Supplementary Information for the Contribution of Biomass and Waste Resources to Decarbonizing Transportation and Related Energy and Environmental Effects

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S1 Biomass availability: current and future

It is estimated that about 378 MM dry tons of biomass resources are consumed in the current economy (2019), with 57% consumed for heat and power and 39% for biofuel production. There is a potential of an additional 297 MM dry tons totaling 675 MM dry tons of biomass resources that could be consumed in the 2050 business-as-usual scenario (at $40/ton) and an additional 889 MM dry tons totaling 1267 MM dry tons of biomass resources that could be consumed in the 2050 billion ton scenario (at $60/ton) based on 2016 billion ton report.

The current primary sources of biomass are agricultural, forestry/wood resources, municipal solid wastes (MSW), and other wastes resources. The agricultural biomass resources are majorly used to produce fuels and bio-based chemicals. The woody biomass, and the biogenic portion of MSW, and other waste biomass are utilized in the production of heat and power for various sectors while animal manure is consumed in heat and power production for farm use. Fig.S-1 and Fig.S-2 provide an overview of biomass resources availability at ≤$40 and ≤$60 per dry ton biomass selling price. The potential additional biomass resources into the future come from the development of energy crops, increased use of agricultural residues, unused forestry/wood wastes resources, and increased contribution from animal manure and the biogenic portion of municipal solid wastes (MSW).

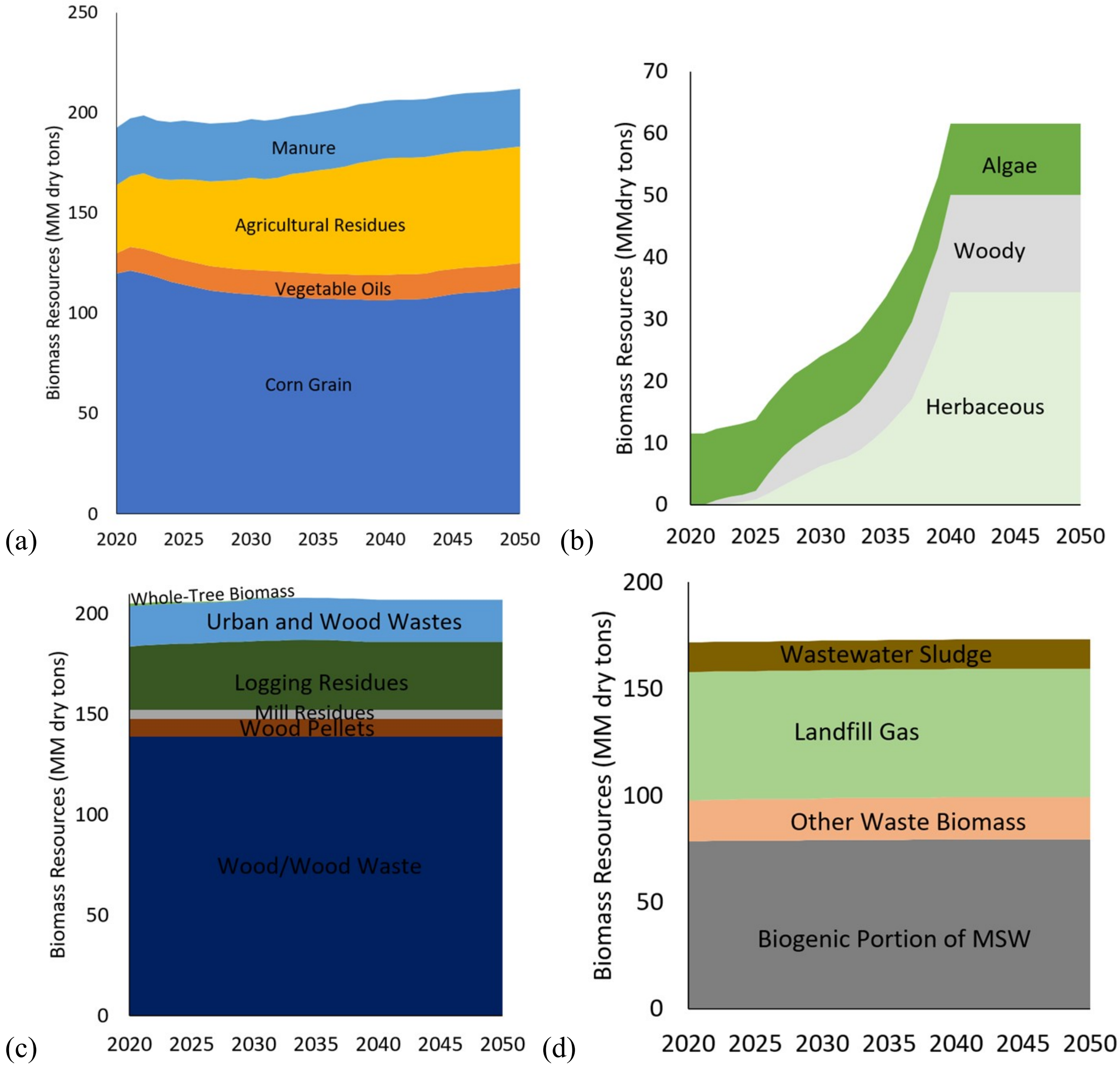
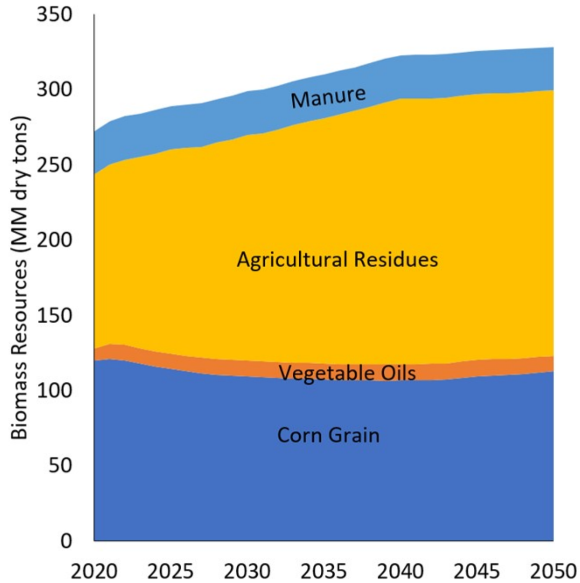
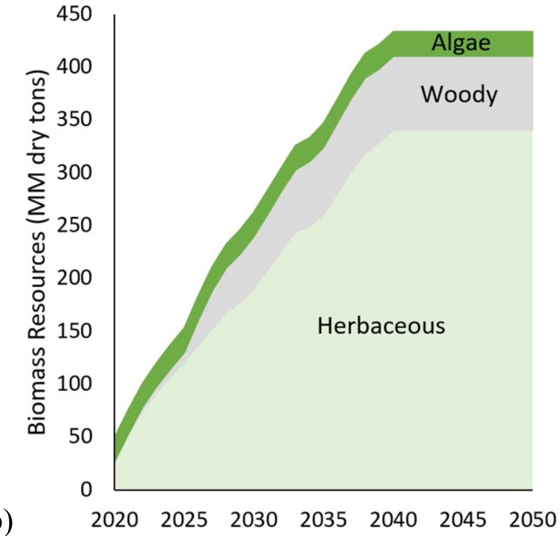


Fig. S-1. Resources availability at ≤$40 per dry ton biomass selling price (BAU) (a) Agricultural, (b) energy crops, and algae, (c) forestry/wood, (d) MSW/other wastes.[1,2]



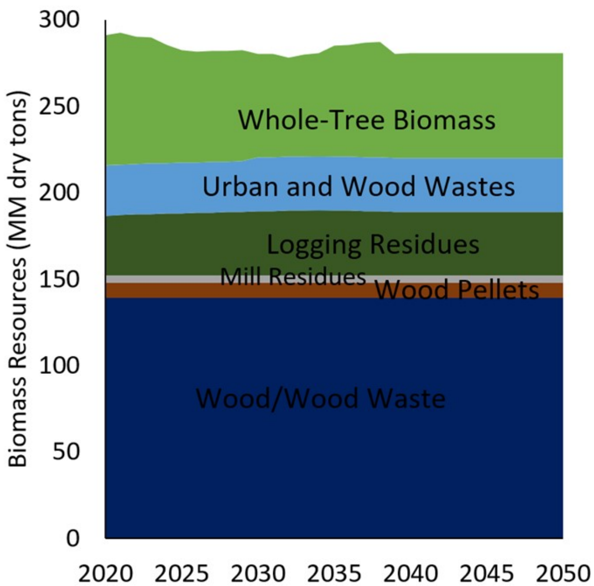
350
300
250
200
150
100
50
0
Biomass Resources (MM dry tons)
Manure
Agricultural Residues
Vegetable Oils
Corn Grain
2020
2025
2030
2035
2040
2045
2050

(a)



450
400
350
300
250
200
150
100
50
0
Biomass Resources (MM dry tons)
Algae
Woody
Herbaceous
2020
2025
2030
2035
2040
2045
2050

(b)



(c) (d)

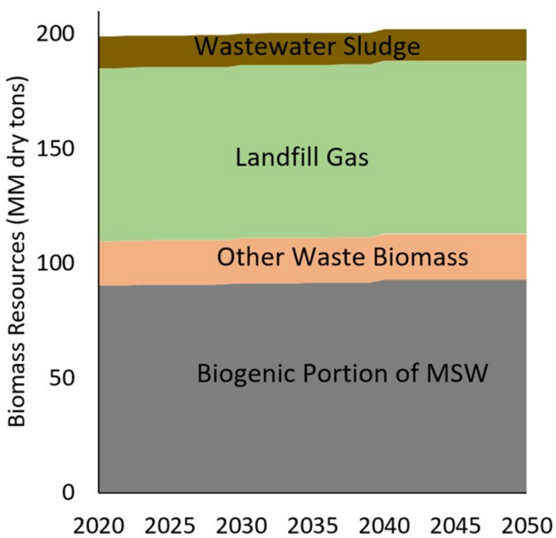
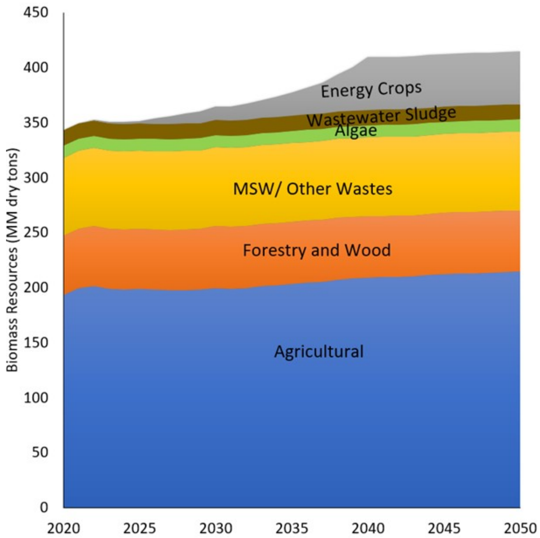


Fig. S-2. Resources availability at ≤$60 per dry ton biomass selling price (BTB) (a) Agricultural, (b) energy crops, and algae, (c) forestry/wood, (d) MSW/other wastes.[1,2]

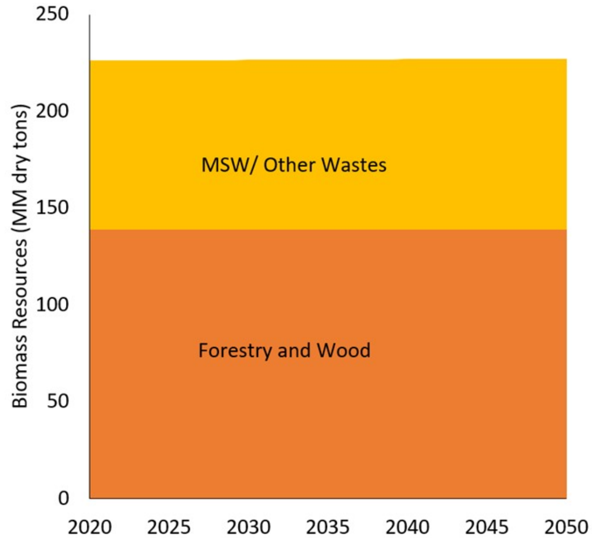
S2 Resources allocation to various end uses

The available biomass resources are distributed to different end uses in the economy such as fuel, heat and power, biobased chemicals, and wood pellets. We follow Rogers et al.[3] allocation procedure. Most resources are allocated to transportation fuels. For fuel production, it is assumed that the portion of corn grain, vegetable oils, and other fats that will be consumed into the future is based on AEO 2020 ethanol and biodiesel production projection until other potential biofuels are introduced in the market. The amount of corn and soybeans consumed in the year before the market introduction of other potential biofuels (2027 in most scenarios) then remains constant until 2050. Additionally, 18.7% of landfill gas consumed in the current economy is utilized for transportation fuels. This share stays constant with the balance being used for power generation. Based on Rogers et al.[3] 4.6% of agricultural residues, energy crops, and algae are allocated to bio-based chemicals in the projected bioeconomy; the rest go to fuel production. These scenarios assume that renewable non-carbon options such as solar and wind will be increasingly used to meet energy demand for electricity generation. Animal manure, which is consumed in heat and power production in the current economy, is accordingly allocated to fuel production. Wood/wood wastes and biogenic municipal solid wastes (MSW) consumed for power production in the current economy are assumed to remain constant until 2050 (not treated as manure), while the additional wood/forestry biomass and MSW are allocated to fuel production. Fig.S-3 and Fig.S-4 show the biomass resources allocated for fuel, heat and power, biobased chemicals, and wood pellets in the BAU and BTB biomass availability scenarios. Note that manure is included with the agricultural category in Fig.S-3 and Fig.S-4a



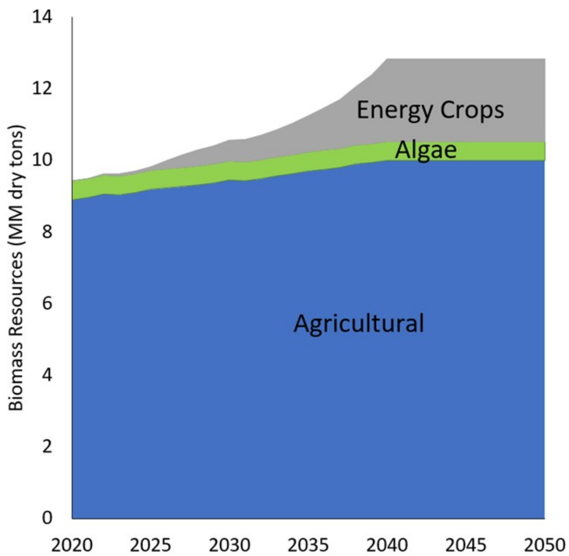
Energy Crops
Wastewater Sludge
Algae
MSW/ Other Wastes
Forestry and Wood
Agricultural
Biomass Resources (MM dry tons)
450
400
350
300
250
200
150
100
50
0
2020
2025
2030
2035
2040
2045
2050

(a)



MSW/ Other Wastes
Forestry and Wood
Biomass Resources (MM dry tons)
250
200
150
100
50
0
2020
2025
2030
2035
2040
2045
2050

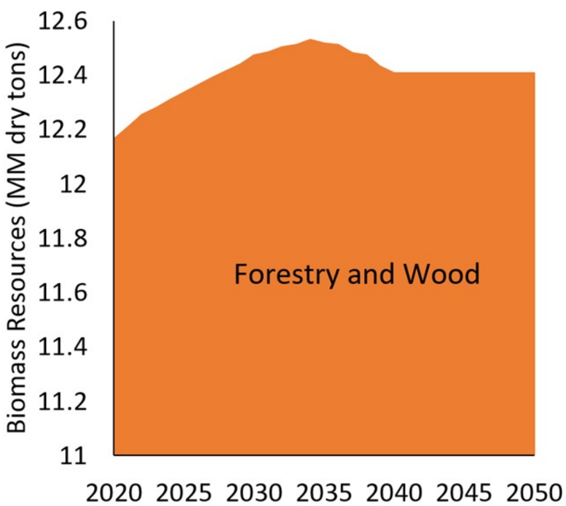
(b)



Energy Crops
Algae
Agricultural
Biomass Resources (MM dry tons)
14
12
10
8
6
4
2
0
2020
2025
2030
2035
2040
2045
2050

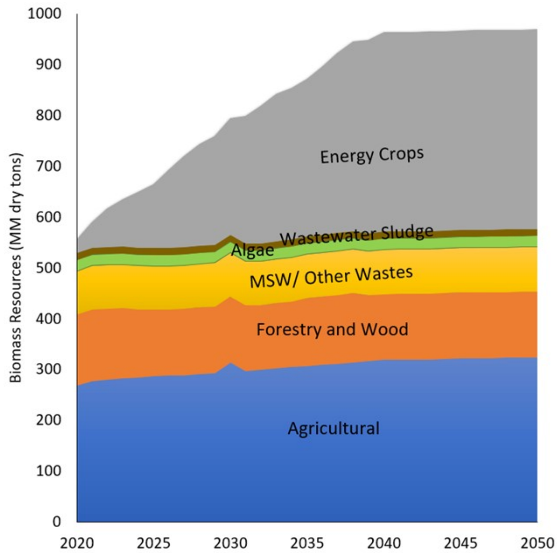
(c)

(d)

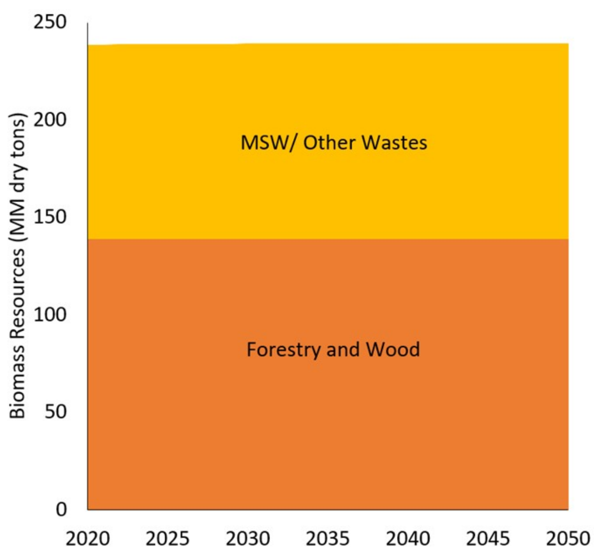


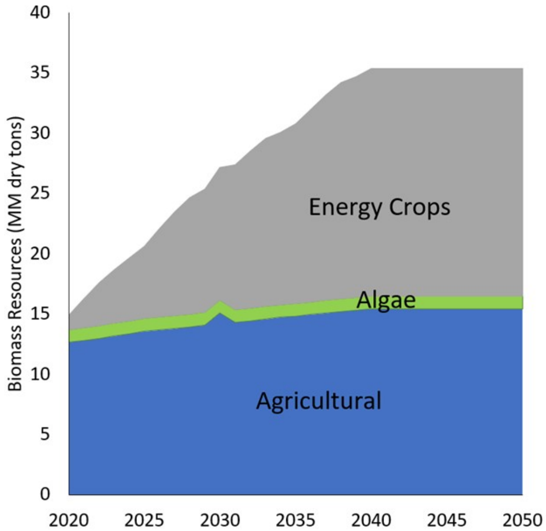
Forestry and Wood
Biomass Resources (MM dry tons)
12.6
12.4
12.2
12
11.8
11.6
11.4
11.2
11
2020
2025
2030
2035
2040
2045
2050

Fig. S-3. Biomass allocation for energy and energy products in the BAU (≤$40/dry ton) availability scenario (a) fuel production, (b) heat and power generation, (c) biobased chemicals, and (d) wood pellets.



(a) (b)



(c) 

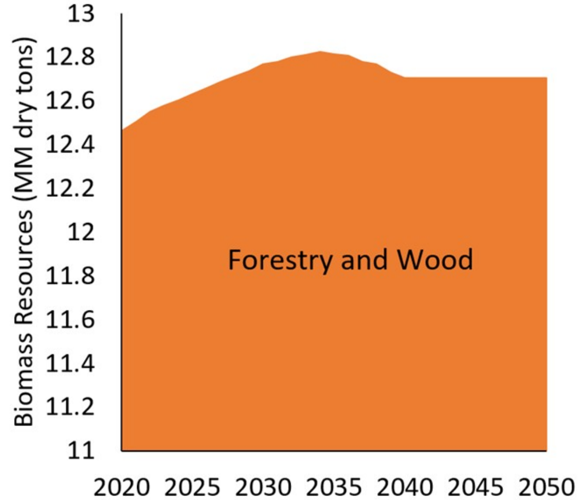
(d) 

Fig. S-4. Biomass allocation for energy and energy products in the BTB (≤$60/dry ton) availability scenario (a) fuel production, (b) heat and power generation, (c) biobased chemicals, and (d) wood pellets.

S3 Pathway to the target biofuel blend level

Linear approach

Using this approach, we assume a minimum biofuel blend level of 1% (v/v) for all biofuel in each sector when the biofuel is introduced in the market except for pyrolysis oil which is set at 2%. This blend level is assumed to increase linearly at a fixed rate per year until 2050 depending on the scenario. The fixed yearly increase rate may vary across sectors in the same scenario depending on the level of energy consumption, target biofuel market share (blend level), and resource availability.

Technology adoption curve

Estimating how quickly or widely a technology will be accepted in the market is vital to predict its future adoption. We use technology adoption curves to estimate the growth rate in the biofuel market share by 2050 at a minimum market share of 1% (v/v) for each biofuel across each sector when the biofuel is introduced in the market except for pyrolysis oil which is set at 2%.

Technology adoption curves characteristically have an S-curve shape with four stages: the initial slow growth in market share, the fast growth in market share, the late-stage slow growth, and no growth in market share. The last stage (no growth in market share) in our analysis is determined by resource constraints.

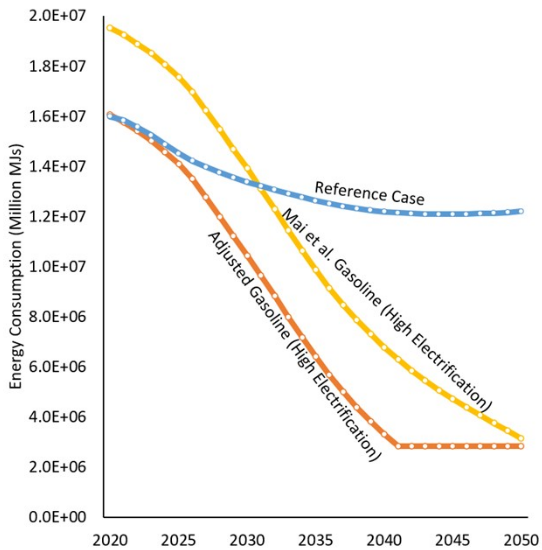
Many equations can generate an S-curve; however, the most used is the logistic equation as shown in equation 1, which is what we use in this analysis.[4]

$$S(X) = min + (max - min)\left[\left(1 \middle/ \left(1 + exp(-K(X - X_0))\right)^a\right)\right] \quad (1)$$

Where x is the simulation period, x_o is the mean of the simulation period, k and a are >0 and are parameters that control the shape, min is the minimum biofuel blend level (vol%) in the introduction year and max is the maximum biofuel blend level target at the end of the simulation period. Parameters k and a can vary in their value and could be greater than zero. The larger the k value, however, the longer it takes for the initiation of rapid growth in market share. In addition, the lower the value of a, the sooner fast growth starts. Also, the growth curve is less steep. For our analysis, we set k and a at 0.5 and 1, respectively, to balance these considerations.

S4 Additional information on the light and heavy-duty high electrification

We consider high electrification scenario based on the optimistic case in Mai et al.[5] to assess the extent to which electrification will penetrate the LDV and HDV sectors. However, Mai et al.[5] 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 as in Fig. S-5 , especially for gasoline and electricity consumption. This adjustment is not made for other fuels but instead uses AEO reference data for the other fuels in the high electrification scenarios. The results indicate a significant reduction (above 80%) in gasoline energy demands in 2050 relative to 2019 due to the high penetration of electrification in the light-duty sector. The adjusted gasoline consumption remains constant from 2040-2050 (Fig.S-5) because this is the minimum gasoline consumption achieved in Mai et al.'s high electrification data.

(a) 

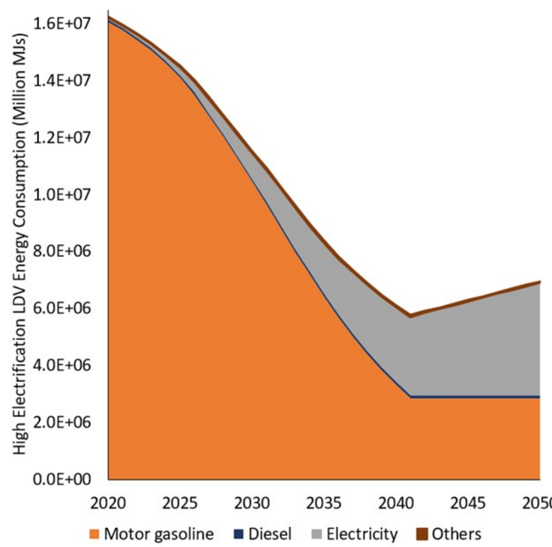
(b) 

Fig. S-5. Overview of LD high electrification energy consumption.

In the high electrification scenario for the heavy-duty sector, it was assumed that the high adoption of electric vehicles for the MD/HD sector would expand to both short and long-distance uses. This scenario assumed that electric vehicles will be 50% and 41% sale shares of MDV and HDV in 2050, respectively. Like the light-duty sector, Mai et al.[5] 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 as in Fig.S-6. The results indicate that a 42% reduction in petroleum diesel energy demands in 2050 relative to 2019 is possible due to the high penetration of electrification in both medium heavy-duty vehicles and heavy-duty trucks. By 2050, Electricity will make up 27% of total HDV energy demand, with more than 60% of energy demand still expected to come from petroleum diesel.

(a) (b)

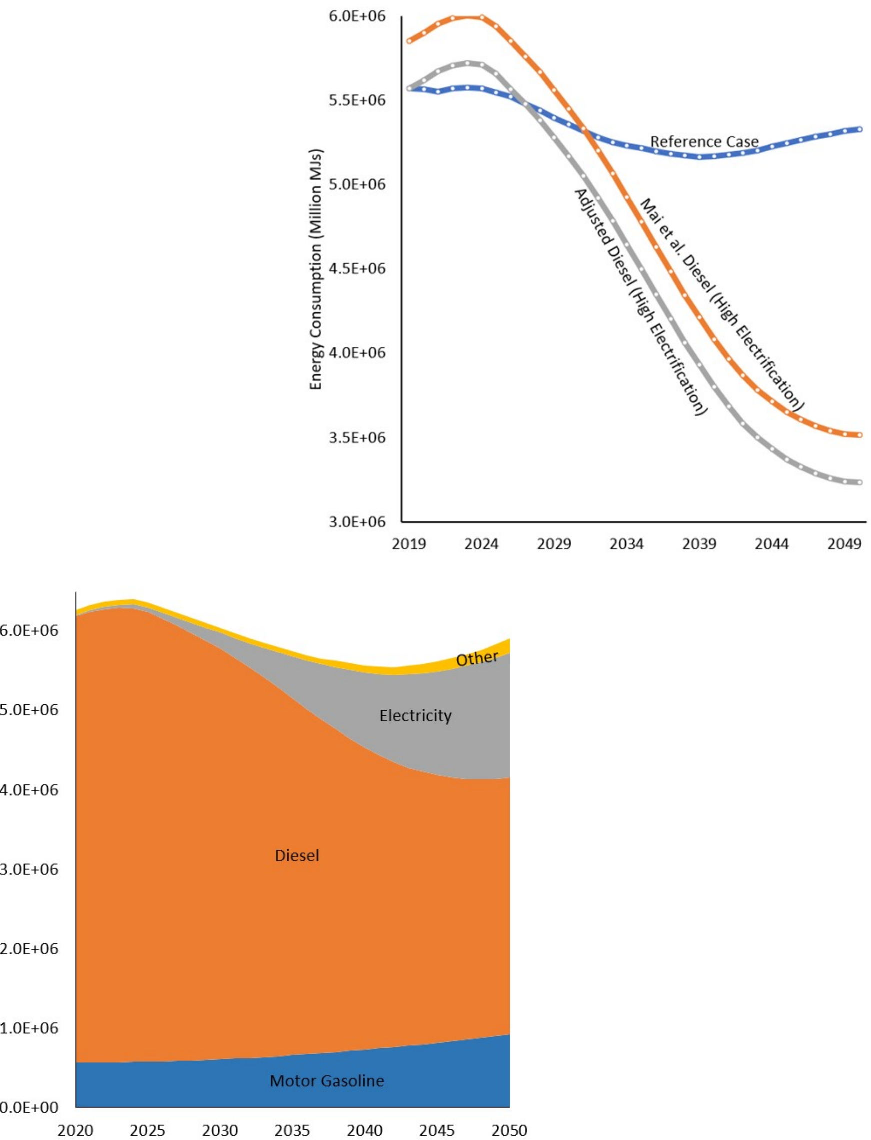


Fig. S-6. Overview of HD high electrification energy consumption.

S5 Additional information on decarbonization allocation scenarios

Fig. S-7 gives an example of the two pathways taken to achieve a set feasible biofuel target. The figure provides an overview of ethanol market penetration in the LD and HD sector from 2028 (assuming the same blend level with reference case until 2027), reaching a 30% (v/v) target in 2050. Although the starting point and the endpoint in the two approaches are the same, the market penetration rate differs across the years. The adoption curve starts with a slower adoption rate in the first few years of market introduction but picks at a high rate after 2038 reaching the target level by 2047 compared to the linear approach that reached the target point in 2050. Corn ethanol demand in 2027 in the high electrification scenario based on the ethanol content per AEO projection is 42 billion liters. However, the amount of ethanol required to meet the 30% (v/v) target (Fig.S-8) of ethanol in motor gasoline by 2050 is about 36.8 billion liters. This results in about 5.2 billion liters of excess corn ethanol that could be redirected to the aviation or heavy-duty sector as LD becomes electrified.

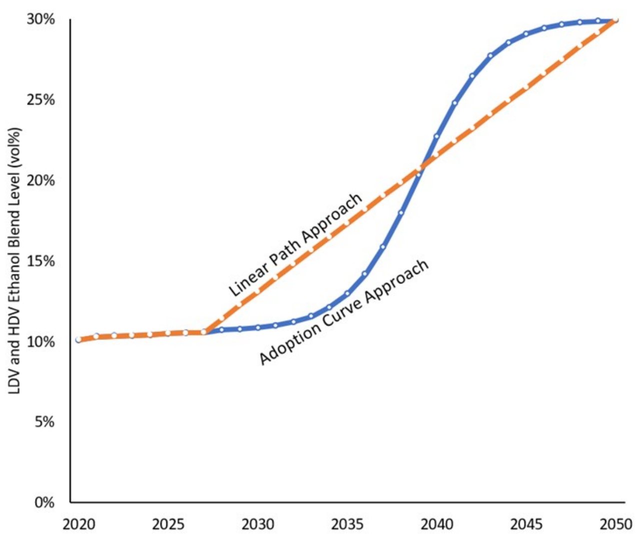


Fig. S-7. Ethanol blend level in motor gasoline.

Biofuel market penetration at $40/dry ton

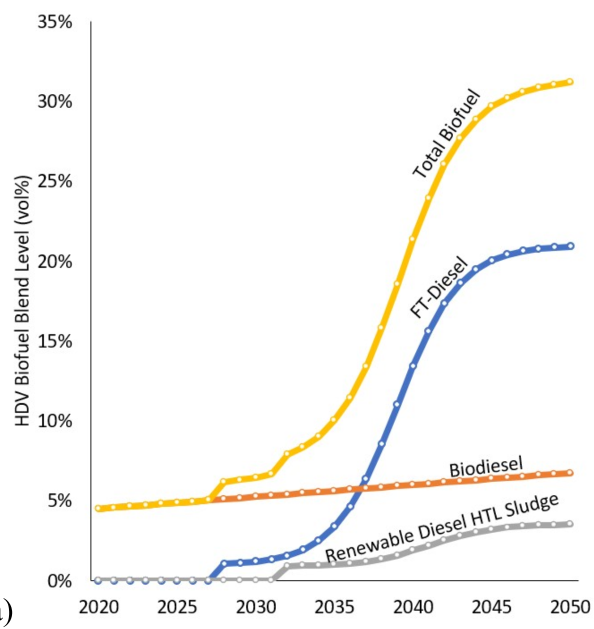
Scenario 1: Similar blend levels for heavy-duty, aviation, and marine sectors (low technology scenario)

Heavy-duty sector

Based on the potential new biomass available and energy demand for each sector as projected by AEO 2020,[6] it is estimated that biofuels from the new potential biomass can contribute up to 24% (v/v) of the major fossil fuels consumed in each sector by 2050. The heavy-duty sector uses more energy than the aviation and marine sectors. It is allocated about 139 MM dry tons (49%) of the total 285 MM dry tons of the new potential biomass available in 2050 to meet this set target. This allocation targets the production of Fischer-Tropsch diesel (FTD) and renewable diesel to displace petroleum-based diesel. Various renewable diesel fuels considered in the study are categorized based on the feedstock used, conversion pathways, technology readiness level and heating value to mention but few.

The rate at which biofuel penetrates the heavy-duty sector is given in Fig.S-8. The heavy-duty sector depends on biodiesel (currently at ~5% (v/v)) from soybean as a major biofuel from 2020 to 2027, assuming that the amount of biodiesel consumed in 2027 remains constant until 2050. FTD is introduced in the market in 2028 with production reaching 29.2 billion liters in 2050 displacing 21% (v/v) of petroleum diesel. Renewable diesel from wastewater sludge is introduced in the market in 2032, with production reaching 4.9 billion liters equivalent to 3.5% (v/v) of 2050 diesel demand. With about 6.5% (v/v) contribution from biodiesel in 2050, biofuels make up 31% (v/v) of diesel consumption in the heavy-duty sector (Fig.S-8).

(a)



(b)

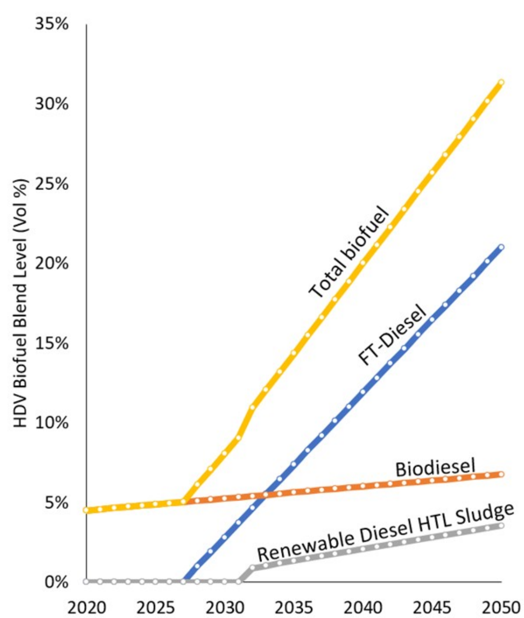


Fig. S-8. Feasible biofuel level in HD sector (a) adoption curve path (b) linear path.

Aviation sector

It is projected that energy demand in the aviation sector will continue to grow until 2050 as air travel grows by 70%.[6] It is worth mentioning that our base case relies on the AEO 2020 projection which may have not taken the impact of the pandemic on air travel into consideration. 43% (124 MM dry tons) of the potential new biomass resources are allocated towards meeting the feasible target of 24% (v/v) biofuel market share in the aviation sector in 2050. The potential new biomass are directed toward Fischer-Tropsch (FT) jet fuel reaching ~24.4 billion liters in 2050.

We estimated that corn used for ethanol production in 2028 could produce approximately ~1.7 MM tons of corn oil (at ~0.014ton corn oil/ton corn), which can be directed towards hydroprocessed renewable jet (HRJ). The HRJ from corn oil provides an additional 1.6 billion liters of renewable jet fuel in 2028, displacing 2% (v/v) of conventional jet fuel required in that year. However, as the corn allocated to ethanol production remained constant until 2050, the volume of HRJ produced also remained constant, displacing 1.6% (v/v) of conventional fuel in 2050. 5.2 billion liters of corn ethanol are retracted from the LD sector, and additional 4.2 billion liters of cellulosic ethanol from the potential new biomass are directed towards producing ethanol to jet (ETJ) fuel reaching 3.6 billion liters in 2050 account for 3.5% (v/v) of aviation fuel demand. Fig.S-9 provides an overview of sustainable aviation fuels market penetration from 2028-2050, with bio-based jet fuel reaching 29% (v/v) of jet fuel demand in 2050.

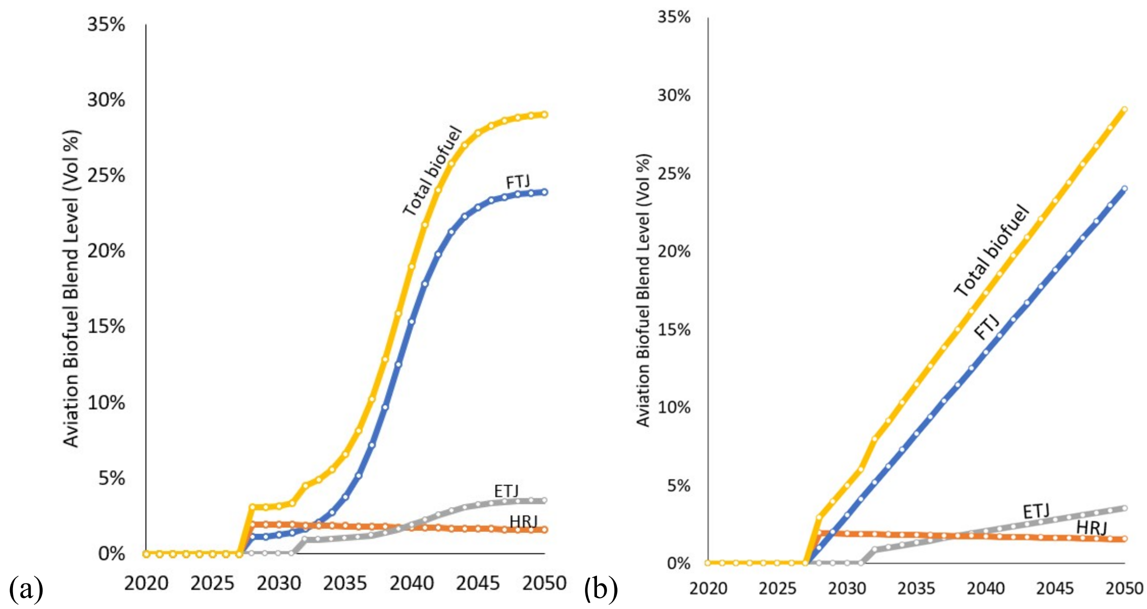


Fig. S-9. Feasible biofuel level in aviation Sector (a) adoption curve path (b) linear path.

Marine sector

In this scenario, we allocate 8% (22 MM dry tons) of the potential new biomass towards the production of pyrolysis oil and FTD/RD as alternative fuels for petroleum-based heavy fuel oil (HFO), and distillate fuel oil (DFO) consumed in the maritime sector. Currently, DFO consumption in the USA has a biodiesel content of 5 % (v/v). FTD is introduced to the market in 2028, with production reaching 2 billion liters in 2050, making up 21%(v/v) of the total DFO demands. On the other hand, RD is introduced to the market in 2032, reaching 328 million liters in 2050. Biodiesel, FTD, and RD together displaced 32% (v/v) of petroleum-based DFO demands in 2050 (Fig.S-10).

The market introduction year for pyrolysis oil is 2032 (based on the TRL level), accounting for 2% (v/v) of HFO consumed in that year, with production reaching 4.6 billion liters in 2050. This makes up 38% (v/v) of HFO demands (Fig. S-10) and accounts for 22% (energy basis) of HFO energy demand in 2050.

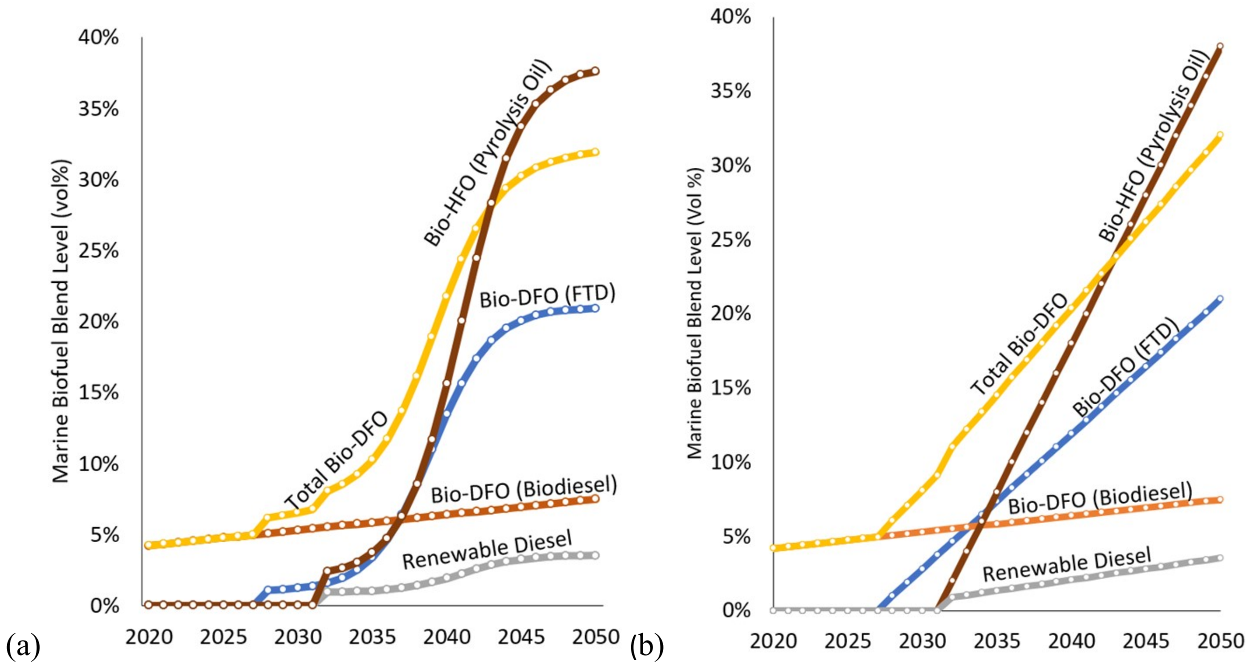


Fig. S-10. Feasible biofuel level in aviation Sector (a) adoption curve path (b) linear path.

Scenario 2: Biofuels prioritized for aviation

Aviation sector

Allocating all the potential new biomass towards bio-based jet reached about 27 billion liters in 2040, with additional 1.6 billion liters HRJ from corn oil and 1.2 billion liters ETJ from ethanol. The 29.8 billion liters are enough to displace 32% (v/v) of conventional jet fuel demands in that year. With the resources available in 2050, production reached approximately 51.4 billion liters, sufficient to meet the 2050 US aviation demands based on the current maximum blend permissible (50/50 petroleum bio-based blend),[7] as shown in Fig.S-11.

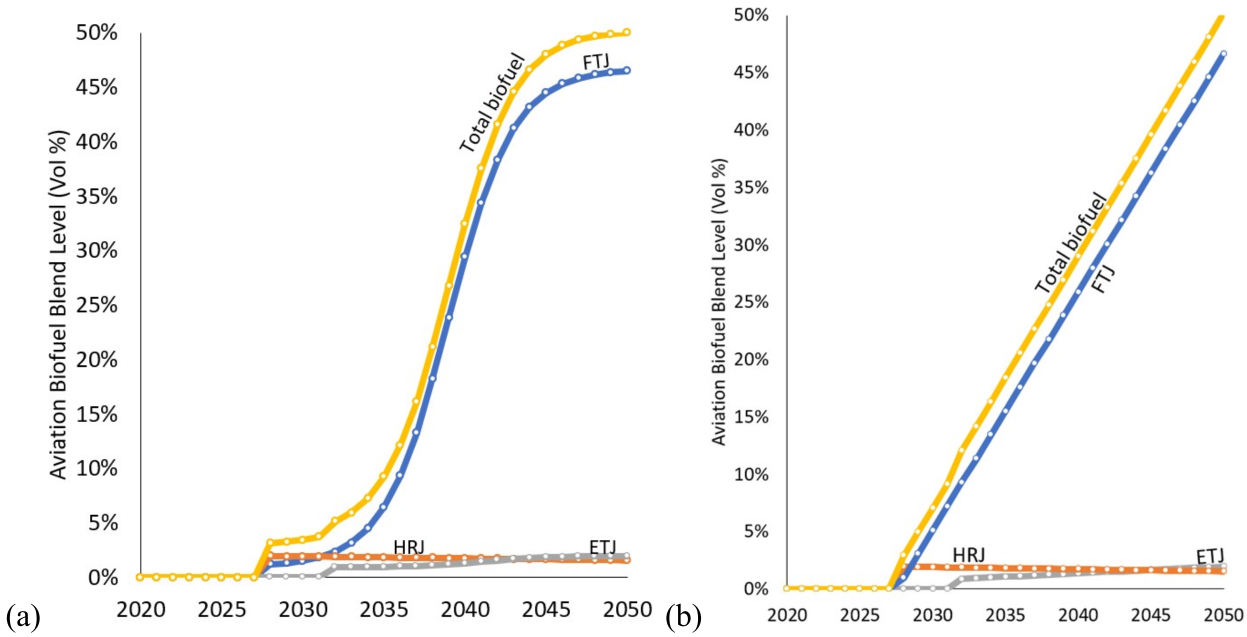
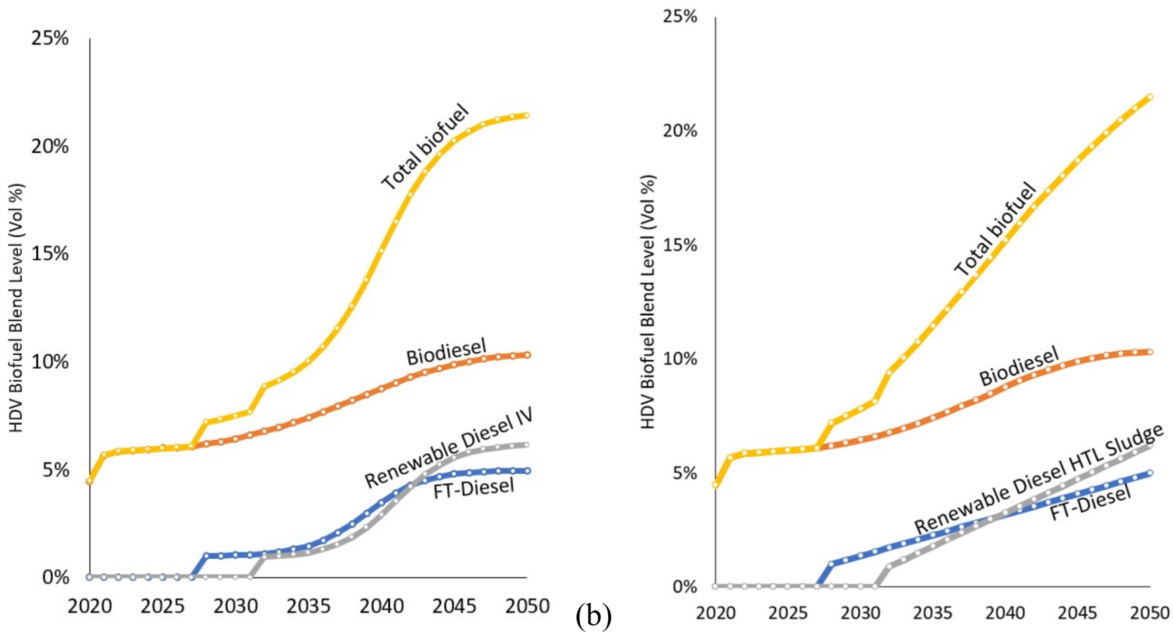


Fig. S-11. Feasible biofuel level in the aviation sector (a) adoption curve path (b) linear path.

Heavy-duty sector

The remaining biomass after jet allocation (landfill gas and manure excluded) are directed towards

FTD/RD production. FTD and RD production reached 9.4 billion liters in 2050, with the market introduction in 2028 and 2032, respectively, enough to displace 11% (v/v) of fossil-based diesel demands in HDV. Together with biodiesel (assuming the volume of biodiesel used in 2027 remain constant until 2050), biofuel production reached 19 billion liters in 2050, displacing 21% (v/v) of petroleum-based diesel demands (Fig.S-12).



(a) (b)

Fig. S-12. Feasible biofuel level in HD Sector (a) adoption curve path (b) linear path.

Marine sector

In the near term, the maritime sector is looking to reduce SOx, and other criteria air pollutant emissions.[8] Natural gas can potentially help with this. However, due to methane loss along the natural gas supply chain and methane slip from ship engines, and the fact it is still a fossil fuel, the potential to reduce GHG using methane is limited.[9] Renewable natural gas (RNG) is an option, although currently, the price is much higher than that of fossil natural gas. Besides, the supply may be limited, and supply chain losses and methane slip also remain an issue for RNG.

Therefore, we direct waste feedstocks such as landfill gas and animal manure toward renewable RNG production. 40 MM dry tons of landfill gas and manure are allocated for RNG production, resulting in 142.1 billion MJs of energy production in 2050. By 2050 the available RNG will displace 38% of DFO energy demands in that year, making up 15% of total marine energy demand (Fig. S-13).

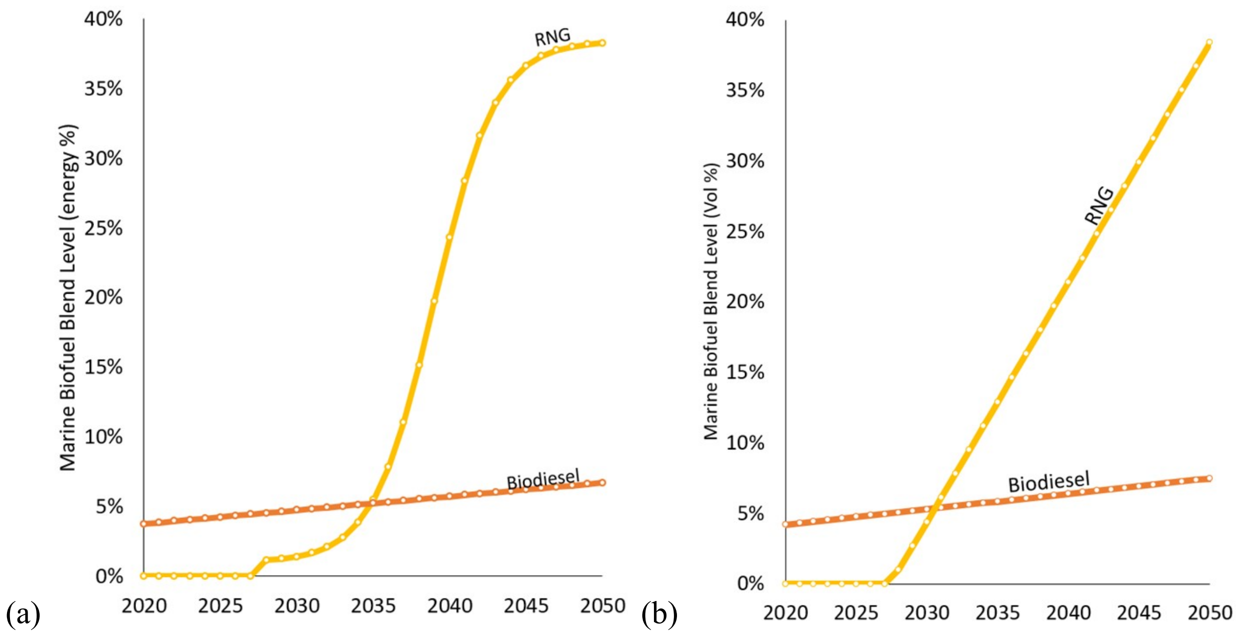


Fig. S-13. Feasible biofuel level in the marine sector (a) adoption curve path (b) linear path.

Scenario 3: Similar blend levels for the aviation and heavy-duty sectors

This scenario assumes that the available resources will be distributed between aviation and heavy-duty sector based on their share of total transportation fuel demand on an energy basis.

This set of assumptions results in up to 24 billion liters of FTJ production in 2050. With an additional 1.6 billion liters from corn oil and 2 billion liters from ethanol, bio-based jet annual production reached about 27 billion liters in 2050, equivalent to 27% (v/v) of 2050 jet fuel demands (Fig.S-14)

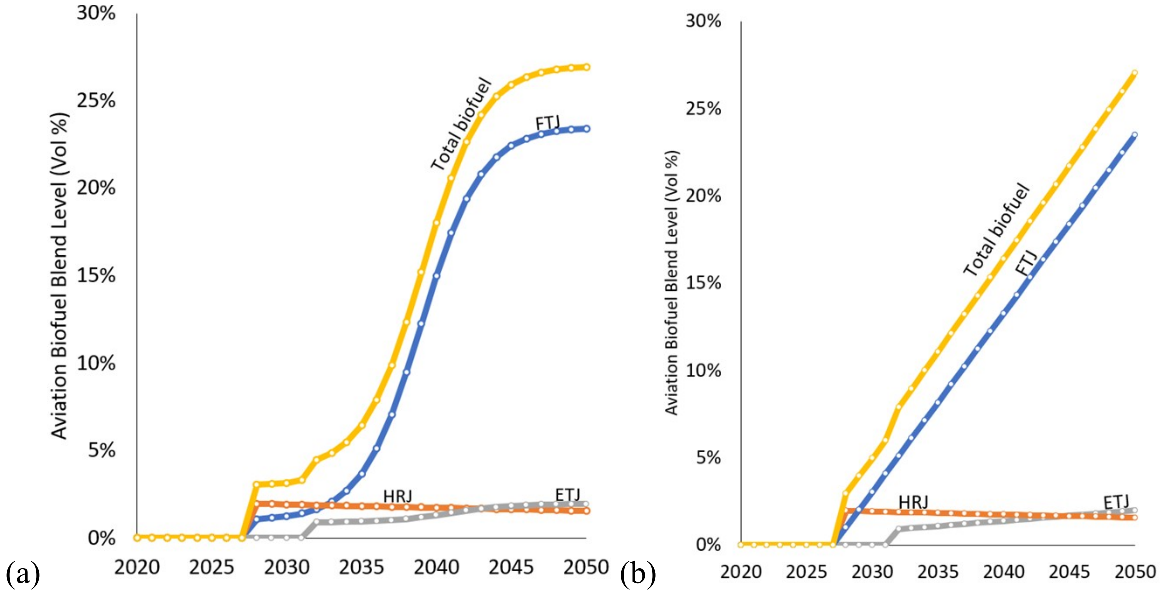


Fig. S-14. Feasible biofuel level in the aviation sector (a) adoption curve path (b) linear path.

In the HD sector, the production of FTD/RD reached about 33 billion liters in 2050, equivalent to 24% (v/v) of petroleum-based diesel demands in that year. With an additional annual biodiesel production of up to 9.3 billion liters, bio-based diesel fuels reached 42.3 billion liters, enough to displace 30% (v/v) of 2050 US diesel demands (Fig.S-15).

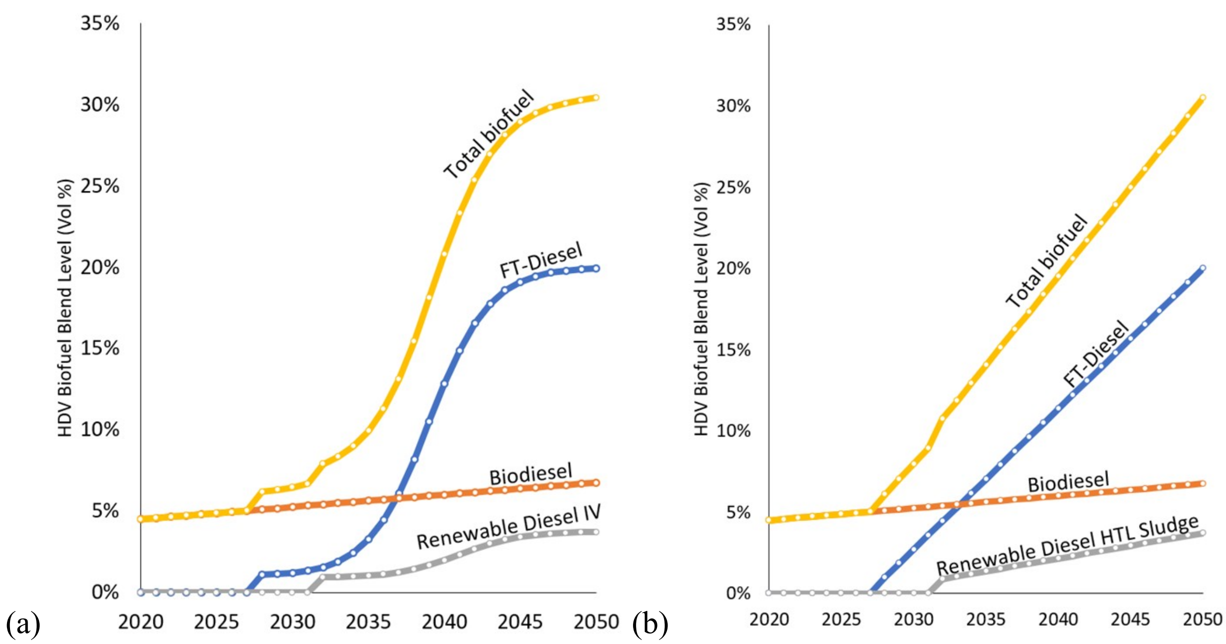


Fig. S-15. Feasible biofuel level in the HD sector (a) adoption curve path (b) linear path.

For the marine sector, we applied the same assumptions in scenario 2 regarding manure and landfill gas.

Biofuel market penetration at $60/dry ton

Scenario 1: Similar blend levels for heavy-duty, aviation, and marine sectors (low technology scenario)

Heavy-duty Sector

At $60/dry ton biomass price, the availability of more resources results in additional assumption regarding biofuel production in the HDV and marine sectors as follows:

- Start with F-T diesel with high TRL in 2028 but limit the blend level to 20%(v/v) by 2050.
- Transition to low TRL biofuel in the later year as more resources become available (RDII through pyrolysis, and RDIV through HTL).

FTD is introduced in the market in 2028 with production of about 1.5 billion liters displacing 1% (v/v) of petroleum diesel required in the heavy-duty sector in that year. By 2050, FTD production reaches 27.8 billion liters displacing 20% (v/v) of petroleum diesel. Renewable diesel (RDIV and RDII) is introduced in the market in 2032, with production reaching 4.9 billion liters and 79.5 billion liters equivalent to 3.5% (v/v) and 64.8% (v/v) of 2050 diesel demand, respectively. By 2050, biofuels make up 95% (v/v) of diesel consumption in the heavy-duty Sector (Fig.S-16), accounting for 78% (energy basis) of 2050 total heavy-duty energy demand (Fig.S-17).

Aviation Sector

Fig.S-16 provides an overview of how sustainable aviation fuel penetrates the aviation market from 2028-2050, with bio-based jet fuel reaching 50% of jet/aviation (6.2% ETJ, 1.6% HRJ and

42.2% FTJ) fuel demand by volume and accounting for ~49% (energy basis) of aviation energy demand in 2050 (Fig.S-17). Although biomass resources available at this price could provide more than 50% (v/v) of aviation fuel by 2050, as seen in the other sectors. However, because the maximum permissible blend level in the aviation sector is 50%,[7,] we kept this constant for every scenario.

Marine Sector

In 2028, FTD accounts for 1% (v/v) of DFO consumed in the marine sector but reaching 20% (v/v) by 2050. As more resources become available over the years, renewable diesel (RDIV and RDII) is introduced in the market in 2032, reaching 54.4 billion liters in 2050. Biodiesel, FTD and RD together displaced 96% (v/v) (Fig. S-16) of petroleum-based DFO demands accounting for 83% of marine DFO energy demand in 2050 (Fig.S-17). The market introduction year for pyrolysis oil is 2032 (based on the TRL level), accounting for 2% (v/v) of HFO consumed in that year. By 2050, pyrolysis oil makes up 95% (v/v) of petroleum-based HFO demand in the marine sector.

Scenario 2: Biofuels prioritized for aviation

Although the aviation sector is prioritized in this scenario, there are more than enough resources to produce the 50% (v/v) maximum permissible blend level required for aviation and supply the demand from heavy-duty and marine sectors at this biomass price.

Heavy-duty Sector

In this scenario, the high electrification of HDV reduced diesel energy demand by approximately 40% in 2050 relative to the reference case and other scenarios. With significant penetration of electrification, biofuels make up 100% (v/v) (20% FTD, 10% biodiesel, 6% RD IV and 63% RDII) of 2050 HDV diesel demand (Fig. S-16) and account for 53% (energy basis) of HDV total energy demand.

Marine Sector

At $40/dry ton biomass price, this scenario assumed RNG would take off in the maritime sector, displacing some fraction of DFO, and therefore we directed waste feedstocks such as landfill gas and animal manure toward renewable natural gas production. However, the high penetration of electrification minimizes the amount of biomass resources required in the HD sector; hence, more resources are retracted to the marine sector. With the available biomass, 82.6% (energy basis) of energy demand in the marine sector in 2050 can come from RNG, pyrolysis oil, biodiesel, and renewable diesel (Fig.S-17).

Scenario 3: Similar blend levels for the aviation and heavy-duty sectors

While the biofuel blend level in the aviation sector is held constant at 50% (v/v), the resources available after aviation allocation can produce 100% (v/v) of diesel demand in the HD sector by 2050 and provide 32% (energy basis) of marine energy demand.

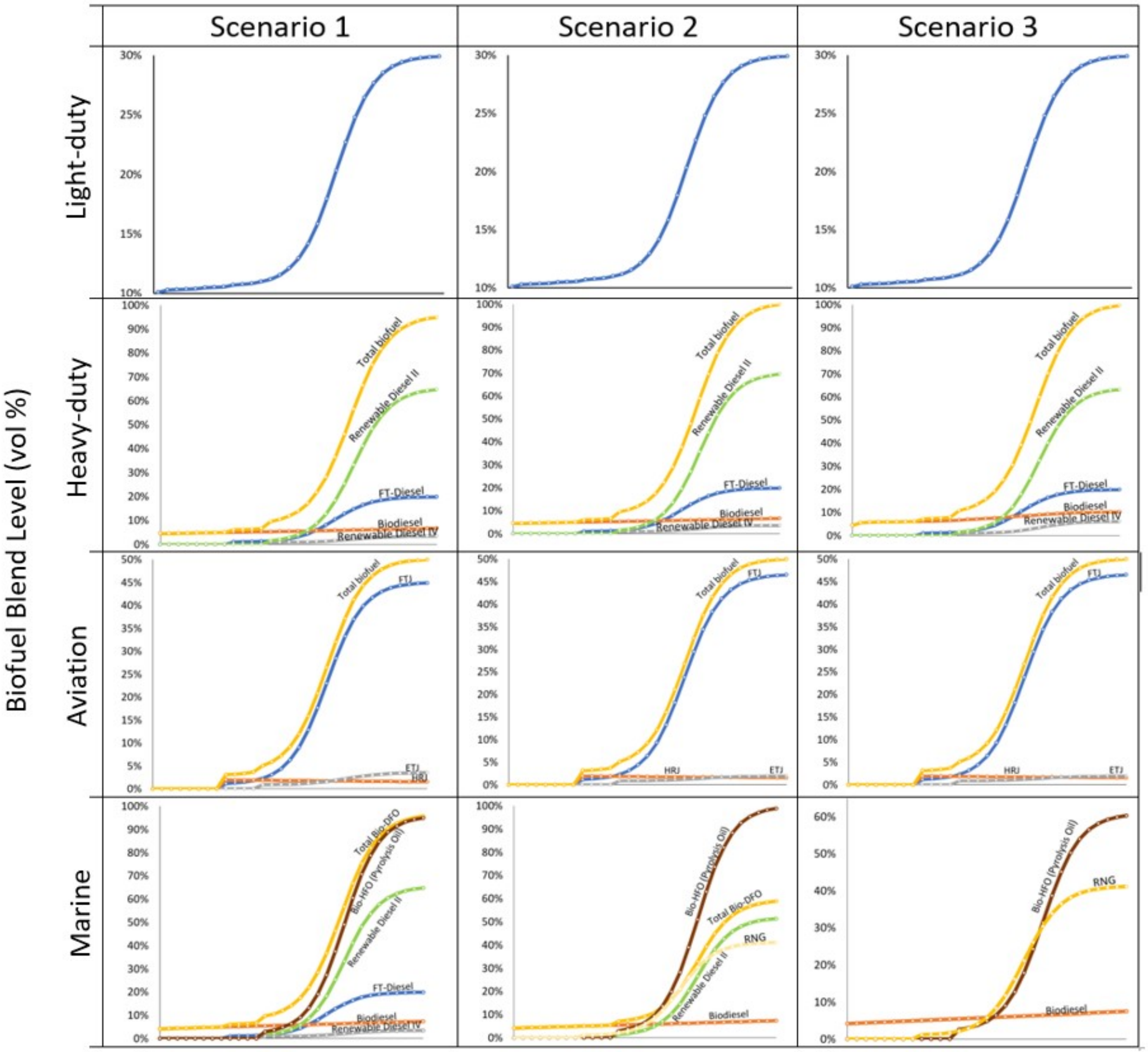


Fig. S-16. Summary of biofuels market penetration at $60/dry ton.

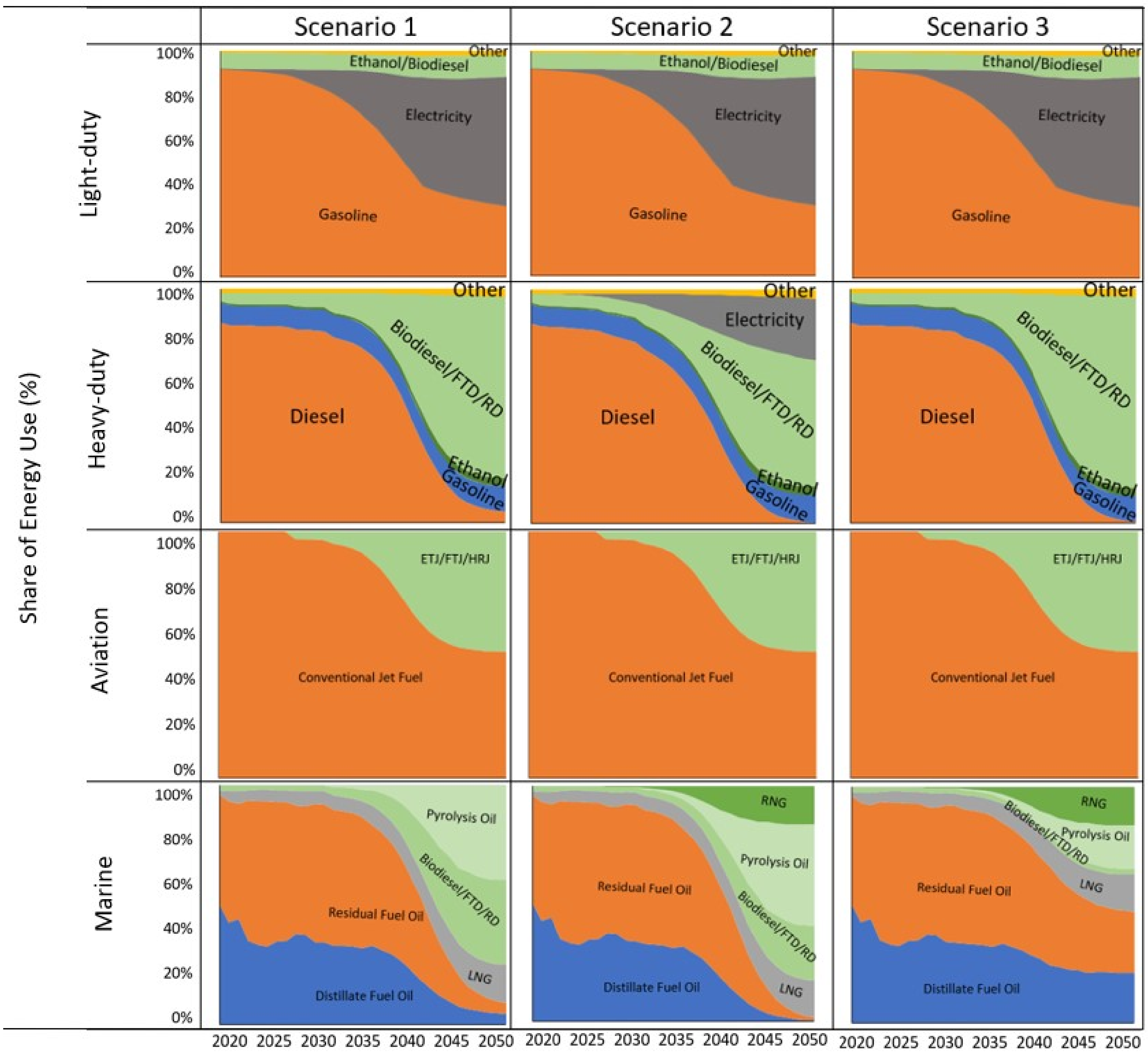


Fig. S-17. Share of energy use by sector at $60/dry ton.

Biomass allocation at $40/dry ton

Scenario 1

We prioritize the allocation of feedstocks to various sectors based on the greenhouse gas emissions (GHG) intensities of fuels produced from a particular feedstock relative to conventional fossil fuels. Meeting the biomass resources demand in each sector with a single feedstock was feasible until 2034 in most cases (except for pyrolysis oil with single feedstock throughout the simulation period). However, as the biofuel market shares increased and due to increased energy demand in sectors such as aviation, combining multiple biomass feedstocks to meet the demand became necessary (Fig.S-18). Accordingly, we have assumed that biorefineries are feedstock agnostic and fuel composition and properties vary minimally depending on feedstock type in any given conversion process. Feedstocks such as logging residues are mostly allocated to the marine sector to produce pyrolysis oil.

In contrast, a significant portion of municipal solid waste (MSW) and agricultural residues are allocated to aviation and heavy-duty sectors. Feedstocks such as landfill gas and animal manure are allocated to the three sectors to produce FT-fuels, wastewater sludge is allocated to marine and heavy-duty sectors to produce renewable diesel, while algae is assigned to the heavy-duty sector and aviation. From 2028 when most of the biofuels are first introduced in the market until 2040, each sector's demands are met by waste feedstocks. We, however, ramp up the use of energy crop with waste to avoid a sudden impact on land use in the latter year. Energy crops are introduced in 2030 at a 1% yearly increase. Due to the rise in energy demand, the 1% yearly increase no longer apply by 2044. Energy crops account for up to 24% of feedstocks (new potential biomass) consumed in the heavy-duty sector in 2050 and 12% of new potential biomass consumed in the aviation sector.

Scenario 2

Fig.S-18 provides a general overview of how biomass resources are allocated to each sector in this scenario. Due to priority given to the aviation sector with an allocation of 217 MM dry tons of biomass (76% of the new biomass resources) to meet the 2050 target, resources available to meet the HDV demands became limited. As shown in Fig.S-18, the remaining waste resources available for the HDV sector are for a specific period in the earliest year of biofuel market introduction, after which energy crops are used to meet the demand in this sector. The availability of wastewater sludge and Algae (with higher biofuel yield compared to other feedstocks) played a vital role in supplementing other leftover feedstocks from aviation in meeting the demand in the HD sector.

Scenario 3

Both Aviation and HDV sectors have equal opportunities for the available resources depending on their energy demand in this scenario. 50% and 35% of the potential new biomass are allocated to HD and aviation sectors to achieve equal biofuel market share in both sectors in 2050. While the aviation sector demands are met by waste resources, HD required additional resources from energy crops in the latter year due to high energy demand compared to aviation. The remaining biomass, mostly manure and landfill gas, are allocated to the marine sector for RNG production. The allocation of resources at $60/dry ton follows the same trend.

The summary of biomass use and biofuel produced in 2050 for the scenarios under the business as usual and billion-ton biomass availability are given in Table S-1 –Table S-4 while Table S-5 provides a summary of life cycle GHG emission and criterial air pollutant of biofuels considered.

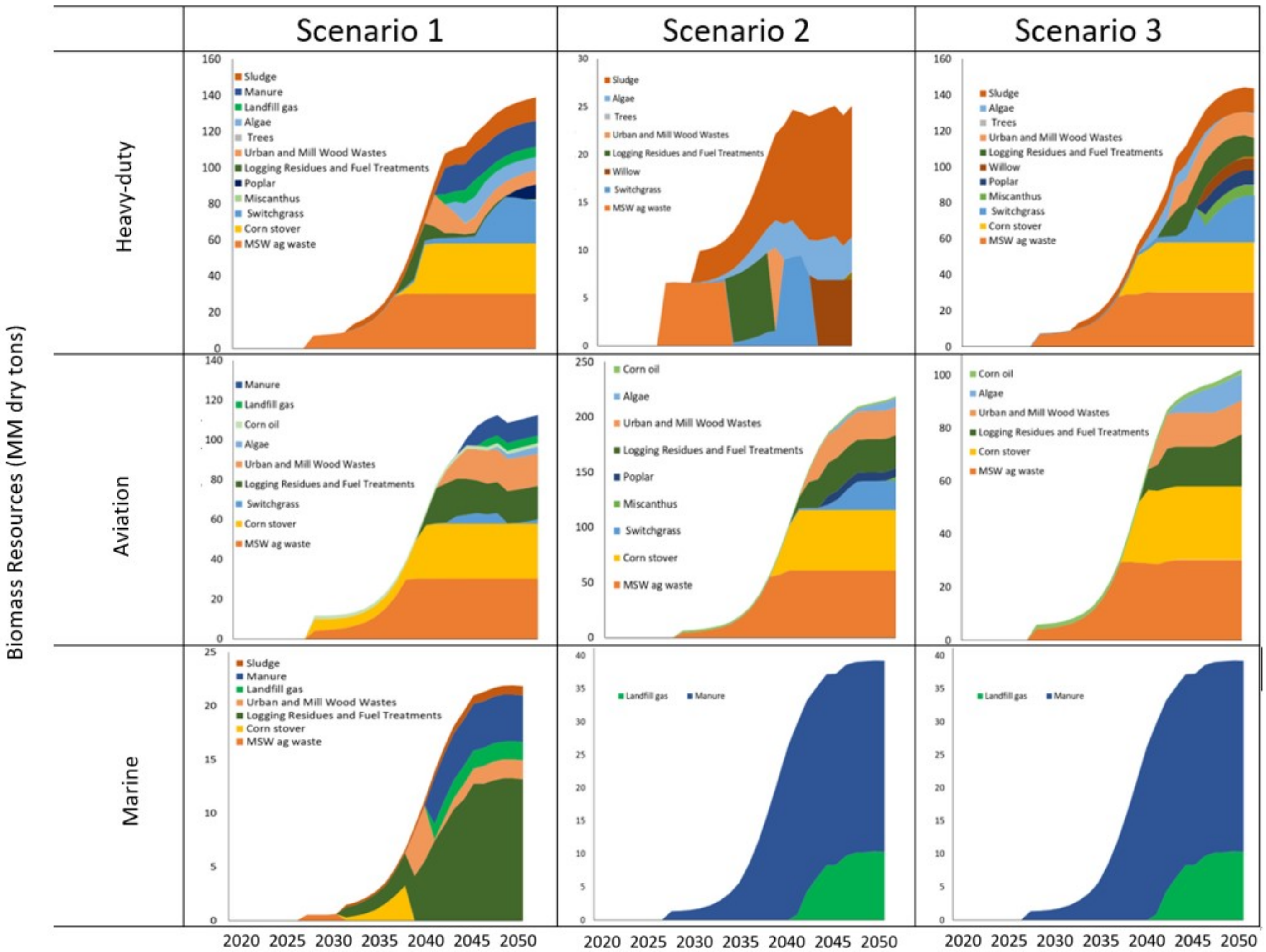


Fig. S-18. Resource allocation at $40/dry ton biomass price.

Table S-1. Biomass use in 2050 for the scenarios under the business as usual, 40 USD2016/dry ton biomass availability. Values represent biomass use in million tons.

		Scenario 1: Low technology				**Scenario 2: Biofuels to aviation first**				**Scenario 3: Biofuels to aviation and heavy-duty first**				**Other uses, same for all scenarios**		
		Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Heat and power	Chemicals	Wood pellets
Agricultural	Corn Grain	63	20	12		63	20	12		63	20	12			7.0	
	Soybean (Vegetable oils)	0.20	9.2		0.60	0.20	9.2		0.60	0.20	9.2		0.60		0.38	
	Agricultural Residues		27.7	28				55			28	28			2.7	
	Manure		15	10	4.3				29				29			
Forestry/ Wood	Wood/Wood Waste													139		
	Wood Pellets															8.6
	Logging Residues			17	13			30			10	20				3.8
	Urban and Mill Wood Waste		7.7	16	1.8			28			12	13				
	Whole-tree biomass		0.040				0.040				0.040					
Energy Crops	Herbaceous		25	8.2			3.3	30			33				1.6	
	Woody		8.1	6.9			6.9	8.1			15				0.70	
	Algae		7.4	3.6			3.6	7.4			0.90	9.9			0.50	
Other Wastes	Biogenic Portion of MSW		30	30				61			30	30		19		
	Other Waste Biomass													20		
	Landfill Gas		5.6	3.9	1.7				11				11	49		
	Wastewater sludge		13		0.90		14				14					
	Total	63	168	136	23	6	57	229	41	63	173	112	41	227	13	12

Table S-2. Biomass use in 2050 for the scenarios under the billion-ton availability, 60 USD2016/dry ton biomass availability. Values represent biomass use in million tons.

		Scenario 1: Low technology				**Scenario 2: Biofuels to aviation first**				**Scenario 3: Biofuels to aviation and heavy-duty first**				**Other uses, same for all scenarios**		
		Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Heat and power	Chemicals	Wood pellets
Agricultura l	Corn Grain	63	20	12		63	20	12		63	20	12			7.0	
	Soybean (Vegetable oils)	0.20	9.2		0.60	0.20	9.2		0.6	0.20	9.2		0.60		0.38	
	Agricultural Residues		84	84			62	106			62	106			8.1	
	Manure		9.9	10	4.3				29				29			
Forestry/ Wood	Wood/Wood Waste													139		
	Wood Pellets															8.6
	Logging Residues			18	14			32				32				4.1
	Urban and Mill Wood Waste			23	13		36				36					
	Whole-tree biomass		26	13	22			13	16		23	13	25			
Energy Crops	Herbaceous		311	13			167		22		324				16	
	Woody		24	12	31				43		67				3.2	
	Algae		15	7.2			22				22				1.1	
Other Wastes	Biogenic Portion of MSW		37	37				74				74.0		19		
	Other Waste Biomass													20		
	Landfill Gas		9.2	4.9	1.7				14				14	61		
	Wastewater sludge		13		0.90		14				14					
	Total	63	558	234	88	63	330	238	124	63	577	238	68	239	35	13

Table S-3. Biofuels produce in 2050 in the scenarios under the business as usual, 40 USD2016/dry ton biomass availability. Values represent fuel amount in MJ except for heat and power, chemicals and wood pellets which are in million tons.

		Scenario 1: Low technology $\times 10^9$				Scenario 2: Biofuels to aviation first $\times 10^9$				Scenario 3: Biofuels to aviation and heavy-duty first $\times 10^9$				Other uses, same for all scenarios		
		Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Heat and power	Chemicals	Wood pellets
Agricultural	Corn Grain	654	212	71		654	212	71		654	212	71			7.0	
	Soybean (Vegetable oils)	7.5	333		23	7.5	333		23	7.5	333		23		0.38	
	Agricultural Residues		213	210				419			213	210			2.7	
	Manure		111	77	33				99				99			
Forestry/ Wood	Wood/Wood Waste													139		
	Wood Pellets															8.6
	Logging Residues			127	91			227			79	149				3.8
	Urban and Mill Wood Waste		59	123	14			194			99	97				
	Whole-tree biomass		0.29				0.29				0.29					
Energy Crops	Herbaceous		189	39			26	223			252				1.6	
	Woody		62.3	30			53	61			115				0.70	
	Algae		167	61			81	126			20	168			0.50	
Other Wastes	Biogenic Portion of MSW		233	229				459			233	229		19		
	Other Waste Biomass													20		
	Landfill Gas		43	30	13				43				43	49		
	Wastewater sludge		169		11		179				179					
	Petroleum	2,297	4,475	2,698	586	2,297	3,277	1,917	617.5	2,297	4,517	2,772	618	227	13	12.4

Table S-4. Biofuels produce in 2050 in the scenarios under the business as usual, 60 USD2016/dry ton biomass availability. Values represent fuel amount in MJ except for heat and power, chemicals, and wood pellets which are in million tons.

		Scenario 1: Low technology $\times 10^9$	Scenario 2: Biofuels to aviation first $\times 10^9$	Scenario 3: Biofuels to aviation and heavy-duty first $\times 10^9$	Other uses, same for all scenarios

		Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Light-Duty Vehicles	Heavy-Duty Vehicles	Aviation	Marine	Heat and power	Chemicals	Wood pellets
Agricultural	Corn Grain	654	212	71		654	212	71		654	212	71			7.0	
	Soybean (Vegetable oils)	7.5	333		23	7.5	333		23	7.5	333		23		0.38	
	Agricultural Residues		724	637			533	806			533	806			2.7	
	Manure		76	77	68				99				99			
Forestry/ Wood	Wood/Wood Waste													139		
	Wood Pellets															8.6
	Logging Residues			137	98			244				244				3.8
	Urban and Mill Wood Waste			172			309				309					
	Whole-tree biomass		219	100	168			99	107		194	99	171			
Energy Crops	Herbaceous		2,607	56			1,359		192		2,668				1.6	
	Woody		206	88.9	217				294		574				0.70	
	Algae		334	122			495				495				0.50	
Other Wastes	Biogenic Portion of MSW		284	280				560				560		19		
	Other Waste Biomass													20		
	Landfill Gas		70	37					54				54	49		
	Wastewater sludge		169		11		179				179					
	Petroleum	2,297	1,014	1,919	83	2,297	733	1,919	13	2,297	753	1,919	435	226.7	13	12

Table S-5. Biofuel production pathways and their life cycle environmental impact[10]

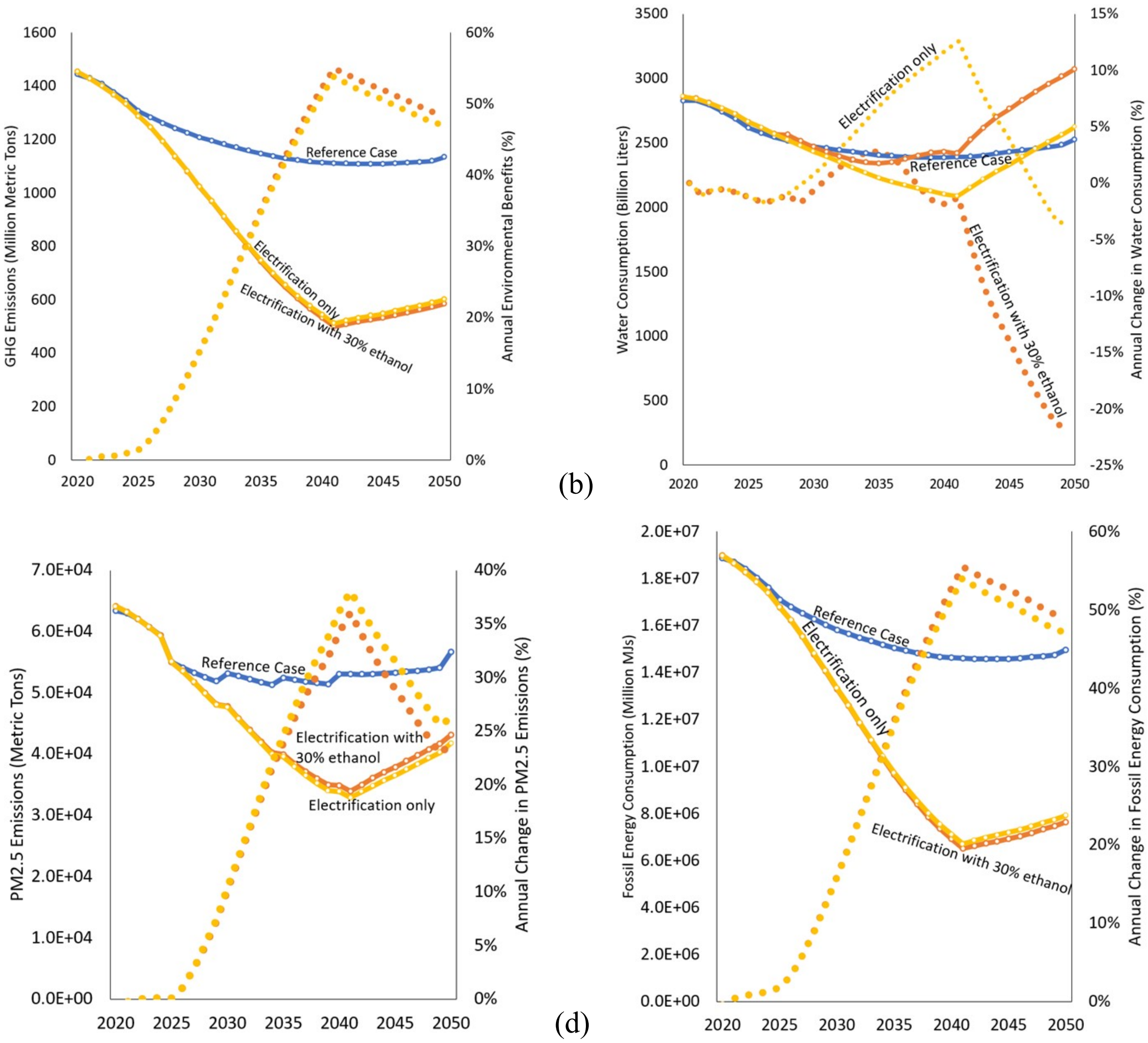
Conversion pathway	**Feedstocks**	**Biofuels**	**Yield, MJ fuel/ton feedstock** ($\times 10^3$)	**Life cycle GHG emission (g/MJ)**	**Life cycle $PM_{2.5}$ emission (g/MJ)**	**Life cycle PM_{10} emission (g/MJ)**
Gasification + Fischer Tropsch Synthesis	MSW, agricultural residues, forest residue, energy crops	• Renewable jet • Renewable diesel	7.1-7.3	4.8-11 5.5-12	0.0020-0.0030 0.0040-0.0050	0.0030-0.0040 0.0080-0.010
Pyrolysis	MSW, agricultural residues, forest residue, energy crops	Renewable diesel	7.3	16-26	0.0040-0.0090	0.0010-0.0080
Pyrolysis+	Woody biomass	Pyrolysis oil	6.9	11	0.018	0.019

upgrading						
Fermentation	Agricultural residues, forest residue, energy crops, MSW	Cellulosic ethanol	6.8	-3.2-12	0.0070-0.0090	0.019-0.020
Hydrotreated Esters and Fatty Acids HEFA/HRJ	Algae, corn oil	Renewable jet	15.9-29.7	22-61	0.0010-0.0060	0.0020-0.0080
Hydrotreatment	Algae	Renewable diesel	19.1	26	0.0040	0.0070
Transesterification	Vegetable Oils	Biodiesel	33.7	31	0.0040	0.0070
Anaerobic digestion (AD) to biogas +FT-synthesis	Landfill gas, manure	• Renewable jet • Renewable diesel	6.9-9.2	-134-24 -132-26	0.0010-0.0050 -0.0030-0.0030	0.0030-0.0050 0.0010-0.0090
AD biogas and upgrading	Landfill gas, manure	Renewable natural gas (RNG)		-11-28	-0.00060-0.0050	-0.00020-0.0060
Hydrothermal liquefaction (HTL)	Wastewater sludge	Renewable diesel	13.1	38	0.0050	0.0080
Ethanol to Jet	MSW, agricultural residues, forest residue, energy crops, Corn	Renewable Jet	5.8-8.7	5.2-69	0.028-0.072	0.0020-0.0050

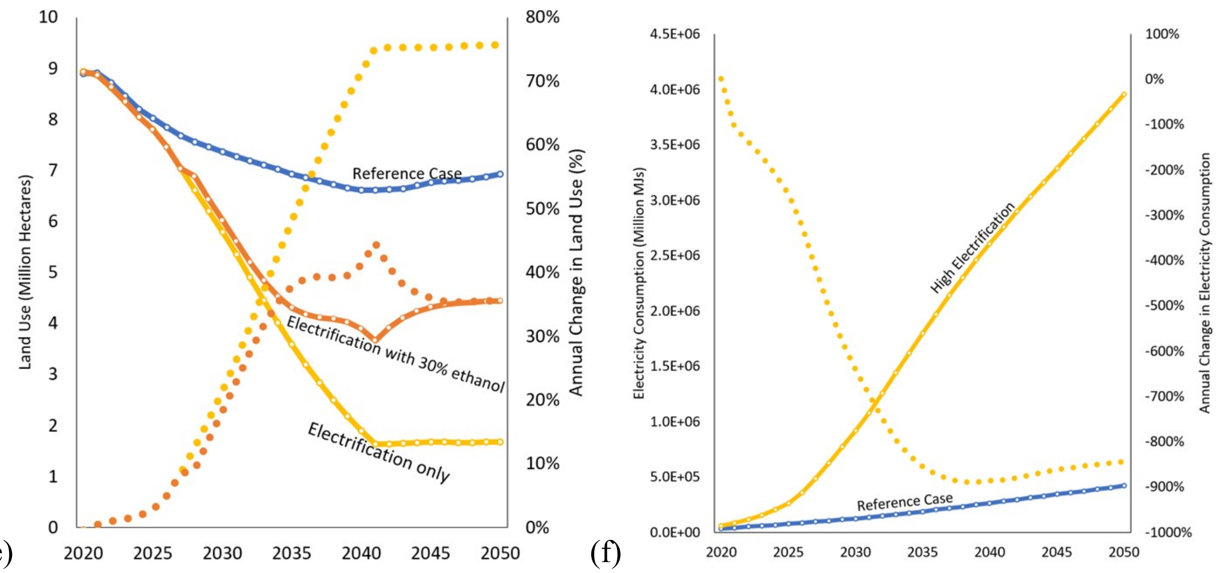
S6 Sectoral Environmental Benefits Assessment: $40/dry ton

Light-duty sector

Fig. S-19a shows the annual light-duty sector GHG emissions compared to the reference case. Note that LD sector underlying assumptions are uniform for scenarios 1-3 (30% ethanol in motor gasoline by 2050) at both biomass prices.



(a) (b) (c) (d)



(e) (f)

Fig. S-19. LD sector decarbonization and reference case scenarios (a) GHG emissions, (b) water consumption, (c) $PM_{2.5}$ emissions (d) fossil energy consumption, (e) land use, and (f) electricity consumption.

Initially, more stringent fuel economy standards drive GHG emissions, fossil energy, and water consumption lower in the reference case. Increasing vehicle kilometers traveled (VKT) eventually outpace these fuel economy improvements. Compared to the reference case, the decarbonization scenarios offer GHG emissions reductions of 549 million metric tons (48.4%) in 2050, 2% higher reduction than case with electrification only. The cumulative reduction over 2019-2050 is 27.2%. This reduction is driven by high penetration of electrification (~88% in 2050) coupled with 30% (v/v) ethanol blend level in motor gasoline in the LD sector. Trends in fossil energy consumption are similar. The decarbonization scenarios' life-cycle fossil energy consumption in the LD sector is 49% lower in 2050 compared to the reference case.

Trends in water consumption (Fig.S-19b) are primarily driven by the relative water intensity of electricity (0.53-0.68 L/MJ), gasoline (0.19 L/MJ), and ethanol (1.2 L/MJ). In the decarbonization scenarios, the quick and extensive uptake of EVs drives an increase in water consumption. For example, water consumption increases from 2041 to 2050 by 3381.5 billion liters because of EV penetration. In the decarbonization scenarios, water consumption is 22% higher in 2050 than in the reference case and cumulatively, water consumption increases by 4%.

Increasing adoption of EV (0.008g $PM_{2.5}$/km) in the LD fleet cut into gasoline consumption (0.011 g $PM_{2.5}$/km) and initially lower $PM_{2.5}$ emissions in the reference case (Fig.S-19c). Decarbonization scenarios' $PM_{2.5}$ reductions are 13,519 metric tons (23.9%) in 2050. Cumulative $PM_{2.5}$ reductions over the analysis period are 16.7%.

Land use in the reference case decreased initially due to reduced E10 consumption but later increased due to growth in energy demand (Fig.S-19e). Compared to the reference case, land use decreased by 76% in the electrification-only case due to the significant uptake of EVs (which increase electricity consumption above 800%). However, with 30% ethanol content in motor gasoline, land use reduced by 36%.

Heavy-duty sector

Fig.S-20 shows heavy-duty sector GHG emissions in the reference case and the three decarbonization scenarios. Initial declines in GHG emissions in the reference case stem from fuel efficiency standards. In 2040, emissions start to increase because a rise in economic activity drives up heavy-duty truck travel.

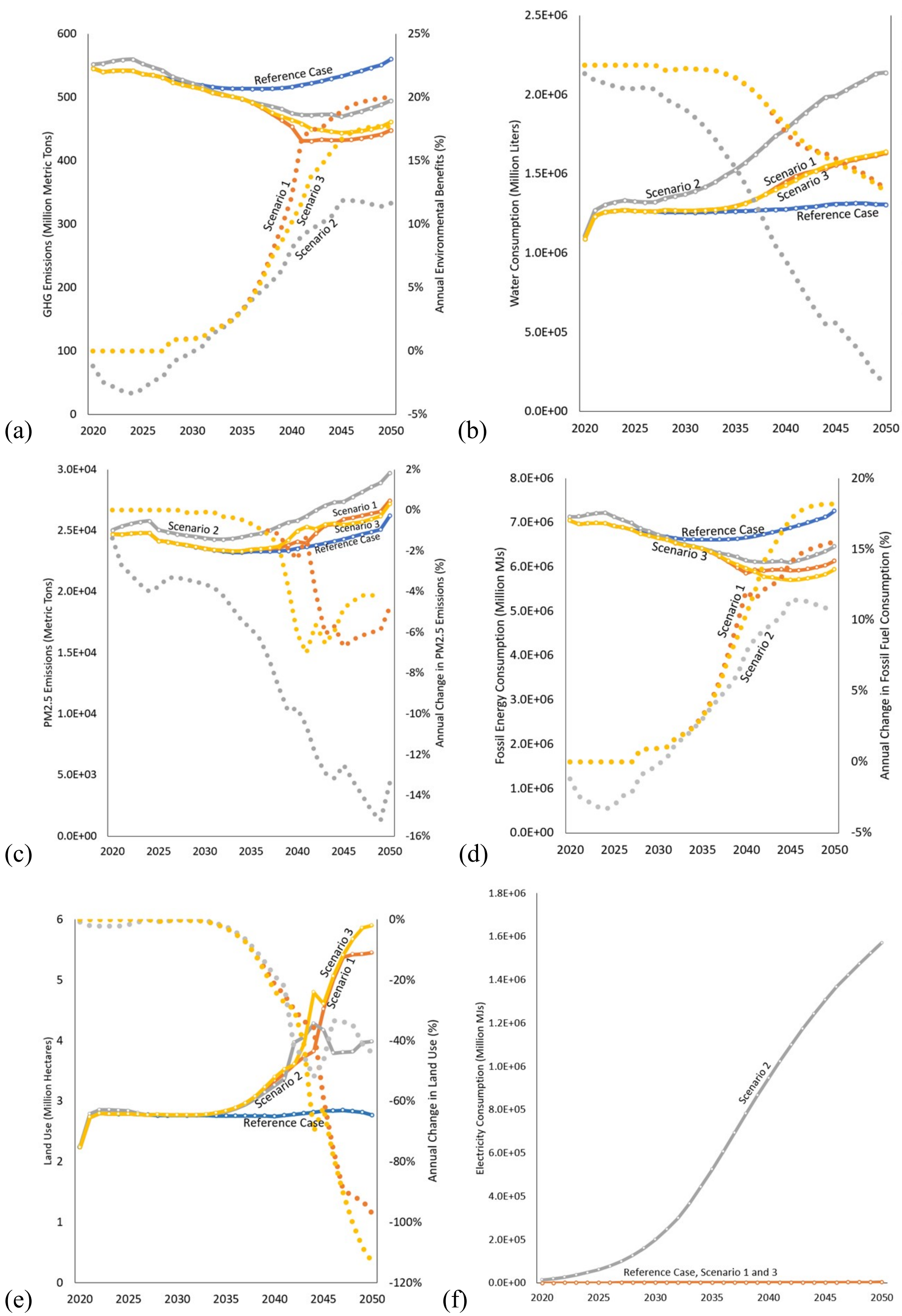

(a)
GHG Emissions (Million Metric Tons)
Annual Environmental Benefits (%)
Reference Case
Scenario 1
Scenario 3
Scenario 2
(b)
Water Consumption (Million Liters)
Annual Change in Water Consumption (%)
Scenario 2
Scenario 1
Scenario 3
Reference Case
(c)
PM2.5 Emissions (Metric Tons)
Annual Change in PM2.5 Emissions (%)
Scenario 2
Scenario 1
Scenario 3
Reference Case
(d)
Fossil Energy Consumption (Million MJs)
Annual Change in Fossil Fuel Consumption (%)
Reference Case
Scenario 3
Scenario 1
Scenario 2
(e)
Land Use (Million Hectares)
Annual Change in Land Use (%)
Scenario 3
Scenario 1
Scenario 2
Reference Case
(f)
Electricity Consumption (Million MJs)
Scenario 2
Reference Case, Scenario 1 and 3

Fig. S-20. Heavy-duty sector decarbonization and reference case scenarios (a) GHG emissions, (b) water consumption, (c) $PM_{2.5}$ emissions (d) fossil energy consumption, (e) land use; and (f) electricity consumption.

After 2030, all three decarbonization scenarios exhibit lower GHG emissions than the reference case. The discrepancy between the Mai et al.[5] and AEO[6] reference cases drives the initial increase in scenario 2 GHG emission. In 2050, scenarios 1, 2, and 3 exhibit GHG reductions of 112 (20%), 65 (12%), and 98 (18%) million metric tons of emission reductions, respectively. Cumulative reductions are 8%, 4%, and 7%. An increase in biofuel (21-31% v/v blending levels) consumption is one factor behind these emissions reductions. Feedstock type influences differences between GHG emissions in Scenarios 1 and 3. Manure is one of the feedstocks for FTD in Scenario 1 in which all sectors receive equal priority for decarbonization. Diesel fuel produced from manure is 100% less GHG intensive than conventional diesel fuel. In scenario 3, however, manure is allocated strictly to RNG production in the maritime sector; hence more energy crops are allocated to FTD. Electrification has a more prominent role in the HD sector in scenario 2. Altogether, petroleum diesel consumption is lower in scenario 2 (51% relative to the baseline case compared to 24% and 25% in scenarios 1 and 3, respectively). But electricity is behind much of that reduced petroleum consumption in which biofuels are blended at 21% (v/v) by 2050. Electricity's life cycle GHG emissions are 38% higher than conventional diesel. Furthermore, most biofuels in scenarios 1 and 3 have GHGs emission intensities about 70% less than petroleum diesel's. As a result, scenario 2 GHG emissions are higher than in the other decarbonization scenarios despite a greater decrease in diesel consumption.

Water consumption in the reference case (Fig.S-20b) goes up in 2020-2023 and remains somewhat constant until 2040 because diesel consumption is declining. Water consumption starts to increase in the 2040s due to increased E10, natural gas, and diesel consumption. Water consumption increases compared to the reference case by 327 (25%), 834 (64%), and 334 (26%) billion liters in 2050, respectively. Cumulative increases are 8%, 27% and 8%. The prominence of water-intensive electricity as a fuel in scenario 2 dominates its water consumption.

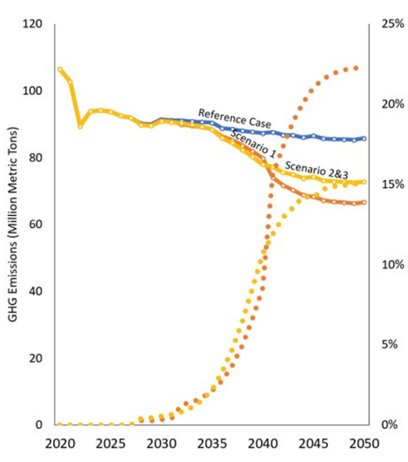
As with other emissions, the PM2.5 emissions go up in 2020-2023 in the reference case (Fig.S-20c) and then begin to decrease in 2024-2035 due to reduced energy consumption. PM2.5 emissions then go up again after 2040 primarily because of the increase in energy demand. Compared to the reference case, PM2.5 emissions increased by 1243 (5%), 3503 (13%), and 978 (4%) metric tons in 2050. Cumulative emission increases were 2%, 7%, and 2%. Again, the increased consumption of electricity, which has higher life cycle $PM_{2.5}$ emissions than other fuels, including diesel and biofuels we considered in this study, drives the greater $PM_{2.5}$ emissions in scenario 2. For example, $PM_{2.5}$ emissions are 98% greater per MJ for electricity than for diesel fuel.

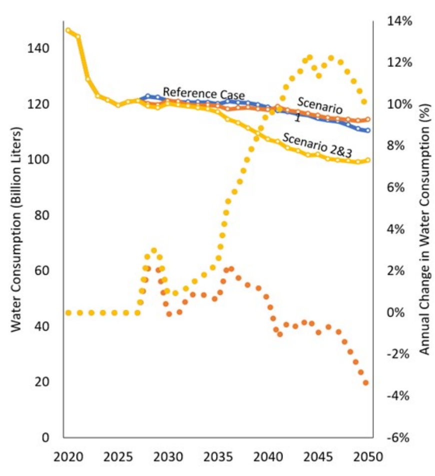
In the reference case, the annual fossil energy consumption decreases in earlier years primarily because of improved fleet fuel economy but later increases (from 2040-2050) due to increased E10, natural gas, and diesel consumption. Fossil energy decrease were 16%, 11%, and 18% lower than the reference case in 2050. Cumulative reductions were 6%, 4%, and 7%. As with the other metrics we are considering, life cycle fossil energy consumption is higher (by 35%) for electricity than for other fuels, including diesel fuel. This factor causes fossil fuel consumption to be higher in scenario 2 than in the other decarbonization scenarios. Fossil energy reduction differs between scenarios 1 and 3 because the fossil energy intensity of biomass resources used in FTD production vary.

The land use in the three decarbonization scenarios increased by 2.7 (97%), 1.2 (44%) and 3.1(113%) hectares due to the increased use of energy crops (Fig.S-20e). The lower land use in scenario 2 is because a higher percentage of energy crops are used in the aviation sector (aviation is prioritized for biomass resources). Electricity consumption in scenario 2 increased significantly due to the high uptake of electric trucks (Fig.S-20f).

Marine sector

Fig.S-21a shows the marine sector GHG emissions in the reference case and decarbonization scenarios. Biofuel usage assumptions are identical in scenarios 2 and 3. GHGs emissions in the reference case fluctuate according to variations in energy demand. In later years liquefied natural gas (LNG) usage increases, supplanting residual fuel oil consumption, which also contributes to reductions. Scenarios 1-3 offer GHGs emissions reduction compared to the reference case in the 2028-2050 period with emissions reductions of 19 (22%) and 13 (15%) million metric tons in 2050. Cumulative reductions are 7% and 5%, respectively. These emission reductions are driven by the increase in biofuels displacement of marine distillate fuel oil (MDO) and residual fuel oil in scenario 1. In scenarios 2 and 3, the penetration of RNG to displace some portion of MDO contributes to GHGs emissions reduction.

(a)


(b)


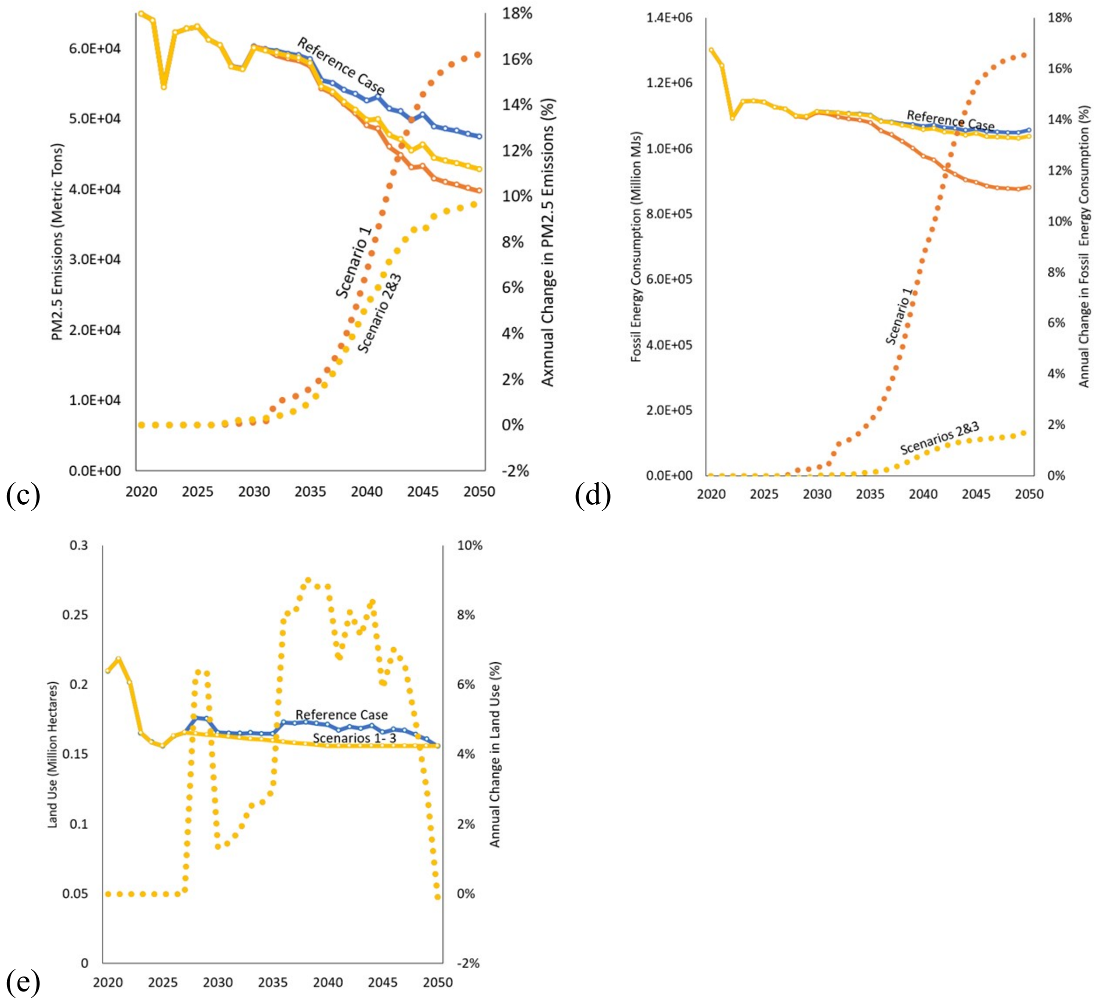


Fig. S-21. Marine sector decarbonization and reference case scenarios (a) GHG emissions, (b) Water consumption, (c) PM2.5 emissions (d) Fossil energy; and (e) Land use.

Water consumption declines in the reference case (Fig.S-21b) in the period 2020-2026, followed by a short period of increase until 2028. Water consumption then starts to decline until 2050 as consumption of residual fuel oil declines and liquefied natural gas usage with 82% lower water intensity relative to residual fuel oil increases. In scenario 1, water consumption decreases slightly from 2028-2040 compared to the reference case but eventually exceeds reference case water consumption. Cumulatively over the analysis period, water consumption decreased by 0.1% compared to the reference case. One factor that underlies water consumption in scenario 1 is the use of somewhat water-intensive FTD produced from manure. Scenarios 2 and 3, however, offer a reduction in water consumption because the RNG that displaces MDO is less water-intensive. Reductions between 2028-2050 in scenarios 2 and 3 reach 11billion liters in 2050 (5% cumulative reduction).

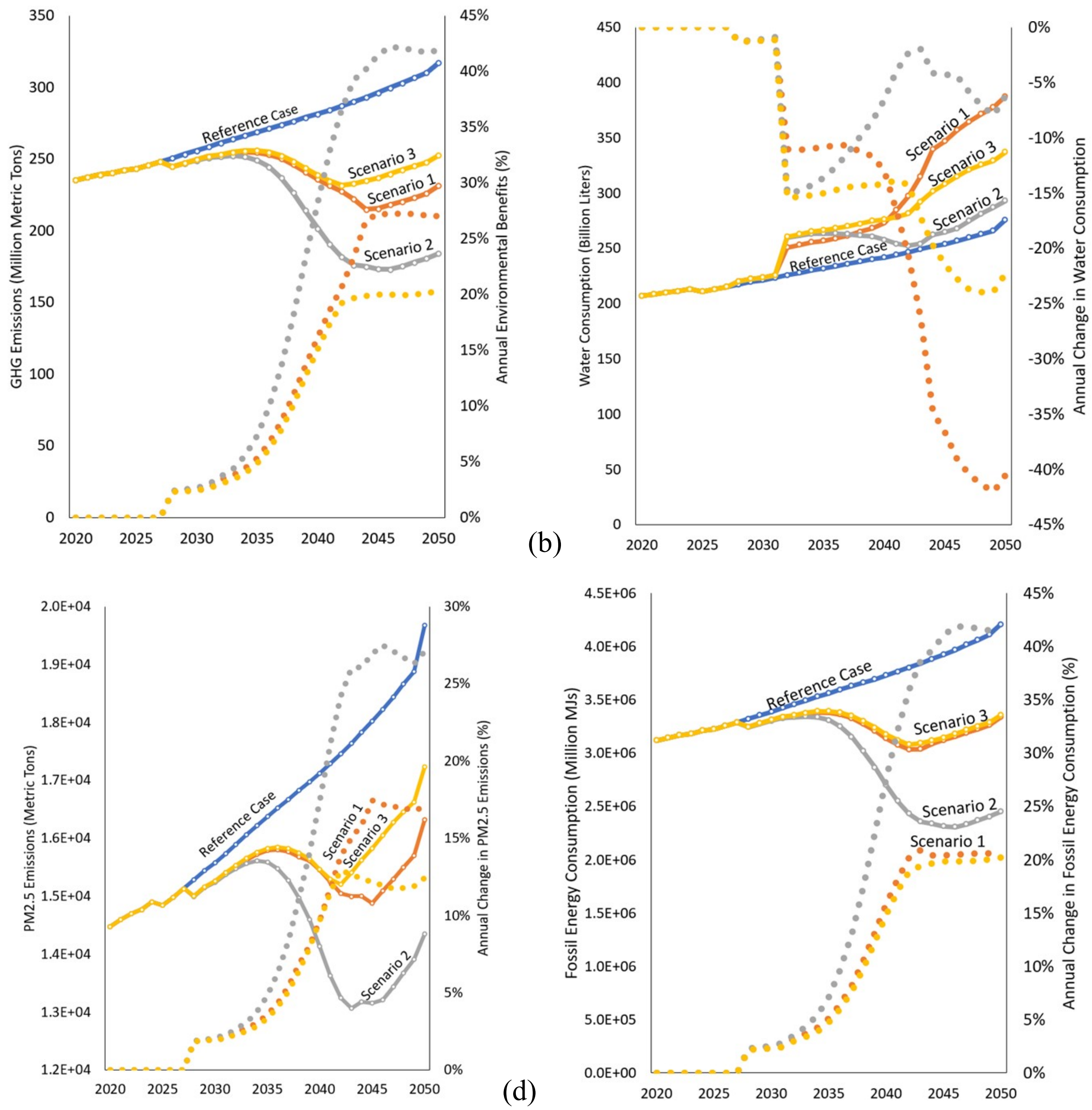
The $PM_{2.5}$ emissions in the reference case (Fig.S-21c) fluctuate. Biofuels that come on line in the decarbonization scenarios have lower life cycle $PM_{2.5}$ emissions. Correspondingly, PM_2.5 emissions are lower (16 and 10%, in 2050, for scenarios 1 and 2 and 3, respectively).

The higher fossil energy reduction in scenario 1 is driven majorly by the overall increase in biofuels penetration compared to only RNG available in scenarios 2 and 3. Cumulatively, fossil energy consumption decreased by 5%, and 1% in scenarios 1 and 2 and 3, respectively. Land use in the reference case fluctuates according to variations in DFO energy demand (Fig.S-21e). With waste resources used for biofuels production in the decarbonization scenarios, land use reduced from 2028-2049 due to the assumption that biodiesel consumed in 2027 remain constant until 2050. However, land reduction reaches 0% in 2050 due to decreased biodiesel consumption in the reference case (DFO energy demand reduced as LNG usage increases).

Aviation Sector

Fig.S-22a shows the aviation sector GHG emissions in the reference case and the three decarbonization scenarios. The reference case GHG emissions, which increase over time, reflect an increase in energy demand in this sector stemming from increased travel that outpaces the growth in aircraft efficiency.

Scenario 1-3 in 2050 exhibited GHG emissions below the reference case by 86 (27%), 133 (42%) and, 65 (20%) million metric tons in 2050, respectively. Cumulative reductions were 11%, 18%, and 9%. The lower life-cycle GHG emissions (around 27-94% compared to petroleum jet fuel) of biofuels that penetrated the market in the decarbonization scenarios drove these emission reductions.



(a) (b) (c) (d)

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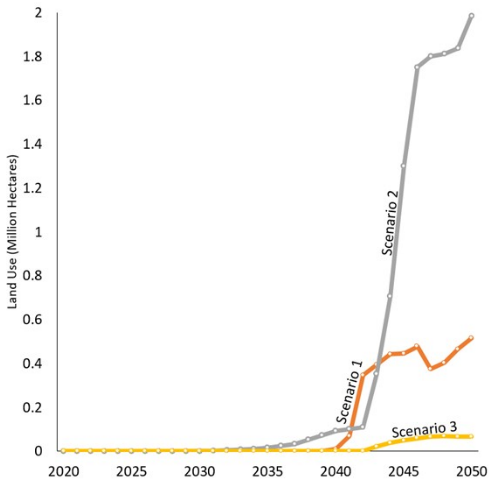


Fig. S-22. Aviation sector decarbonization and reference case scenarios (a) GHG emissions, (b) water consumption, (c) $PM_{2.5}$ emissions (d) fossil energy; and (e) land use.

The addition of algae to the feedstock mix coupled with the continuous increase in energy demand contributes to the slight increase in GHGs emissions in the later years of the analysis time horizon. Algae-derived renewable jet fuel has higher life-cycle GHG emissions than renewable jet fuel produced from other feedstocks.

In the reference case, increasing jet fuel demand translates to increased water consumption (Fig.S-22b). Some renewable jet fuels in scenarios 1-3 are water-intensive, and their increasing market share drives up water consumption. For example, the water intensity of producing RJF from corn oil and algae is about 98% higher relative to petroleum jet fuel. In addition, depending on the feedstocks used in the ethanol-to-jet pathway, the resulting jet fuel can be more than 200% water-intensive than conventional jet fuels. The use of more algae in scenarios 1 and 3 coupled with a high share of ethanol to jet in scenario 1 contributes to higher water consumption than scenario 2 (despite the higher biofuel market penetration in scenario 2). Overall, water consumption increases by 111, 17, and 50 billion liters in 2050 in scenarios 1-3.

Like GHG emissions and water consumption, $PM_{2.5}$ emissions and fossil energy consumption in the reference case (Fig.S-22c and d) increase because demand for conventional jet fuel increases. Scenario 1-3 offer $PM_{2.5}$ emissions reduction benefits of 3352 (17%), 5325 (27%), and 905 (12%) metric tons in 2050. As biofuels with lower life-cycle $PM_{2.5}$ emissions than conventional jet fuels penetrate the market, emissions of this important air pollutant drop. The maximum cumulative reduction in fossil fuel energy consumption was 42% in scenario 2.

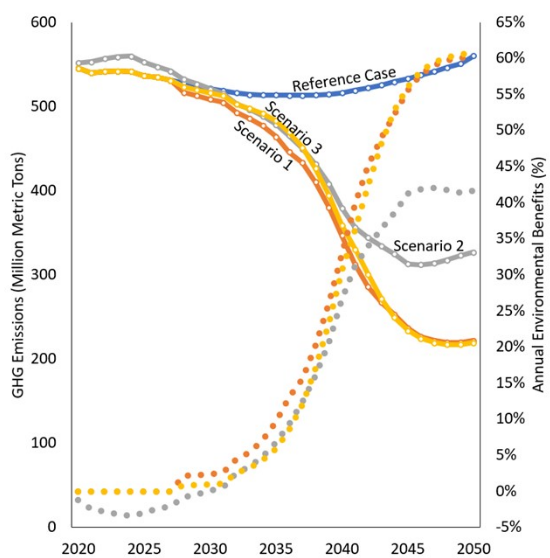
While there is no land use in the reference case, scenarios 1-3 require land associated with energy crops usage as biofuel consumption increases in the aviation sector. The amount of land required varies across the scenarios based on the underlined assumption regarding resource allocation in each scenario. The sudden increase in land use from 2042-2045 in scenario 2 was because, during these periods, waste resources could no longer meet the biofuel production demand to reach the 50% (v/v) target, hence the rapid increase in land use.

S7 Sectoral Environmental Benefits Assessment: $60/dry ton

Fig.S-23 - Fig.S-25 give an overview of the sectoral environmental impact at $60/dry ton biomass price. Like in the $40/dry ton availability case, GHG emissions and fossil energy consumptions reduced across each sector in all scenarios compared to the reference case, although with a higher reduction at this biomass price driven by increased biofuels market penetration. While aviation and heavy-duty sectors see an increase in water consumption in all decarbonization scenarios due to the higher life cycle water intensities of some biofuels compared to conventional fuels, water consumption in the marine sector decreased driven by lower life cycle water intensities of pyrolysis oil and RNG compared to conventional distillate and residual fuel oils. Biofuels that come on line in the decarbonization scenarios in the aviation and marine sectors have lower life-cycle PM2.5 emissions, hence reduction in $PM_{2.5}$ emissions. However, $PM_{2.5}$ emissions increase in the heavy-duty sector because the life cycle $PM_{2.5}$ of the dominant biofuel (renewable diesel) can be 137% higher than conventional diesel depending on the feedstock.

In all cases, land use increased in all decarbonization scenarios compared to at $40/dry ton biomass price as energy crops account for a significant portion of biomass resources available at $60/dry ton biomass price.

Heavy-duty Sector



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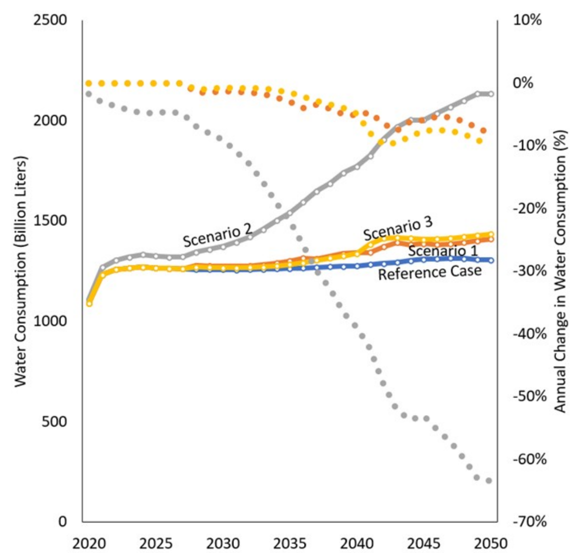

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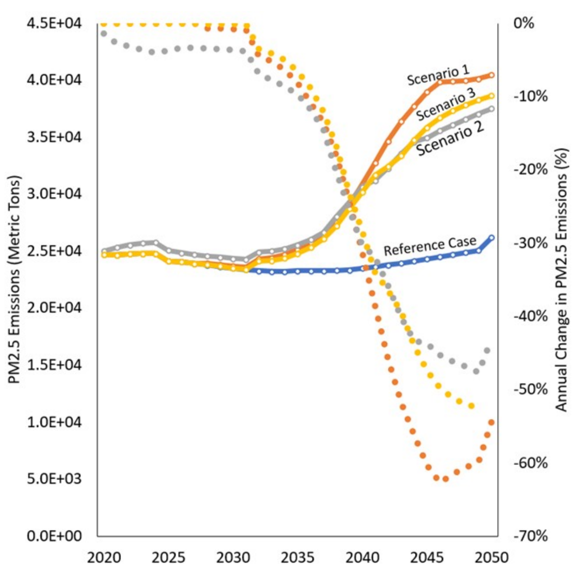

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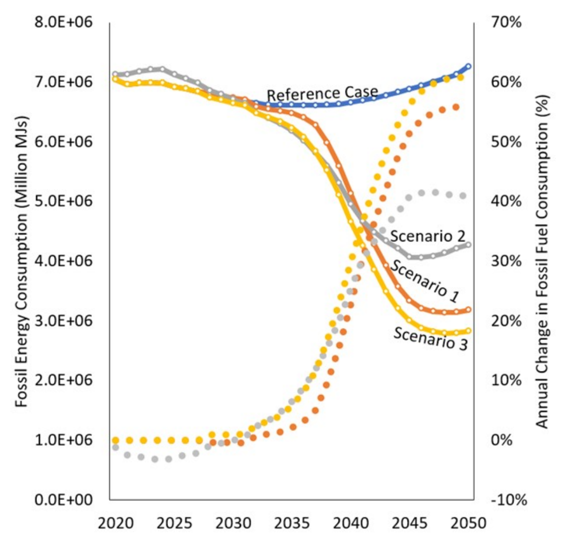

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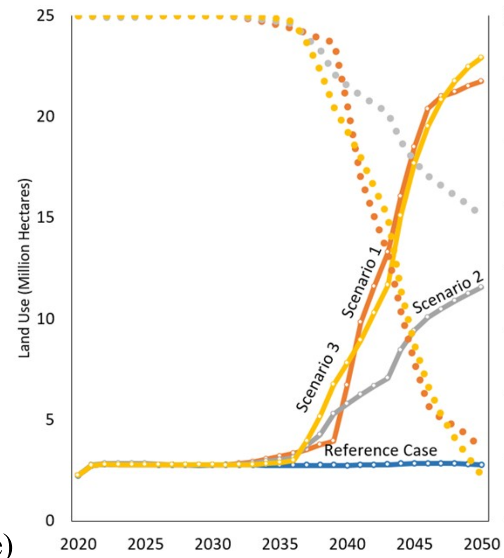

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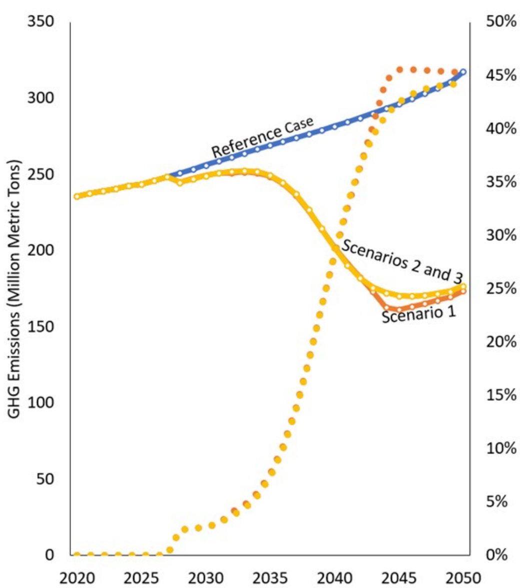
(f)

Fig. S-23. Heavy-duty sector decarbonization and reference case scenarios (a) GHG emissions, (b) water consumption, (c) $PM_{2.5}$ emissions (d) fossil energy consumption, (e) land use; and (f) electricity consumption.

Aviation Sector



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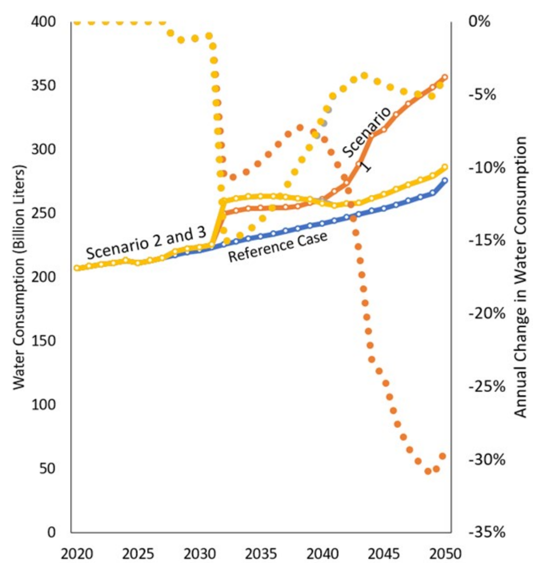

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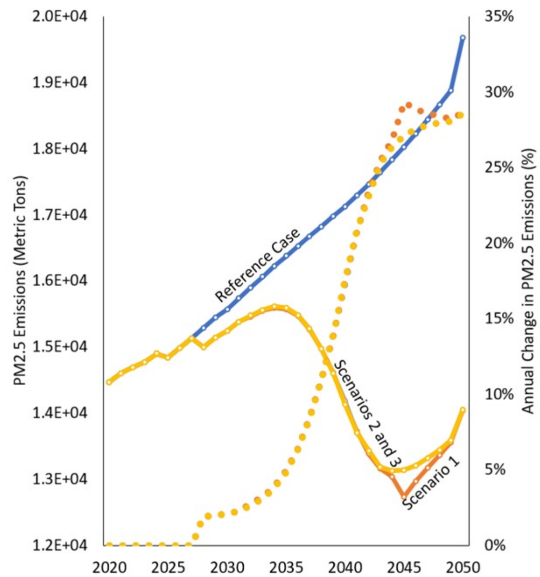

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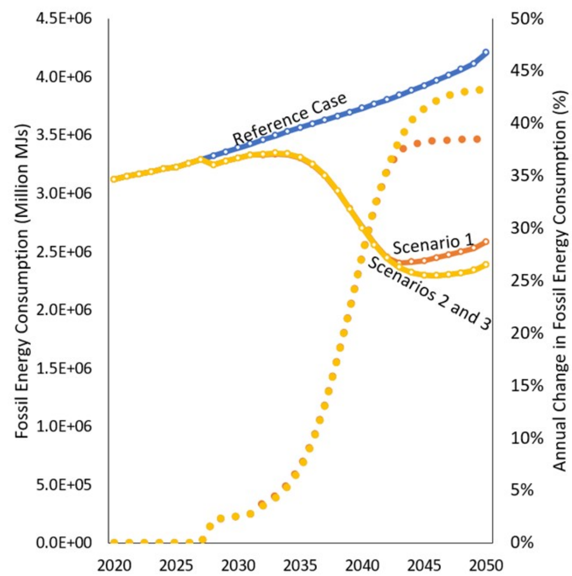

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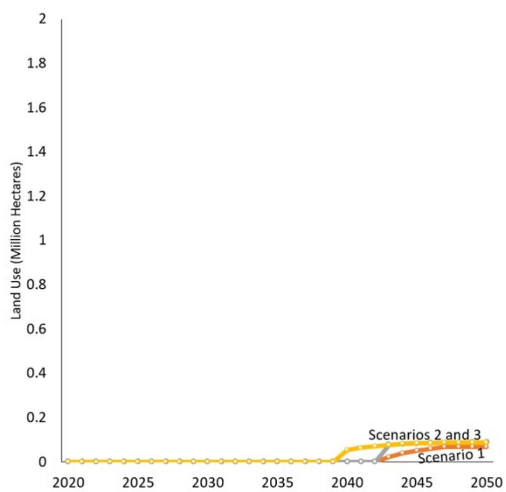

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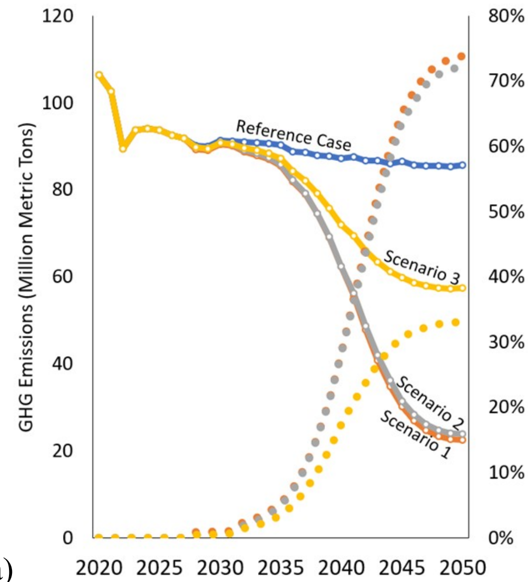
Fig. S-24. Aviation sector decarbonization and reference case scenarios (a) GHG emissions, (b) water consumption, (c) $PM_{2.5}$ emissions (d) fossil energy; and (e) land use.

Marine Sector



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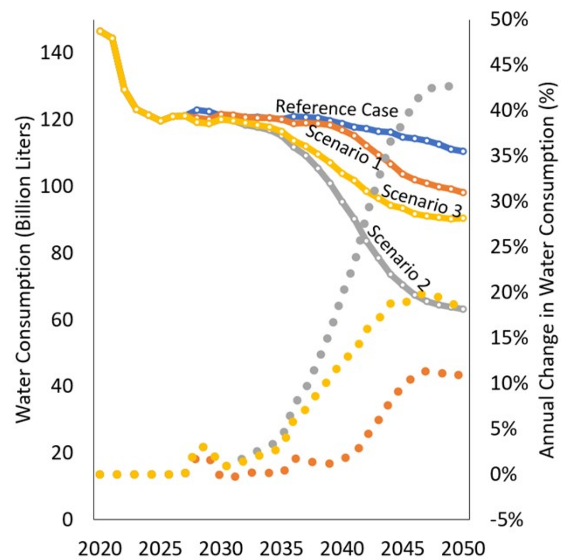

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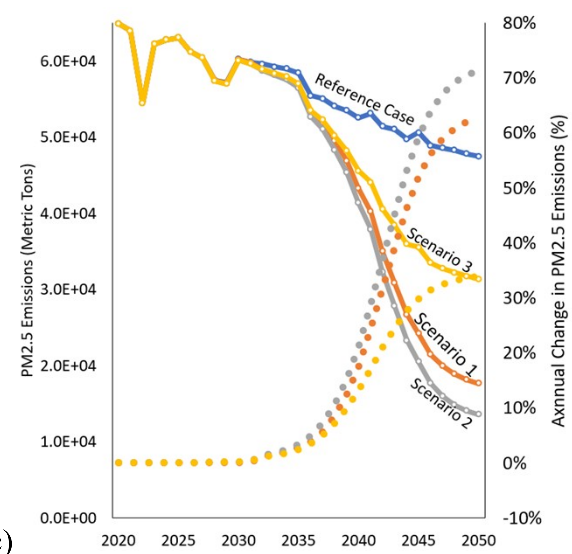

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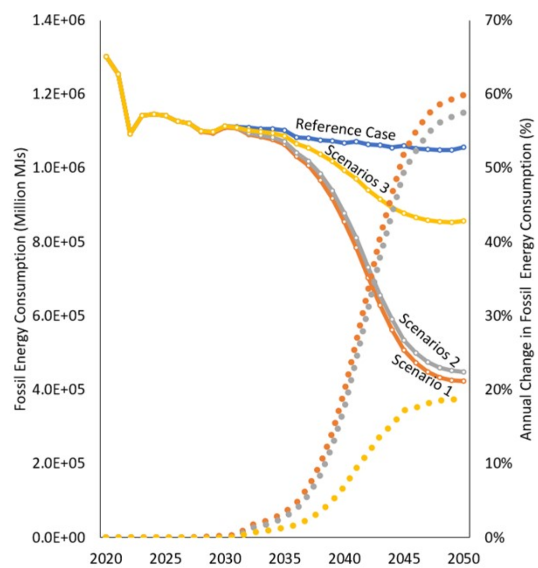

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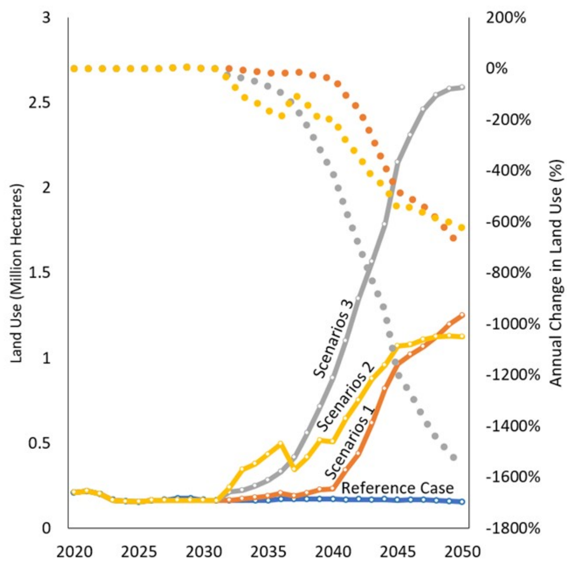

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Fig. S-25. Marine sector decarbonization and reference case scenarios (a) GHG emissions, (b) water consumption, (c) $PM_{2.5}$ emissions (d) fossil energy; and (e) land use.

S8 Sensitivity Analysis

Sensitivity analysis is performed to assess the impact of the electricity generation mix on GHG emissions in the high electrification scenarios for both the light and heavy-duty sectors. We compare the reference case grid mix results to the grid mix represented in the low renewable cost EIA AEO scenario.[11] The US average electricity generation mix for the two cases is depicted in Fig.S-26. The share of coal, natural gas, and nuclear decrease in the low renewable cost generation mix while the share of renewable sources increases by 50% compared to the reference case mix.

The results show higher GHG emissions reduction with the low renewable grid mix in both the LD and HD sectors. The emission reduction increases by 6% in the LD sector and 7% in the HD sector with the low renewable cost generation mix.

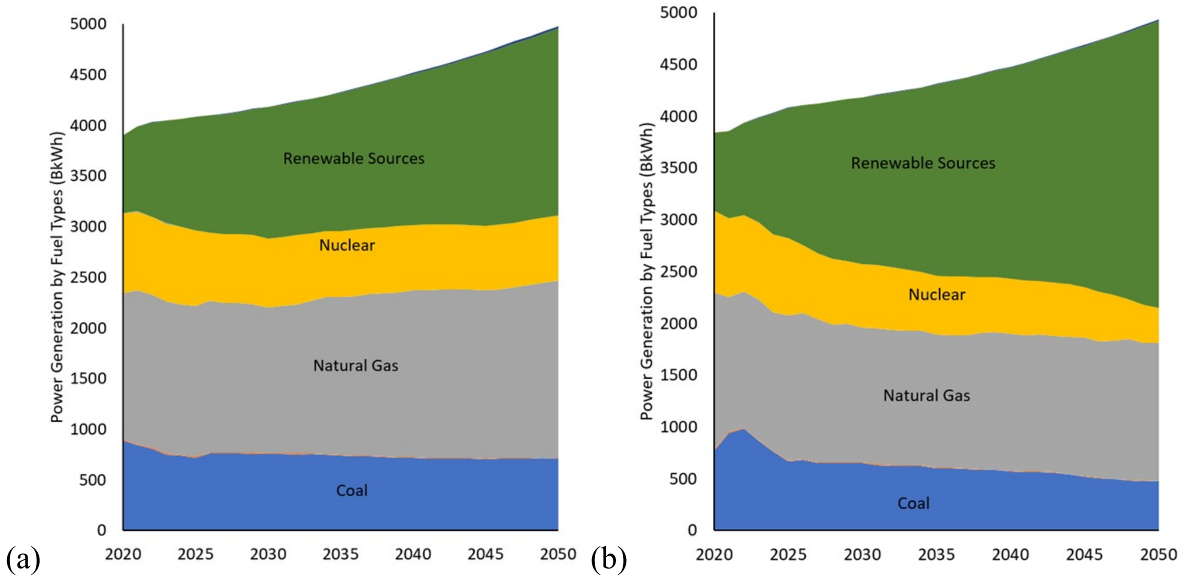


Fig. S-26. Electricity generation mix (a) reference case; and (b) low renewable cost.

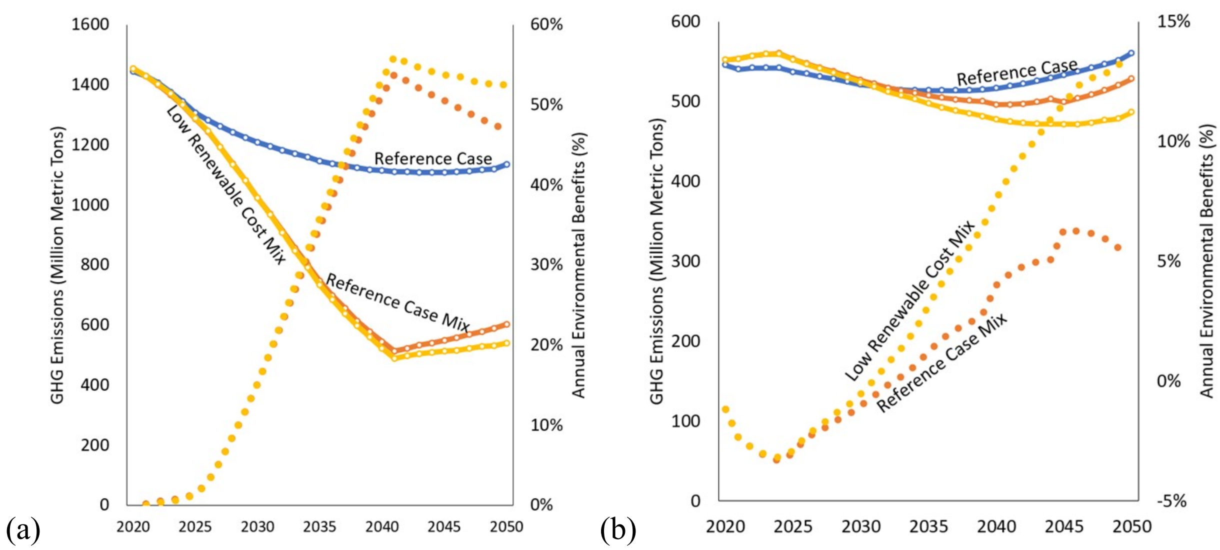
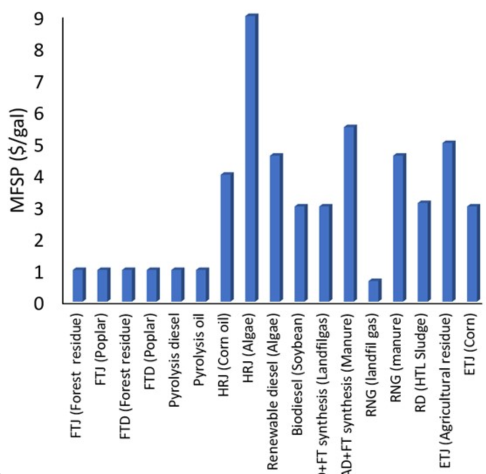


Fig. S-27. Effect of grid mix on GHG emissions in the high electrification scenarios (a) light-duty; and (b) heavy-duty.

S9 Additional information on minimum fuel selling price (MFSP) and abatement cost

The MFSP of various biofuel conversion pathways considered based on data from literature and government agency reports[12-19] are given in Fig. S-28 (a). In contrast, petroleum fuel prices are based on the reference case of 2021Annual Energy Outlook projection (AEO 2021)[11] as depicted in Fig. S-28 (b). While we note that conventional fuel prices are subject to fluctuation, we have adopted the prices as projected in AEO 2021. The MFSP for the biofuels ranges from as low as \$1/gal (\$0.26/L) to as high as \$9/gal (\$2.4/L) depending on the conversion pathway and the feedstock, while the price of conventional fuels is projected to grow from 2020 to 2050.



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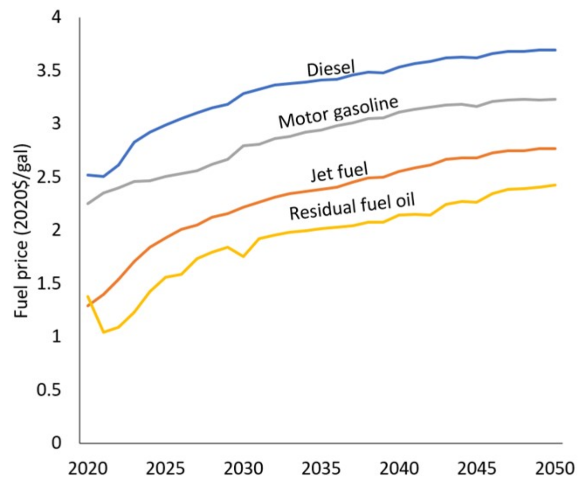

(b)

Fig. S-28. (a) MFSP of biofuels considered (b) fuel price for conventional fuels.

Based on these fuel prices, we estimated the GHG abatement cost using equation 2.

$$Cost\ of\ abatement = \frac{cost\ of\ biofuel\left(\frac{\$}{MMbtu}\right) - conv.\ fuel\ price\ \left(\frac{2020\$}{MMbtu}\right)}{carbon\ intensity\ of\ conv.\ fuel\ per\ MMbtu - carbon\ intensity\ of\ biofuel\ per\ MMbtu}$$

(2)

The results show variation in the abatement cost across the sectors considered. In the heavy-duty and marine sectors (Fig. S-29 (b and c)), abatement costs are negative by 2050 in all conversion pathways except anaerobic digestion (AD) to biogas +FT-synthesis using manure as feedstock (\$59/ton CO_2e). The negative abatement cost in these sectors by 2050 can be attributed to lower target MFSP for most biofuels, while petroleum diesel price is projected to increase to about \$3.7/gal (\$1/L) in 2050. The costs of abatement in the aviation sector show significant variation across different pathways (Fig. S-29 (a)). While some biofuels have negative abatement costs (-\$157/ton CO2e) by 2050, in most cases, the cost ranges from \$39 to \$244/ton CO_2e depending on the conversion pathway and feedstock used.

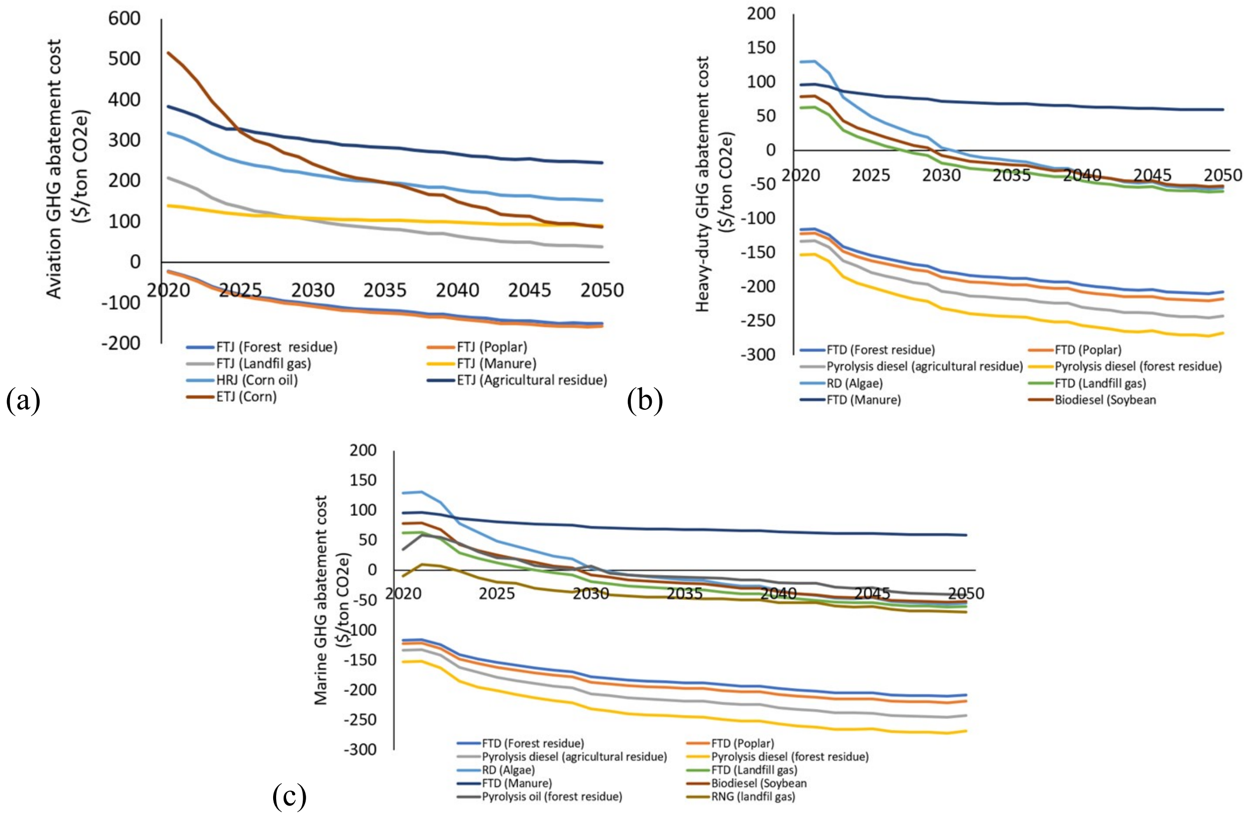

Fig. S-29. GHG abatement cost (a) Aviation (b) Heavy-duty; and (c) Marine.

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