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The contribution of biomass and waste resources to decarbonizing transportation and related energy and environmental effects†

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Various technologies to reduce emissions from the transportation sector have emerged in the past decades, including biofuels and electric vehicles. Electrification is vital to decarbonization, but it is insufficient alone and may not apply to all transportation sectors. There is considerable interest in biofuels to complement electrification in decarbonizing transportation. In this study, we evaluate the extent to which biomass can contribute to the decarbonization of the transportation sector as electrification of the light-duty fleet increases. Using two biomass availability scenarios established at two different price points (≤\$40 per dry ton and ≤\$60 per dry ton), the study examines how electrification and biomass resources can be used to meet near-term societal transportation needs when biomass use is prioritized towards different transportation sectors. We consider the transportation sector as a whole, including the light-duty, heavy-duty, marine, and aviation sectors. The results show that biofuels could fulfill about 27% of energy demand across the heavy-duty, aviation, and marine sector at ≤\$40 per dry ton and more than 50% at ≤\$60 per dry ton by 2050, while electrification could be the primary means of decarbonizing light-duty vehicles. While in 2050 transportation-related greenhouse gas emissions could be 26% lower than in the baseline case with extensive electrification of the light-duty sector, this percentage could be increased to 37% and 52% at ≤\$40 per dry ton and ≤\$60 per dry ton, respectively, with increased market penetration of biofuels in the other transportation sectors.

1. Introduction

Achieving climate goals requires decarbonizing the economy. Transportation accounts for 26% of U.S. energy consumption and 28% of direct greenhouse gas (GHG) emissions.[1,2] While electrification is largely viewed as a primary technology for decarbonizing light-duty vehicles (LDVs) and perhaps medium-duty vehicles (MDVs) as well, heavy-duty vehicles (HDVs), aviation, and marine transportation face challenges related to electrification.[3] There is considerable interest in expanding biofuels' use to complement electrification. For HDV, marine, and aviation applications where high power and long range are key factors, biofuels offer relatively higher energy density and quick refueling.[4] While biofuels are promising pathways for decarbonizing, biomass resources are limited.[5–9] In the coming year, a number of factors will determine the fate of available biomass resources and their contribution to decarbonization.[10]

A number of studies have estimated the potential for emissions reduction in the transportation sector using different emissions reduction strategies. Rogers *et al.*[11] carried out an analysis to assess the environmental and economic benefit associated with the use of a billion-ton biomass resource in 2030. They analyzed different scenarios of biomass allocation that favor ethanol, bio-based jet fuel, heat and power, and chemical production under two scenarios of biomass availability. Their results indicate that 446 million tons of GHG emissions could be avoided in 2030 with biomass resources. Dunn *et al.*[12] evaluated changes in GHG emissions, energy and water consumption, and criteria air pollutant emissions in the light-duty (LD) sector when biofuels that increase combustion engine efficiency are deployed. In their study, cumulative emissions reductions reached 7% in 2050. A study carried out by Staples *et al.*[13] on the potential of alternative jet fuel (AJF) to reduce aviation's CO_2 emissions showed that AJF could reduce life-cycle GHG emissions from aviation by a maximum of 68.1% in 2050. However, achieving this percentage depends on prioritizing the biomass resources for AJF production over other potential uses, combined with policies that rapidly incentivize waste feedstocks and bioenergy production. Calvo-Serrano *et al.*[14] examined the potential optimal use of biomass for

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chemicals, transport fuels, and electricity in an European Union (EU) context. Using a network-based life-cycle optimization approach, they combined environmental criteria with resource availability and demand constraints to identify optimal biomass use. Their results suggest significant savings in both costs and environmental impacts (52% reduction in global warming potential) with proper utilization of the biomass resources available. They emphasized that meeting the total annual demand for chemicals, electricity, and transport fuels using biomass may not be realistic because of limited biomass availability. For example, depending on the solution strategy they evaluated, biomass resources could provide 48% of electricity demand and up to 11% of transport fuel demand of the EU while the demand for chemical is satisfied by conventional means.

Sharmina *et al.*[15] compared economy-wide modeling of 1.5 °C and 2 °C temperature-rise scenarios to analyze decarbonization of aviation, shipping, road freight transport, and industry. They developed a framework to examine and track mitigation progress in these sectors. They reported that emissions reductions in these economy-wide modeling scenarios are tied to low carbon energy and increased energy efficiency. They suggest that additional efforts such as reducing activity in each sector are required to increase the chances of achieving net zero CO_2 emissions. Blas *et al.*[16] applied an integrated assessment model to study four global transportation decarbonization strategies for 2050. They compared the conventional efficiency improvement and technological substitution scenarios with a scenario that included drastic changes in mobility patterns. Their findings emphasized the inability of electrification alone to achieve GHG reductions consistent with climate stabilization. They argued that a rapid and radical shift to electric vehicles (EVs) combined with a drastic decline in total transportation demand is necessary to achieve the desired stable emissions reduction.

Vishwanathan[17] conducted a cursory life-cycle analysis comparing a medium-duty (Class 6–7) EV and a propane-fueled vehicle to evaluate the U.S. State-level difference in GHG emissions between the two vehicles. Using five simulated scenarios, this study provided an alternate hypothesis for decarbonization using propane and its blends. They suggested that aggressive investment in production of alternative fuels such as propane and dimethyl ether (DME) is vital because relying on electrification to decarbonize all sectors without improvement in the state of the U.S. electrical grid in the near term will be counterproductive, and concluded that vehicles using blended renewable fuels (propane and DME) offer a better solution than medium- and heavy-duty EVs. Other studies reviewed various decarbonization strategies for the hard-to-decarbonize transportation sectors; their findings suggested that a combination of different approaches such as technological, operational, policy measures and the use of alternative fuels would be necessary to achieve significant decarbonization.[18–25]

While the majority of these studies acknowledged the value of a combination of mitigation strategies in achieving the transportation emissions reduction goal, no peer-reviewed work has included a detailed analysis of decarbonizing the transportation sector as a whole using biomass resources in combination with electrification. The study by Rogers *et al.*[11] is limited to a single year (2030) and considered biomass use in the LD and aviation, together with Calvo-Serrano *et al.*[14] (that focused on LD and heavy-duty), they did not consider transportation sector as a whole. Therefore, the present study aims to bridge this gap by accounting for decarbonization of the whole transportation sector, considering the time series availability of biomass supply and fuel demand to provide complete insight into feasible GHG emissions reduction trends over time.

The focus is on evaluating to what extent biomass can contribute to the decarbonization of the transportation sector as electrification of the LD fleet increases. We examine how electrification and biomass resources can be used to meet near-term societal transportation needs. We focus on how the available biomass resources could be allocated in fulfilling the role of liquid fuels in the hard-to-decarbonize transportation sectors without compromising biomass use in other sectors. This paper aims to contribute to the existing body of research on sustainable transportation technologies by providing insights into how the U.S. biomass resources, as defined in the 2016 billion-ton study (BTS16) from the U.S. Department of Energy,[5] can be used holistically towards decarbonizing the transportation sector. It directly addresses the extent to which biomass could contribute to the decarbonization of transportation if biofuel cost is not a barrier, focusing on the use of biomass to decarbonize the heavy-duty (HD), marine, and aviation sectors, given the increasing role of electrification in the LD sector.

2. Method

2.1. Scope

The scope of this analysis includes the operational energy use by the LD, medium/heavy-duty, marine, and aviation transportation sectors in the United States. The performance of these sectors is evaluated for two cases reflecting biomass availability at \$40 and \$60 per dry ton (dt) of biomass including waste, conventional, and cellulosic (see ESI S1†), and three scenarios for the allocation of biomass resources to final uses. We evaluate the sectoral (*e.g.*, LD, HD, aviation, and marine) and overall change in fossil energy consumption, water consumption, GHG emissions, and criteria air pollutants such as $PM_{2.5}$ emission in these three scenarios. Land use associated with each scenario is estimated based on the national average yield of biomass resource as reported in BTS16.[5]

2.2. Transportation energy use projections

Liquid fuels for these sectors, *i.e.*, LD, HD, aviation and marine, were modeled on the basis of the reference case of the U.S. Energy Information Administration 2020 Annual Energy Outlook (AEO) projection.[26] For each scenario, we consider significant electrification of the LD sector, as projected by Mai *et al.*[27]

2.3. Biomass resource availability and end use

The biomass resource use in the current economy (2019) for different applications was estimated from U.S. and other government agency reports: ethanol and biodiesel,[26,28] heat and power,[26,29] and biobased chemical.[30] We based future (through 2040) biomass availability in the United States on the Billion Ton Study,[5] which was published by the department of energy in 2016. The Billion Ton Study (BT16) considers biophysical, economic, and sustainability factors that determine biomass availability. It assesses the impact of different factors such as price, crop yields, climate change impacts, logistical operations, and systems integration across production, harvest, and conversion. In adopting biomass availability estimates from the BT16, the analysis we present accounts for these factors that dictate the amount of deployable biomass for decarbonization strategies. Biomass availability also depends on the price farmers can receive for it. At higher prices, farmers will produce more biomass. We therefore include two biomass price points from BT16, \$40 and \$60 per dry ton for this analysis. The scenario for the higher biomass price corresponds to a case with more aggressive use of biomass, which could for example be driven by greater policy incentives. BT16 biomass resource availability estimates end in 2040; we assumed biomass availability remains constant from 2040 to 2050. Also, the BT16 did not estimate wastewater sludge availability, so we adopted values from Skaggs *et al.*[7] for the year 2018. We assumed that wastewater resource availability will remain constant from then until 2050.

We establish two biomass resource availability cases, based on two biomass selling-price levels: \$40 per dt (the business-as-usual or BAU case) and \$60 per dt (the billion-ton-biomass or BTB case), as shown in Fig. 1. In the BTB case, we see much more biomass and therefore an opportunity to use it to decarbonize transportation. At \$60 per dry ton biomass price, farmers are willing to produce and sell more biomass than if they earn \$40 per dry ton. The growth in biomass availability stems from increased production of herbaceous grasses and agricultural residues, whereas corn grain, soybeans, and wet wastes remain constant. The ESI (Section S1†) provides a breakdown of biomass by type as assumed in this analysis from 2019 to 2050 for both \$40 per dt and \$60 per dt selling prices. Although the growth, availability, and end use of biomass resources might be affected by policy, market factors, and technology, our analysis assumed that potential biomass supply and demand at these price points are equal.

The biomass resources in the two cases are distributed to fulfill the demand for fuel, heat and power, biobased chemicals, and wood pellets as shown in Table 1, using assumptions that mirror an earlier study.[11] However, the current analysis explores in detail how, within the transportation sector, biomass might best be allocated taking into account qualitative considerations regarding the current status and anticipated evolution of other technologies. This analysis is necessary to identify the best uses for biomass resources, especially in hard-to-decarbonize transportation, which has been relatively unexplored. We consider the HD, LD, aviation, and marine sectors individually.

2.4. Biomass resource allocation scenarios

In addition to the two biomass availability cases, this analysis considers different scenarios for the allocation of the available biomass resources towards renewable fuel production to fulfill liquid-fuel demands in the transportation sector (Tables S-1 and S-2 in the ESI†). We investigate three scenarios that take different approaches to decarbonizing the HD, marine, and aviation sectors, as described below. In all scenarios, we assume extensive LD-sector electrification by 2050. The level of electrification used in this analysis is based on the optimistic case described by Mai *et al.*,[27] which indicates that EVs would make up 88% and 81% of LD cars and trucks, respectively, on U.S. roads in 2050, of which most will be battery electric vehicles (BEVs). However, Mai *et al.*[27] adopted a higher fuel consumption in 2020 than our base case, AEO 2020. Accordingly, we adjusted Mai *et al.*'s scenario to align with AEO 2020 (see the ESI Section

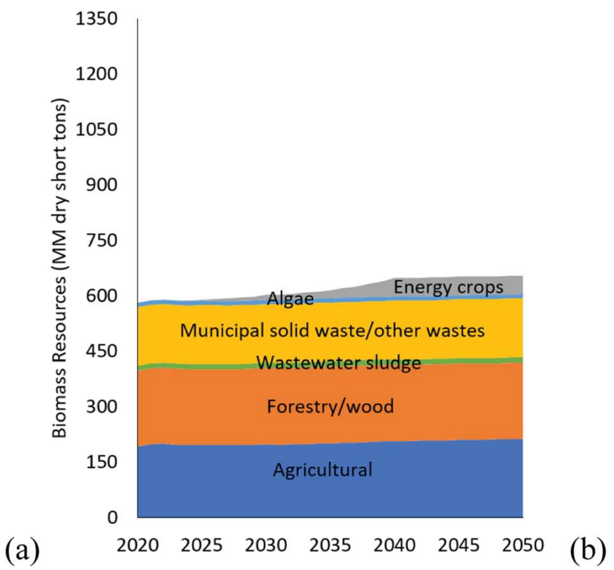

Fig. 1 Available biomass resources into the future (a) business-as-usual and (b) billion-ton cases.[5]

Table 1 Allocation of biomass resources

	Total biomass (MT) (2019–2050)		Allocation to sectors			
Biomass resource category	BAU: \$40 per dt	BTB: \$60 per dt	Transportation	Heat and power	Bio-based chemicals	Wood pellets
Agricultural	**6230**	**9590**				
Corn grain[a]	3390	3390	Ethanol projection[b]		100%[c]	
Vegetable oils[a]	329	329	Biodiesel projection[b]		100%[c]	
Other fats, oils, and greases[a]	59.2	59.2	Biodiesel projection[b]			
Agricultural residues[a]	1540	4900	95.4%		4.6%	
Manure	909	909	100%			
Forestry/Wood	**6570**	**8920**				
Wood/Wood waste[a]	4450	4450		100%		
Wood pellets [a]	275	275				100%
Mill residues[a]	143	143	100%			
Logging residues[a]	1050	1130	89%			11%
Urban wood waste[a]	644	950	100%			
Whole-tree biomass[a]	8.60	1970	100%			
Energy crops	**822**	**9010**				
Herbaceous[a]	528	7450	95.4%		4.6%	
Woody[a]	294	1560	95.4%		4.6%	
Municipal solid waste (MSW)/Other wastes	**5000**	**5860**				
Biogenic portion of MSW[a]	2470	2860	100%[d]	100%[c]		
Other waste biomass[a,e]	619	619		100%		
Landfill gas[a]	1910	2380	18.7%[f]	81.3%		
Wastewater sludge	**443**	**443**	100%			
Algae	**357**	**713**	95.4%		4.6%	

[a] Allocations based on Roger *et al.*[11] [b] Based on AEO projection. [c] Of the amounts used in the current economy. [d] Of new biomass potential. [e] Category include biosolids, trap grease, food processing wastes and utility tree trimmings. [f] Based on the percentage consumed in the current economy.

S4† for details). To meet the liquid-fuel demand and increase biofuel market share in the LD sector, we assume the same ethanol content in motor gasoline as projected in the AEO 2020 reference case until 2027 but target 30% (v/v) ethanol content in motor gasoline as the limit for a drop-in blend in non-flex-fuel vehicles by 2050. The amount of corn ethanol consumed in 2027 is, however, kept constant until 2050.

2.4.1. Scenario 1: similar blend levels for heavy-duty, aviation, and marine sectors (low technology scenario). The low-technology scenario assumes that the medium-and heavy-duty, aviation, and marine sectors are hard to electrify and therefore will experience no or low electrification before 2050. All the biomass resources available for fuel production are allocated to these three sectors, targeting equal biofuel blend levels with incremental increases in biofuel usage in each sector. The biomass resource allocation to each sector depends on its energy demand projection in the AEO 2020 reference case.[26] The share of biomass and the types of biomass allocated to each sector are determined by the type of biofuel to be produced and the energy density of each biofuel. This scenario evaluates the feasibility of ramping up cross-sectoral biofuel production at the same rate.

2.4.2. Scenario 2: biofuels prioritized for aviation. The aviation sector has championed the use of low-carbon fuels as a primary route to reducing GHG emissions of air travel, and so is a likely large-scale early adopter. Other alternative energy systems such as batteries, fuel cells, and natural gas available as options for other transportation sectors will not likely be used in this sector in the near to medium term. Therefore, this scenario assumes that the available biomass resources (except for landfill gas and manure) will primarily be directed to renewable jet-fuel production, targeting a 30% (v/v) market share by 2040 and 50% (v/v) (the maximum blend level approved for aviation fuel) by 2050.[31] After the demand in aviation is met, the remaining biomass is directed towards meeting the HD sector's energy demand. However, the biofuel market share in the HD sector will depend on the remaining resources after allocation to bio-based jet fuel production. Electrification is assumed to make up the difference for decarbonizing the HD sector. We chose a high-electrification scenario to analyze the extent to which electrification can penetrate the HD sector, based on the optimistic scenario of Mai *et al.*,[27] which assumed that EVs will make up 50% and 41% sale shares of MDVs and HDVs, respectively in 2050.

This scenario assumes that renewable natural gas (RNG) will penetrate the marine sector. Therefore, some waste feedstocks such as landfill gas and animal manure are dedicated to the production of RNG. It is assumed that the RNG produced will displace some fraction of distillate fuel oil and carbon capture with heavy fuel oil to make up the difference in decarbonizing the marine sector.

2.4.3. Scenario 3: similar blend levels for the aviation and heavy-duty sectors. This scenario assumes that the available resources will be distributed between the aviation and HD sectors in accordance with their share of total transportation fuel demand on an energy basis. We assume the same percent market penetration in the two sectors by 2050 (*i.e.*, biofuels to account for the same percentage of energy demand in the HD and aviation sectors) based on the resources available. Scenario 2 assumptions for the marine sector are also applied in this scenario.

2.4.4. Blend levels for each sector. The biodiesel content in most diesel consumed in the U.S. (by the HD and marine sectors) is currently about 5% (v/v), while ethanol content in motor gasoline (LD sector) is around 10% (v/v). We determined the feasible biofuel market share (*i.e.*, maximum blend-level targets) for all new biofuels in the aviation, HD, and marine sectors by 2050 on the basis of the resource availability, and limited the ethanol use in the LD sector to a 30% blend level, while excess ethanol was directed to aviation *via* ethanol-to jet fuel pathway. Then we evaluated both linear and adoption-curve-based approaches in achieving the feasible target (see ESI Section S3† for details on the two methods). It is worth noting that the maximum blend-level target may differ for the same sector across each scenario.

2.4.5. The reference case scenario. We define a BAU scenario on the basis of the reference case of the 2020 AEO, against which the aforementioned scenarios are evaluated. We account for biofuel share (ethanol from corn and biodiesel from soybean) in each sector as reported in this base case projection.

2.5. Biofuels' technology readiness level

Table 2 summarizes biofuels considered in this study, biomass feedstocks for their production, their conversion routes from biomass, and their technology readiness level (TRL).

The technology readiness level (TRL) of the conversion pathways considered in this study are determined based on various report in literature.[32–37] Technology developers characterize the TRL of their technology using TRL scale that ranges from 1 to 9 to describe the progress of a technology towards commercialization. The TRL scale assigned to a particular technology will depend on whether it is still at basic research and development stage or has reached commercialization stage operating under the full range of expected conditions among many other factors.

One of the key issues in the analysis is determining the market introduction year for each biofuel considered. We, therefore, tie the year a fuel comes on the market to its TRL (Table 2). We assume 2028 as the market introduction year for biofuels with TRL between 6 and 9, and 2032 for others. This assumption is based on an optimistic aggressive rollout given the urgency of climate change.

2.6. Bioeconomy AGE

Bioeconomy AGE (Air emissions, Greenhouse gas emissions, and Energy consumption),[11] a Microsoft Excel-based model, was developed to evaluate different biomass resource allocation scenarios by adjusting key variables such as biomass availability and type, biofuels market penetration, and growth in the transportation sector. With this tool, we can explore how major sectors of the economy interact and change during

Table 2 Biofuel production pathways and their technology readiness levels[32–37]

Conversion pathway	Feedstocks	TRL	Biofuels	Market introduction year	Displaced fuels
Gasification + Fischer–Tropsch (FT) synthesis	MSW, agricultural residues, forest residue, energy crops	6–8	• Renewable jet • Renewable diesel • Renewable gasoline	2028	Petroleum-based jet fuel, diesel, and gasoline
Pyrolysis	MSW, agricultural residues, forest residue, energy crops	4–6	Renewable diesel	2032	Petroleum-based diesel
Pyrolysis + upgrading	Woody biomass	4–6	Pyrolysis oil	2032	Residual fuel oil
Fermentation	Agricultural residues, forest residue, energy crops, MSW	6–8	Cellulosic ethanol	2028	Petroleum-based gasoline
Hydrotreated esters and fatty acids HEFA/HRJ	Algae, corn oil	6–9	Renewable jet	2028	Petroleum-based jet
Hydrotreatment	Algae	6–9	Renewable diesel	2028	Petroleum-based diesel
Transesterification	Vegetable oils	6–9	Biodiesel		Petroleum-based diesel
Anaerobic digestion (AD) to biogas + FT synthesis	Landfill gas, manure	6–9	• Renewable jet • Renewable diesel	2028	Petroleum-based jet and diesel
AD biogas + upgrading	Landfill gas, manure	6–9	RNG	2028	Marine distillate fuel oil
Hydrothermal liquefaction	Wastewater sludge	1–4	Renewable diesel	2032	Petroleum-based diesel
Ethanol to jet	MSW, agricultural residues, forest residue, energy crops, corn	3–5	Renewable jet	2032	Petroleum-based jet

transportation-sector decarbonization scenarios considering multiple metrics. We can examine the relative, competing, and complementary benefits of liquid fuels and electrification in decarbonization strategies. Changes to the Bioeconomy AGE framework since the study by Rogers *et al.*[11] include, but are not limited to; integration of time-series emission factors from Argonne National Laboratory's GREET™ (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model and detailed analysis of the transportation sector.

2.7. Calculation of life-cycle metrics

Life-cycle metrics are calculated using the GREET™ model, which provides energy and environmental results for numerous fuel pathways.[38] The use of electricity as a fuel in the LD and HD sectors accounts for the changes to the grid as it decarbonizes over time (based on the AEO projection) for the simulation period as defined in GREET. The GREET™ model was used to generate the life-cycle petroleum consumption, GHG emissions, water consumption, and air pollutant emissions of various biofuel and conventional-fuel pathways. These results were then built into Bioeconomy AGE to evaluate the environmental and energy effects of each scenario under consideration. Annual environmental benefit is calculated as the difference between the reference case environmental impact and the design case (each decarbonization scenario) environmental impact.

3. Results and discussion

3.1. Decarbonization allocation scenarios

The summary of the share of energy use by sectors under the three scenarios is provided in Fig. 2 for the BAU biomass demand at a biomass selling price of $40 per dt. Fig. S17† provides the shares for the $60 per dt case. The extensive

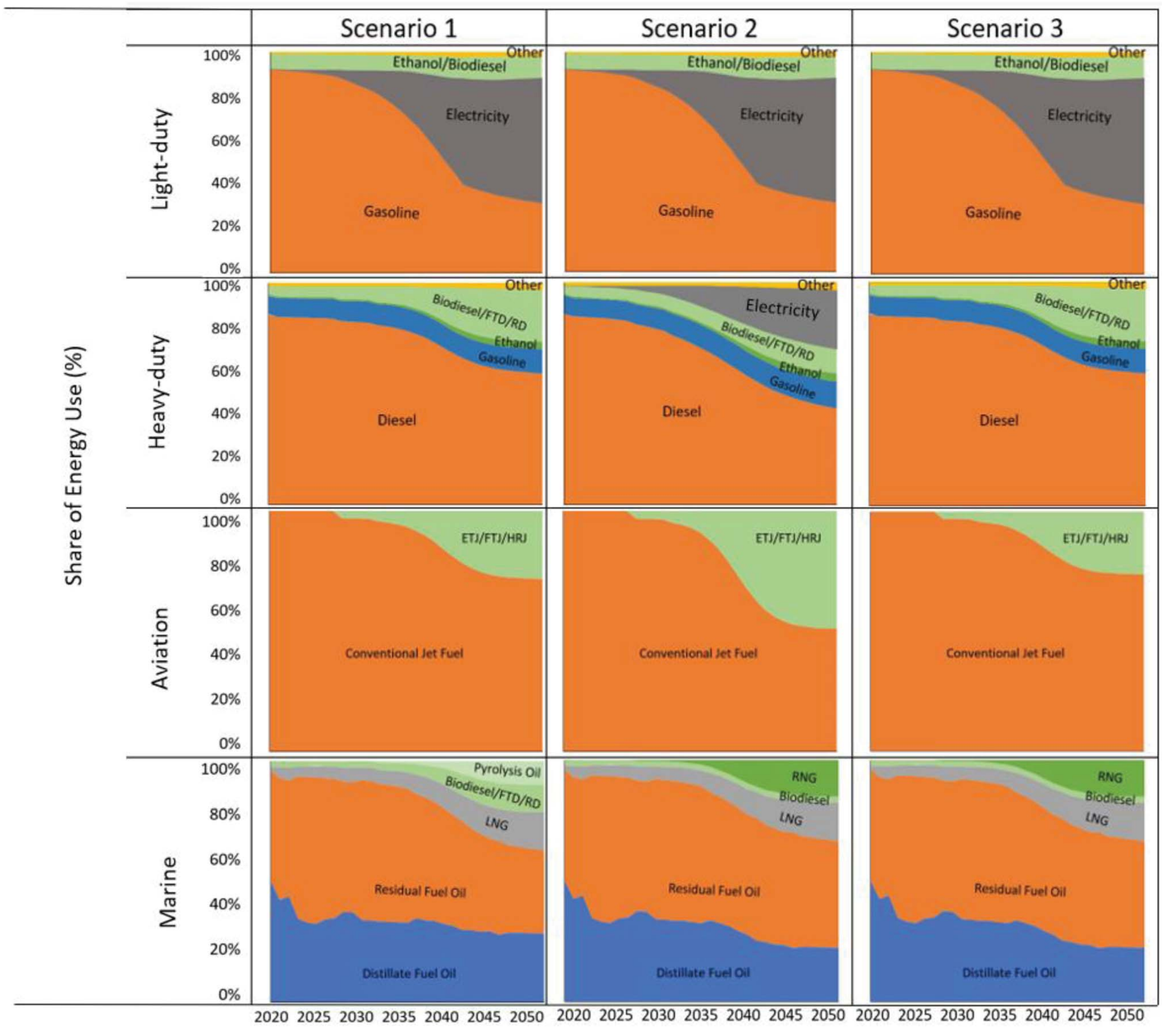

Fig. 2 Share of energy use by sector in all decarbonization scenarios at $40 per dt biomass price.

electrification of the LD sector results in a significant reduction (above 80%) in gasoline energy demands in 2050 relative to 2019. By 2050, electricity makes up more than 50% of the total LDV energy demand, while biofuel accounts for ~10% (mainly ethanol), with our scenarios focusing on directing new biofuels to the HD, aviation, and marine sectors. Gasoline still accounts for 32% of LDV energy demand in 2050.

Following from the above, biofuels could account for ~27% of energy demand across HDV, aviation, and marine use. For the BAU case (≤$40 per dt), under scenario 1 where all sectors are given equal preference for biomass resources, biofuels comprise 28% of demand in the HD sector, 28% for aviation, and 21% for marine. Under scenario 2, where the aviation sector is prioritized, biofuels comprise 49% of aviation, 15% of HDV, and 18% of marine energy demand in 2050. In this scenario, GHG emissions from the HD sector are still reduced by the significant penetration of electrification. Electricity accounts for 27% of HDV energy demand in 2050. Under scenario 3, biomass resources are split between HD and aviation while, as in scenario 2, RNG is directed toward the marine sector. In this case, biofuels account for 26% of energy demand in the HD and aviation sectors and RNG and biodiesel account for 18% of energy demand in the marine sector.

Under the higher biomass price case (≤$60 per dt of biomass), while the biofuel allocation for LDVs remains the same as for the $40 per dt BAU case, biofuels account for 57–69% of transportation energy demand across the HD, aviation, and marine sectors (Fig. S17†). Under scenario 1, biofuels comprise 78% of demand in the HD sector, 49% for aviation, and 75% for marine. Under scenario 2, biofuels comprise 49% of aviation energy demand, 53% of HDV energy demand, and 83% of marine energy demand in 2050. In scenario 3, biofuels account for 80% of energy demand in the HD sector and 37% of energy demand in the marine sector, while the share of biofuel

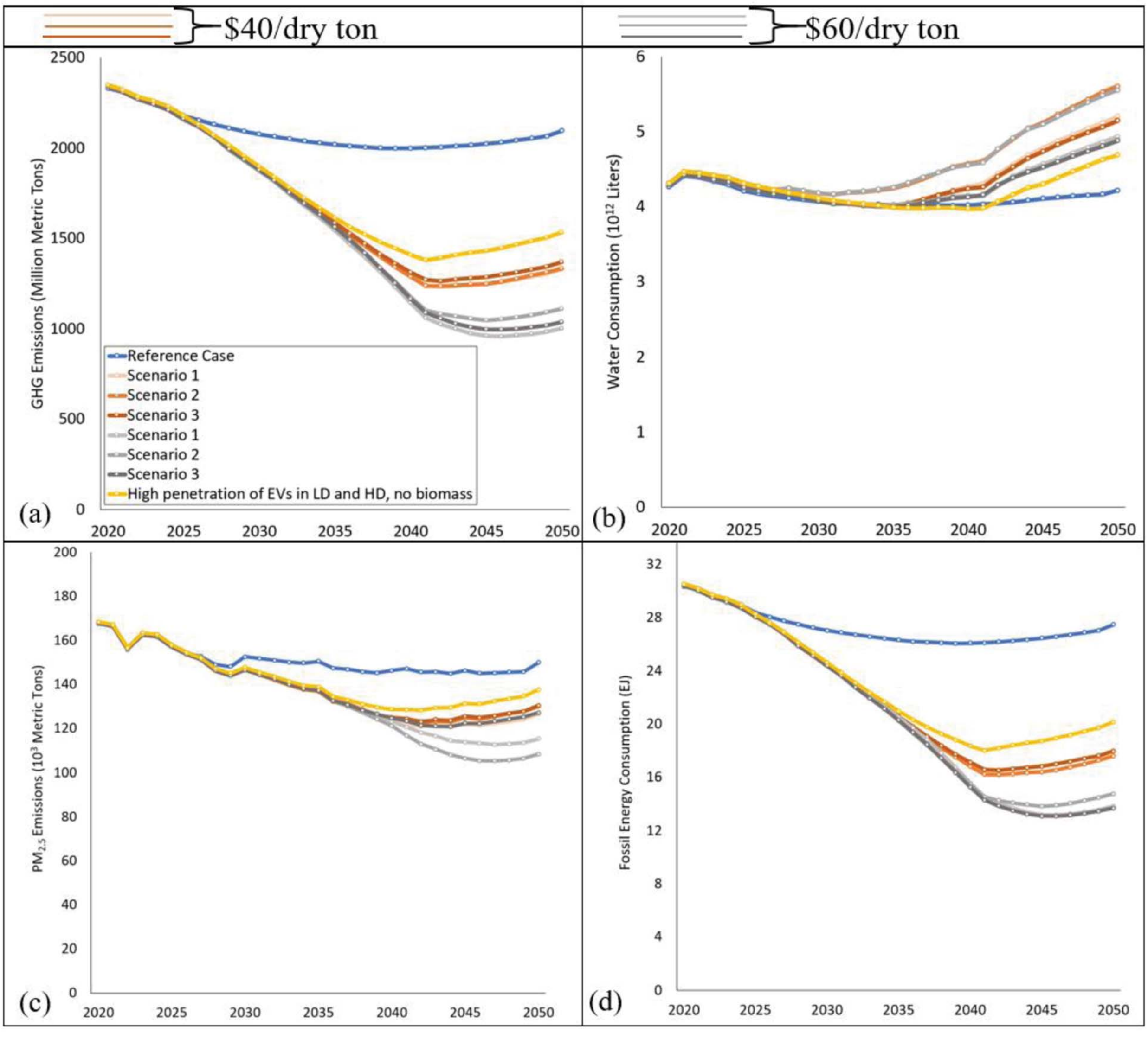

Fig. 3 Overall transportation decarbonization and reference case scenarios: (a) GHG emissions (CO_2e), (b) water consumption, (c) $PM_{2.5}$ emissions, and (d) fossil energy consumption.

demand in the aviation sector remains the same as in scenarios 1 and 2. The increase in biomass availability at this price point drives more production of biofuels and the replacement of conventional fuels with the assumption that biofuel cost is not a barrier.

3.2. Energy and environmental effects

3.2.1. Overall environmental benefit assessment under different biomass price scenarios. Fig. 3a shows the overall GHG benefits for the various scenarios.

The contribution of electrification of LDVs and HDVs is added for context (yellow line on the figure); most of this benefit is from electrification of LDVs, which account for a 26% reduction in the annual transportation GHG emissions in 2050. Electrification of the HD fleet contributes only 2%, as only a small share of the HD fleet is anticipated to be electrified by 2050.

The results for scenarios 1–3 at biomass selling prices of $40 per dt and $60 per dt show clearly that the amount of biomass supplied for biofuel is of primary importance to the resulting GHG reductions, while the specific biofuel pathways and the particular sector using the biomass—HD, aviation, or marine—play a less significant role. In both cases, scenarios 1–3 exhibit similar trajectories. This finding should alleviate concerns that a policy or sector-level strategy might somehow incorrectly use biomass resources. However, in all cases, increased emissions reductions are possible in scenario 1, in which nearly equal biofuel blend levels across the marine, aviation, and HD sectors are achieved by 2050 rather than when individual sectors like aviation are prioritized for biomass resources. With the increased market penetration of biofuels in these three sectors, overall emissions reductions increase to 37% and 52% at ≤$40 per dt and ≤$60 per dt, respectively, in scenario 1. In Fig. 3, for most plots, there is a generally decreasing trend that flattens and slightly increases from 2045 to 2050. The decrease in GHG emissions, PM emissions, and fossil energy consumption are due to increases in electrification, coupled with renewable electricity for light-duty vehicles and increases in biofuel use for heavy-duty, aviation, and marine. The slight increase is due to the fact that around 2045 the renewables have saturated, and the trend returns to follow slight growth in transportation energy demand. In addition, the little dip in the graph around 2040 originates from the adjustment made to the high electrification data used for the light duty sector (this could be seen clearly in Fig. S5 in the ESI†). During this period, there is no further reduction in gasoline consumption as can be seen in Fig. S5 (in the ESI†). Fig. 4 details the contribution of each sector to the overall GHG emissions change in all decarbonization scenarios. For example, in scenario 1 at $40 per dt, 69% of the overall emissions reduction comes from LDV electrification, and 39% from biofuels by 2050. However, with more resources available at $60 per dt, the contribution from biofuels increases to 51%. It is worth noting that assumptions regarding biomass allocation in each sector also play a role in the different decarbonization levels that are achieved (see the ESI Section S5† for the allocation details).

Water consumption increases compared to the reference case in all decarbonization scenarios (Fig. 3b). The higher water consumption at $40 per dt is due to the higher life-cycle water intensity of Fischer–Tropsch diesel (FTD) (the dominant fuel at $40 per dt) compared to renewable diesel (RDII, which dominates at $60 per dt). The prominence of water-intensive electricity as a fuel in scenario 2 dominates that scenario's water consumption.

As with GHG emissions, $PM_{2.5}$ emissions and fossil energy consumption decline in all decarbonization scenarios compared to the reference case (Fig. 3c and d). The details of the variation in all scenarios and the contribution of each sector can be found in the ESI (Sections S6 and S7†).

3.3. Impacts of scenarios on land use

One of the crucial environmental impacts of increasing biofuel use in the transportation sector is the associated increase in land use for biomass production. This section assesses the impact of increased biofuel use on land use under the two biomass prices considered within the framework adopted in BTS16.

3.3.1. At $40 per dry ton biomass price. Land use in the reference case is mainly associated with the production of first-generation biofuels (ethanol and biodiesel). Land use in the reference case increased in 2020 because of increased soy-based biodiesel demand in the marine sector (marine distillate fuel oil energy demand increased by 25% from 2019 to 2020) (Fig. 5a). Land use then starts to decline until 2040 because of decreasing demand for E10 in the LD sector. When energy demand increases from 2040 to 2050, land use rises accordingly.

Compared to the reference case, scenarios 1–3 offer a reduction in land use between 2020 and 2040, after which land use starts to increase because of growth in the use of energy crops (Fig. 5a). As electrification penetrates the LD (scenarios 1, 2, and 3) and HD (scenario 2) sectors, coupled with the assumption that the amounts of corn ethanol and biodiesel used in 2027 remain constant until 2050, the amount of croplands in all scenarios is reduced by 0.7 million hectares (a 7% reduction) relative to the reference case.

Although the amount of biomass allocated is the same across the scenarios, land use differs because of different factors such as the type of energy crop allocated per time in each scenario, the yield, and the difference in the biofuel blend-level target. Fig. 5c illustrates the details of land-use changes in scenario 1. In general, cropland areas decline while areas planted in major energy crops expand. In 2050, 2.2 million hectares of land will be required to supply the energy crops needed in scenario 1, with a significant portion of this land allocated to switchgrass. Most of the land producing these energy crops is currently classified as marginal.[5] Emery *et al.*[39] estimated the availability of marginal land in the United States to be between 59 and 127 Mha. If we consider the land needed for energy-crop growth in the decarbonization scenarios to be a portion of this marginal land and use the average of the range reported by Emery *et al.*[39] (93 Mha), scenario 1 requires 2.4% of the marginal land for growing energy crops.

3.3.2. At $60 per dry ton biomass price. At a biomass price of $60 per dt, the land use in scenarios 1–3 significantly

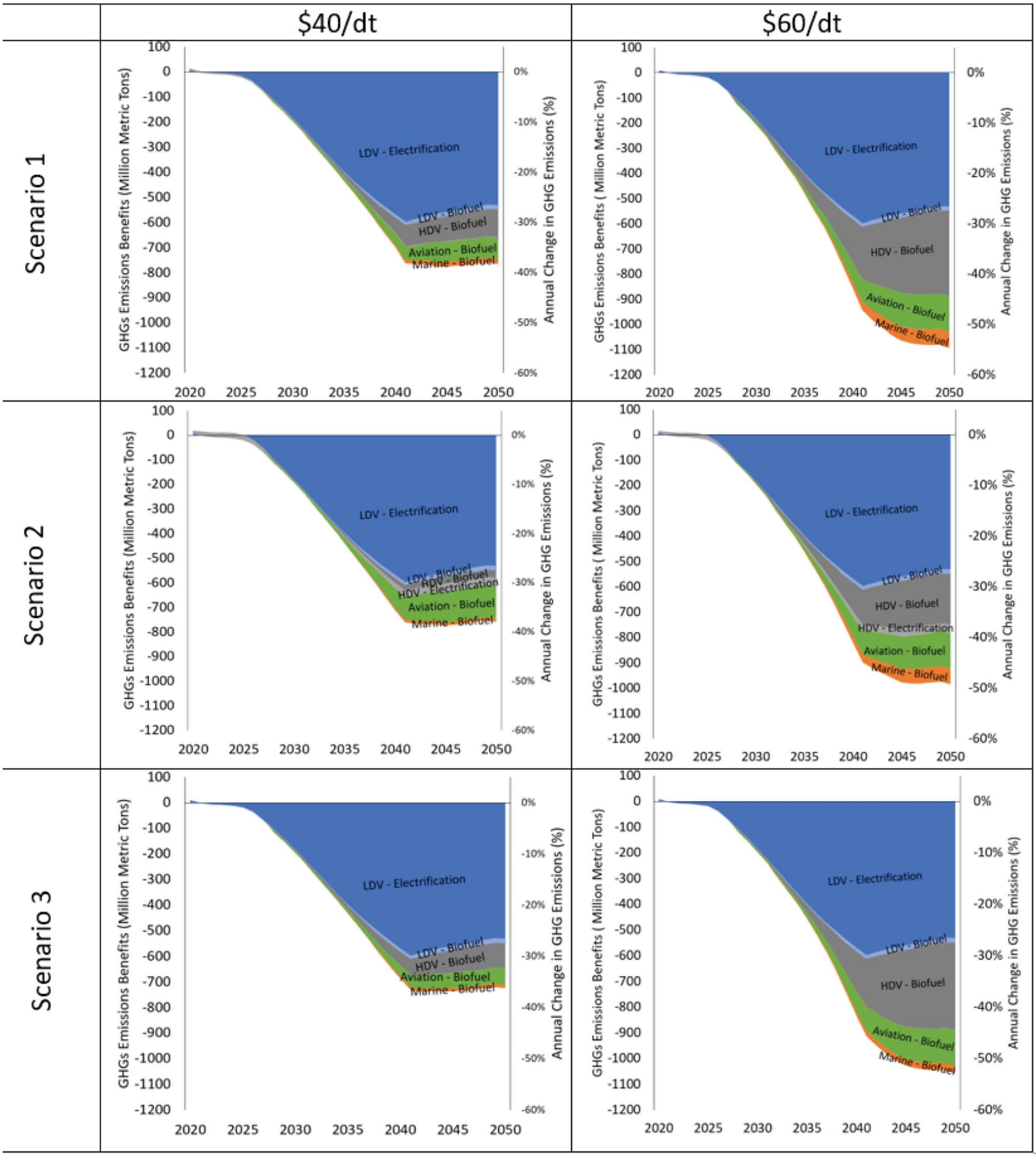

Fig. 4 Contributions of each transportation sector to change in GHG emissions (CO_2e) for all scenarios and both biomass prices.

increases compared to the reference case (Fig. 5b) and to a price of $40 per dt. The availability of energy crops in large quantities, predominantly herbaceous energy crops, allows the biofuel market penetration target to increase in all scenarios compared to what is feasible at a biomass price of $40 per dt. In scenarios 1 and 3, an additional 21 Mha of land (23% of the midpoint marginal-land estimates of Emery *et al.*) is needed in 2050 to support the growth of energy crops compared to the 10 Mha (11% of Emery *et al.*'s midpoint marginal land estimates) required in scenario 2.

The lower amount of land required to grow energy crops in scenario 2 can be attributed to the high penetration of electrification in the HD sector in this scenario. Scenario 2 prioritized the aviation sector for biomass resources, followed by the HD sector. The marine sector uses RNG as a predominant fuel. However, at this biomass price, the use of other biofuels such as

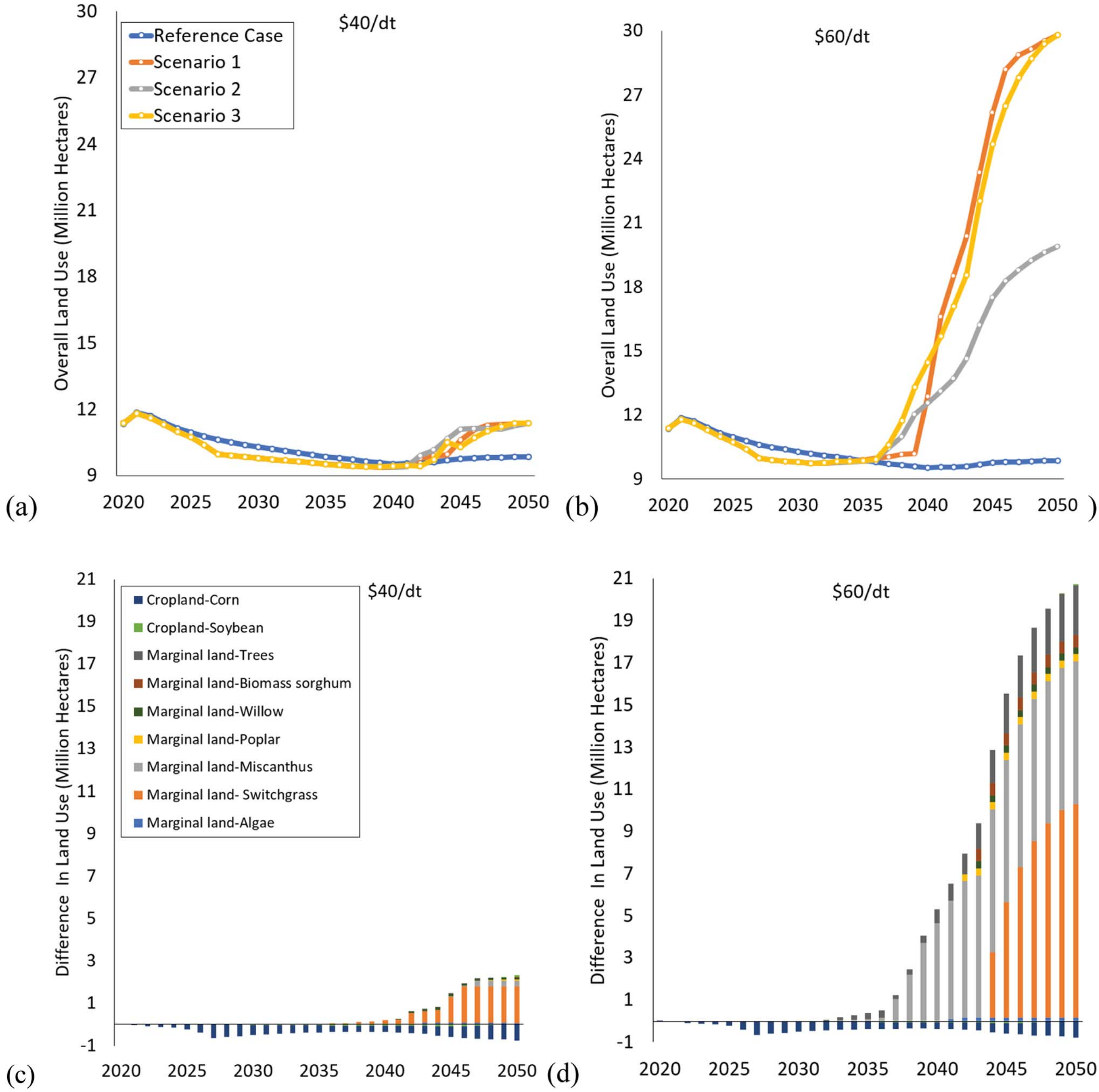

Fig. 5 Overall land use (a and b) and change in land use (c and d) in scenario 1.

pyrolysis oil, FTD, and renewable diesel in the marine sector increases as resources are available in abundance to support their production. In scenario 2, less biofuel is needed for the HD sector as it becomes electrified, and diesel demand declines by 40% in 2050 relative to the reference case and other scenarios. Hence, more resources are directed to the marine sector, and less land is required because of excess unused biomass (about 191 MM dt of energy crops and whole-tree biomass) in 2050.

3.4. Impact of high electrification on the electric sector

As electrification becomes common in both the LD and HD sectors, demand for electricity will increase. Meeting the electricity demand in these scenarios will require 1099 billion kW h of electricity, a level 837 billion kW h higher than in the reference case (Fig. 6).

Compared to the reference case, scenario 2 sees a rapid increase in the sales of EVs in both the LD and the HD sectors, resulting in more electricity demand than scenarios 1 and 3. The electricity demand in scenario 2 increases by 436 billion kW h, 28% higher than in scenarios 1 and 3.

AEO 2020 (the reference case) projected 4984 billion kW h of power generation in 2050, with natural gas, nuclear, and coal as the significant sources of generation. However, the share of renewable sources is projected to grow through 2050 (Fig. 7). Of

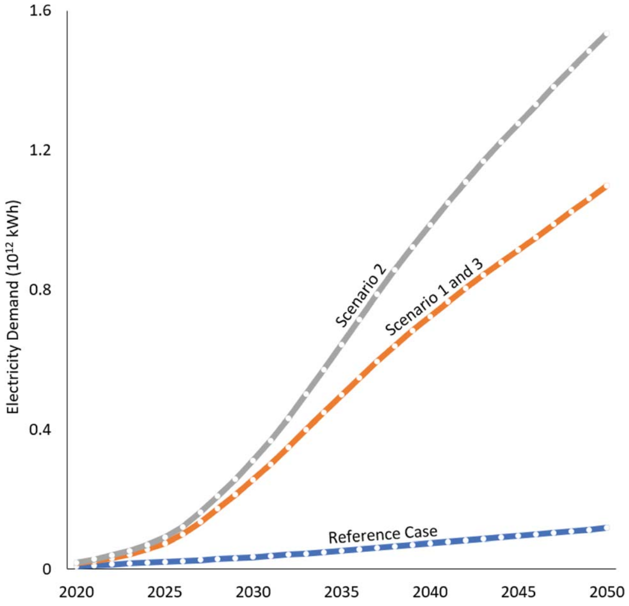

Fig. 6 Electricity demand under different scenarios.

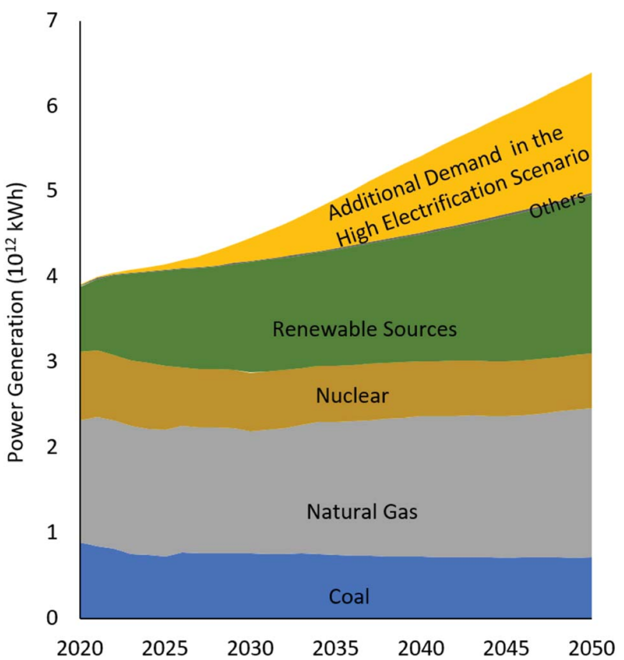

Fig. 7 Electricity generation based on the AEO 2020 reference scenario[26] and additional electricity required to meet the high-electrification-of-transportation scenario.

the 4984-billion-kW h generation projection, in the EIA Annual Energy Outlook reference case,[26] the whole transportation sector is projected to consume 130 billion kW h in 2050, far lower than the demand from the LD and HD sectors in the high-electrification scenarios.

Meeting the high demand for electricity consumption in scenarios 1 and 2 without compromising electricity use in other transportation sectors will require generating an additional 1.4 trillion kW h of electricity in 2050. This additional demand in the transportation sector increases overall electricity generation by 28% in 2050.

3.5. Impact on demand for petroleum refinery products

Fig. 8 shows the potential impact of electrification and the growth in the future biofuel market share on petroleum fuels demand under the two biomass price cases. The higher the increase in electrification and biofuel market penetration, the more the tendency for petroleum refineries to cut down on their operations or perhaps convert some portion of their capacity to biofuel refining. As electrification penetrates the LD sector, the demand for gasoline declines by 81% in 2050 relative to 2019, compared to 22% in the reference case (Fig. 8). The same trend is observed for other refinery products (diesel, jet fuel and residual fuel oil (RFO)) as the biofuel market share increases in scenarios 1–3. In the reference case, the overall petroleum fuel demand decreases by 13% in 2050. Compared to the reference case, the high-electrification scenario results in a 52% overall decline in demand for petroleum products by 2050, while a 60–68% reduction in product demand (at $40 per dt) and a 78–80% reduction (at $60 per dt) are observed in scenarios 1–3.

In all cases, the ratio of gasoline: diesel: jet: RFO decreases compared to the reference case. In the reference case, this ratio declines (except for jet fuel) from 12 : 4 : 2 : 0.4 in 2019 to 10 : 3.7 : 3 : 0.3 in 2050. For a case in which biofuels replace some diesel, jet, and RFO (using scenario 1 biofuel production as the basis), the ratio decreases to 10 : 3 : 2 : 0.2 (at $40 per dt) and 10 : 0.3 : 1 : 0.02 (at $60 per dt) in 2050. For the case where electrification offsets gasoline use by LDVs and biofuels offset the use of other fuels, the ratio decreases to 2 : 3 : 2 : 0.2 (at $40 per dt) and 2 : 0.3 : 1 : 0.02 (at $60 per dt). From this analysis, it is possible to conclude that using biofuels to replace diesel, jet, and RFO could help "balance" refineries to maintain a more constant gasoline : diesel ratio. It is possible that this could be accomplished through operational changes within the existing flexibility of refineries to process different feeds towards different products. However, in the high-electrification case, the refinery product slate would change dramatically, requiring shifts in overall refinery configurations or process-unit capacities.[40]

3.6. Minimum fuel selling price (MFSP) and GHG abatement cost

Based on each biofuel conversion pathway's target MFSP as available in literature and government agency reports (details in Section S9 of the ESI†), we estimated the GHG abatement cost for each conversion pathway (Fig. S29 in the ESI†). The target-case MFSP of the biofuels considered could be as low as $1–3 per gal ($0.26–0.79 per L), implying that most of these biofuels will be cost-competitive with their fossil-derived counterparts. The abatement cost of GHG emissions depends significantly on the feedstock used per conversion pathway. In all cases, the results show that most biofuels considered have a cost of GHG abatement ranging from $116 per ton CO_2e to $356 per ton CO_2e. This range extends below the recent Low Carbon Fuel

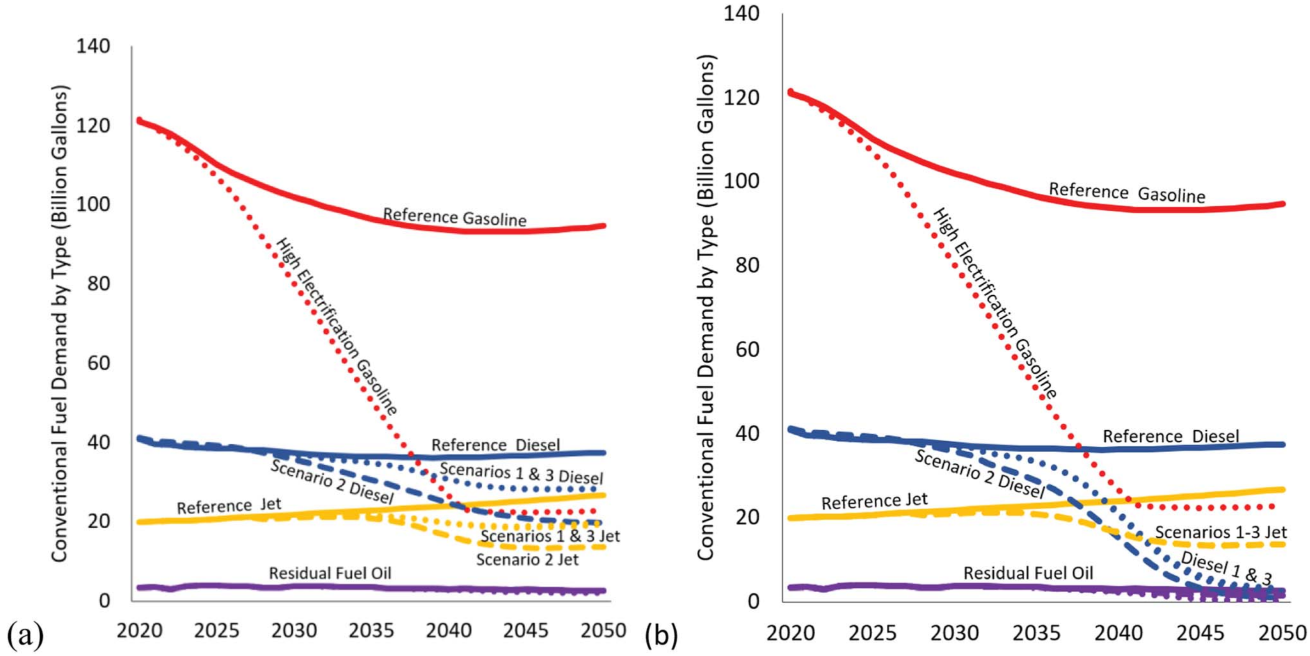

Fig. 8 Demand for refinery products in the reference case and decarbonization scenarios: (a) \$40 per dt biomass price and (b) \$60 per dt biomass price.

Standard (LCFS) credit price of ~\$200 per ton CO_2e and reflects the fact that the analysis is focused on sectors which will be costlier to decarbonize. Algae-derived hydrotreated esters and fatty acids (HRJ using algae) had notably higher costs, which ranged up to \$1608 per ton CO_2e in 2050. This suggests that without significant improvements to the technology, this pathway is more unlikely than some others. Accordingly, for some of the pathways, such as algae HRJ, we're optimistically assuming some technological breakthrough may be possible to make algae to jet fuel commercializable.

4. Discussion

While electrification will play a significant role in the LD sector, the use of biofuels in decarbonizing the aviation, marine, and HD sectors, which are harder to electrify, would speed GHG emissions reductions. This study has highlighted the finding that even under the BAU biomass availability case, biofuel can supply 27% of the energy demand across the hard-to-decarbonize sectors we considered by 2050 and can reduce GHG emissions by 202 million tonnes CO_2-eq. or 11% more compared with their levels based on electrification alone. This finding highlights that alongside electrification, biofuels will likely need to play a significant role in decarbonizing the HD, marine and aviation sectors.

A key finding is that using low-carbon biofuels provides a significant benefit associated with the displacement of higher-carbon petroleum fuels, regardless of the petroleum fuel and end use that are displaced. This is because the emissions from the various petroleum fuels are relatively similar, while the fuel pathways presented in this analysis were all selected for their low life-cycle GHG emissions. While conversion efficiency also affects the amount of energy that can be displaced by the biofuels produced, this effect did not cause significant differences across the scenarios analyzed here.

Our analysis also shows that even when transportation fuels are prioritized, U.S. biomass resources are not sufficient to meet projected U.S. demand. First, this means that electrification beyond the levels analyzed here could further augment GHG reductions, provided it comes from low-carbon sources. For example, batteries or fuel cells could further augment decarbonization in MDVs and HDVs and light marine applications such as ferries and other inland vessels. Using industrial wastes, such as carbon dioxide, together with electricity to produce electro-fuels is another means of leveraging low-carbon electricity to decarbonize transport. Electro-fuels could potentially supplement biofuels to further decarbonize the HD, aviation, and marine sectors. However, further research is needed to address the performance and cost challenges for CO_2-derived fuels.[41] Second, this means that under a long-term deep-decarbonization scenario, it is unlikely that U.S. bioenergy resources would be exported for fuel use in other countries. Conversely, the U.S. could potentially import additional biomass resources or biomass-derived fuels to further offset petroleum fuels and reduce transportation GHG emissions. Meanwhile, about 6 million tons of wood pellets were exported by the U.S. for biofuel use in Europe in 2018, making the U.S. the largest trading partner in wood pellets across Europe. Therefore, understanding the potential for biofuel technologies in the context of competition for biomass is important.[42]

There is a long way to go to decarbonize transportation, and biofuels can only bring us part of the way. Biofuels may offer a lower-cost, nearer-term option for decarbonizing HDVs, while electrification could have benefits in the longer term. Marine represents another sector where a significant amount of biofuel could also potentially be used. Meanwhile, biofuels for aviation have distinct risks because of the sensitive nature of air travel and the increased need for reliability.

Our analysis does not address the potential effect of concerted efforts to reduce transportation energy demand through breakthrough efficiency improvements and mode shifting. For gasoline engines, advanced engine technologies, coupled with high-octane/performance-advantaged fuels, have the potential to increase vehicle energy efficiency. Additionally, hybrid and plug-in hybrid drivetrains can significantly increase the efficiency of fuel use. Further, increased use of public transport could displace energy use for LD transport, while shifting freight from truck to rail or inland water could further reduce energy use for HD transport.[43,44]

Our analysis showed that LD and HD electrification would increase demand for electricity significantly. Expanded use of lithium-ion batteries for EVs will also drive up demand for expensive metals that have a high environmental and social impact.[16] However, circular-economy strategies will increase battery recycling, which will help meet the demand for these resources.[45] Other significant areas of impact are the potential investments needed for these transitions in terms of capital investment for biofuel production facilities,[12] investment/time to convert the LD fleet to electric, and additional electricity generation and distribution infrastructure. However, with drop-in-fuels like renewable diesel, for example, which is compatible with most existing engines with little or no modification, the impact on vehicle owners and manufacturers may be minimal. If significant modifications are required, the increased biofuel market share in these sectors may require stakeholders to adapt their businesses to produce alternative vehicles. This may be challenging for these stakeholders unless policies are in place with regulations to offset the increased production and infrastructure cost.[33]

The analysis showed that increased electrification and biofuels use will have a significant impact on demand for petroleum fuels. We also found that increased use of biofuels to replace diesel fuels could help maintain a more constant gasoline : diesel ratio over time as electrification displaces significant amounts of gasoline use by LDVs. This development could potentially help smooth the transition for refineries as other technologies displace petroleum fuels.[40] However, cost is viewed as a key driver for alternative fuels. The high production cost of biofuels compared with petroleum-based fuels is a major barrier to their increased market penetration, and electrification or other methods to decarbonize would be even more costly because of high infrastructure cost. For example, the relatively low cost of fuels for the marine sector is seen as a barrier to biofuels adoption.[46] Decreased demand for petroleum fuels would serve to depress their prices, as has been seen clearly as a result of the pandemic. Therefore, it will be important to address the price of petroleum fuels if BEVs and biofuels are to be competitive.[47–49]

We need to continue to consider additional technologies and strategies such as energy efficiency, mode shifting (for freight), public transport, and reducing transportation demand to reduce transportation energy use. Coupled with biofuels and electrification, these strategies could bring us closer to zero GHG emissions.

This study can be extended to include incorporating full techno-economic analysis to allocate feedstocks to fuel production pathways and to consider the potential effects of policies in the different sectors and the potential for competition for biomass among sectors (and for export to meet international demand). In addition, in all scenarios considered, water consumption is greater than in the reference case. This increase comes from greater consumption of electricity, which is more water-intensive than petroleum fuels, and from high water consumption in several biomass-to-biofuel conversion pathways. Accordingly, optimizing water consumption in biomass conversion processes merits further research. In summary, this analysis provides insight into how the nation's substantial biomass resources can complement increasing electrification in efforts to reduce transportation GHG emissions and address the urgent challenge of climate change.

Conflicts of interest

There are no conflicts to declare.

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