Comparative efficiency and driving range of light- and heavy-duty vehicles powered with biomass energy stored in liquid fuels or batteries

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This study addresses the question, "When using cellulosic biomass for vehicular transportation, which field-to-wheels pathway is more efficient: that using biofuels or that using bioelectricity?" In considering the question, the level of assumed technological maturity significantly affects the comparison, as does the intended transportation application. Results from the analysis indicate that for light-duty vehicles, over ranges typical in the United States today (e.g., 560–820 miles), field-to-wheels performance is similar, with some scenarios showing biofuel to be more efficient, and others indicating the two pathways to be essentially the same. Over the current range of heavy-duty vehicles, the field-to-wheels efficiency is higher for biofuels than for electrically powered vehicles. Accounting for technological advances and range, there is little basis to expect mature bioelectricity-powered vehicles to have greater field-to-wheels efficiency (e.g., kilometers per gigajoule biomass or per hectare) compared with mature biofuel-powered vehicles.

With ever increasing indications that resource use is exceeding the earth's capacity (1), it is clear that humankind must initiate and largely achieve a "sustainability revolution" within the current century (2). A shift to energy sources involving very low or zero carbon emissions is a key part of this challenge, with transportation among the most challenging sectors. Transportation accounts for about 19% of global energy use and 23% of energy-related CO_2 emissions today (3). Given current trends, global transportation energy use is projected to increase nearly 50% by 2030 and more than 80% by 2050 (3).

Among sustainable primary energy alternatives, cellulosic biomass can be converted to either high-performance liquid fuels or electricity, or both. In recognition of this, as well as land constraints associated with large-scale biomass production, an important question regarding bioenergy for transportation is, "Which field-to-wheels pathway is more efficient: that using biofuels or that using bioelectricity?"

A key aspect of any such comparison is the assumed level of technological maturity for the various pathway alternatives considered. In this case, electricity generation is a rather mature technology, as is that for vehicles with energy stored as liquid fuels, although the efficiency of both may well increase in the future due to a combination of technological advances, changes in economic incentives (affected by policy and other factors), and consumer choice. By contrast, on-vehicle battery energy storage and cellulosic biofuel production are not mature with large improvements anticipated (4, 5).

Here we compare the efficiency of mobility chains based on cellulosic biomass featuring transportation energy storage via biofuels and biopower. We consider light-duty and heavy-duty vehicles (LDVs and HDVs) at both current and advanced levels of technological maturity.

Table 1 lists field-to-tank efficiencies—e.g., megajoules delivered to the vehicle per megajoule of biomass feedstock—for biofuel and biopower. In feedstock conversion to liquid fuel for current technology, we assumed simultaneous saccharification and fermentation to ethanol, and for future technology, consolidated bioprocessing of cellulose and hemicellulose to ethanol, combined with thermochemical conversion of residual lignin to Fischer–Tropsch diesel and gasoline (6). For power generation, we assumed a conventional Rankine steam cycle for current technology, and an integrated gasification combined cycle for future technology (7). For both current and future technology, we used values from the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (8) for the efficiency of transporting and distributing liquid fuel from the biorefinery to the vehicle fuel tank, and the power transmission efficiency. The Nissan Leaf serves as the basis for battery charging technology (9); for future technology, we used an efficiency value corresponding with a current-pumped charging system developed by Chen et al. (10).

In our assessment of LDVs, we used two scenarios for current technology, one in which a Toyota Camry [an internal combustion engine vehicle (ICEV)] is paired with a Nissan Leaf [a battery electric vehicle (BEV)], and another in which a Toyota Prius (a hybrid ICEV) is paired with a Leaf. For future technology, we developed scenarios based on two prominent reports, a 2013 study by the National Research Council (NRC) (11) that considered six LDV types—three cars (small, medium, and large), two multipurpose vehicles (small and large), and a light-duty truck—and a 2008 study from Heywood and coworkers at the Massachusetts Institute of Technology (MIT) (12) that evaluated a midsized car and a light-duty truck. The NRC scenarios used here are based on that study's most aggressive "2050 optimistic" case for which the estimates are "potentially attainable, but will require greater successes in R&D and vehicle design." The MIT study, which has a 2035 timeframe, assumes more moderate, but still significant, technological advances.

Significance

This paper addresses the question, "When using cellulosic biomass for vehicular transportation, which field-to-wheels pathway is more efficient: that using biofuels or that using bioelectricity?" Distinguishing features of this study relative to prior work are the consideration of technological maturity, both in fuel/electricity production and vehicular advancement, as well as the intended transportation application. Whereas prior studies have deemed bioelectricity as being the more efficient option, we find here that, for ranges characteristic of driving patterns in the United States, there is little basis to expect mature bioelectricity-powered vehicles to have greater field-to-wheels efficiency as compared with mature biofuel-powered vehicles.

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Table 1. Field-to-tank stage efficiencies for cellulosic biofuel and biopower

Scenario	Feedstock conversion, MJ energy carrier:MJ biomass	Fuel/power distribution, MJ distributed:MJ energy carrier*	Vehicle charge, MJ onboard:MJ distributed	Field-to-tank efficiency, MJ onboard:MJ biomass[†]
Current biofuel	0.40[‡]	0.996	1	0.398
Current biopower	0.33[§]	0.92	0.85[‖]	0.258
Future biofuel	0.70[¶]	0.996	1	0.697
Future biopower	0.49[§]	0.92	0.95**	0.428

*Estimated based on the Argonne National Laboratory's GREET model (8).

[†] Field-to-tank efficiency represents the product of feedstock conversion, fuel distribution, and vehicle charge efficiencies.

[‡] Laser et al. (31).

[§] Jin et al. (7).

[¶] Laser et al. (6).

[‖] Based on the charge efficiency for the Nissan Leaf (32).

**Chen et al. (10).

Design information for the LDV scenarios is listed in Tables 2 and 3—Table 2 lists BEV weight (without battery), battery-specific energy, and base range (i.e., design range); and Table 3 lists tank-to-wheels fuel economies (average of city and highway driving cycles). The specific energy of the battery for the current technology case is 140 W·h/kg—equal to that of the Nissan Leaf. For the NRC advanced technology case, the battery-specific energy is 200 W·h/kg, which is the long-term goal of the US Advanced Battery Consortium (USABC) for electric vehicles (13). The MIT advanced case uses a value of 150 W·h/kg, the minimum USABC goal for long-term commercialization.

In our evaluation of HDVs, we again developed scenarios built around two prominent studies, a 2008 report by the NRC reviewing the 21st Century Truck Partnership (14), and a 2008 report by the Rocky Mountain Institute (RMI) (15). Each has a comparable estimate for current fuel economy [6.1 miles per gallon (mi/gal) gasoline equivalent for NRC; 5.9 for RMI]. The RMI future case has a higher fuel economy relative to NRC (11.1 versus 10.4 mi/gal gasoline equivalent). We based the scenarios on a class 8 tractor-trailer having a gross weight limit of 80,000 pounds (lb) (16), an unloaded truck weight of 30,000 lb (15), and a fuel tank capacity of 150 gallons (17). The specific energy of the battery for the current technology cases is 110 W·h/kg—comparable to that of the Balqon MX30, a class 8 battery electric truck (18). For the advanced technology cases, the battery-specific energy is 200 W·h/kg—the long-term USABC goal, as noted above. For current technology, we assumed the BEV fuel economies to be 74% higher than that for the ICEVs based on the Balqon MX30. For future technology, we reduced this advantage to 37%, in alignment with light-duty vehicles, for which the ratio of BEV to ICEV efficiency decreases by about half as technology advances to maturity (11, 12). Table 4 lists the HDV hauling efficiency in terms of cargo mass times distance traveled per fuel consumed (e.g., ton miles per gallon).

Table 2. BEV weight, specific energy, and base range

Scenario	Vehicle weight without battery, kg	Battery-specific energy, W·h/kg	Base range, km*
Current			
Nissan Leaf	1,335	140	121
Future: NRC[†]			
Small car	769	200	161
Midsized car	1,041	200	161
Full-sized car	1,143	200	161
Small MPV	1,143	200	161
Large MPV	1,279	200	161
Light-duty truck	1,894	200	161
Future: MIT[‡]			
Midsized car	1,027	150	322
Light-duty truck	1,712	150	322

*Base range for Nissan Leaf represents the Environmental Protection Agency test value for the 2013 model (24). Base ranges for NRC and MIT scenarios represent values used in those respective reports (11, 12).

[†] Values from the NRC (2050 optimistic case) (11).

[‡] Values from MIT (12).

Overall field-to-wheels performance is obtained by taking the product of field-to-tank efficiency (megajoules energy onboard vehicle per megajoules biomass) and tank-to-wheels fuel economy (kilometers per megajoule for LDV; Megagram kilometers per gigajoule for HDV). Tables 5 and 6 list the field-to-wheels performance for LDV and HDV scenarios, respectively. For current LDVs—evaluated at the design range for the Leaf (121 km; 75 mi)—the ratio of biopower-to-biofuel field-to-wheels efficiency is 2.6 and 1.5 for the Camry:Leaf and Prius:Leaf scenarios, respectively. For future LDVs, the ratio is 1.2–1.4 for the NRC scenarios (base range = 161 km; 100 mi), and 1.1–1.2 for the MIT scenarios (base range = 322 km; 200 mi). The ratio is 1.1 for current HDV scenarios and 0.9 for future HDV scenarios. The HDV ratios represent the most conservative upper limit, as they correspond to a fully loaded truck at zero range (i.e., no battery).

Based on these results, one might conclude that LDV transportation using biopower is always more efficient than biofuels, but this does not account for the impact of vehicle range, i.e., the maximum distance traveled on a single battery charge or tank of fuel. Greater ranges require heavier batteries, which in turn require added support weight (19), all of which reduces vehicle efficiency.

LDV battery mass (in kilograms), M_B, is a function of vehicle range (in kilometers), R, the specific energy content of the battery (in megajoules per kilogram), E_B, and the fuel economy of the vehicle (in kilometers per megajoule), FE:

$$M_B = \left(\frac{R}{E_B \cdot FE}\right). \quad [1]$$

As noted above, an increase in range requires a larger battery; the added weight of the battery, however—and the necessary additional support weight—reduces the fuel economy of the vehicle. The fraction increase in vehicle mass (vehicle plus battery plus support weight) relative to the base vehicle mass (i.e., without battery) is

$$\text{fraction mass increase} = \frac{f_S M_B}{M_{vehicle}}, \quad [2]$$

where f_S is a mass compounding factor to account for added support weight associated with the battery. We assumed f_S equals

Table 3. LDV tank-to-wheels fuel economies

	ICEV*		BEV†	
Scenario	mi/gal GE‡	km/MJ	mi/gal GE‡	km/MJ
Current				
Prius/Leaf	49.6	0.65	115.0	1.51
Camry/Leaf	28.7	0.38	115.0	1.51
Future: NRC§				
Small car	160.5	2.11	351.7	4.62
Midsized car	150.9	1.98	302.7	3.98
Full-sized car	130.9	1.72	259.5	3.41
Small MPV	113.6	1.49	238.2	3.13
Large MPV	107.4	1.41	220.1	2.89
Light-duty truck	72.1	0.95	149.7	1.97
Future: MIT¶				
Midsized car	76.9	1.01	140.9	1.85
Light-duty truck	49.1	0.65	91.7	1.20

Values represent a weighted average, assuming 55% city and 45% highway miles. GE, gasoline equivalent.

*Future ICEV is assumed to be hybridized.

†Base BEV range: 75 mi for current, 100 mi for the NRC (11), and 200 mi for MIT (12).

‡Assumes the gasoline lower heating value = 116,090 British thermal unit/gal.

§Fuel economies from the NRC (2050 optimistic case) (11).

¶Fuel economies from MIT (12).

1.5 (i.e., every kilogram of battery requires 0.5 kg of support weight) (12).

The effective fuel economy, FE_e, is determined from this fraction mass increase by using a factor, f_L, that relates the percent increase in mass to the percent decrease in vehicle fuel economy:

$$FE_e = \frac{FE}{\left(1 + f_L f_S \frac{M_B}{M_{vehicle}}\right)}. \qquad [3]$$

We assumed f_L equals 0.67 (i.e., every percent increase in vehicle weight results in a 0.67% reduction in vehicle efficiency) (11). $M_{vehicle}$ represents the mass of the vehicle, not including the weight of the battery.

Knowing the effective vehicle efficiency, we then calculate battery mass using the following recursive formula in which n refers to the iteration number:

$$M_{B_n} = \left(\frac{R}{E_B \cdot FE_{e_{n-1}}}\right) = \left(\frac{R}{E_B FE}\right)\left(1 + f_L f_S \frac{M_{B_{n-1}}}{M_{vehicle}}\right). \qquad [4]$$

Eq. **4** is iterated upon until the battery mass converges (i.e., $M_{Bn} = M_{Bn\text{-}1}$).

For HDVs, battery mass also increases with increasing range according to Eq. **1**. Cargo mass for the HDV is equal to the difference between the gross weight limit and the weight of the empty truck, minus the battery. Therefore, cargo mass decreases as range increases. As noted above, hauling efficiency is given by cargo mass times distance traveled per fuel consumed. Values for the parameters used in these calculations are listed in Table S1. Dataset S1 contains all calculations used in this study.

By calculating battery mass as a function of vehicle range, one can determine the break-even range beyond which the biopower mobility chain ceases to be advantageous, as is done in Fig. 1 *A* and *B*, which plot the ratio of biopower to biofuel field-to-wheels performance for LDVs and HDVs, respectively. As shown in Fig. 1*A*, the break-even ranges for the current LDV scenarios are 459 km (285 mi) and 737 km (464 mi) for the Prius:Leaf and Camry:Leaf scenarios, respectively. For future LDV technology, break-even ranges are 660–815 km (410–507 mi) for NRC scenarios, and 436–464 km (271–288 mi) for MIT scenarios. Fig. 1*A* also indicates that over ranges typical of today's LDVs [560–820 km (350–510 mi), based on the top ten best-selling vehicles in the United States in 2012], the current Prius:Leaf and future MIT scenarios have ratios <1 (i.e., biofuel more efficient), whereas the Camry:Leaf scenario and aggressive future National Academy of Sciences scenarios all break even.

Table 4. HDV tank-to-wheels hauling efficiencies

	ICEV		BEV	
Scenario	ton·mi/gal GE*	Mg·km/GJ	ton·mi/gal GE*	Mg·km/GJ
Current				
NRC†	152.2	1,814	267.3	3,186
RMI‡	145.5	1,734	255.5	3,046
Future				
NRC†	257.4	3,068	356.0	4,243
RMI‡	288.1	3,433	398.3	4,747

*Assumes the gasoline lower heating value = 116,090 British thermal unit/gal.

†Fuel economies from the NRC (14); current = 6.1 mi/gal GE; future = 10.4 mi/gal GE; unloaded truck weight = 30,000 lb; truck gross weight limit = 80,000 lb; ICEV fuel weight ~475 kg; BEV fuel economy assumed to be 74% higher than ICEV.

‡Fuel economies from the RMI (15); current = 5.9 mi/gal GE; future = 11.1 mi/gal GE; unloaded truck weight = 30,000 lb for current scenario and 27,000 lb for future scenario; truck gross weight limit = 80,000 lb; ICEV fuel weight ~475 kg; BEV fuel economy assumed to be 74% higher than ICEV.

Considering HDVs, Fig. 1*B* indicates that the break-even range for current technology is 146 km (91 mi) and 153 km (95 mi) for the RMI and NRC scenarios, respectively. For future technology, biofuels are more efficient for all ranges. Over driving ranges typical of class 8 trucks in the United States [1,310–2,190 km (815–1,360 mi), assuming a fuel tank volume of 450–750 L and average fuel economy of 2.9 km/L (6.8 mi/gal diesel)], all scenarios have ratios <1 (i.e., biofuels are more efficient).

Typical driving patterns for cars in the United States—in which 95% of vehicle trips are less than 30 mi (20)—suggest that LDV BEVs may indeed be a preferable choice at modest ranges. Americans, however, total 1.3 trillion person-miles of long distance

Table 5. LDV field-to-wheels performance for cellulosic biofuel and biopower transportation pathways

Scenario	ICEV, km/MJ biomass	BEV, km/MJ biomass	Power/fuel ratio*
Current			
Prius:Leaf	0.26	0.39	1.5
Camry:Leaf	0.15	0.39	2.6
Future: NRC†			
Small car	1.47	1.98	1.4
Midsized car	1.38	1.70	1.2
Full-sized car	1.20	1.46	1.2
Small MPV	1.04	1.34	1.3
Large MPV	0.98	1.24	1.3
Light-duty truck	0.66	0.84	1.3
Future: MIT‡			
Midsized car	0.70	0.79	1.1
Light-duty truck	0.45	0.52	1.2

*Ratio evaluated at the base BEV range: 75 mi for current, 100 mi for NRC (11), and 200 mi for MIT (12).

†Fuel economies from the NRC (2050 optimistic case) (11).

‡Fuel economies from MIT (12).

Table 6. HDV field-to-wheels performance for cellulosic biofuel and biopower transportation pathways

Scenario	ICEV, Mg·km/GJ biomass	BEV, Mg·km/GJ biomass	Power/fuel ratio*
Current			
NRC[†]	722.6	822.3	1.1
RMI[‡]	690.7	786.0	1.1
Future			
NRC[†]	2,139	1,817	0.9
RMI[‡]	2,394	2,033	0.9

*Ratio evaluated at the BEV range = 0.

[†]Scenario from the NRC (14).

[‡]Scenario from the RMI (15).

travel (more than 50 mi from home) per year on about 2.6 billion long-distance trips, over half of which are for leisure, with personal vehicles accounting for almost 90% of these trips (20). For HDVs, given that more than 80% of freight ton-miles in the US travel more than 250 mi (20), and for longer range LDV travel, ICEVs will likely remain the most viable option. This likelihood is reinforced by another important consideration, battery power density, which must be sufficiently high in heavy-duty BEVs for acceleration and hill climbing. For a given battery type, however, there is a tradeoff between energy density and power density, with higher power batteries having significantly lower energy density, and vice versa (21).

Two important observations from this analysis are as follows: (*i*) the level of assumed technological maturity significantly affects the comparison between biomass electricity and fuels as sources of vehicular energy; and (*ii*) the intended transportation application—e.g., short range versus long range; light duty versus heavy duty—is essential to make a meaningful comparison.

These points were not fully considered in earlier studies by Campbell et al. (22) and Ohlrogge et al. (23), both of which deemed biopower as being the more efficient option—by a factor of 1.1–3.2 in Campbell et al., depending on LDV class and driving cycle, and a factor of 2.5 in Ohlrogge et al. Neither study, for example, considered the possibility of future improvement in fuel conversion efficiency through combining biological conversion of the biomass carbohydrate fraction (i.e., cellulose and hemicellulose) with the thermochemical conversion of the lignin fraction. In mature biomass refineries, however, it is unlikely that the lignin fraction would be left unconverted. Detailed technoeconomic analysis of projected mature biorefining found that the highest yielding (and most profitable) process designs involve both biological and thermochemical conversion (6). At a minimum, lignin residue would be used to generate electricity via a conventional Rankine cycle for net export. One could therefore easily envision transportation scenarios involving plug-in hybrid electric vehicles fueled by biofuels and biopower produced from the same production facility.

Similarly, potential future gains in ICEV efficiency through hybridization were not fully recognized in the earlier studies. Ohlrogge et al. (23) did not include hybridization at all; Campbell et al. (22), meanwhile, assumed an extremely modest efficiency gain of 1.3× through future hybridization, resulting in a fuel economy of about 34 mi/gal on an averaged city/highway driving cycle basis—a value lower than that reported for several of today's 2013 hybrid models, including the Toyota Prius (50 mi/gal, combined city and highway), Honda Civic (44 mi/gal, combined), Ford Fusion (39 mi/gal, combined), and Hyundai Sonata (37 mi/gal, combined) (24). Future midsize hybrid cars are projected to realize fuel efficiencies of more than 80 mi/gal by 2030 (25). Furthermore, the earlier studies did not examine the effect of vehicle range on the comparison, nor did they consider HDVs.

A comparison made today of the range of vehicles powered by bioelectricity and biofuel is in many ways parallel to comparisons made in the 1980s of criteria pollutant emissions for conventional vehicles and vehicles featuring alternative fuels or propulsion systems. At that time, it was correctly observed that alternative fuels and propulsion systems could have much lower criteria pollutant emissions than did the ICEVs of the day. Such emission reductions were in fact achieved (26, 27), but as a result of improvements to ICEVs rather than more radical changes to the vehicle fleet. Indeed, German observed in 2004 that further reduction of criteria pollutants is in general not a substantial

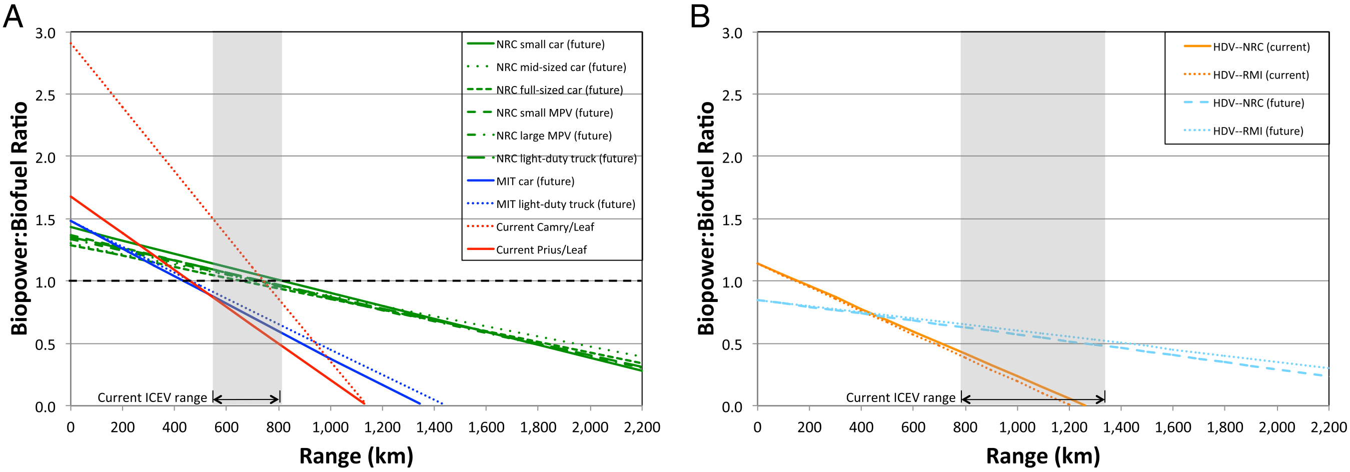

Fig. 1. (*A*) Ratio of biopower-to-biofuel field-to-wheels efficiency as a function of vehicle travel range for LDVs under current and future technology scenarios. Current technology includes a Toyota Prius:Nissan Leaf scenario and a Toyota Camry:Nissan Leaf scenario. Future technology scenarios are based on two studies: (*i*) NRC, *Transitions to Alternative Vehicles and Fuels* (11), and (*ii*) MIT, *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions* (12). The NRC scenario employs that study's 2050 optimistic case. For all future scenarios, ICEVs are hybridized. The current ICEV range is based on the top 10 selling vehicles in the United States in 2012. (*B*) Ratio of biopower-to-biofuel field-to-wheels efficiency as a function of vehicle travel range for HDVs under current and future technology scenarios. Scenarios are based on two studies: (*i*) NRC, *Review of the 21st Century Truck Partnership* (14), and (*ii*) RMI, *Transformational Trucks: Determining the Energy Efficiency Limits of a Class-8 Tractor-Trailer* (15). ICEV range assumes fuel tank volume ranging from 450 to 750 L and an average fuel economy of 2.9 km/L.

motivation for considering alternative fuels and propulsion systems (28). When comparing the efficiency of vehicles powered by bioelectricity and biofuels, we should be careful not to repeat the mistake of underestimating improvements to in-use technology. Although over 80% of electric LDV charging in the United States today occurs using existing residential circuits (29), mainstream use of electric vehicles involving widespread fast-charging and/or battery switching networks will involve massive capital expenditure—more than $325 billion over the next two decades according to a 2009 University of California, Berkeley study (30)—that are only likely to happen as a result of strong public motivation and policy support. In the presence of such motivation and support, it is reasonable to assume that the efficiency of vehicles with energy stored as liquid fuels could improve a great deal as well.

In summary, the level of assumed technological maturity must be consistent for both pathways to obtain a meaningful comparison, and, the intended transportation application significantly affects the comparison. Whereas bioelectricity-powered LDVs appear to be the more efficient option over shorter ranges, for longer LDV ranges and heavy-duty operations such as long-haul trucking, our analysis indicates that biofuel-powered vehicles are more efficient, especially assuming advanced technology. Overall, accounting for technological advances and range, there is little basis to expect mature bioelectricity-powered vehicles to have greater field-to-wheels efficiency (e.g., kilometers per gigajoule biomass, or per hectare) compared with mature biofuel-powered vehicles, especially for heavy-duty applications requiring long transportation distances and large power densities.

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