTENSION (Apr. 4, 2014), http://www.extension.org/pages/28006/oilseed-crops-for-biodiesel-production#.VbLe6iT3V0s.

[272] It is worth noting that a substantial expansion in funding for algae research at DOE occurred because of the American Recovery and Reinvestment Act (ARRA) in 2009. This resulted in a spike of funding and the establishment of a significant amount of infrastructure. Unfortunately, this infrastructure is at risk because post-ARRA funding levels have not been maintained. *See supra* note 247, at 1-14.

[273] NAT'L RES. COUNCIL, *supra*, note 38.

[274] Sean A. Lynch & Ryan T. Gill, *Synthetic Biology: New Strategies for Directing Design*, 14 METABOLIC ENG'G 205 (2012); *see also* Javier A. Gimpel et al., *Advances in Microalgae Engineering and Synthetic Biology Applications for Biofuel Production*, 17 CURRENT OP. CHEM. BIOLOGY 489 (2013) (for a specific review of synthetic biology applications to biofuel production from algae). The essential paradigm in synthetic biology is that sizable portions of the genomic DNA in microalgae can be chemically synthesized and introduced into the living cells, where it augments or replaces part of the existing chromosome. Either new genes

effort depends on prior knowledge of the complex metabolic networks in microalgae.[275] Engineering of algae lipid metabolism has already allowed the production of new strains with higher levels of membrane lipids, so that more biodiesel can be produced from the same volume of cell culture.[276] Attention to the processes of industrial-scale aquaculture is also warranted, since proper management of microalgal diversity and species composition, especially in open pond systems susceptible to invasion, may lead to more productive systems.[277]

In synthetic biology, the initial experiments can readily be done in small laboratories at the bench scale, because the essential new breakthroughs required are at the level of the molecular design of the cell. Engineered cells with potentially new, favorable properties such as enhanced CO_2 uptake or lipid production can be established in small-scale cultures in the individual laboratory, prior to testing scale-up in industrial facilities. In addition to DOE and DOD, synthetic biology of microalgae can also be sponsored by programs at the National Science Foundation (NSF) and even the National Institutes of Health (NIH). The NSF already funds dozens of projects relating to algal biofuels production,[278] although its capacity for expansion is limited by a small overall budget and mandate to broadly fund basic science research and education.[279] NIH presently funds programs related to climate change because of its clear impacts on human health,[280] consistent with the agency's Congressional mandate. Research on synthetic biology directed toward fossil fuel replacements thus plausibly falls within its scope of funding as well.

Large-scale implementation of algaculture involving engineered microalgae implicates the environmental release of genetically modified organisms (GMOs). This is especially apparent for applications involving open ponds. All genetically engineered microbes are regulated as toxic substances under the Toxic Substances Control Act (TSCA), which is administered by EPA.[281] Field trials for intergeneric

---

or modified versions of existing algae genes from other microorganisms can be introduced, so that the effective available gene pool from which to draw is very large. Pamela P. Peralta-Yahya et al., *Microbial Engineering for the Production of Advanced Biofuels*, 488 NATURE 320 (2012).

[275] The networks convert light into chemical energy, fix the CO_2 into cellular metabolites, and manage the uptake, assimilation, and excretion of essential elements such as sulfur, nitrogen and phosphorus from the surrounding media. Caroline Baroukh et al., *A State of the Art of Metabolic Networks of Unicellular Microalgae and Cyanobacteria for Biofuel Production*, 30 METABOLIC ENG'G 49 (2015).

[276] Emily M. Trentacoste et al., *Metabolic Engineering of Lipid Catabolism Increases Microalgal Lipid Accumulation Without Compromising Growth*, 110 PROC. NAT'L ACAD. SCIS. 19748 (2013).

[277] Jonathan B. Shurin et al., *Industrial Scale Ecology: Tradeoffs and Opportunities in Algal Biofuel Production*, 16 ECOLOGY LETTERS 1393 (2014).

[278] Information on actively funded and past awards can be obtained by searching the NSF website. NAT'L SCI. FOUND., www.nsf.gov/awardsearch (last visited Mar. 23, 2017).

[279] The 2016 NSF budget is $7.5 billion, which supports its original 1950 Congressional mandate to promote the progress of science; to advance the national health, prosperity, and welfare; and to secure the national defense. *NSF at a Glance*, NAT'L SCI. FOUND., http://www.nsf.gov/about/glance.jsp (last visited Mar. 23, 2017).

[280] WHITE HOUSE, THE HEALTH IMPACTS OF CLIMATE CHANGE ON AMERICANS (June 2014), https://www.whitehouse.gov/sites/default/files/docs/the_health_impacts_of_climate_change_on_americans_final.pdf.

[281] David Markell, *An Overview of TSCA, Its History and Key Underlying Assumptions, and Its Place in Environmental Regulation*, 32 WASH. U. J. L. & POL'Y 333 (2010); *Microbial Products of Biotechnology; Final*

microorganisms first require approval of a TSCA Experimental Release Application (TERA), while manufacture or import for commercialization requires approval of a Microbial Commercial Activity Notice (MCAN).[282] While TERAs are regularly approved by EPA,[283] very few MCAN submissions are successful.[284] Companies seeking to market biodiesel from engineered microalgae will need to negotiate this regulatory hurdle—a process that may become more demanding if the number of engineered varieties proliferates, and EPA's resources to manage the program become limiting.[285]

2. Closing the Green Investment Gap

Research and development alone will not be enough to transform algaculture from a promising idea to a mature energy technology that can be widely applied. The process by which the research findings can be scaled and monetized to create a viable petrodiesel alternative also require specific attention. As a precommercial technology still in the development stage, algaculture must overcome a variety of challenges. Even when the cultures are well-supplied with CO_2, nitrogen and phosphorus, yields of oil are still low because of difficulties in achieving high cell densities in culture, susceptibility of open ponds to invasion by other microorganisms, inefficient cell harvesting and oil extraction methods, and low lipid levels inside the cells.[286] Therefore, potential investors clearly face much higher risks when making a commitment to algaculture, compared with other liquid fuels technologies such as petroleum refining or corn ethanol production. The need for high capital costs to build infrastructure and the relative unfamiliarity of the technology are further deterrents. To overcome these disadvantages, mobilizing private investment through "targeted deployment of public finance" offers an established set of instruments and mechanisms by which the green investment gap can be closed.[287]

---

regulation Under the Toxic Substances Control Act, 62 Fed. Reg. 17,910 (Apr. 11, 1997) (final EPA regulations governing GE microbes under TSCA).

[282] ENVTL. PROT. AGENCY, MICROBIAL PRODUCT OF BIOTECHNOLOGY SUMMARY OF REGULATIONS UNDER THE TOXIC SUBSTANCES CONTROL ACT (Sept. 2012), https://www.epa.gov/sites/production/files/2015-08/documents/biotech_fact_sheet.pdf.

[283] For a list of approved TERAs from 1998 to the present, see https://www.epa.gov/regulation-biotechnology-under-tsca-and-fifra/tsca-biotechnology-notifications-status#mcan.

[284] MCANs from fiscal year 1998 to the present are also available at https://www.epa.gov/regulation-biotechnology-under-tsca-and-fifra/tsca-biotechnology-notifications-status#mcan.

[285] SARAH R CARTER ET AL., J. CRAIG VENTER INST., SYNTHETIC BIOLOGY AND THE US BIOTECHNOLOGY REGULATORY SYSTEM: CHALLENGES AND OPTIONS (May 2014); *see generally infra*, Section IV.B.2 (for other environmental pollution laws relevant to algaculture).

[286] Gimpel, *supra* note 274, at 489.

[287] WORLD ECON. FORUM, GREEN GROWTH ACTION ALL., THE GREEN INVESTMENT REPORT: THE WAYS AND MEANS TO UNLOCK PRIVATE FINANCE FOR GREEN GROWTH 18-24 (2013). This report is the product of the Green Growth Action Alliance. Formed at the 2012 G20 meeting in Mexico City, the Alliance is a partnership of private companies from the finance, infrastructure, agriculture, and energy sectors, joined with public finance institutions, with a purpose to catalyze the development of renewable energy, water resource infrastructure, transportation initiatives, and water-smart agriculture in countries throughout the world, with a particular emphasis on developing nations. *Green Growth Action Alliance (G2A2)*, WORLD ECON. FORUM, http://www3.weforum.org/docs/WEF_GreenGrowthActionAlliance_Overview_2012.pdf (last visited Mar. 24, 2017).

Public-private partnerships have a long history of success in the United States.[288] These partnerships are contractual arrangements between public agencies and private entities, through which the skills and assets of both partners are mobilized to deliver facilities or services for the general public.[289] Although many different organizational forms have been described, a key common feature is that both parties to the transaction obtain benefits that would otherwise put the projects out of reach.[290] Given tightly constrained public budgets, state and federal agencies wishing to promote renewable energy clearly benefit greatly from the infusion of cash provided by private investment, while investors are similarly motivated by the commitment of public funds. Given the extremely high level of technical complexity and need for extensive infrastructure associated with building a new industry, there is virtually no possibility that either partner, acting alone, could be successful. Another motivating factor is likely to be that the risk of failure is shared between the public and private sectors.[291] For projects involving renewable energy, additional benefits to the public sector include improved energy security and increased employment, while the companies that participate may obtain a competitive edge against other firms, and insights into meeting regulatory requirements.[292]

A potential disadvantage to public-private partnerships is that any joint algaculture projects involving larger-scale activities, such as construction of outdoor pilot or demonstration facilities requiring acquisition of land or water rights, could constitute major federal actions that will significantly affect the quality of the human environment, and thus be subject to requirements of the National Environmental Policy Act (NEPA).[293] The NEPA process can be perceived as burdensome by private firms, as it requires preparation of a comprehensive Environmental Impact Statement (EIS) or a somewhat more concise Environmental Assessment (EA) documenting the effects of the project on local and broader resources, and requiring specification of project alternatives and mitigation strategies.[294] Any impacts on endangered or threatened species also triggers requirements under the Endangered Species Act (ESA) for the action agency in the partnership (such as DOE) to consult with the U.S. Fish and Wildlife Service (FWS) or National Marine Fisheries Service (NMFS) to develop specific mitigation measures.[295] However, private firms facing this requirement should recognize that the commercial-scale operations they ultimately hope to construct will be major industrial facilities that will have to comply with a large number of state and federal environmental

---

[288] Daniel T. Plunkett & Erin M. Minor, *Public-Private Partnerships: Primer, Pointers and Potential Pitfalls*, 13-7 BRIEFING PAPERS 1, 3-4 (June 2013).

[289] *Id.*

[290] *Id.* at 2.

[291] *Id.* at 5-6.

[292] FERRELL & SARISKY-REED, *supra* note 37, at 109.

[293] The National Environmental Policy Act of 1969, Pub. L. 91-190, 42 U.S.C. §§ 4321-4347 (1970) (as amended by Pub. L. 94-52 (July 3, 1975); Pub. L. 94-83 (Aug. 9, 1975); Pub. L. 97-258, § 4(b) (1982)).

[294] 42 U.S.C. §4332 (2)(C)(i))(for the EIS requirement); 40 C.F.R. §§ 1501.3, 1508.9 (for regulations regarding the EA). At the present stage of algaculture developments, most projects are likely to be of limited scope, for which an EA would likely suffice.

[295] 16 U.S.C. § 1536(a)(2).

pollution laws, including major statutes such as the Clean Air Act (CAA), Clean Water Act (CWA), and Resource Conservation and Recovery Act (RCRA). In this context, assisting a public partner agency with its preparation of an EA or EIS for a pre-commercial pilot facility should be viewed by a private firm as a productive investment of resources towards informing itself of its eventual much larger obligations. The EA for Sapphire Energy's algaculture facility in New Mexico provides a model for the process that should be useful for other firms.[296]

A key feature of the public-private partnerships in algaculture is the central role of public and/or private universities.[297] This is appropriate to the still-early phase of development, since results from small-scale laboratory investigations can, through this mechanism, find an immediate partner in the private sector to carry out larger scale studies.[298] The process is expected to be particularly important for evaluating the results of synthetic biology experiments to construct new, engineered algae strains with improved performance.[299] The industry partner reaps very large benefits from this process, because it accesses the intellectual resources of top universities and so largely bypasses the need to fund its own expensive, long-term basic research studies of uncertain outcome. Moreover, it also gains a competitive edge against other firms that are not so engaged. There is, of course, a significant cost because universities will retain a portion of the intellectual property rights to the inventions associated with the project.[300] However, this process has been successfully negotiated in many areas of biotechnology, and should not be regarded as a major detriment, considering potential highly lucrative gains.

Major public-private partnerships that have tackled algaculture include the $49 million project grant from DOE to the National Alliance for Advanced Biofuels and Bioproducts (NAABB), a nationwide consortium of fourteen academic institutions, twelve private industry partners and two national laboratories.[301] The project included an additional $20 million contribution from the private firms, and sought to address the major bottlenecks to the production of algal biodiesel using both experimental and computational modeling approaches.[302] In addition to bio-

---

[296] SAPPHIRE ENERGY, SUPPLEMENTAL ENVIRONMENTAL ASSESSMENT: SAPPHIRE ENERGY INC.'S INTEGRATED ALGAL BIOREFINERY (IBR) FACILITY (2012). This EA served as a basis for a finding of no significant impact (FONSI) issued by USDA and, a year later, by DOE. Issuance of the FONSI then permitted the project to go forward.

[297] FERRELL & SARISKY-REED, *supra* note 37, at 109.

[298] It is expected that the private sector share of the funding contributions will increase later as the technology is commercialized and disseminated. Kelly S. Gallagher et al., *Energy-Technology Innovation*, 31 ANN. REV. ENV'T RES. 193 (2006).

[299] *See generally supra* Section IV.B.1.

[300] Under the Bayh-Dole Act of 1980, universities are entitled to retain ownership of intellectual property rights for inventions made in the course of projects that receive federal funding, rather than being obligated to assign those rights to the government. 35 U.S.C. §§ 200-212 (2000).

[301] Jose A. Olivares, *Overview of NAABB's Algal Biofuels Consortium*, BIOMASS MAG. (Apr. 19, 2011), http://biomassmagazine.com/articles/6969/overview-of-naabbundefineds-algal-biofuels-consortium. The author is the executive director of NAABB.

[302] NAT'L ALL. FOR ADVANCED BIOFUELS & BIO-PRODUCTS, SYNOPSIS REPORT, http://energy.gov/sites/prod/files/2014/06/f16/naabb_synopsis_report.pdf. (last visited Mar. 24, 2017).

diesel production, the project was also oriented towards exploring efficient strategies for the production of economically valuable coproducts. Although this dual emphasis may have subtracted from a more focused attack on biodiesel production, the short and medium-term viability of private firms invested in algaculture likely depends on the generation of alternative salable products.[303]

The NAABB project was active from 2010 to 2013 and was funded under the auspices of the one-time boost to many areas of research provided by the American Recovery and Reinvestment Act of 2009 (ARRA).[304] In a final report, the consortium asserted that their research showed that " . . . a sustainable algal biofuels industry is possible and that further interdisciplinary research can produce both the incremental improvements necessary to be sustainable and the breakthrough advancements that can revolutionize the production of advanced biofuels."[305] The report documents progress achieved in many of the areas targeted, including the isolation of new algae strains with superior production potentials, and new innovations in cell harvesting and oil extraction methods that dropped the cost of produced fuel from estimates of over $50 per gallon before the project was funded, to below $8 per gallon using the new strain.[306] Given what appears to be substantial progress in a short time period, it is disappointing that DOE has not continued funding. The NAABB's demise exemplifies the failure of the U.S. federal government to maintain its commitment to renewable energy research and infrastructure development since ARRA-funded projects completed their initial funding periods.

Other prominent public-private partnerships in the biofuels area include the Energy Biosciences Institute (EBI), funded in 2007 by a $500 million, ten-year grant by fossil fuels industry leader British Petroleum (BP).[307] This consortium includes three public entities (Lawrence Berkeley National Laboratory (LBNL), the University of California, Berkeley, and the University of Illinois), and is targeting a broad range of biofuels research areas, including algaculture.[308] The public partners acquire intellectual property rights to inventions, while BP retains an automatic nonexclusive license in exchange for funding the work. Another example is the algae-focused Arizona Center for Algae Technology and Innovation (AzCATI),[309] which was created by a grant from Science Foundation Arizona (SFAz), a 501(c)(3) public/private nonprofit organization created from the collaboration of three Arizona CEO business organizations, which commit to funding SFAz's core costs via corporate and individual philanthropy.[310] SFAz leverages funds from state, federal, industry and philanthropy sources to link industry needs

---

[303] A prominent example is the decision by Sapphire Energy to emphasize coproducts over biofuels production, driven at least in part by the recent collapse in crude oil prices. Bigelow, *supra* note 122.

[304] NAT'L RES. COUNCIL, *supra* note 38.

[305] Olivares, *supra* note 301, at 27.

[306] *Id.* at 15-24.

[307] *Energy Biosciences Institute*, U. CAL. BERKLEY, http://vcresearch.berkeley.edu/research-unit/energy-biosciences-institute (last visited Mar. 24, 2017).

[308] The EBI has been described as the largest biofuels public-private partnership in the world. *Id.*

[309] *See generally About Us*, ARIZ. CTR. FOR ALGAE TECH. & INNOVATION, azcati.com/about (last visited Mar. 24, 2017).

[310] *See generally Home,* SCI. FOUND. ARIZ., www.sfaz.org (last visited Mar. 24, 2017).

with university research.[311] The AzCATI program was funded by a $7.7 million grant from SFAz, establishing a national facility on the Arizona State University campus. From this investment, AzCATI has generated $35 million in state and federal funding, including a $15 million DOE grant. A new private firm, Heliae, Inc. was also spun off from this investment.[312]

NAABB, EBI and AzCATI provide models for three distinctive public-private partnership strategies in the algaculture and biofuels fields. If these prominent examples provide any guide to what will be successful in the future, they clearly counsel that reliance on too much federal government funding is not likely a winning strategy. However, over-reliance on a single industry partner, as at EBI, also appears hazardous should that entity decide that its goals are not being met. The AzCATI model, in contrast, has the most broadly-based network of funding and appears to be on solid ground because it generates its own income stream by providing services to the industry community.[313] Much of AzCATI's income comes from state contracts.[314] Through these contracts, public investment from Arizona state coffers is matched with contributions from private sector entities. Arizona, through this innovative mechanism, is clearly positioning itself as a leader in the algaculture industry.

3. Algaculture as Agriculture

Large-scale cultivation of algae has many features in common with aquaculture, an industry that was first designated as a branch of agriculture by Congress in the 1977 Farm Bill.[315] In the National Aquaculture Act of 1980, enacted to provide for the development of aquaculture in the United States, aquaculture was defined as the propagation and rearing of aquatic species in controlled or selected environments,[316] where aquatic species include fish, amphibians, reptiles, and aquatic plants.[317] It is not clear whether algae fit this definition.[318] A definitive

---

[311] SFAz's total income in 2007-2014 was nearly $150 million, of which 95% was invested into its programs. SCI. FOUND. ARIZ., SEVEN-YEAR IMPACT REPORT SUMMARY: A GLOBALLY COMPETITIVE ARIZONA 2 (2014), http://www.sfaz.org/wp-content/uploads/2015/05/7YearImpactReport-ScienceFoundationArizona1.pdf.

[312] *About Us*, HELIAE, heliae.com/company (last visited Mar. 24, 2014).

[313] The ATP^3 algae testbed provides education and training, analytical services to measure algal growth, biomass production and maintenance assistance, and other programs of utility to the algaculture community. ATP^3 provides third party validation on production metrics for algaculture firms. ATP^3 is funded by the DOE and managed by AzCATI. *See generally Service*, ALGAE TESTBED, atp3.org/services/ (last visited Mar. 24, 2017); Press Release, Algae Testbed, Blue Ocean Partners with AzCATI and ATP^3 (July 24, 2014), atp3.org/news/blueocean-partners-with-azcati-and-atp3/.

[314] SCI. FOUND. ARIZ., *supra* note 310.

[315] 7 U.S.C. § 3103(9)(D) (2017).

[316] 16 U.S.C. § 2802(1) (2017).

[317] 16 U.S.C. § 2802(3). *See generally Aquaculture*, NAT'L OCEANIC & ATMOSPHERIC ADMIN., http://www.nmfs.noaa.gov/aquaculture/index.htm (last visited. Mar. 24, 2017).

[318] This is because aquatic plants, like terrestrial plants, contain a vascular structure for internal transport of water and nutrients. Neither microalgae nor the much larger macroscopic algae (such as seaweeds and kelps) possess such a structure. All algae are in a separate phylogenetic kingdom, the Protista, while all plants are in the Kingdom Plantae. *See Algae v. Plants*, SIMPLY SCI. (June 2, 2011), http://simply-science-nbep.blogspot.com/2011/06/algae-vs-plants.html. However, it is uncertain whether Congress really intended to exclude algae from aquaculture. A popular source describes algae (and mosses) as "non-vascular" plants. *Non-Vascular Plant*, WIKIPEDIA (last updated Mar. 6, 2017), https://en.wikipedia.org/wiki/Non-vascular_plant.

resolution of this question by USDA or Congress would be helpful since it could determine whether algaculture comes under the regulatory auspices of the 1980 law.[319]

The USDA administers many programs to support both the food and energy aspects of agriculture operations in the United States. In addition to the BRDI and Sun Grant mechanisms for funding basic research,[320] USDA offers three other programs that support biofuels, two of which are relevant to algaculture.[321] First, the biorefinery, renewable chemical, and biobased product manufacturing assistance program (Biorefinery program) assists in the development of new and emerging biofuels.[322] It provides loan guarantees to support the development of new manufacturing facilities for any advanced biofuel, including biodiesel from algae. The selection criteria for loans under this program do not require that the new biofuels technology already be established at the commercial scale, although they do demand a technical and economic feasibility analysis conducted by a third party.[323] This Biorefinery program can provide an important boost to the developing algaculture industry; a good example is the $54.5 million loan guarantee provided to Sapphire Energy, Inc. for the development of its pilot facility in New Mexico, in December, 2009.[324] The Biorefinery program, however, has limited funding of just $50 million for each of the years 2015 and 2016.[325] Congress should expand this investment significantly in upcoming years to accelerate the transition of algaculture from pre-commercial to commercial status.

The Bioenergy Program for Advanced Biofuels provides subsidies to producers based on the formation of a contract with USDA that demands proof that the fuel has been produced.[326] The amount of the payment depends on the quantity and duration of production and the extent to which the fuel has an energy content that is nonrenewable.[327] Unfortunately, funding was cut dramatically in the 2014 Farm Bill, from $105 million in 2012 to $15 million per year in 2014 to 2018.[328] The program could provide valuable support for algaculture after commercialization is achieved. Restoration of funding to prior levels or above would provide a positive signal for investors in advanced biofuels generally.

It was recently argued that the USDA should grant algae a more defined place in agriculture so that the industry can better benefit from its programs.[329] Unlike other bioenergy crops, such as corn and soybeans, algae lacks an official position

---

[319] *See supra,* note 317.

[320] *See generally supra* Section IV.B.1.

[321] The third program is The Biomass Crop Assistance Program (BCAP), which promotes the recovery of renewable biomass harvested directly from the land. The program provides payments to assist agricultural and forest land owners to collect and transport eligible biomass material to processing facilities. 7 U.S.C. § 8111.

[322] 7 U.S.C. § 8103 (2017).

[323] 7 U.S.C.A. §8103(d)(B)&(C).

[324] *Sapphire Energy Pays Back USDA Loan Guarantee*, ALGAE INDUS. MAG. (July 30, 2013), http://www.algaeindustrymagazine.com/sapphire-energy-pays-back-usda-loan-guarantee/.

[325] 80 Fed. Reg. 36,410, at 36,412.

[326] 7 U.S.C. § 8105(c) (2017).

[327] 7 U.S.C. § 8105(d).

[328] 7 U.S.C. § 8105(g).

[329] Trentacoste et al., *supra* note 243.

within title 7 of the U.S. Code.[330] For example, Congress has decided that it is in the national interest to strengthen the soybean's position in existing markets and to develop new markets for this crop.[331] Assessments in the amount of 0.5% of sales are levied on soybean producers, and these revenues support a program of promotion, research, consumer information, and industry information.[332] A United Soybean Board exists to review and implement the program.[333] Thus, investors in the soybean industry have the certainty of knowing that Congress values the enterprise, and this provides a measure of stability that diminishes perceived risks. Certainly, Congressional action to add algaculture to title 7 could offer similar benefits, especially if coupled with promotional funding so that algae investors would not need to pay the additional cost. This could form part of a more concerted federal interagency effort to recognize and promote the transition of algal biofuels to commercial scale.[334] Of course, state efforts to institutionalize algaculture-as-agriculture would also be beneficial. Ohio, Arizona and Illinois have each already acted to promote the emerging industry through lowering of property taxes and favorable zoning ordinances that also apply to traditional farms,[335] thus positioning themselves as preferred sites for investors.

Algaculture has end uses in both the energy and food sectors, since distinct, highly specialized strains are available for each purpose separately. Algae are presently eligible for some agricultural support programs if they are grown to generate neutraceutical food supplements or animal feed, but not if the purpose of the particular operation is to generate biofuel.[336] For example, the USDA operates a Noninsured Crop Disaster Assistance Program (NAP), for which aquaculture species that are grown as food for human consumption are eligible.[337] This could include large multicellular algae (such as seaweed) or microalgae such as *Spirulina* (used as a dietary supplement). However, other species of microalgae that are grown for biodiesel do not qualify for assistance, raising important general questions about U.S. agriculture policy. The framework in which USDA operates was established when food was the only product of the land—but this is changing rapidly, as is most evident from the dedication of some 40% of corn acreage to ethanol production. Although new engineered hybrid corn species are emerging that are better suited to ethanol production,[338] in general much of the commodity corn produced for food and feed purposes can also be fermented to ethanol, so the many farm support benefits given to corn are essentially provided to a crop that has a mixed use in food and energy sectors. New third generation engineered

---

[330] *Id.* at 306.

[331] 7 U.S.C. §§ 6301-6311 (2017).

[332] 7 U.S.C. § 6301; 7 C.F.R. § 1220.223 (2017).

[333] 7 U.S.C. § 6304.

[334] Trentacoste et al., *supra* note 243, at 312-13.

[335] *Id.* at 311, 313.

[336] *Id.* at 309.

[337] 7 C.F.R. § 1437.303(a)(1).

[338] Holly Jessen, *Field-Grown Enzymes*, ETHANOL PRODUCER MAG. (Sept. 23, 2013), http://www.ethanolproducer.com/articles/10278/field-grown-enzyme.

crops are now also envisioned to produce pharmaceuticals and other commodities.[339] Expanding federal supports to non-food purposes of agricultural lands would benefit all growers of crops for energy, medicinal and commodity production. For algae and some cellulosic ethanol plant sources, these programs should apply to nonarable as well as arable land.

If algaculture becomes more fully situated within the pantheon of U.S. agriculture, and achieves commercial success and large-scale penetration into the biofuels sector, then—like other types of agriculture—it will also be subject to federal and state pollution control statutes. In particular, algaculture investors and firms will need to be cognizant of agriculture-specific programs under the Clean Water Act.[340] For example, discharges from aquaculture facilities acting as point sources will require a National Pollutant Discharge Elimination System (NPDES) permit.[341] This is relevant to commercial scale algaculture because of the benefits associated with using nutrient-rich effluent streams that would normally constitute wastes for processing at sewage treatment plants. For example, it is possible to envision that municipal effluent waste streams, especially from combined sewer systems that mix rainwater runoff, domestic sewage, and industrial wastewater,[342] could be transported through discrete conveyances (point sources) to feed algaculture ponds or PBRs at an industrial scale. This could beneficially reduce both waste treatment and freshwater demand burdens for the over 772 cities that use such combined systems and that could potentially host nearby algaculture operations.

Effluent streams discharged from algaculture facilities will likely also be subject to Clean Water Act regulation as point sources, since the general agricultural exemption, in which farm runoff is treated as a nonpoint source, would probably not apply to the enclosed ponds or PBRs.[343] However, given the benefits associated with recycling pondwater and recovering unused portions of biomass for anaerobic digestion, coproduct synthesis, or other uses, the amount of polluting runoff should not be large. Algaculture should ultimately function as a component of a future economy in which waste streams are both absorbed and recycled, with minimum unwanted discharge to the environment.[344]

V. CONCLUSION

The end may be in sight for ethanol's domination of the U.S. biofuels industry. Initially enabled by the political power of farm states and an available manufacturing process, as the twenty-first century progresses the industry is likely to be increasingly challenged by decreased market demand caused by electrification of

---

[339] J. FERNANDEZ-CORNEJO ET AL., U.S. DEP'T AGRIC., ECON. RES. SERV., GENETICALLY ENGINEERED CROPS IN THE UNITED STATES (Feb. 2014).

[340] *See generally Agriculture*, EVTL. PROT. AGENCY (last updated Mar. 16, 2017), http://www.epa.gov/agriculture/.

[341] 33 U.S.C. §§ 1311, 1342 (describing NPDES permit requirements).

[342] ENVTL. PROT. AGENCY, COMBINED SEWER OVERFLOWS (CSOS), https://www.epa.gov/npdes/combined-sewer-overflows-csos (last visited Mar. 24, 2017).

[343] 33 U.S.C. § 1362(14) explicitly excludes agriculture stormwater discharges and return flows from irrigated agriculture from the definition of a "point source."

[344] NAT'L RES. COUNCIL, *supra* note 38, at 83-86.

the light vehicle fleet. This dynamic has arisen from both aggressive new fuel efficiency standards and better technology that is reducing costs and improving driving efficiency of electric cars. However, reducing emissions from the distinct diesel fuels market sector to meet deep decarbonization goals still requires urgent attention from law and policymakers. A very effective way for state and federal government to further the development of biodiesel is to provide incentives for developing the technology improvements that will permit diesel-burning engines to function as well on B100 biodiesel as they presently do on petroleum diesel. On the supply side, reformulation of the federal renewable fuels standard to provide greater credits for biodiesel over ethanol will promote increased production of biodiesel and, perhaps, the shifting of land use from corn to soybeans, allowing increases in crop biodiesel production without making further inroads into arable land. Further, despite substantial challenges in providing sufficient nutrients to industrial-scale cultures, increased federal support for research and development into algae is well worth the investment, because algaculture also offers the potential for wastewater remediation and production of other commodity products. State-level policies, including low-carbon fuel standards that follow the California model, and innovative public-private partnerships such as the AzCATI program in Arizona, also have tremendous potential to drive the regional development of biodiesel markets. Finally, it is worth noting that rapid growth of the domestic renewable biodiesel industry, in addition to its environmental benefits, will also accelerate the U.S. transition to energy independence. This should provide some common ground for lawmakers to work from, as they develop policies that both addresses climate change and satisfies the needs of commerce.