From Geology to Agriculture: How Biofuels Are Reshaping the Geography of Transportation Fuel Production

Introduction

Recent energy crises have renewed interest in biofuels not only as renewable energy sources but also as tools for improving energy security.[1] Conflicts or shipping disruptions thousands of miles away can cause fuel shortages and increase transportation costs, affecting the daily lives of people around the world. While these situations are often discussed as political or economic issues, they also reveal an important geographic reality, that transportation fuel production is constrained differently across regions. Petroleum production depends on the location of geological deposits and is therefore concentrated in relatively few regions, whereas biofuel production systems can develop wherever suitable environmental conditions are combined with agriculture, technology, infrastructure, and public policy. Despite growing interest in electric vehicles, biofuels remain the dominant renewable fuel used in transportation. According to the Renewable Energy Policy Network for the 21st Century (REN21), biofuels account for 3.5% of total transportation energy consumption, compared to 0.4% from renewable electricity. As a result, biofuels supplied about 89% of all renewable energy used in transportation.

[1] "Renewable Energy Market Update - June 2023." *Analysis - IEA*, 1 June 2023, www.iea.org/reports/renewable-energy-market-update-june-2023.

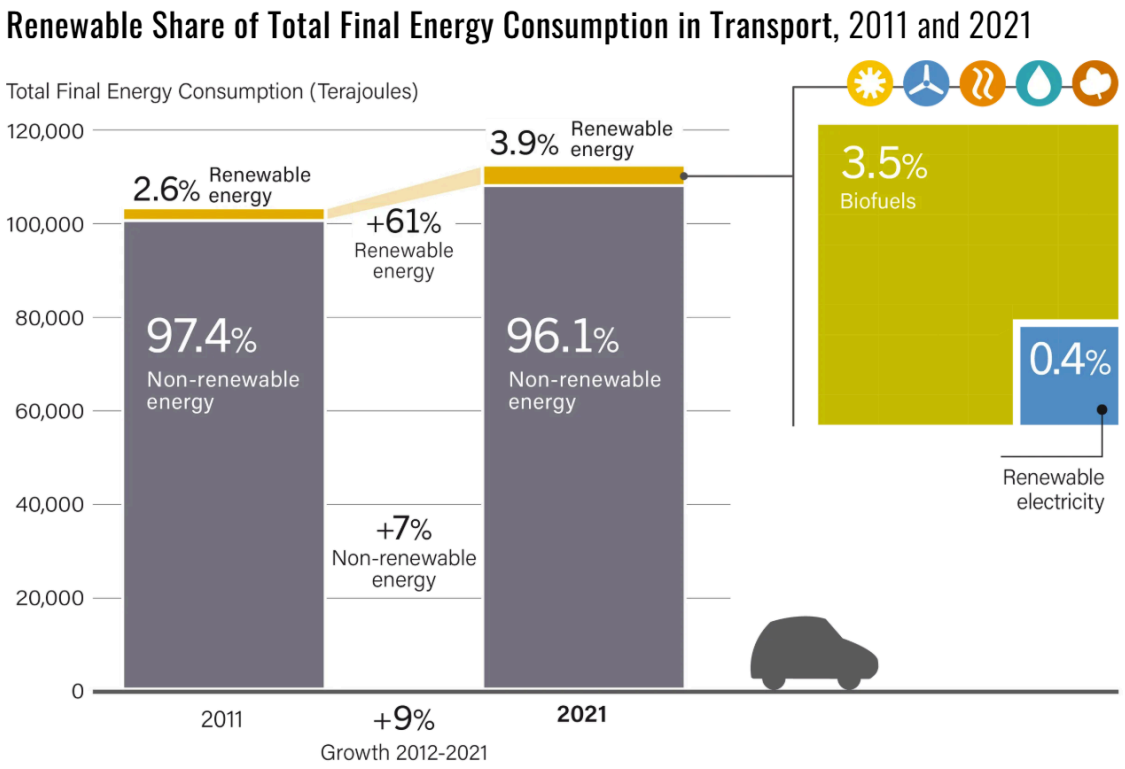

Figure 1. Renewable share of global transportation energy consumption. Source: REN21 (2024).

This reflects the importance of liquid fuels in transportation and the ability of biofuels to be used in existing vehicle fleets and sectors that are difficult to electrify, such as aviation, maritime transport, and heavy freight. Biofuel discussions often focus on climate change, emissions technology, or economics. However, one key difference between biofuels and petroleum is geographic. Petroleum production depends on the location of geological deposits, whereas biofuel production depends on climate, land availability, agricultural development, and human decision-making. Oil still provides about 90% of the world's transportation fuel and roughly one-third of the global energy supply. Understanding how much these human choices can reshape transportation fuel geography is the central question of this study.

This study approaches biofuels through the lens of human geography. Through a case study of Brazil and examples from the United States, India, Thailand, Europe, and other

biofuel-producing regions, together with a primary-source interview with Silvia Mine of the Centro de Tecnologia Canavieira (CTC), one of Brazil's leading sugarcane research organizations, this study investigates how geography and human decisions shape biofuel production and use.

Biofuels and Transportation Geography

Despite the rapid growth of renewable energy, transportation systems worldwide still rely heavily on liquid fuels. Petroleum-based fuels continue to provide approximately 90% of global transportation fuel consumption,[2] while biofuels remain the main renewable transportation fuel.[3] Unlike most renewable energy sources, such as wind, solar, and hydropower, which primarily generate electricity, biofuels can directly replace gasoline, diesel, and aviation fuel, making them important to transportation geography. While renewable electricity has expanded rapidly in passenger transportation, sectors such as aviation, maritime transport, and heavy freight still largely depend on liquid fuels. One advantage of biofuels is that they can often be integrated into existing transportation systems that rely on fuel combustion.

According to the U.S. Energy Information Administration, biofuels are transportation fuels produced from biomass.[4] Common examples include ethanol from sugarcane or corn, and biodiesel produced from vegetable oils. Unlike petroleum, which depends on the location of geological deposits, biofuel production depends on agricultural geography, including climate,

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[2] *Statistical Review of World Energy*. Energy Institute, www.energyinst.org/statistical-review. Accessed 10 June 2026.

[3] *Global Bioenergy Statistics Report 2025*. World Bioenergy Association, 18 Nov. 2025, www.worldbioenergy.org/uploads/251118%20GBSR%20Summary.pdf.

[4] "Biofuels explained." Biofuels explained - U.S. Energy Information Administration (EIA), 28 Feb. 2024, www.eia.gov/energyexplained/biofuels/ .

land availability, water resources, crops, technology, and human choices. Biofuels do not eliminate geographic constraints, but they allow societal decisions to play a greater role in transportation fuel production. As noted by Silvia Mine, biofuel production is not limited to sugarcane. Different regions can produce different biofuels depending on local agricultural conditions, using feedstocks such as sugarcane, corn, vegetable oils, and crop residues. Biofuels allow a wider range of regions to participate in transportation fuel production than would be possible through petroleum alone.[5]

Brazil: Reshaping Transportation Fuel Geography

Brazil provides one of the clearest examples of how societal decisions can influence the geography of transportation fuels. The country has large offshore oil reserves and is also one of the world's largest producers of sugarcane ethanol, demonstrating how biofuels can complement rather than replace petroleum-based fuel systems. Brazil has highly suitable agricultural conditions, including a tropical climate, abundant rainfall, fertile soil, extensive agricultural land, and long-standing agricultural expertise. Sugarcane cultivation has existed in Brazil since the 1530s. During the colonial period, sugarcane, one of Brazil's major crops, was primarily used for sugar production. Later, its production became concentrated in the country's Center-South, where climate, infrastructure, and market access supported the expansion of the sugar industry.

[5] Mine, Silvia. Regulatory and Government Affairs Lead, Centro de Tecnologia Canavieira (CTC). Personal interview. June 4, 2026.

Figure 2. Distribution of ethanol production facilities in Brazil in 2024. Source: *Ethanol Producer Magazine* (2024).

Brazil's climate and soils provided favorable conditions for sugarcane cultivation, but human decisions determined how those favorable conditions would be used. Investments in technology, research, infrastructure, and public policy transformed that geographic potential into a large-scale ethanol industry.[6] Industrial-scale sugarcane ethanol production existed before the oil crisis. During this time, in the 1920s and 1930s, experiments with blending ethanol into gasoline were already underway, showing that the idea of ethanol as a transportation fuel predated the oil crises of the 1970s. After the oil crisis of 1973-74, Brazil launched Proálcool, a government program that triggered an expansion of ethanol production, ethanol-powered

[6] Mine, Silvia. Regulatory and Government Affairs Lead, Centro de Tecnologia Canavieira (CTC). Personal interview. June 4, 2026.

vehicles, fueling infrastructure, and research investments. The Brazilian government actively promoted ethanol through subsidies, guaranteed purchases, loans, research support, and vehicle incentives. After the launch of Proálcool, ethanol-powered light-duty passenger vehicles grew as consumers responded to lower fuel costs and government incentives. By the mid-1980s, around 90% of new light-duty passenger vehicles sold in Brazil were ethanol-powered. However, in the late 1980s and early 1990s, sugar prices rose, and ethanol shortages occurred, raising concerns about fuel availability. Consumers began purchasing more gasoline vehicles again, and ethanol-only vehicle sales declined sharply. In response, flex-fuel vehicles were introduced in 2003. Flex-fuel technology was a turning point because it allowed the same vehicle to operate on gasoline, ethanol, or any mixture of the two. This innovation reduced the risk for consumers because drivers could choose between gasoline and ethanol depending on fuel prices at a given time, allowing ethanol to act as a partial buffer against fluctuations in petroleum prices. As a result, flex-fuel vehicles encouraged broader ethanol adoption throughout Brazil's transportation system. By 2009, about 90% of new passenger cars sold in Brazil were flex-fuel vehicles. As demand for flex-fuel technology increased, manufacturers expanded the technology from compact economy cars to larger and more expensive models. This evolution showed that government policy alone could not reshape transportation geography. Consumer acceptance and industry adaptation were also necessary to integrate biofuels into Brazil's transportation system. Brazil developed an ethanol transportation system built upon centuries of sugarcane cultivation, government investment, and transportation-system adaptation.[7] Instead of using ethanol only as a gasoline additive, ethanol became integrated into Brazil's transportation system through flex-fuel

[7] Yu, Abraham Sin Oih, et al. "Evolution Of Flex-Fuel Technology: A Case Study On Volkswagen Brazil." *Arquivo ANPAD*, 25 Sept. 2010, arquivo.anpad.org.br/diversos/down_zips/53/gct1500.pdf.

vehicles, fueling infrastructure, and consumer adoption. This made the country less vulnerable to petroleum imports and international fuel disruptions. In 2026, *The Economist* called Brazil's ethanol industry a "secret weapon" against oil shocks. The geographic significance is that Brazil could use a domestic agricultural resource to reduce its exposure to global fuel disruptions and price volatility.[8]

Brazil's experience illustrates that favorable climate, soils, and land availability created the conditions for sugarcane cultivation, but technological innovation, public policies such as Proálcool, infrastructure development, and transportation-system adaptation transformed those geographic advantages into one of the world's largest ethanol industries.[9] Brazil demonstrates that biofuel geography is shaped not only by geographic conditions but also by policy, technology, and consumer decisions.

Comparative Perspectives: Biofuels Beyond Brazil

Brazil is not unique. Similar relationships between geography and human decision-making can be observed elsewhere. Biofuel production has developed across many regions of the world, but the crops used and the transportation strategies that emerge may vary according to geography and policy. The interview suggests that ethanol is not limited to sugarcane. Depending on regional geography, ethanol can be produced from sugarcane, corn, wheat, cassava, sorghum, and sugar beet. The United States provides a useful comparison with Brazil. The U.S. is both a major oil and ethanol producer. Biofuels can supplement transportation

[8] "Brazil has a secret weapon against oil shocks." Brazil has a secret weapon against oil shocks - The Economist, 26 Mar. 2026, www.economist.com/the-americas/2026/03/26/brazil-has-a-secret-weapon-against-oil-shocks .
[9] Karp, Susan G., et al. "Bioeconomy and biofuels: the case of sugarcane ethanol in Brazil." *Bioeconomy and biofuels: the case of sugarcane ethanol in Brazil - Karp*, 19 Feb. 2021, scijournals.onlinelibrary.wiley.com/doi/10.1002/bbb.2195.

fuel production even in countries that already possess large oil reserves. According to the World Bioenergy Association, global ethanol production reached 118 billion liters in 2024, with the U.S. and Brazil together accounting for about 80% of global output.[10] Most U.S. ethanol is produced from corn, as it is the most suitable crop for the temperate climate. In the United States, ethanol is used primarily as a gasoline blend (E10, E15), and the transportation system remains overwhelmingly gasoline-centered. The United States increased ethanol production without changing how Americans fuel their vehicles. Both countries became major ethanol producers, but they integrated ethanol into transportation systems in different ways. Similar levels of biofuel production can therefore create different transportation geographies depending on policy choices, infrastructure development, and consumer behavior. Europe relies heavily on rapeseed biodiesel, Indonesia and Malaysia on palm-oil biodiesel, while India and Thailand rely on sugarcane ethanol. Thailand also illustrates how favorable geography alone is not enough. Although its ethanol industry is much smaller than Brazil's, favorable conditions for sugarcane cultivation, combined with public blending policies, support domestic fuel production, reduce dependence on imported fuels, and strengthen energy security. Together, these examples suggest that biofuel geography emerges from the interaction of geographic conditions and human choices rather than from either factor alone.[11]

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[10] Global Bioenergy Statistics Report - 12th Edition, 2025. *251118 GBSR Summary.pdf*, 18 Nov. 2025, www.worldbioenergy.org/uploads/251118%20GBSR%20Summary.pdf .

[11] Ritchie, Hannah, and Pablo Rosado. "Bioenergy and Biofuels." *Bioenergy and Biofuels - Our World in Data*, 2026, ourworldindata.org/bioenergy-biofuels

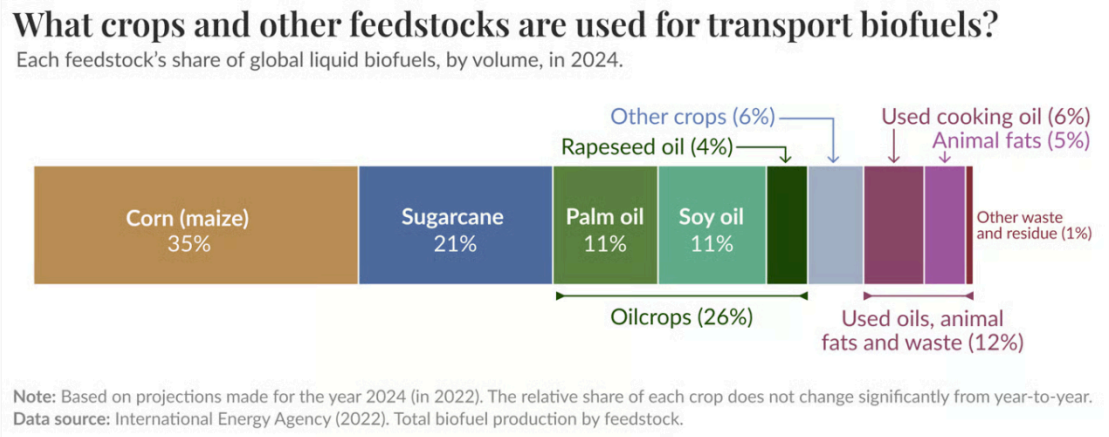

Figure 3. Major crops and feedstocks used in global biofuel production. Source: *Our World in Data* (2025).

Geographic Constraints and Human Influence

The experiences of Brazil, the United States, and other biofuel-producing countries suggest that societies can influence the geography of transportation fuel production to a much greater extent than is possible with petroleum. However, societal decisions operate within environmental and geographic constraints rather than replacing them. Oil can only be extracted where geological deposits are found. Biofuel production differs because societies can decide which crops to cultivate, where to invest, and how to build the infrastructure needed for production. Geography still matters, but societies have much greater influence over where and how biofuels are produced than they do over petroleum production. As mentioned by Silvia Mine, technological advances initially increase productivity in regions where geography is already favorable, before gradually expanding into less favorable areas. The expansion of sugarcane cultivation from traditional areas of São Paulo into parts of Brazil's Center-West illustrates how technology can expand the geographic range of biofuel production without eliminating environmental constraints. Despite these advances, technology does not eliminate geography. Iceland is unlikely to become a major producer of tropical biofuels, and Singapore

cannot replicate Brazil's sugarcane-based ethanol system because climate, available land, and agricultural conditions still matter. Human choices can expand biofuel production, but geography continues to set boundaries on what is possible. According to Karp et al. (2021), factors such as rainfall, sunlight, temperature, soil quality, altitude, and topography continue to influence where biofuel production can be successfully developed.[12] Geography influences more than where biofuels are produced. From a human geography perspective, societal decisions can also shape how biofuels are distributed, blended, and consumed.

Policy, Industry, and Transportation Systems

For decades, Brazilian gasoline has contained some of the world's highest ethanol blending rates (20%-27%), and even drivers who never use pure ethanol still consume fuel partially produced from sugarcane.[13] Because ethanol was blended directly into gasoline, many consumers used biofuels without changing their fueling habits. The introduction of flex-fuel vehicles in 2003 allowed drivers to fuel the same vehicle with ethanol, gasoline, or any mixture of the two, while the move toward E30 gasoline (30% ethanol) in 2025-2026 further increased ethanol use. The policy was intended to reduce dependence on gasoline imports and strengthen national fuel security. Brazil is not alone in adopting blending policies. In 2026, India introduced E85 fuel (85% ethanol) and priced it lower than the standard E20 blend to encourage the use of flex-fuel vehicles.[14] Turning a crop into a transportation fuel requires more than crop selection

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[12] Karp, Susan G., et al. "Bioeconomy and Biofuels: The Case of Sugarcane Ethanol in Brazil." *Biofuels, Bioproducts and Biorefining,* 19 Feb. 2021, scijournals.onlinelibrary.wiley.com/doi/10.1002/bbb.2195.

[13] "Biofuels explained." *U.S. Energy Information Administration (EIA)*, 28 Feb. 2024, www.eia.gov/energyexplained/biofuels/.

[14] Lane, Jim. "Biofuels Mandates Around the World 2026." *The Daily Digest*, 29 Dec. 2025, biofuelsdigest.com/biofuels-mandates-around-the-world-2026/.

and ethanol production. It also requires affordable prices, vehicles capable of using ethanol blends, and distribution networks that make the fuel widely available.[15] Biofuel blending mandates have been adopted by dozens of countries across the Americas, Europe, Asia, Africa, and Oceania, indicating that biofuels are becoming an increasingly important component of transportation fuel systems worldwide. [16]

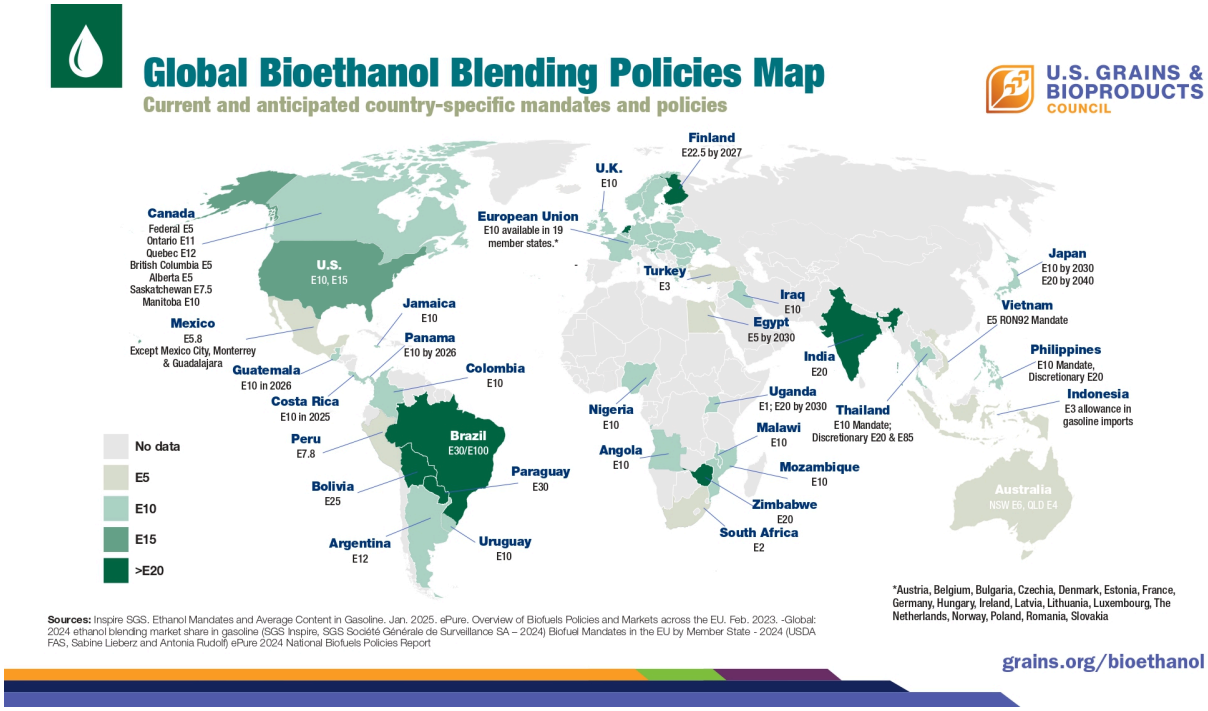

Figure 4. Global bioethanol blending policies and mandates. Source: U.S. Grains & BioProducts Council using IEA policy data.

The Brazilian experience also illustrates the importance of private-sector participation. Government policies can encourage biofuel production and consumption, but transportation

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[15] Reuters. "India launches gasoline blended with 85% ethanol at a Lower Price." *Reuters*, 5 June 2026, www.reuters.com/business/energy/india-launches-gasoline-blended-with-85-ethanol-lower-price-2026-06-05/

[16] *Policies Database*. International Energy Agency, www.iea.org/policies?type[]=Biofuel+blending+mandate. Accessed 10 June 2026.

systems cannot change unless manufacturers produce ethanol-fueled vehicles that consumers are willing to buy. Under Proálcool, Brazil’s automakers were encouraged through government incentives and industry agreements to produce ethanol-fueled vehicles. As ethanol became part of Brazil’s fuel system, manufacturers continued adapting vehicle technologies to local conditions. Companies such as Toyota later developed ethanol-hybrid models that combine biofuels with electrification, adapting vehicle technologies to Brazil’s ethanol-based fuel infrastructure in response to consumer demand.[17] Historically, biofuels have been used in road transportation. However, the emergence of Sustainable Aviation Fuel (SAF) may extend the use of biofuels to aviation, one of the most difficult sectors to electrify. If adopted on a larger scale, SAF could allow agricultural regions to play a greater role in aviation fuel production, extending the geographic influence of biofuels beyond road transportation.[18] Biofuels, therefore, illustrate a unique form of energy geography in which environmental conditions remain important, but human choices play a much larger role in determining where transportation fuel is produced and how it is used. Petroleum geography is largely inherited, whereas biofuel geography is partly inherited and partly created through agriculture, infrastructure, technology, and public policy.

Conclusion

This study examined the extent to which human decisions can influence the geography of transportation fuel production through biofuels. The Brazilian case study and examples from the United States, India, Thailand, and Europe demonstrate that although geographic conditions

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[17] "Brazil's Unique Decarbonization Efforts Build on 50 Years of Technological Progress." *Top | Toyota Times*, 31 Aug. 2023, toyotatimes.jp/en/spotlights/1039_1.html.

[18] "Net Zero CO2 Emissions Roadmap." *Finance-net-zero-roadmap.pdf*, Sept. 2024, www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/finance-net-zero-roadmap.pdf .

remain important, societal choices play a much greater role in shaping biofuel production than they do in shaping petroleum production. Petroleum production remains where nature placed it, whereas biofuel feedstocks can be introduced into suitable agricultural regions chosen by humans, subject to environmental constraints, as explained by Silvia Mine.

Biofuels do not eliminate geography, but they give societies greater influence within existing geographic limitations. Petroleum production depends on fixed geological deposits, while biofuels can be produced from agricultural resources shaped by crop selection, technological innovation, infrastructure development, and public policy. As a result, biofuels expand participation in transportation fuel production beyond the regions favored by geology alone. Increasingly, biofuels are also viewed as tools for energy security, fuel diversification, and reducing vulnerability to fuel-market disruptions. Viewed through the lens of human geography, biofuels illustrate how societies can reorganize transportation fuel systems while continuing to operate within geographic constraints.

Geography still matters, but unlike petroleum, biofuels give societies greater control over where transportation fuels are produced and how they are used. Petroleum reflects the geography that societies inherit, while biofuels reflect a geography that societies can partially shape.

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