

The Role of Renewable Biofuels in a Low Carbon Economy

Complementary Strategies to Reduce GHG in the Northeast & Mid-Atlantic States



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Acknowledgements

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This independent report, *The Role of Renewable Biofuels in a Low carbon Economy*, explores the potential benefits of renewable biofuels, as a complementary strategy to electrification, to achieve significant greenhouse gas reductions in the Northeast and Mid-Atlantic states. This report is intended to inform and assist government officials and stakeholders within the region, as they undertake efforts to address the challenges of climate change and adaptation, while striving to further improve local air quality.

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This report reflects the analysis and judgment of the authors only and does not necessarily reflect the views of the National Biodiesel Board or the Coalition for Renewable Natural Gas

This report is available at www.mjbradley.com.

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M.J. Bradley & Associates, LLC (MJB&A), founded in 1994, is a strategic consulting firm focused on energy and environmental issues. The firm includes a multi-disciplinary team of experts with backgrounds in economics, law, engineering, and policy. The company works with private companies, public agencies, and non-profit organizations to understand and evaluate environmental regulations and policy, facilitate multi-stakeholder initiatives, shape business strategies, and deploy clean energy technologies.

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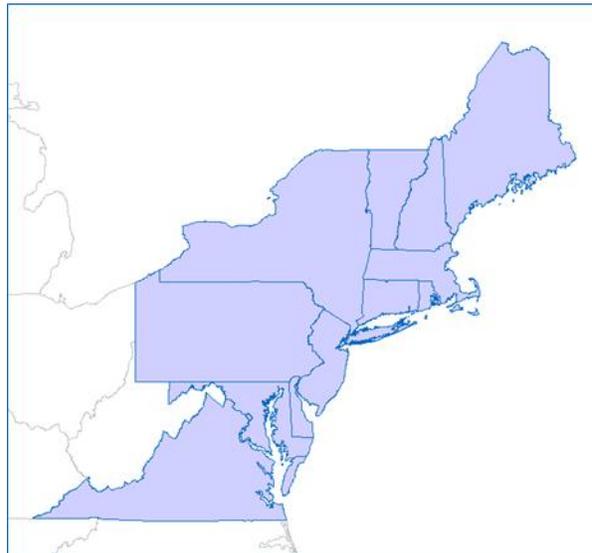
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Executive Summary

This analysis explores the potential benefits of using renewable biofuels in medium- and heavy-duty onroad vehicles, as well as residential and commercial heating, as a complementary strategy to electrification and other efficiency measures, to significantly reduce greenhouse gas (GHG) emissions in the Northeast and Mid-Atlantic states. Our results indicate that a moderately aggressive electrification strategy within this 12-state region (Maine to Virginia, plus DC) could reduce annual emissions from these three sectors of the economy by 11 percent from current levels in 2030, and by 14 percent in 2050.

However, after this moderately aggressive electrification, more than 2 trillion cubic feet of natural gas use¹, and more than 8.5 billion gallons of distillate fuel use would remain in these sectors of the region's economy in 2050.



The complementary use of renewable natural gas and biomass-based diesel fuel, as a substitute for fossil fuels to satisfy this residual gaseous and liquid fuel demand, could further reduce annual GHG emissions by as much as 52 million metric tons (MT) in 2030 (19 percent reduction from today), and by as much as 194 million MT in 2050 (47 percent reduction from today). Between 2020 and 2050, the cumulative additional GHG reductions from the use of renewable biofuels in these sectors could exceed 2.8 billion MT in the region. Unlike electrification, expanded use of biomass-based liquid and gaseous fuels will not require significant infrastructure investments or changes in the vehicle fleet or building equipment stock. As such, use of these fuels could provide significant near-term GHG reductions in synergy with the longer transition to electric applications, in harder to transition vehicle duty cycles and residential/commercial heating.

In addition to significantly reducing GHG emissions, renewable biofuels could reduce net annual upstream nitrogen oxide (NOx) emissions from fuel production and transport by up to 800,000 MT in 2050 and reduce net annual upstream particulate matter (PM_{2.5}) emissions by up to 80,000 MT.² Additional reductions in tailpipe NOx emissions could be achieved by replacing older engines with ultra-low-NOx natural gas engines, but this analysis did not quantify these potential benefits.

The cumulative monetized value of the additional emissions reductions (GHG, NOx and PM_{2.5}) that could be achieved using renewable biofuels within this 12-state region is projected to be \$109 billion - \$280 billion through 2050, with approximately 75 percent due to additional GHG reduction, and 25 percent from upstream NOx and PM reduction.

An overall conclusion of this work is that low carbon biofuels are an effective complement to efforts to promote efficiency and electrification of vehicles and buildings—especially in applications with long-lived existing capital stock, or where electrification is currently high cost. Renewable natural gas and biomass-based diesel fuels can supply significant additional near-term reduction in greenhouse gases, and displacement of petroleum fuels, when incentivized as part of a balanced portfolio of low carbon technologies.

¹ This does not include natural gas used for electricity generation.

² Not all of these reductions would be within the Northeast and Mid-Atlantic region.

Transportation & Climate Initiative

The Transportation Climate Initiative (TCI), a bi-partisan group of states in the Northeast and Mid-Atlantic region, has been developing a “regional low-carbon transportation policy proposal that would cap and reduce carbon emissions from the combustion of transportation fuels, through a cap-and-invest program or other pricing mechanism.” In December 2019 TCI released preliminary results of modeling conducted to assess the effects of different policy designs. Their modeling encompasses on-road transportation within the region, including light-duty and medium- and heavy-duty vehicles.

The TCI modeling predicts that continuation of “business as usual” policies will result in a 6 – 19 percent reduction in annual GHG emissions from these sectors between 2022 and 2032, a reduction of 15 – 48 million MT. These reductions result from turnover of the fleet to more efficient vehicles, as well as increased penetration of electric vehicles, primarily in the light-duty fleet. The reference case (19 percent reduction) assumes that by 2032 11 percent of cars and light trucks in the region will be electric. The highest modeled cap-and-invest policy scenario (25 percent cap) results in an additional 10 million MT reduction in GHG emissions in 2032, from investments to increase electric vehicle uptake, expansion of transit, investments to increase pedestrian and bike trips, and investments in system efficiency. Under this policy scenario light-duty EV penetration is assumed to increase to 16 percent of vehicles in 2032.

The modeling conducted for this report partially overlaps with the TCI modeling, through inclusion of medium- and heavy-duty vehicles. For this M/HDV sector our “moderately aggressive” electrification case assumes higher levels of electric vehicle penetration than assumed in either TCI’s baseline case or 25 percent cap policy case.

Unlike the TCI modeling, the modeling presented here did not include light-duty vehicles but did include non-transportation energy use for residential and commercial heating, which was not included in the TCI modeling.

Methodology

Having made significant progress in curbing air pollution from power plants, the Northeast and Mid-Atlantic states, including Washington, D.C., have begun discussing options to address emissions from other sectors of the economy, including from transportation and from residential and commercial heating [1]. The transportation sector, including cars, buses, trucks, and other vehicles, is the largest contributor to the region's carbon dioxide (CO₂) emissions, accounting for approximately 43 percent of total emissions in 2017; fossil fuel use in residential and commercial buildings contributed an additional 22 percent [2]. In the absence of meaningful progress to address emissions from these sectors, states in the region will be unable to meet their economy wide GHG reduction targets.

This report evaluates the benefits of using renewable biofuels, in combination with vehicle and appliance electrification, to address the emissions from these sectors of the economy. The analysis focuses on the use of both liquid and gaseous biofuels – specifically renewable natural gas (RNG) as a substitute for fossil

What is Biomass-based Diesel?

The term biomass-based diesel includes both biodiesel and Renewable Hydrocarbon Diesel (RHD), which are liquid fuels that can be substituted for petroleum diesel. However, unlike petroleum these fuels are made from a diverse mix of renewable feedstocks, including plant- or animal-derived fats and oils, and recycled cooking oils. Plant-based oils used for biodiesel and RHD production include soybean and canola oil, as well as inedible corn oil.

Biodiesel is made via transesterification and esterification, by combining the oil(s) with an alcohol in the presence of a catalyst. Fuel-grade biodiesel must be produced to strict industry specifications in order to ensure proper performance. Biodiesel must meet specifications for legal diesel motor fuel (ASTM D975) and also the ASTM definition for biodiesel itself (ASTM D6751). Raw vegetable oil cannot meet these diesel fuel specifications and therefore is not considered biodiesel.

RHD is produced from the same feedstocks as biodiesel but using different production processes. Today, most RHD is produced using a hydrotreating process, similar to those used in traditional petroleum refineries, that converts triglycerides into paraffinic compounds. RHD can also be produced using gasification, pyrolysis, or hydrothermal processes [3]. RHD must meet the standards of ASTM D975 (U.S.) or EN 590 (Europe) for motor diesel fuel. There is also a new European standard specifically for RHD fuels (EN 15940).

All medium and heavy-duty truck Original Equipment Manufacturers (OEMs) approve the use of biodiesel in their engines up to a 5 percent blend with petroleum diesel (B5), and about 90 percent of OEMs approve biodiesel use up to a B20 blend. At least seven major OEMs have also approved the use of RHD in their engines at blends up to 100 percent, if the fuel meets ASTM D975, EN 590, or EN 15940 standards [4]. Both fuels can also be used in boilers and furnaces – without any equipment modification - either neat or blended with petroleum-based heating oil.

In 2018 U.S. companies produced 2.3 billion gallons of biomass-based diesel, but existing plants have the capacity to produce almost twice as much [5].



natural gas, and biomass-based diesel - both biodiesel (BD) and renewable hydrocarbon diesel (RHD)³ - as a substitute for liquid distillate fuels produced from petroleum. RNG can be used interchangeably with fossil natural gas to fuel natural gas vehicles, or in natural gas furnaces and boilers, for both water heating and space heating. Biodiesel and RHD can be used as a substitute for diesel fuel (in vehicles) or heating oil (in furnaces/boilers for water and space heating).

Within the transportation sector this analysis focuses only on medium- and heavy-duty onroad vehicles, including single-unit trucks, transit and other buses, and combination trucks (also known as tractor trailer trucks or semis). These vehicles are primarily powered by diesel fuel (and to a lesser extent natural gas) and accounted for an estimated 19 percent of the region’s transportation-related carbon emissions in 2017. Within the region most personal vehicles (cars and light-trucks) are powered by gasoline, with very little penetration of either diesel or natural gas vehicles. As such, the medium and heavy-duty fleet represents a more likely candidate for the types of biofuels under consideration. This analysis only addresses on-road medium and heavy-duty vehicles – it excludes air travel, non-road freight transport (rail, water, and pipeline), and other non-road vehicles (e.g., construction equipment, port handling equipment). These segments of the

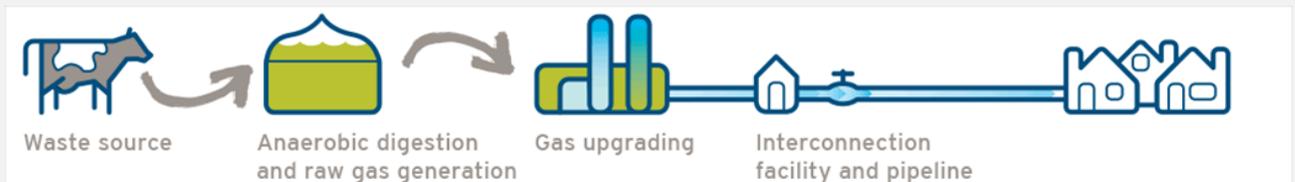
What is RNG?

Renewable Natural Gas (RNG) is produced by collecting, processing and cleaning methane-rich gas - also referred to as biogas - from one or more waste streams, to create a pipeline-quality gas that is fully interchangeable with traditional fossil natural gas.

Biogas is naturally produced by landfills, wastewater treatment plants, and manure lagoons at dairies and other livestock operations, via anaerobic digestion of biomass. Food waste and other municipal organic waste can also be diverted from landfills to special digesters for production and collection of biogas from anaerobic digestion. In anaerobic digestion, microorganisms break down organic material in a zero-oxygen environment, producing methane and carbon dioxide. Biogas can also be created using thermo-chemical conversion, in which woody biomass, crop residuals, or dedicated energy crops are processed at high temperatures to break down the material at the molecular level without combustion. The resulting hydrogen and carbon monoxide gases are then converted to methane and carbon dioxide using a process called methanation.

This raw biogas can often be used locally to produce on-site electricity or heat, with minimal processing. However, to produce RNG this raw biogas must be processed or “upgraded” to meet pipeline quality standards, so that it can be injected into distribution pipelines, for delivery to customers to be used interchangeably with conventional gas. The primary upgrading step is to remove most of the CO₂.

There are two other processes under development that could be used to produce significant amounts of RNG in the future: power-to-gas and artificial photosynthesis. Rather than creating RNG using biogenic feedstocks, these processes convert water to hydrogen, which can then be combined with CO₂ to create methane. Power-to-gas uses renewable electricity to split water into oxygen and hydrogen. Artificial photosynthesis does the same but using sunlight rather than electricity to split water molecules.



³ RHD is also sometimes referred to as “green diesel” or “hydrogenation-derived renewable diesel (HDRD)”

transportation system are also dominated by vehicles that use diesel fuel; they offer further opportunities to reduce GHG emissions using renewable distillate fuels but were beyond the scope of this study.

Within the commercial and residential sectors this analysis includes all fuel used for space heating, water, heating, and cooking. Most of the region has high winter heating demand in both of these sectors; about 76 percent of this direct energy demand is currently met using natural gas and 16 percent using heating oil⁴. These fuels are burned in boilers and furnaces, for both building space-heating and water heating.

Figure 1 **Baseline and Abatement Scenario Assumptions**

	M/HDV Transportation 	Residential/Commercial Heat 
BASELINE	<p>Current fuel economy and GHG emission standards through MY2027</p> <p>ELECTRIFICATION: By 2050: 75% of transit buses, 30% of other buses and single unit trucks, 5% of combination trucks electric</p> <p>RENEWABLE FUELS: Biodiesel 5% of total diesel use by 2050. No RNG use</p>	<p>ELECTRIFICATION: 5% of current NG/Oil user base converted to electric heat pumps by 2030, 30% by 2050</p> <p>RENEWABLE FUELS: Existing state-level heating oil biodiesel mandates: 5% in NY, RI</p> <p>No RNG use</p>
MEDIUM	<p>Baseline GHG standards and electrification</p> <p>RENEWABLE FUELS: Biodiesel 20% of diesel use by 2030, 40% by 2050</p> <p>RNG 80% of NG use by 2030, 100% by 2050</p>	<p>Baseline electrification</p> <p>RENEWABLE FUELS: Biodiesel 25% of heating oil use by 2030, 50% by 2050</p> <p>RNG 5% of NG use by 2030, 20% by 2050</p>
HIGH	<p>Baseline GHG standards and electrification</p> <p>RENEWABLE FUELS: Biodiesel 30% of diesel use by 2030, 50% by 2050</p> <p>RNG 100% of NG use by 2030</p> <p>In-use NG fleet increases 3% above baseline by 2050</p>	<p>Baseline electrification</p> <p>RENEWABLE FUELS: Biodiesel 50% of heating oil use by 2030, 100% by 2050</p> <p>RNG 10% of NG use by 2030, 60% by 2050</p>

Figure 1 summarizes the three abatement scenarios modeled for this project (Baseline, Medium Case, and High Case) and the assumptions included in each scenario. Based on current projections from the Energy Information Administration, this study assumes that medium- and heavy-duty vehicle miles traveled (VMT) will grow by 0.71 percent for buses and single-unit trucks and 1.15 percent for combination trucks annually in the region (compound annual growth rate). Lower VMT growth would result in greater net GHG reductions (compared to current emissions) than those summarized here, while higher VMT growth would result in lower net GHG reductions.

The Baseline scenario incorporates moderately aggressive efforts to electrify medium- and heavy-duty transportation, as well as electrification of space and water heating within both the residential and commercial sectors of the economy. Transportation electrification assumes replacement of existing diesel vehicles with battery-electric vehicles, increasing to 75 percent of transit buses, 30 percent of other buses and single unit trucks, and 5 percent of combination trucks by 2050. Electrification of residential and commercial heating load assumes replacement of natural gas and fuel oil-fired furnaces and boilers with heat

⁴ The remaining 8 percent comprises primarily wood and propane, with small amounts from kerosene, geothermal, and off-grid solar resources.

pumps, to displace 5 percent of natural gas and heating oil use by 2030, and 30 percent by 2050.

The baseline also incorporates current federal fuel efficiency and GHG standards applicable to new medium- and heavy-duty engines and vehicles. These standards require annual reductions in fuel use and GHG emissions from new trucks and buses through the 2027 model year⁵; in model year 2027 the certified fuel economy of new trucks is required to be 24-28 percent higher than model year 2020 trucks.

Within the region only a small percentage of current diesel fuel used for transportation is biodiesel⁶, but the states of New York and Rhode Island require 5 percent of heating oil used in each state to be biodiesel; while not mandated a small amount on bio-mass based heating oil is also used in Massachusetts. The baseline assumes that these state Bioheat® mandates will continue but not expand, and that biodiesel use for transportation will increase to 5 percent of total diesel fuel use even without further mandates or incentives.

The medium and high scenarios maintain baseline electrification levels for transportation and residential/commercial heat but assume much higher levels of renewable fuel use within the remaining natural gas and distillate fuel demand. Under the medium scenario biodiesel increases to 20 percent of total diesel use for transportation and 25 percent of heating oil use by 2030, and to 40 percent of diesel and 50 percent of heating oil use by 2050. RNG also increases to 80 percent of natural gas use for transportation and to 5 percent of natural gas use for residential and commercial heating by 2030, rising to 100 percent for transportation and 20 percent for heating by 2050.

Under the high scenario, by 2030 biodiesel is 30 percent of diesel use for transportation and 50 percent of heating oil use, increasing to 50 percent of diesel use and 100 percent of heating oil use by 2050. RNG reaches 100 percent of transportation natural gas use and 10 percent of natural gas use for heating by 2030. Use of RNG in the heating sector then rises to 60 percent of total natural gas use by 2050.

⁵ There are currently no announced plans by the Department of Transportation and Environmental Protection Agency to mandate further increases in new vehicle fuel economy after model year 2027. This analysis assumes all new vehicles between model year 2027 and model year 2050 will achieve mandated model year 2027 fuel economy.

⁶ The only state in the region with a bio-diesel mandate for onroad vehicles is Pennsylvania, which requires that two percent of onroad diesel fuel be biomass-based.

Study Results

M.J. Bradley & Associates used our State Emissions Pathway (STEP) tool to model fuel use of the two abatement scenarios (Medium Case and High Case) within the study region, relative to the Baseline scenario. These results, along with emissions data from the GREET® model, and emissions damage estimates from the Environmental Protection Agency, were then used to evaluate the scale and monetized value of the projected emissions reductions from greater use of renewable biofuels under each scenario. The methodology is discussed in more detail in Appendices A and B.

The major benefit of renewable natural gas and biomass-based diesel fuel use is a significant reduction in lifecycle greenhouse gas (GHG) emissions, as well as reductions in net upstream emissions of nitrogen oxides (NO_x) and particulate matter (PM_{2.5}).

The projected monetized value of these reductions stem from reduced societal costs related to climate change (GHG reductions) and reduced human health impacts (NO_x and PM_{2.5}).

The study results are described further below.

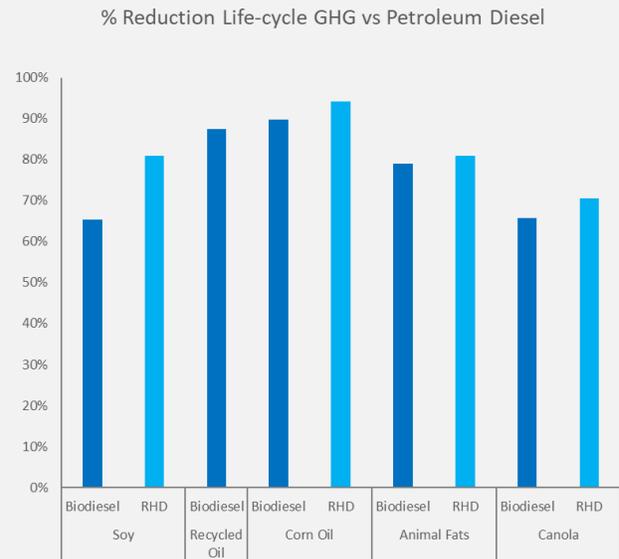
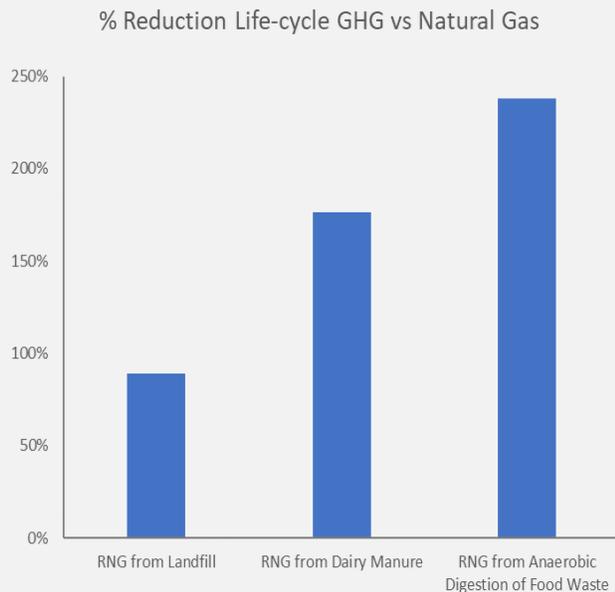


How Renewable Fuels Reduce GHG Emissions

All fuels, including biofuels, produce CO₂ when burned in a truck engine or furnace; this CO₂ is often referred to as the fuel’s “end-use” emissions. All fuels also require energy to produce them and transport them to the end user; this energy use produces additional CO₂. Most fuel production processes also result in emissions of methane (CH₄) and nitrous oxide (N₂O), which are powerful greenhouse gases with greater global warming potential than CO₂. These emissions from production and transport are referred to as “upstream” emissions – together with end use emissions they comprise a fuel’s “life-cycle” or “wells to wheels” GHG emissions.

Renewable biofuels made from energy crops (for example biodiesel produced from soybean oil) remove CO₂ from the air as the crops used to produce them grow – this recycling of carbon reduces net life cycle GHG emissions, resulting in significant reductions compared to fossil fuels. Depending on the feedstock and other factors, biodiesel and RHD can have 64 – 94 percent lower lifecycle GHG emissions than petroleum diesel.

RNG made from waste streams – for example from biogas collected from a landfill or animal manure operation – has even lower life-cycle GHG emissions because the methane that is collected and used as RNG would have otherwise been flared (at landfills), or just released to the atmosphere (manure operations). RNG produced from manure and food waste has negative life cycle GHG emissions – the GHG benefit from not releasing methane directly to the atmosphere is greater than end-use CO₂ from burning the fuel plus the other upstream emissions from processing and transport.



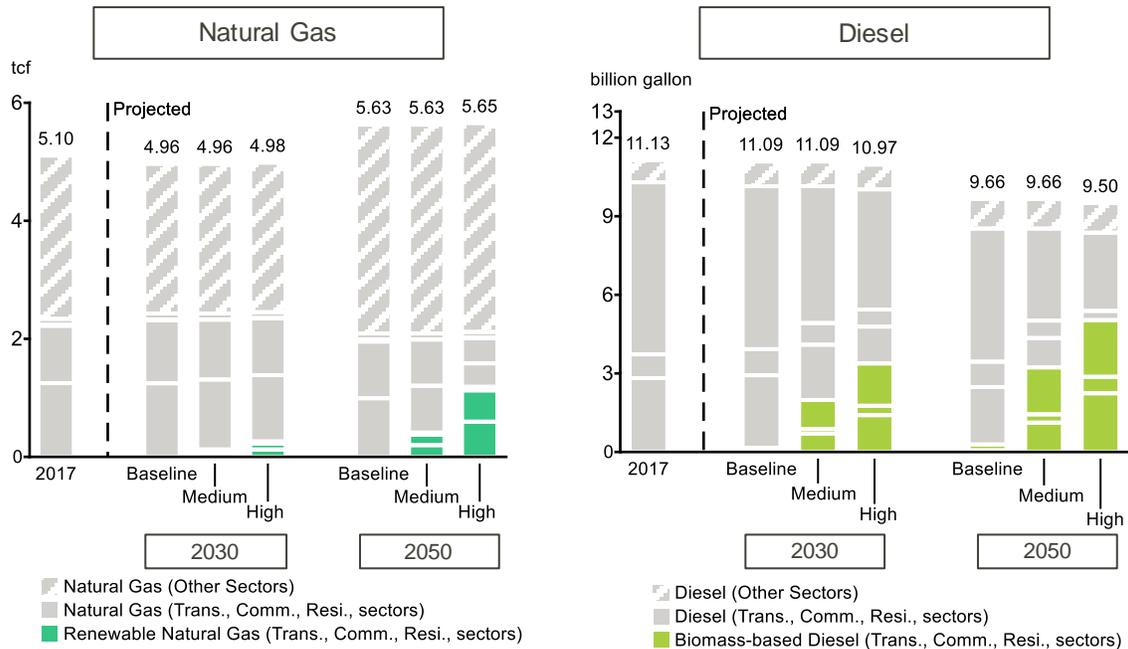
Changes in Energy Use

Both Abatement Scenarios (Medium Case and High Case), require a significant shift from reliance on motor diesel fuel, heating oil, and natural gas to gaseous and liquid biofuels produced from renewable sources.

Under the medium scenario the use of gaseous biofuel (RNG) in the region increases to 125 billion cubic feet (bcf) in 2030, and 411 bcf in 2050; under the high scenario RNG use reaches 261 bcf in 2030 and 1.2 trillion cubic feet (tcf) in 2050. Current RNG use within the Northeast and Mid-Atlantic region is essentially zero, but in California annual RNG use in transportation has gone from less than 0.2 bcf in 2011 to over 15 bcf in 2018, in response to financial incentives under California’s Low Carbon Fuel Standard [5].

ICF, in a study conducted for the American Gas Foundation, estimates that the total technical resource potential in the U.S. for production of RNG from anaerobic digestion and thermal gasification, is 12.8 tcf/yr. Accounting for technical and economic constraints ICF estimates that annual RNG production in the U.S. could reach 1.5 tcf/yr in 2030, and 3.5 tcf/yr in 2040 [6]. Based on ICF’s state-level estimates, about 12 percent of 2040 RNG production could be within the TCI region; in the short term an even higher percentage of total production could come from within the region, as it contains 17 percent of nationwide resource potential for production of RNG using anaerobic digestion. Based on economics, ICF estimates that these resources will likely be developed earlier, with RNG from thermal gasification developed later.

Figure 2 Energy Consumption by Sector and Fuel Type



Under the medium scenario the use of liquid biofuels (biodiesel and RHD) increases to 2 billion gallons in 2030, and 3 billion gallons in 2050; under the high scenario the use of liquid biofuels reaches 3.3 billion gallons in 2030 and 5 billion gallons in 2050.

To put this in perspective, in 2018 the U.S. produced 2.3 billion gallons of biodiesel and RHD and imported another 325 million gallons [7]. EPA reports current annual capacity of over 4 billion gallons registered to produce biomass-based diesel under the Renewable Fuel Standard.

The oils used to produce biodiesel and RHD are primarily a by-product from production of protein, prepared foods, and animal feed; demand for these products is projected to continue to increase, resulting in excess oils that could be used for additional biomass-based diesel production. LMC International estimates that North America could produce nearly three billion gallons of biomass-based diesel by 2025 and nearly four billion gallons by 2030, using projected surpluses of soybean oil and distillers corn oil [8].

Further, given the moderately aggressive levels of electrification included in the baseline and both renewable fuel scenarios – for medium- and heavy-duty transportation, as well as of space and water heating in the residential and commercial sectors - overall electricity demand in the TCI region is projected to rise by about 21 TWh in 2030 and nearly 130 TWh in 2050, or just over 3 percent and 19 percent of 2017 levels.

On average, electrification of space and water heating in the residential and commercial sectors is responsible for more than 80 percent of the projected increase in electricity demand, while electrification of medium- and heavy-duty vehicles accounts for the remainder. This level of electrification also reduces annual economy-wide demand for distillate fuel and natural gas. Distillate fuel use (diesel and heating oil) falls by 404 million and 2.2 billion gallons in 2030 and 2050, respectively, compared to projected fuel use without electrification. Natural gas use falls by 9 bcf and 120 bcf in 2030 and 2050, respectively.

For context, in 2017 the TCI region consumed 5.1 tcf of natural gas and 11.1 billion gallons of diesel fuel.

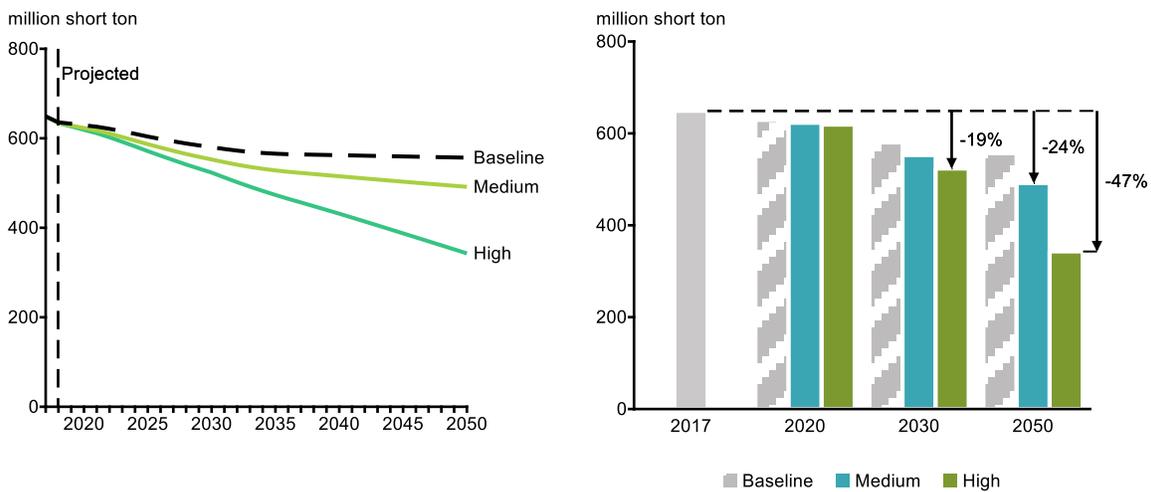
Overall GHG Reduction

The two modeled scenarios of increased renewable fuel use produce significant reductions in lifecycle GHG emissions from medium- and heavy-duty vehicles and residential/commercial heating. The medium scenario reduces GHG emissions from these sectors by 15 percent (from current levels) in 2030 and 24 percent in 2050. The high scenario reduces GHG emissions by 19 percent and 47 percent, respectively, in 2030 and 2050.

Between 2020 and 2050 the medium scenario results in an additional one billion metric tons (MT) of GHG reduction compared to the baseline scenario; the high scenario results in an additional 2.8 billion MT reduction through 2050.

This level of additional GHG reduction is equivalent to removing between 9.9 million and 26.7 million light-duty vehicles from the region's roads between 2020 and 2050.⁷ In 2017 there were an estimated 48 million cars and light trucks in the 12-state region, and this number is projected to grow to over 57 million by 2050.

Figure 3 Projected GHG Emissions under Modeled Scenarios

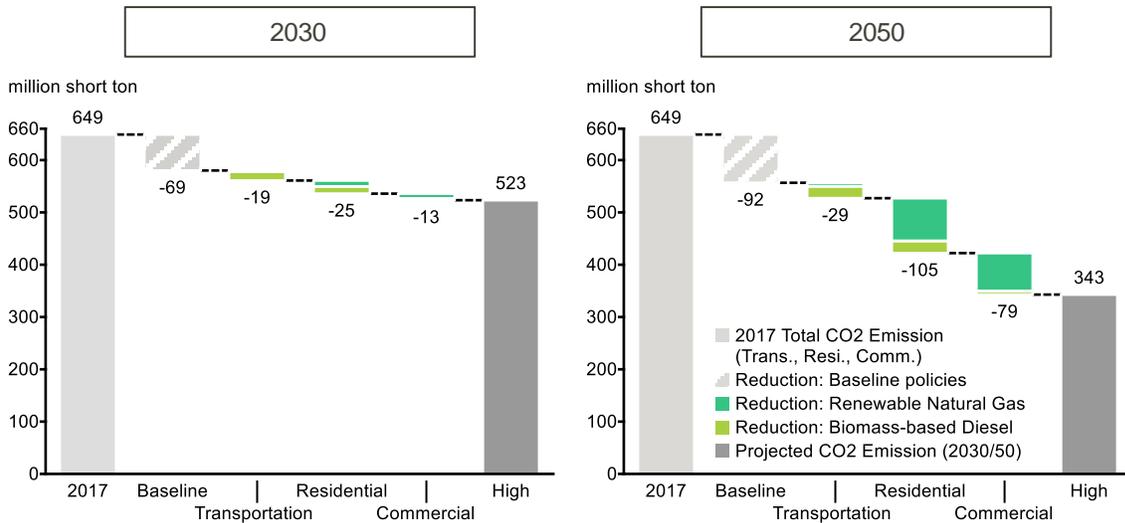


⁷ This is based on projected baseline LDV GHG emissions within the region between 2020 and 2050, which average 104 MT/vehicle over this 30-year period, or an average of 3.5 MT/vehicle/year. This average reflects projected turnover to more efficient vehicles (as mandated by current new car efficiency standards) but does not reflect significant penetration of electric vehicles. This includes both tailpipe and upstream GHG emissions.

GHG Abatement by Sector and Fuel Type

Relative to the Baseline scenario, which assumes little to no gaseous and liquid biofuel use (see Figure 1), increased use of RNG and biomass-based diesel in the transportation sector (medium- and heavy duty vehicles) and for heating in the residential and commercial sectors result in annual lifecycle GHG reductions of 52 million and 194 million metric tons in 2030 and 2050 respectively (relative to Baseline scenario).

Figure 4 GHG Reductions by Fuel Type and Sector – High Case



While both RNG and biodiesel use contribute to these reductions in all years, in the early years the increased use of biodiesel accounts for a dominating share, with more than 60 percent of the total in 2030 attributable to higher levels of biodiesel use in the three sectors (under the High scenario). This is due to two reasons—the relatively large share of diesel (which biodiesel displaces) in the transportation sector and a slower ramp up of RNG use assumed in the residential and commercial sectors. In terms of sectoral distribution of GHG emission reduction, in 2030 the residential and commercial sectors account for two-thirds of the total, with transportation making the remaining third.

By 2050, however, most of the reductions come from RNG use in the residential and commercial sectors. Of the 194 million MT reduction projected in that year, RNG use in the three sectors (more than 95 percent is in the residential and commercial sectors) account for three-quarters of the total. By contrast, GHG emission reductions from the use of biomass-based diesel, which accounts for 25 percent of total reductions in 2050, come for the most part from the transportation and residential sectors, the former due to its large pool of displaceable diesel consumption, and the latter because about 16 percent of residential sector energy use in the TCI region is still met by burning heating oil in furnaces.

Air Quality Benefits

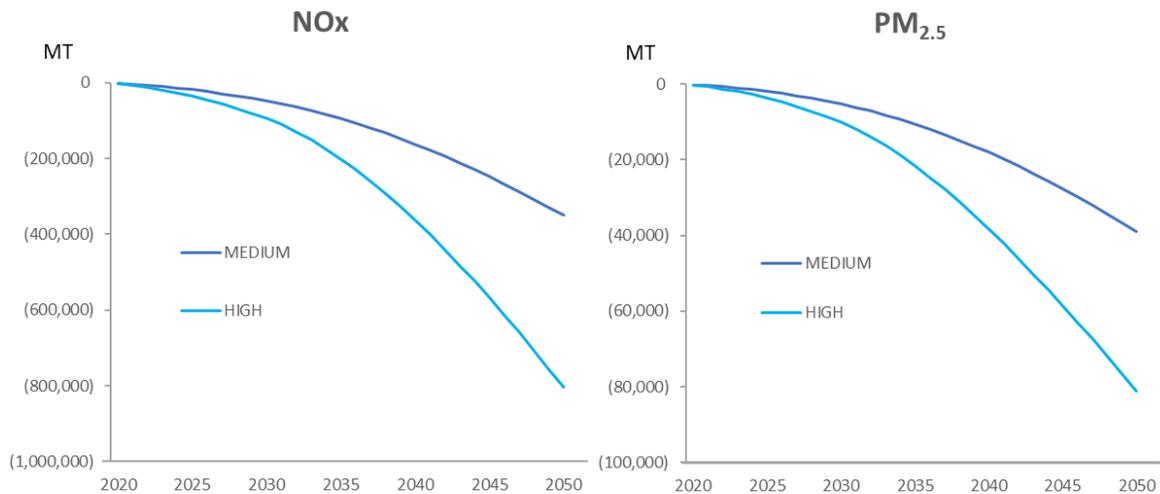
In addition to significant GHG reductions, the modeled renewable fuel strategies also reduce net economy-wide nitrogen oxide (NO_x) and particulate matter (PM_{2.5}) emissions. End-use NO_x and PM emissions (tailpipe, exhaust stack) are not expected to change significantly when substituting biomass-based diesels for petroleum diesel or RNG for conventional natural gas, but upstream emissions from production and transport of biofuels are lower than upstream emissions from production and transport of fossil fuels.

When diesel vehicles are replaced with natural gas vehicles equipped with ultra-low-NO_x engines, tail-pipe NO_x emissions can also be reduced by up to 90 percent, increasing net NO_x reductions from RNG use [9]. Diesel engines sold prior to 2010 are being retired through natural turnover and are being replaced with low-NO_x diesel vehicles; this analysis conservatively assumed relatively low levels of diesel – natural gas vehicle conversion, consistent with historical regional trends. The analysis did not attempt to estimate potential NO_x co-benefits of increased adoption of ultra-low-NO_x natural gas engines beyond those expected trends.

By 2030 annual emissions of NO_x are projected to fall by 6,800 MT under the Medium Case abatement scenario and by 13,700 MT under the High Case abatement scenario⁸. Annual emissions of PM_{2.5} are projected to fall by 780 MT under the Mid Case abatement scenario and by 1,500 MT under the High Case abatement scenario.

By 2050 annual NO_x and PM_{2.5} emissions will fall by 21,700 MT and 2,400 MT, respectively, under the Mid Case abatement scenario, and by 800,000 MT and 81,000 MT, respectively, under the high Case abatement scenario.

Figure 5 Cumulative NO_x and PM_{2.5} Reductions Relative to Base Case



As shown in Figure 5, between 2020 and 2050 cumulative NO_x reductions are projected to total 350,000 MT under the Mid Case abatement scenario and 805,000 MT under the High Case abatement scenario. By 2050 cumulative net PM_{2.5} reductions are projected to total 39,000 MT under the Mid Case abatement scenario and

⁸ Some, but not all reductions will occur within the Northeast and Mid-Atlantic region.

81,000 MT under the High Case abatement scenario. Approximately 97 percent of these reductions come from the use of RNG, and 3 percent from the use of liquid biofuels.

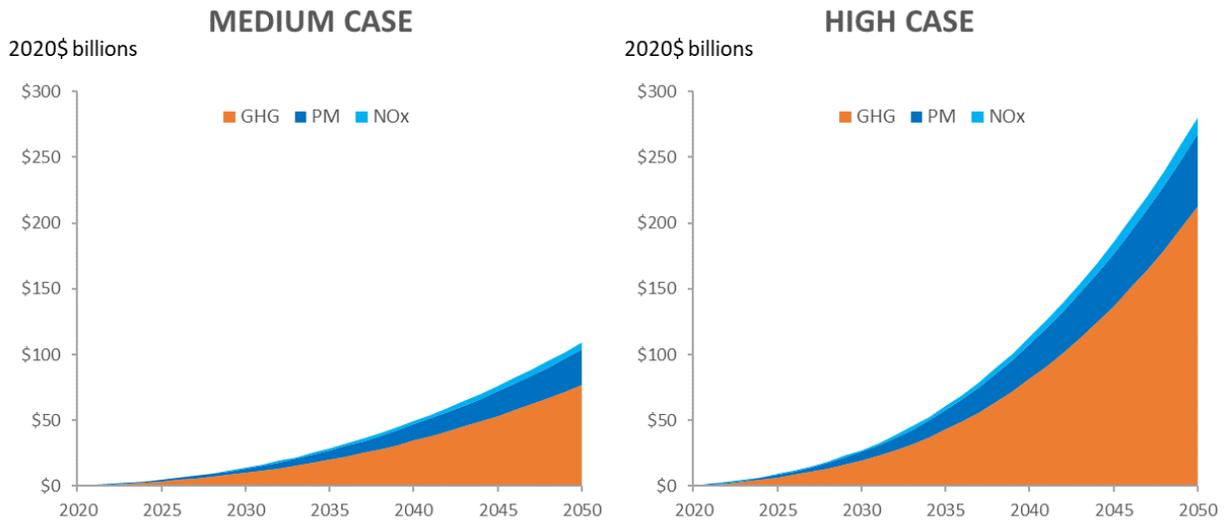
Monetized Emission Reductions

See Figure 6 for a projection of the cumulative monetized value of emissions reductions under the modeled renewable fuel abatement scenarios, relative to the baseline. The monetized value of GHG reductions represents potential societal cost savings from avoiding the negative effects of climate change, if GHG emissions are reduced enough to keep long term warming below two degrees Celsius from pre-industrial levels. The monetized value of NOx and PM_{2.5} reductions represent the value of avoided human health impacts when emissions of NOx and PM_{2.5} are reduced, including the value of reduced sick days and hospital visits, and the value of avoided premature deaths that would otherwise result from poor air quality⁹. The values shown in Figure 6 are in constant 2020 dollars, not including projected future inflation.

By 2030 the cumulative monetized value of emission reductions are projected to be \$14 billion under the Medium Case abatement scenario and \$28 billion under the High Case abatement scenario. By 2050 the cumulative monetized value of emission reductions are projected to be \$109 billion under the Medium Case abatement scenario and \$280 billion under the High Case abatement scenario.

Approximately 75 percent of the value results from GHG reductions, 20 percent from PM_{2.5} reductions, and 5 percent from NOx reductions.

Figure 6 Cumulative Monetized Value of GHG, NOx, and PM_{2.5} Reductions Relative to Baseline



⁹ EPA’s analysis only accounts for NOx damages from its role as a PM_{2.5} precursor and does not include damages related to the role of NOx as an ozone precursor. There may be additional health benefits related to reductions in ground level ozone, beyond those quantified here.

APPENDIX A – State Emission Pathways Tool (STEP Tool)

Background

In 2017, MJB&A designed and developed the State Emission Pathways Tool (STEP Tool) for policymakers to carry out fast assessments of a single- or multi-state region’s pathways to economy-wide future clean energy and greenhouse gas (GHG) reduction targets. It grew out of efforts to expand MJB&A’s earlier electric sector-only Clean Power Plan Compliance Tool (CPP Compliance Tool) to include other sectors of the economy. The STEP Tool employs a similar analytical framework and retains the same intuitive user interface as the CPP Compliance Tool. [10]

The main purpose of the STEP Tool is to provide a simplified and transparent data-driven framework for federal and state regulators, lawmakers, and stakeholders to engage in clean energy related policy design.

Description of the STEP Tool Model

The STEP Tool is a spreadsheet-based multi-sector model that allows users to analyze state and regional energy use and their CO₂ emission trajectories under a range of economy-wide policy scenarios. It lets users build detailed custom policy scenarios by selecting from various policy options in each sector of the economy—electric, transportation, residential, commercial, and industrial—while tracking in real-time associated overall electricity generation, portfolio mix, total energy use by fuel type, vehicle miles traveled by type, CO₂ emissions, etc. The inclusion of multiple sectors of the economy allows users of the STEP Tool to examine certain energy-use interactions among the different sectors of the economy (e.g.: the impact of electric vehicles on both the electric and transportation sectors, etc.)

To produce scenario projections quickly and efficiently, the STEP Tool uses a non-optimization approach to solve for and calculate future energy use and CO₂ emissions. It does not try to reach any equilibrium condition or optimize the system for any variables. Instead, it records each user selection to construct one or more policy scenarios and then calculates their impacts in terms of changes to existing patterns of energy use. It makes use of heuristics and simplifying assumptions to produce projections at an indicative level.

The STEP Tool relies, for the most part, on several publicly available datasets from federal and state-level government agencies to build up relatively detailed characterizations of historic energy use patterns for each sector of the economy—electric, transportation, residential, commercial, and industrial. For example, for the transportation sector, the focus of this report, the STEP Tool uses the U.S. Department of Transportation Federal Highway Administration’s “Highway Statistics” publication as the starting point for the development of state-by-state statistics on vehicle miles traveled, size of current vehicle stocks, etc. Various sections of the Energy Information Administration’s Annual Energy Outlook and State Energy Data System datasets are used to both add further detail to the final representation of the sectors in the STEP Tool and provide a way to crosscheck against a second calculation of overall energy use and associated emissions in the sector.

By design, the current version of the STEP Tool does not provide any cost estimates.

GHG Emission Scope of STEP Tool

The STEP Tool’s scope is limited to energy-related CO₂ emissions only, which accounted for about 80 percent of all U.S. GHG emissions in 2016. Non-CO₂ GHG gases—CH₄, N₂O, PFCs, SF₆, and NF₃—are not included in the STEP Tool. Also excluded are non-energy related CO₂ emissions (i.e., process related) from the industrial sector.

Use of STEP Tool in This Report

The STEP Tool is used in this report to generate, for each year through 2050, overall CO₂ emissions and total energy use (by fuel type) associated with each modeled abatement scenario (Baseline, Mid-case, High-case) for medium- and heavy-duty vehicles and for commercial and industrial heating. These annual projections

APPENDIX A – State Emission Pathways Tool (STEP Tool)

are then used as inputs to calculate total lifecycle GHG emissions (including upstream emissions) of the fuels used, as well as changes in upstream emissions of nitrogen oxides (NO_x) and particulate matter (PM) for the different scenarios.

Electric Sector Assumptions and Handling of Incremental Electricity Demand

The STEP Tool assumes that individual states in the focus region—12 states plus DC—achieve their renewable electricity procurement obligations stipulated under the states' RPS programs through 2050. On this basis the STEP Tool estimates the cumulative amount of electrical energy (in MWh) that would enter the electrical grid annually in the focus region as a result of all the states' RPS programs currently in force. These RPS driven renewable resource MWhs are then added to the electricity supply pool.

If the additional amount of electricity creates a surfeit of electricity energy supply in the system, the STEP Tool assumes that natural gas combined cycle (NGCC) units will be on the margin for the most part and reduces their total output such that supply and demand remain on balance. On the other hand, if there is a deficit even after electricity from the renewable resources is added to the supply pool, the STEP Tool dials up output from NGCC units to balance supply and demand at all times. See Figure C-13 in Appendix C for an illustration of both overall system resource mix as well as the implied emission rate associated with supply to meet incremental demand from cross-sectoral electrification.

APPENDIX B – Life-Cycle Emissions Calculations

Upstream Emissions

This analysis used the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET®) model developed by the Argonne National Laboratory to estimate upstream emissions associated with liquid and gaseous fuels used by medium- and heavy-duty vehicles, and for residential and commercial heating, under each modeled scenario [11]. For each fuel upstream emissions of CO₂, CH₄, N₂O, NO_x, and PM were estimated by GREET on a mass per unit energy basis (grams per million btu, g/mmBtu). Using GREET assumptions for the energy content and density of each fuel, emissions factors for each fuel were then calculated on a volumetric basis; for liquid fuels grams per gallon (g/gal) and for gaseous fuels grams per cubic foot (g/cf). For each scenario these emission factors were applied to estimated annual fuel volumes from the STEP tool, to calculate total annual upstream emissions from production and transport of the fuel used in the region. Upstream GHG emissions were then added to the end-use CO₂ emissions calculated by the STEP tool to get total lifecycle GHG emissions from the fuel used under each scenario.

For this analysis lifecycle GHG emissions include CO₂ (upstream and end-use) as well as upstream emissions of CH₄ and N₂O, expressed on a CO₂-equivalent basis using their global warming potential over a 100-year period (GWP₁₀₀). The GWP₁₀₀ of CH₄ is assumed to be 34 and the GWP₁₀₀ of N₂O is assumed to be 298, per the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment [12].

Most combustion processes, including diesel and natural gas engines, as well as boilers and furnaces, also produce end-use NO_x, PM, CH₄ and N₂O during fuel combustion. These end-use emissions were not included in this analysis because they are assumed to be the same regardless of whether renewable or fossil fuels are used and would therefore not vary between the modeled scenarios. By design RNG meets transmission and distribution pipeline quality standards that are also applicable to fossil gas moved by the same infrastructure. Of necessity, RNG therefore has similar chemical composition to fossil gas and would be expected to produce similar end-use combustion emissions.

Renewable distillate fuels (biodiesel, RHD) have slightly different chemical composition than petroleum diesel. B100 biodiesel contains up to 10 percent oxygen by weight, whereas both petroleum diesel and RHD have virtually no fuel-bound oxygen. A test program conducted by the National Renewable Energy Laboratory (NREL) in 2006, which tested 1998 and 2004 vehicles burning B20 operated on a chassis dynamometer, showed a 12 – 17 percent reduction in CO, HC, and PM emissions [13]; these emission changes are generally attributed to biodiesel's fuel-bound oxygen. The NREL data also showed that “Individual engines may show NO_x increasing or decreasing, but on average there appears to be no net effect, or at most a very small effect on the order of +/- 0.5%....considering all of the available data, we conclude B20 has no net impact on NO_x”.

Newer diesel engines are equipped with exhaust catalysts to significantly reduce both PM (model year 2007 and newer) and NO_x (model year 2010 and newer) compared to earlier engines. Based on the presence of these catalysts EPA expects that these newer engines “are not anticipated to experience any significant impact on criteria pollutant emissions due to use of these (biodiesel) fuels, compared to petroleum diesel fuel” [14]. The medium- and heavy-duty fleet effectively turns over approximately every 17 years; by 2027 less than 5 percent of M/HDV fleet miles will be operated by pre-2007 trucks. In the modeled scenarios any difference in end-use NO_x and PM emissions from pre-2007 trucks using renewable fuels will be small relative to the calculated changes in upstream emissions associated with manufacture of these fuels.

In the GREET model upstream emissions of CO₂, and in some cases NO_x, PM, CH₄ and N₂O, are negative for renewable biofuels because the model applies “credits” for recycling of carbon into growing energy crops, and/or credits for reduced atmospheric emissions of CH₄-rich biogas (i.e. RNG from manure operations) or reduced CO₂ emissions from flaring of biogas (i.e. RNG from landfills). In the case of RNG from manure operations and from anaerobic digestion of food waste, total lifecycle GHG emissions are negative, even when accounting for end-use CO₂ emissions.

APPENDIX B – Life-Cycle Emissions Calculations

Upstream and total lifecycle emissions also vary significantly for the same end-product fuel (i.e. biodiesel) produced from different feedstock inputs (i.e. soy, corn, or canola oil), based on different energy inputs for both crop and fuel production. This analysis used weighted average emissions factors for each fuel type (RNG, renewable distillates) based on assumed feedstock input fractions that vary over time.

For RNG the analysis assumes that 100 percent of RNG will be sourced from landfills in the near term, but that over time a larger percentage will be sourced from anaerobic digestion of food and other municipal waste diverted to digesters, as well as from livestock manure operations. Under the medium scenario, by 2050 7 percent of RNG comes from municipal digesters, 8 percent from livestock manure, and 85 percent from landfills. Under the high scenario, by 2050 only 29 percent of RNG comes from landfills, with 33 percent from waste digesters and 38 percent from manure. See Appendix B for details of these assumptions.

These assumptions were informed by an analysis of RNG resource potential and cost conducted by ICF [6]. The ICF analysis indicates that landfills are currently the lowest cost source of RNG (\$/mmBtu), followed by wastewater treatment plants, municipal solid waste, dairy manure, and forest and agricultural residue. Based on the ICF cost analysis, which is confirmed by MJB&A's own prior work, this analysis assumes that landfills will be the first RNG sources to be developed, followed by animal manure operations and digestion of food waste and other municipal waste.

ICF estimates that under an aggressive (high) development scenario, which assumes that 50-70 percent of available biomass will be converted to RNG depending on source, by 2040 a total of 1,310 billion cubic feet per year (BCF/yr) of RNG could be produced nationwide, from landfills (61 percent), animal manure (32 percent), and municipal solid waste and wastewater treatment (6 percent). This would be enough RNG to supply the required regional demand through 2050 under the high modeled scenario here, without including RNG produced via thermal gasification from other biomass sources such as agricultural residue (up to 580 BCF/yr), forest product residue (up to 220 BCF/yr), energy crops (up to 770 BCF/yr), and non-biogenic components of municipal solid waste (up to 640 BCF/yr) which taken together more than double annual national RNG potential per ICF. ICF indicates that by 2040 up to 620 BCF/yr of RNG could also be produced economically from water and CO₂ using power-to-gas technologies, but these sources were not considered for this analysis.

For liquid biofuels, this analysis assumes that in the short-term 100 percent of demand will be met with biodiesel, with 50 percent produced from soybean oil and 50 percent from used cooking oils. This mirrors current production from regional producers. After 2030 under the medium scenario, and after 2020 under the high scenario, the analysis assumes that an annually increasing percentage of demand will be met with RHD, growing to 25 percent of total demand in 2050 under the medium scenario and 50 percent under the high scenario. In transportation the use of RHD is projected to increase once demand for biomass-based diesel increases above 20 percent of total fuel use.

The analysis also assumes that over time the feed stock mix for production of demanded biodiesel will shift toward the current U.S. average mix of 56 percent soy oil, 14 percent corn oil, 13 percent recycled oils, 9 percent animal fats, and 8 percent canola oil [17]. In 2018 the U.S. produced 1.85 billion gallons of neat biodiesel (B100), which represented approximately 74 percent of available capacity.

See appendix C for details of projected feedstock mix, and resulting weighed average emission factors, for both RNG and liquid biofuels used in the analysis.

APPENDIX B – Life-Cycle Emissions Calculations

MONETIZED VALUE OF EMISSION REDUCTIONS

Annual reductions in GHG emissions compared to the baseline (million metric tons carbon dioxide equivalent, MMT CO₂-e) were estimated by the STEP Tool for each modeled scenario. To calculate the monetized value of these GHG reductions this study used values for the “Social Cost of CO₂” (\$/MT) which were developed by the U.S. government’s Interagency Working Group on Social Cost of Greenhouse Gases [18].

The Interagency Working Group published social cost estimates based on average modeling results using 2.5 percent, 3 percent and 5 percent discount rates, as well as 95th percentile results using a 3 percent discount rate. For this study the authors used the average values resulting from a 3 percent discount rate, which is in the middle of the range of estimated values. Total monetized CO₂ reduction benefits would be approximately 68 percent lower if using average values resulting from a 5 percent discount rate, 46 percent higher if using average values resulting from a 2.5 percent discount rate, and three times greater if using 95th percentile values resulting from a 3 percent discount rate.

The social value of CO₂ reductions represents potential societal cost savings from avoiding the negative effects of climate change, if GHG emissions are reduced enough to keep long term warming below two degrees Celsius from pre-industrial levels.

See appendix C for the social cost of CO₂ values used.

This analysis also calculated changes in upstream emissions of NO_x and PM from each modeled scenario. The monetized value of the estimated NO_x and PM_{2.5} reductions was calculated using avoided emission damage estimates (\$/MT) developed by EPA [19]. These avoided emission damage estimates represent the value of avoided human health impacts when emissions of NO_x and PM_{2.5} are reduced, including the value of reduced morbidity and reduced premature mortality¹⁰. EPA developed avoided NO_x and PM_{2.5} damage estimates for 17 different economic sectors, including “Electricity Generating Units”, “On-road Mobile Sources”, “Non-road Mobile Sources”, “Refineries”, and “Area Sources”, all of which could contribute to the upstream emissions from production of traditional fossil fuels and renewable fuels¹¹. Across these sectors estimated damage values vary by +/- 50 percent, with estimated damages (\$/MT) highest from onroad mobile sources and lowest from Electricity Generating Units. For this analysis the authors used the damage values for Nonroad Mobile Sources, which are close to the average across these five sectors, and lower than the values for both Area Sources and Refineries; we believe that this is a conservative approach to estimating monetized benefits.

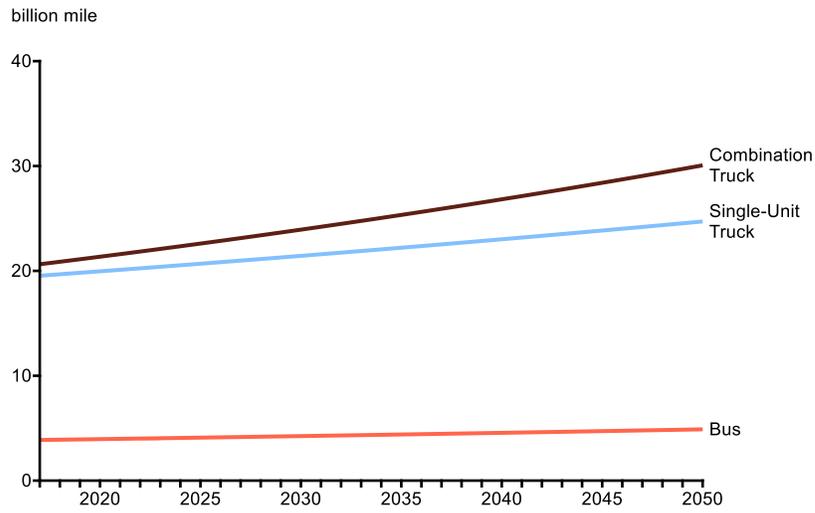
For each sector EPA developed a range of estimates for NO_x and PM_{2.5} damages (\$/MT), based on two different calculation methodologies from the scientific literature, as well as the use of two different discount rates (3 percent and 7 percent). For this study the authors used the average of the values developed by EPA. If using the highest values developed by EPA, the net monetized NO_x and PM_{2.5} benefits would be approximately 44 percent greater than shown here; if using the lowest values developed by EPA, the net monetized NO_x and PM_{2.5} benefits would be approximately 44 percent lower than shown here. See appendix C for the NO_x and PM_{2.5} emission damage values used.

¹⁰ EPA’s analysis only accounts for NO_x damages from its role as a PM_{2.5} precursor and does not include damages related to the role of NO_x as an ozone precursor. There may be additional health benefits related to reductions in ground level ozone, beyond those quantified here.

¹¹ The other sectors estimated by EPA are generally unrelated to upstream emissions from fuel production, for example Pulp and Paper Facilities, Taconite Mines, Iron and Steel facilities, Cement kilns, etc.

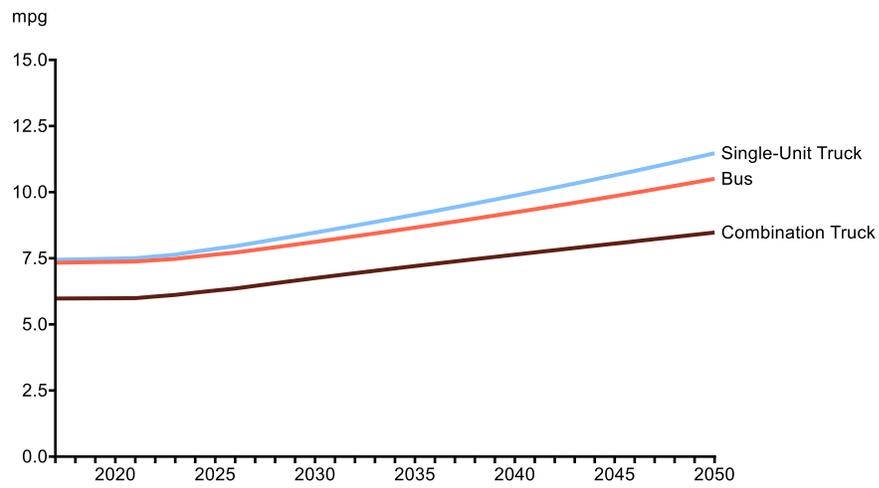
APPENDIX C – Modeling Inputs

Figure C-1 Vehicle Miles Traveled (billion mile)



Source: MJB&A Analysis, Federal Highway Administration 2015, Energy Information Administration, 2018 Annual Energy Outlook

Figure C-2 Medium/Heavy Duty Vehicle Efficiency (mpg)



Source: MJB&A Analysis

APPENDIX C – Modeling Inputs

Figure C-3 M/HDV Electric Vehicle Penetration (% of in-use fleet)

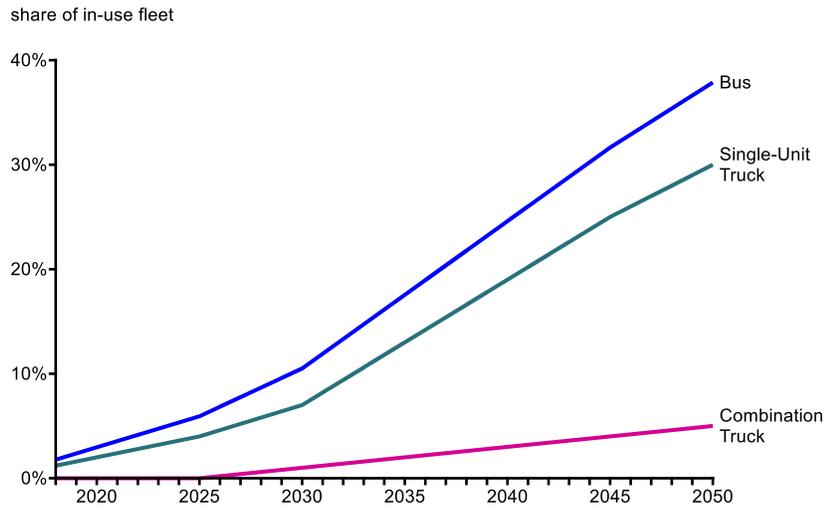
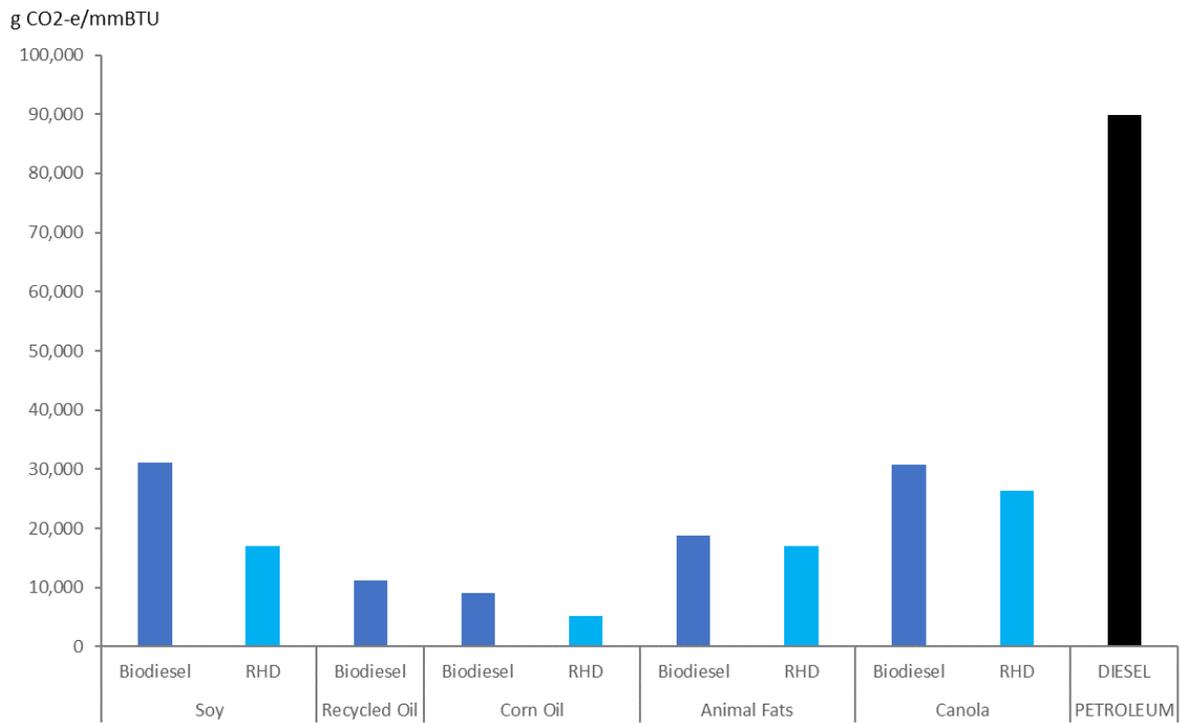


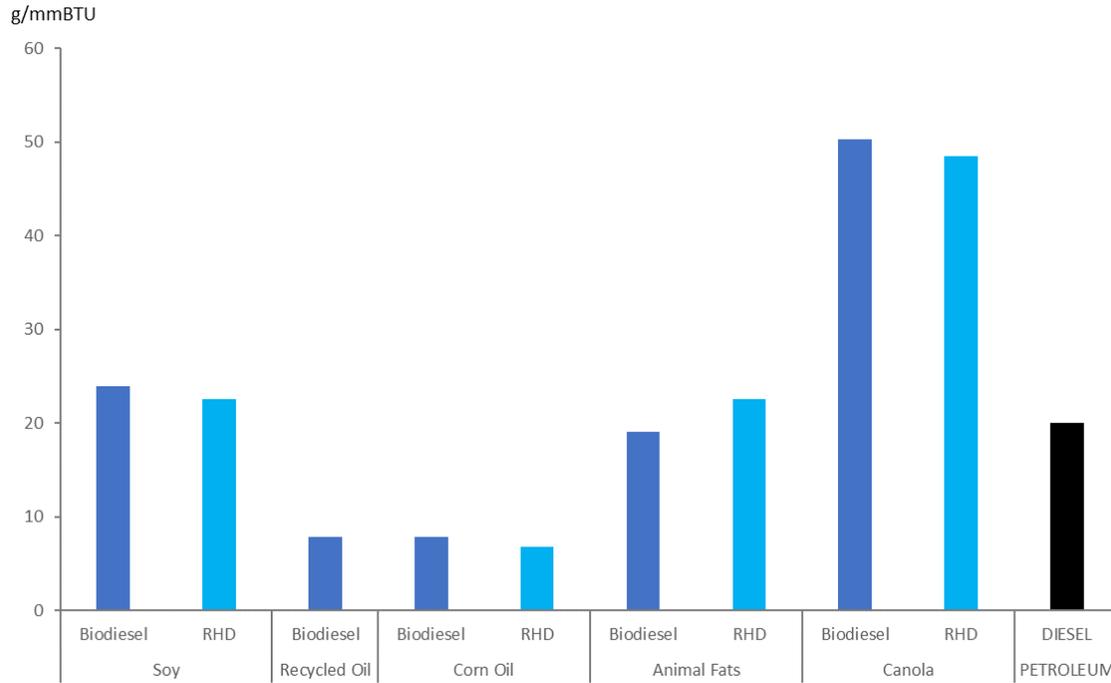
Figure C-4 Life Cycle GHG Emissions -Liquid Fuels



Source: GREET 2019

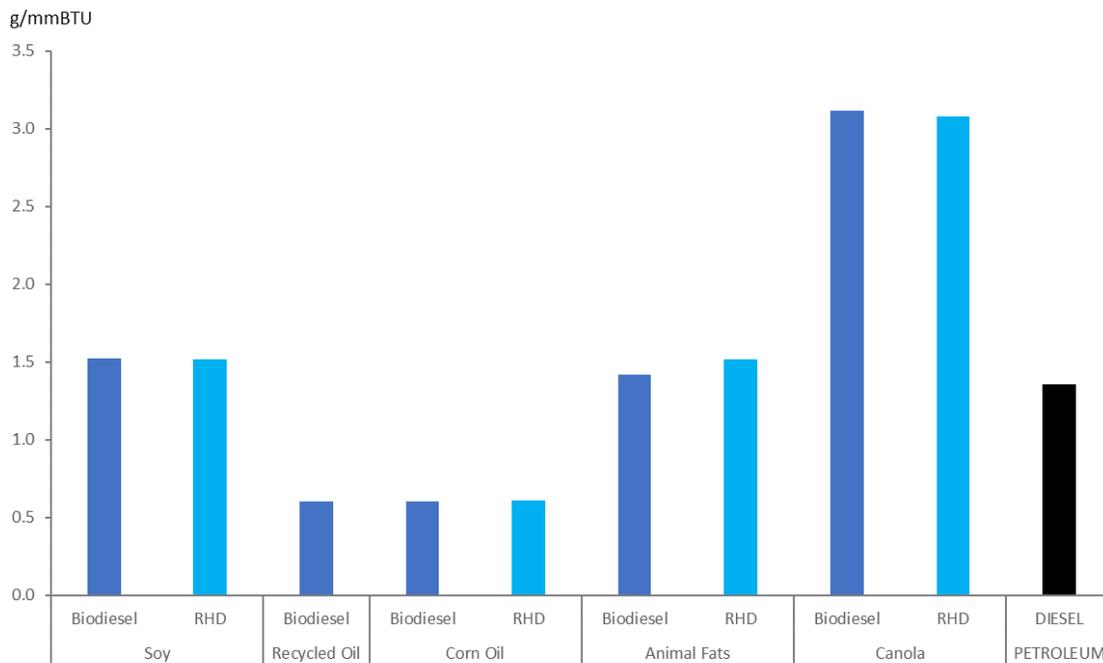
APPENDIX C – Modeling Inputs

Figure C-5 Upstream NOx Emissions -Liquid Fuels



Source: GREET 2019

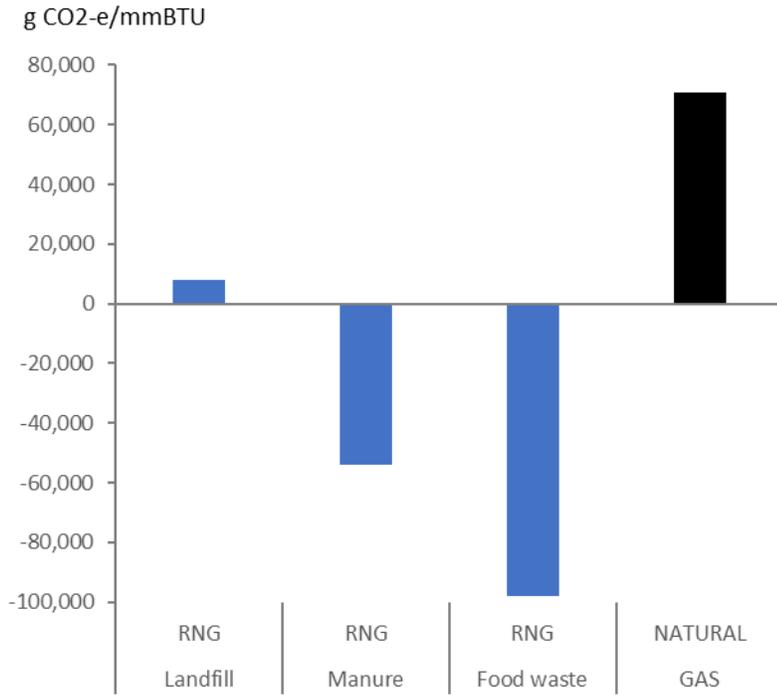
Figure C-6 Upstream PM Emissions -Liquid Fuels



Source: GREET 2019

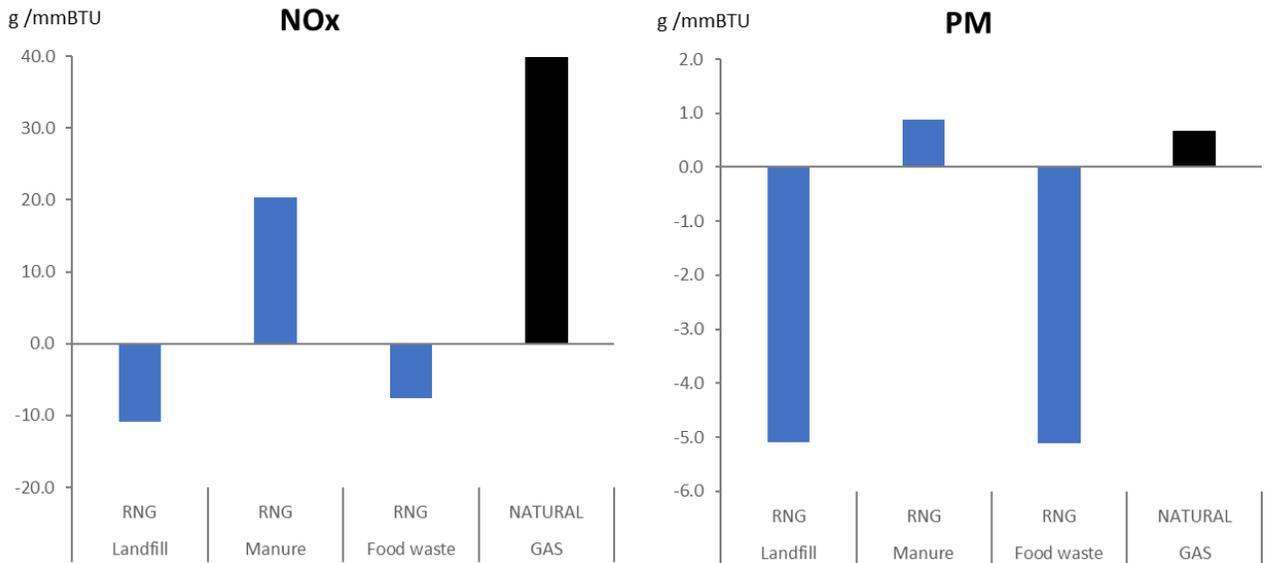
APPENDIX C – Modeling Inputs

Figure C-7 Lifecycle GHG Emissions -Gaseous Fuels



Source: GREET 2019

Figure C-8 Upstream NOx and PM Emissions -Gaseous Fuels



Source: GREET 2019

APPENDIX C – Modeling Inputs

Figure C-9 Assumed Biofuel Feedstock Shares – Medium Scenario

MEDIUM SCENARIO		2020	2030	2040	2050	
RNG	Feedstocks	Landfill	100%	95%	90%	85%
		AD Food Waste	0%	2%	4%	7%
		Dairy Manure	0%	3%	6%	8%
	GHG	CI (g CO ₂ -e/mmBtu)	7,915	3,944	-26	-4,437
		% Reduction ¹	89%	94%	100%	106%
	NOx	Upstream (g/mmBTU)	-10.91	-9.91	-8.90	-8.18
		Upstream (g/cf)	-0.012	-0.011	-0.010	-0.009
		Reduction (g/cf) ¹	-0.055	-0.054	-0.053	-0.052
	PM	Upstream (g/mmBTU)	-5.092	-4.914	-4.735	-4.616
		Upstream (g/cf)	-0.0055	-0.0054	-0.0052	-0.0050
Reduction (g/cf) ¹		-0.0063	-0.0061	-0.0059	-0.0058	
Bio-Liquids	Feedstocks	Soy	50%	56%	49%	42%
		Biodiesel	50%	13%	11%	10%
		Recycled Oils	0%	9%	8%	7%
		Animal Fats	0%	8%	7%	6%
		Canola	0%	14%	12%	11%
		Corn	0%	0%	12%	25%
	RHD	Mixed	0%	0%	12%	25%
	GHG	CI (g CO ₂ -e/mmBtu)	21,116	24,266	23,202	22,049
		% Reduction ²	77%	73%	74%	75%
	NOx	Upstream (g/mmBTU)	15.90	21.28	21.19	21.10
Upstream (g/gallon)		2.03	2.72	2.71	2.70	
Reduction (g/gallon) ²		-0.733	-0.045	-0.056	-0.068	
PM	Upstream (g/mmBTU)	1.064	1.394	1.394	1.395	
	Upstream (g/gallon)	0.136	0.178	0.178	0.178	
	Reduction (g/gallon) ²	-0.0520	-0.0098	-0.0098	-0.0097	

¹ Reduction compared to North American natural gas

² Reduction compared to petroleum diesel fuel

APPENDIX C – Modeling Inputs

Figure C-10 Assumed Biofuel Feedstock Shares – High Scenario

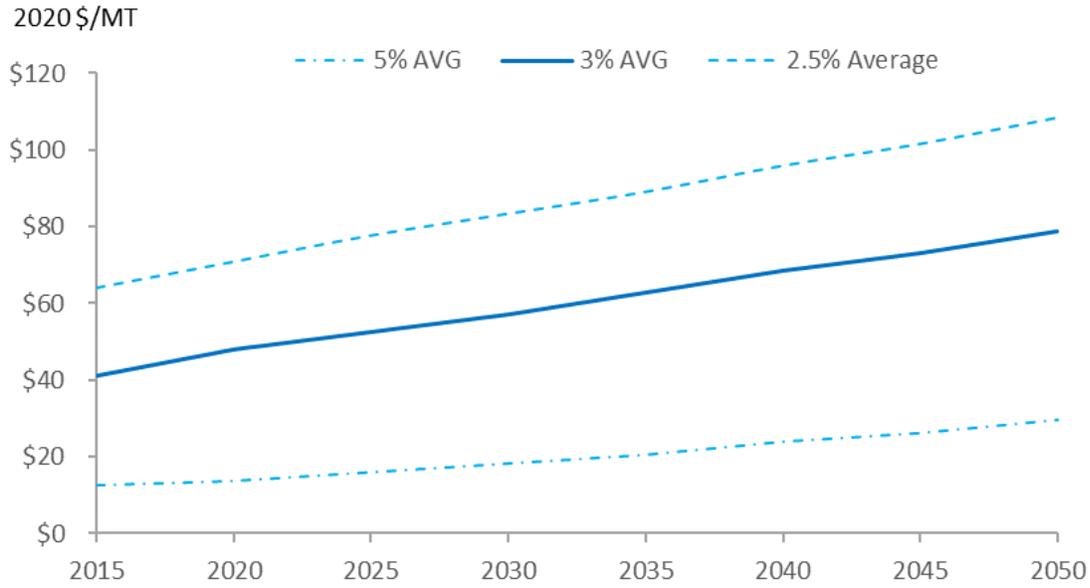
HIGH SCENARIO			2020	2030	2040	2050
RNG	Feedstocks	Landfill	100%	80%	55%	29%
		AD Food Waste	0%	10%	20%	33%
		Dairy Manure	0%	10%	25%	38%
	GHG	CI (g CO ₂ -e/mmBtu)	7,915	-8,847	-28,700	-50,491
		% Reduction ¹	89%	112%	141%	171%
	NOx	Upstream (g/mmBTU)	-10.91	-7.46	-2.45	2.04
		Upstream (g/cf)	-0.012	-0.008	-0.003	0.002
		Reduction (g/cf) ¹	-0.055	-0.052	-0.046	-0.041
	PM	Upstream (g/mmBTU)	-5.09	-4.50	-3.60	-2.83
		Upstream (g/cf)	-0.0055	-0.0049	-0.0039	-0.0031
		Reduction (g/cf) ¹	-0.0063	-0.0056	-0.0047	-0.0038
	Bio-Liquids	Feedstocks	Soy	50%	45%	36%
Biodiesel Recycled Oils			50%	10%	8%	7%
Animal Fats			0%	7%	6%	5%
Canola			0%	6%	5%	4%
Corn			0%	11%	9%	7%
RHD Mixed			0%	20%	35%	50%
GHG		CI (g CO ₂ -e/mmBtu)	21,116	22,493	21,163	19,833
		% Reduction ²	77%	75%	76%	78%
NOx		Upstream (g/mmBTU)	15.90	21.13	21.02	20.92
		Upstream (g/gallon)	2.03	2.70	2.69	2.68
		Reduction (g/gallon) ²	-0.733	-0.064	-0.078	-0.091
PM		Upstream (g/mmBTU)	1.06	1.39	1.40	1.40
	Upstream (g/gallon)	0.14	0.18	0.18	0.18	
	Reduction (g/gallon) ²	-0.0520	-0.0097	-0.0097	-0.0096	

¹ Reduction compared to North American natural gas

² Reduction compared to petroleum diesel fuel

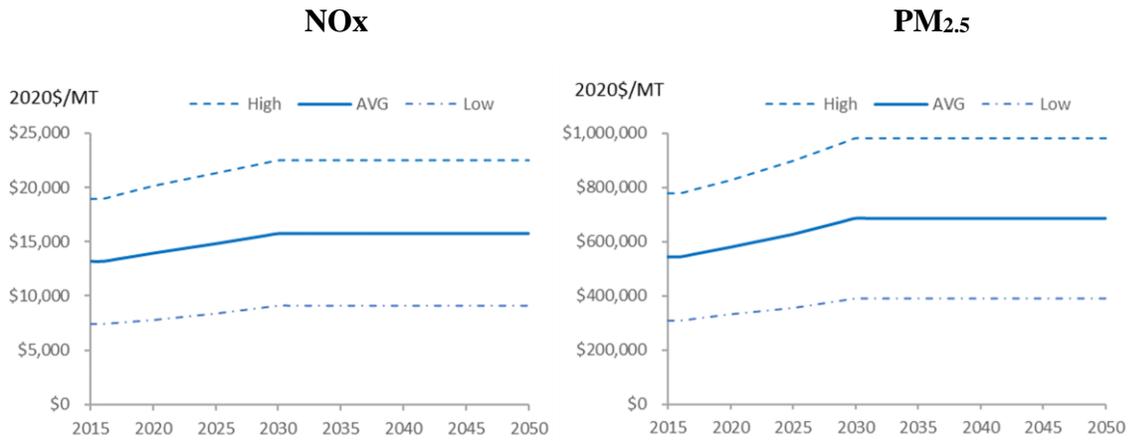
APPENDIX C – Modeling Inputs

Figure C-11 Social Cost of CO₂ (2020 \$/MT)



Source: Interagency Working Group on the Social Cost of Greenhouse Gases, July 2015

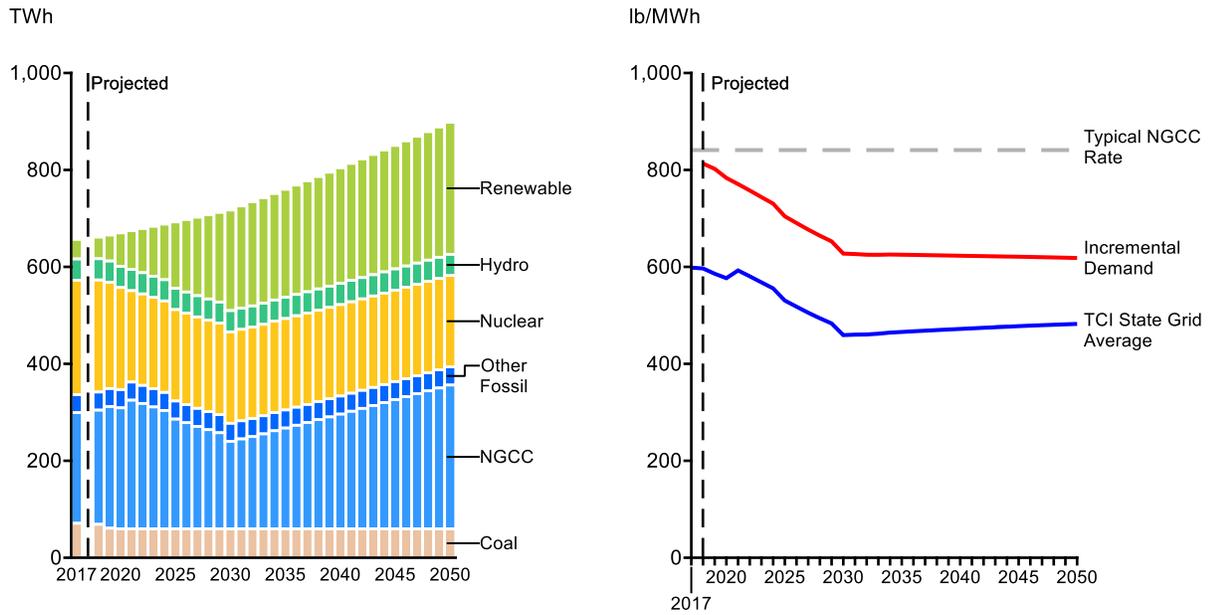
Figure C-12 NO_x and PM_{2.5} Emission Damage Estimates (2020 \$/MT)



Source: Environmental Protection Agency, 17 Sector Study, Nonroad Mobile Sources

APPENDIX C – Modeling Inputs

Figure C-13 Fuel Mix and Implied Emission Rate for Incremental Electricity Demand



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