# THE REFUSE REVOLUTION

## LEADING THE WAY TO A SUSTAINABLE FUTURE

ENERGY VISION

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## Acknowledgements

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## Comments on *The Refuse Revolution*

"A strong, meaningful legislative agenda must include clean transportation and reducing methane emissions. This Energy Vision report shows that businesses can be resourceful in producing the low- and no-carbon fuels and technologies essential for a more fair, just, and sustainable economy."

— **The Honorable Paul D. Tonko**, US Congress, NY-20

“With many non-petroleum technologies competing for space in the transportation sector, this new Energy Vision report presents a strong case for RNG as a cost-effective, low carbon, drop-in fuel for municipalities, private fleet operators, DOE Clean Cities affiliates, and state and federal officials grappling with clean fuel and climate change challenges.”

— **Marianne Mintz**, Principal Transportation Energy Analyst, Argonne National Laboratory

"Thank you, Energy Vision! This report is an excellent resource for fleet operators and climate action planners seeking to implement the most cost effective greenhouse gas reduction strategies."

— **Keith Leech Sr.**, Chief, Fleet Division & Parking Enterprise, Sacramento County

“This new report provides a lot of useful information and is an important contribution to the growing body of knowledge concerning the adoption and utilization of alternative fuels in public and private sector solid waste fleets.”

— **David Biderman**, Executive Director & CEO, Solid Waste Association of North America

"Energy Vision's new report is an essential guide for fleet owners and operators in assessing the low- and no-carbon technologies needed for a sustainable future."

— **Carlyle Khan**, Director, Solid Waste Management Service, The City of Toronto

# Table of Contents

## Foreword

Despite concerted efforts and tangible progress in the push to transition our energy systems and the global economy away from fossil fuels, the extent to which we are still reliant on petroleum is staggering, especially in the transportation sector. Waste and recycling collection trucks and other heavy duty truck and bus fleets are a vital focus. While they make up just 4% of the US vehicle population, they consume a whopping 20% of all vehicle fuel and emit nearly 25% of our transportation greenhouse gases.

With the scale and scope of the race to carbon-neutrality by mid-century, existing and emerging technologies and solutions abound. There is no one silver bullet, and each segment faces its own challenges and opportunities. For the transportation sector – not only the largest source of greenhouse gas emissions but also a major contributor to air pollution – we face an especially tall challenge to wean this country from our dependence on petroleum.

Energy Vision's new report takes an in-depth look at one critical sector of transportation in the U.S. – the 180,000 refuse trucks that tirelessly traverse the streets of virtually every city and town. These essential workhorse vehicles make a critical contribution to the quality of life in our cities and towns. But today, with concerns over how to improve urban air quality, how to reduce transportation's climate impacts, and debates over low-and no-carbon vehicle technology, fleet owners/operators are grappling with challenging decisions. This report offers a comprehensive assessment of the many non-petroleum options and the various environmental, economic and performance considerations necessary to make sound infrastructure investments.

The key question is how can this part of the country's heavy-duty truck fleet become a fully sustainable component of the transportation network needed to achieve our climate and clean air goals.

Energy Vision has for years investigated the range of emerging technologies and fuels that can wean refuse trucks off of high-carbon and polluting diesel fuel that most fleets rely on today, and it has produced a snapshot of options, ranging from drop-in biofuels to hybrid technologies to natural and renewable natural gas to battery electric and hydrogen vehicles. And while the complexities and regional differences within and across refuse fleets suggest different options at present, there is broad recognition that the ultimate goal is for use of proven, cost-effective trucks that use a clean and renewable energy source that makes little or no contribution to climate change or poor air quality.

All the options profiled in this report offer benefits over petroleum diesel-powered trucks, giving fleet owners and regulators many choices. With this audience in mind, Energy Vision's report provides a comprehensive analysis of the key metrics for fleet owners and operators, including: 1) climate impacts/benefits; 2) public health impacts/benefits; 3) cost; and 4) performance. Ultimately, the refuse segment and broader transportation sector will require technology(s) that achieves improvements over petroleum in all four categories.

Public and private sector decision makers are now struggling to determine how best to achieve the greatest and fastest environmental and public health benefits, including dramatic reductions in methane emissions that the international scientific community has flagged at COP26 as essential in the coming decade. The only option that promises carbon-negative greenhouse gas reductions are refuse trucks powered by renewable natural gas (RNG) fuel made from the very "waste" these trucks collect. The RNG choice simultaneously addresses our country's urban air pollution challenge and massive solid waste challenge, by turning the methane biogases emitted by organic wastes into clean fuel plus nutrients that can help replenish the world's poor soils. And RNG fueled trucks are commercial today—this is not a far-away idealized option.

Battery electric trucks have also emerged recently as an exciting option. They are now being piloted by public and private refuse fleets in several locations, but they do not yet have the operational track record of success necessary for widespread adoption and they are considerably more expensive than diesel or natural gas models.

The growing interest in "zero emission" solutions suggests that we will see more demonstrations of this technology, but every vehicle and fuel option has implications for our environment, our climate and public health, well-beyond a vehicle's on-road operations. Therefore, the importance of "lifecycle" assessments to compare and contrast technology and fuel options cannot be overstated.

As the Biden Administration seeks to make our country a model for industrial innovation and green infrastructure deployment, this Energy Vision report makes a groundbreaking contribution to decision makers.

**Brendan Sexton**
*Former Commissioner of Sanitation for New York City*

## Introduction

The Biden Administration has embraced ambitious goals to move this country forward in slashing greenhouse gas emissions, and to play a strong collaborative role in the community of nations that are part of the Paris Climate Accord. In confronting our global dilemma, how important a factor are the roughly 180,000 waste and recycling collection trucks ("refuse" for short) traveling the streets of virtually every city in the US, and the untold number in fleets worldwide? Why is Energy Vision concentrating on them in this report?

In the transportation arena, which generates the largest share of US greenhouse gases, our research has prioritized refuse trucks because they have historically been major polluters of urban air and contributors to climate change. These workhorse vehicles, essential for collecting municipal solid wastes and recyclables, are large consumers of diesel fuel because of their constant stop-and-start mode of operation. Understanding the non-petroleum options for this sector is critical for decision-making by fleet owners and operators as well as for policymakers, municipal officials, financiers, environmentalists, and concerned citizens.

Refuse trucks play a vital role in the quality of life of cities and towns, and every refuse truck purchased today will be on our roadways for the next decade or more. This report therefore addresses the core question: How can they perform their essential tasks while mitigating or eliminating their contribution to climate change? How can they be part of the sustainable economies of the future? In short, it will require a wholesale transition away from petroleum fuel and towards propulsion systems that run on low- or no-carbon renewable resources. This shift ideally must be to a fuel or new technology that eliminates emissions of health-damaging pollutants, reduces noise, and eliminates greenhouse gas emissions on a lifecycle basis (including fuel production, transport, and use).

In this report, Energy Vision has evaluated the various truck technologies and fuels that have been introduced to replace petroleum diesel fuel: their respective costs, performance records and impacts on the environment and public health. We are encouraged that several options have emerged as commercial choices, contributing to the critical shift that must take place.

We hope that this report will help municipal and private fleet owners, state policymakers and regulators, clean energy investors, and environmental and civic organizations pick up the reins and move the "refuse revolution" forward that this country urgently needs.

## Greenhouse Gases (GHGs): Which Impact Change the Most?

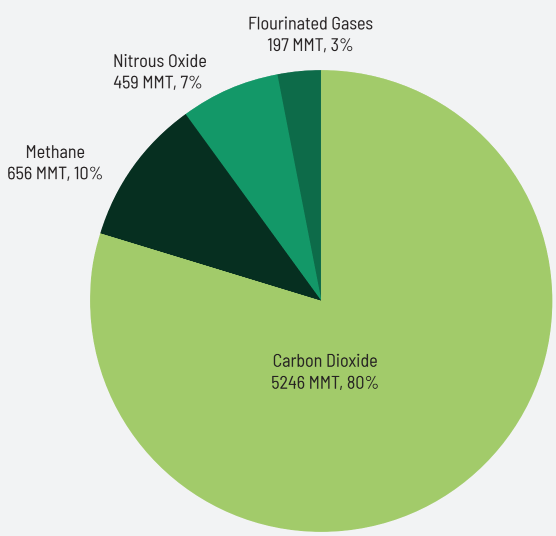
The most common GHGs are carbon dioxide ($CO_2$), which represents 80% of the total; methane ($CH_4$), 10% of the total; and nitrous oxide ($N_2O$), 7% of the total. Fluorinated gases make up the remaining 3%.[1]

Different greenhouse gases have different "global warming potentials," or efficiencies with which they trap heat in the atmosphere. $CO_2$ is the benchmark, with a global warming potential of 1; when different GHGs are being discussed in this report their impacts are generally expressed in terms of "$CO_2$ equivalent," or "$CO_2e$" – the amount of $CO_2$ that would have the same heat-trapping impact.

The chart below left is based on a 100-year timeframe, which gives methane a global warming potential of 25; at this value, methane accounts for 660 million metric tons (MMT) of $CO_2e$, or 10% of total greenhouse gases. However, methane only stays in the atmosphere for about 12 years, and measured over a 20-year time frame its global warming potential (GWP) is actually 86, according to the Intergovernmental Panel on Climate Change (Assessment Report 5). On that basis, and without adjusting any other values, the impact of methane would be better represented by the chart below.

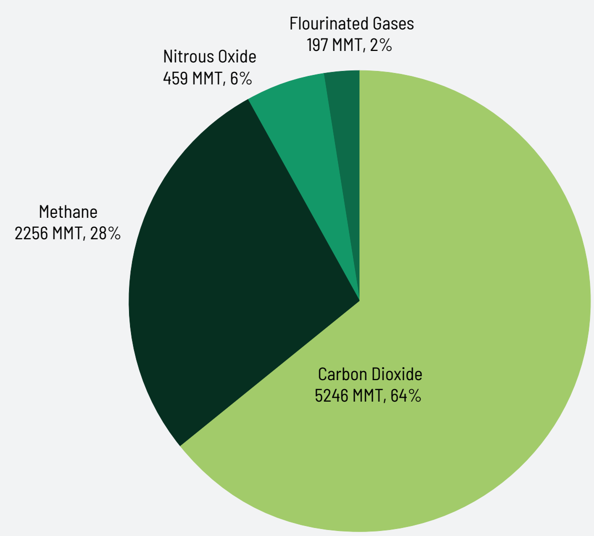
**Methane's Greater Global Warming Potential (GWP), 100 vs 20 Year Time Frame**

In Million Metric Tons (6,558 MMT total), 2019 Inventory




**100 year GWP**

*Source: US EPA*




**20 year GWP**

*Source: Energy Vision, based on US EPA*

Because of methane's potency over 20 years, reducing methane emissions has become a top national priority, and a recent UN report highlights that cutting these emissions 45% by 2030 is achievable and critical for averting the worst impacts of climate change.[2] In addition, landfills are the third largest source of anthropogenic methane emissions in the US, and still the final resting place for most of the materials collected by refuse trucks in every corner of the US. Therefore, this Energy Vision report gives special attention to reduction of methane emissions.

## Refuse Trucks Today

The technologies and fuels needed for the United States to transition to a sustainable economic future must be derived from renewable, pollution- and carbon-free sources of energy. In this report, Energy Vision has analyzed the options for one key sector: the fleets of heavy-duty refuse trucks that service cities and towns across the country. Most depend today on ultra-low-sulfur diesel fuel.

There are an estimated 180,000 refuse trucks in service daily in the US.[3] While these trucks provide an invaluable service, day in and day out, their operations take a significant environmental toll. It is astonishing that heavy-duty buses and trucks represent just 4% of the total vehicles on US roadways, but consume over a fifth of on-road vehicle fuel: nearly 40 billion gallons out of a total of 185 billion gallons per year.[4] (The explanation is actually simple: refuse trucks and buses, like delivery trucks or tractor trailers, are on the road most of the day, while passenger vehicles actually sit unused much of the time.)[5]

The fuel used by heavy-duty fleets has historically been high-carbon petroleum diesel, putting refuse trucks firmly in the category of vehicles that emit high levels of greenhouse gases as well as health-threatening pollutants. Furthermore, because the transfer stations or landfills where refuse trucks operate often border on disadvantaged communities, their emissions have an inordinate impact on those already living in distressed socioeconomic circumstances.

Finding clean fuel solutions for the refuse truck sector is imperative to protect the health of the communities living near refuse-handling operations and landfills, as well as the health of residents along collection routes, and the drivers and refuse collection workers themselves.

## What This Energy Vision Report Covers

**The three primary areas covered in this Energy Vision report:**

**1) The environmental, health and climate impacts of diesel refuse trucks**.

These include:

- Lifecycle emissions of greenhouse gases (GHGs), including those related to fuel production, transport and use
- Tailpipe emissions of the health-threatening airborne “criteria pollutants” nitrogen oxides (NOx) and particulate matter (PM2.5)
- Noise levels, which impact the residents of communities in which they operate as well as the hearing of those driving or otherwise working on the trucks themselves
- Non-emission-related issues associated with fuel extraction (defined below)
- End of life/disposal issues

**2) The alternative technologies and fuels and the extent to which each reduces or eliminates the negative impacts of petroleum diesel**.

Over the last few decades, the research and development of alternatives has expanded greatly. The options explored in this report include:

- Biodiesel
- Renewable Diesel
- Battery Electric Vehicles
- Hybrid Electric/Hydraulic Hybrid Vehicles
- Fossil Natural Gas
- Renewable Natural Gas (RNG) made from organic wastes
- Hydrogen
- Dimethyl Ether (DME)

**3) The cost, practicality, and performance of these options**, including short case studies for each. The specific factors include:

- Stage of technological/road-ready development of fuel and vehicles
- Fuel availability, cost, and relative efficiency
- Availability and cost of compatible vehicles that can use each fuel
- Performance of vehicles and fuel in on-road conditions appropriate to vehicle purpose
- Geographic factors/considerations

In the following sections, references to “diesel” and “diesel fuel” mean ultra-low-sulfur petroleum diesel (ULSD) unless otherwise indicated.

## Summary of Energy Vision's Findings and Conclusions

- **"Lifecycle" analyses** of fuels and technologies are essential to understanding and evaluating their respective climate, environmental and public health impacts. In reality, when using lifecycle accounting metrics, there is no such thing as a "zero emission" vehicle; every fuel/technology creates climate, environmental and public-health impacts, and each comes with trade-offs.

- **Renewable Natural Gas (RNG)** is the one fuel that is becoming widely available, for which affordable commercial engines and vehicles exist, that comes closest to meeting the criteria for sustainability.

  RNG is not a fossil fuel and thus is not produced by drilling. Rather, it is made from a renewable resource: food waste, animal manure, and other types of organic wastes. These organic materials, which predominantly end up in landfills and constitute a third of the US municipal waste stream, have long been considered "garbage." They are now being recognized as a new energy source valuable for combatting climate change.

  RNG is a double climate-change-winner. First, its production involves trapping and refining the methane biogases that are emitted by decomposing organic wastes, which would otherwise escape into the atmosphere with a potent climate warming impact. It is the only fuel that sequesters methane, now recognized by the IPCC and many prominent scientists as the top-priority greenhouse gas to cut in the decade ahead to meet US and global climate change goals.

  Second, RNG fuel can be used to replace high-carbon diesel fuel in heavy-duty vehicles. On a lifecycle basis, RNG fuel cuts greenhouse gases (GHGs) from 50% up to 300% relative to diesel. How can it reduce methane emissions more than 100%? Because producing the fuel in tanks called anaerobic digesters captures more greenhouse gases than are emitted by the vehicles burning it, and as noted above, those GHGs would otherwise have escaped from landfills into the atmosphere. RNG is the only fuel today that can be net carbon-negative. By replacing diesel in refuse trucks, the use of RNG also cuts health-threatening tailpipe emissions of nitrogen oxide (NOx) by 90% or more, and cuts tailpipe particulate matter emissions by 60% or more.[6]

  Trucks with natural gas engines that can burn RNG fuel cost about $35,000 more than diesel models at present, but the lower costs of the fuel and maintenance over their lifetime helps recoup this premium. While most Americans are not yet aware of it, the market for RNG is growing quickly. There are now more than 200 facilities producing RNG (equivalent to 500 million gallons of fuel) from organic waste in the US,[7] up from just 40 in 2016. The potential is far greater.

  Today, approximately 50,000 trucks and buses are already powered by RNG fuel; close to 10,000 of those are refuse trucks. Conservative estimates indicate that

RNG production potential could reduce petroleum demand by approximately 10 billion gallons per year,[8] enough fuel for every urban truck and bus fleet in America and more,[9] or about 25% of the transportation sector's current on-road diesel demand.

- **Fossil Natural Gas**. RNG can now fuel the natural gas engines that were first introduced in the early 1990's to burn chemically-similar fossil natural gas, sought after because it burned more cleanly than gasoline or diesel. These engines are now sophisticated and reliable. And today, there are nearly 8,000 refuse trucks burning fossil natural gas on the road, according to industry estimates. More than half of the refuse trucks on order today are for natural gas models.[10],[11] As with RNG, when burning fossil compressed natural gas (CNG) there are significant reductions in emissions of NOx (90%) and measurable reductions in PM (60%) compared to diesel; consequently, these vehicles are much healthier for workers, and their engines reduce hearing-damaging noise by as much as 50%.[12]

  However, lifecycle GHG emissions from trucks using fossil natural gas fuel are only 5% lower than diesel, based on Argonne National Laboratory's Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) database. Furthermore, fossil natural gas is not a renewable fuel, and the extraction methods used to produce it pose significant environmental risks. The use of fracking techniques has drawn intense opposition across the country for polluting air and water, despoiling landscapes, and threatening wildlife, and methane leakage through extraction and distribution are serious concerns.

- **Battery electric vehicles (BEVs)**, including refuse trucks, are the long-dreamt-of "zero-emission" solution of the future. To date, however, Energy Vision estimates that there are less than 50 fully electric refuse trucks on the road, and their cost is nearly 70% higher than diesel trucks – $500,000 compared to $300,000.[13] The small sample size and limited publicly available data leave questions about the power, torque, and reliability of this technology for the refuse sector.

  BEVs' main advantages are their zero tailpipe emissions and noise-free operations. However, they have other impacts that deserve consideration – impacts that get relatively little discussion by the many environmental groups that see the simple solution to transportation as "electrify everything." The impacts of concern include:

  1. The on-road operation of BEV's aren't truly zero emission. While the tailpipes emit no greenhouse gases or health-threatening pollution, the weight of the batteries required to propel a refuse truck, which leads to range/route concerns, reduced payload capacity; increased wear and tear on brakes, tires, and the road can result in high levels of particulate matter (PM) pollution.
  2. The source of the electricity that powers the batteries, which is still derived primarily from fossil fuels; on average, therefore, BEVs reduce lifecycle greenhouse gases by 58% compared to diesel.

3. The significant local electricity demand necessary to charge medium- and heavy-duty electric trucks.
4. The source of the materials to make batteries – lithium, cobalt and rare earth minerals – and the associated labor conditions, air and water pollution, and health impacts of mining those materials.
5. Significant questions related to safe recycling or disposal of batteries.

- **Renewable Diesel (RD)** is not a fossil fuel; it is made from waste oils and other organic feedstocks (described in more detail below, in Introduction to Alternative Fuels and Technologies). When it was first introduced in 2015 in the US, it showed promise as an easy-to-use "drop in" non-petroleum substitute for diesel fuel, and it has recently gained traction among some refuse fleet operators. There is no need to change engines, so there is little cost in converting to its use.

  RD achieves lifecycle carbon emissions reductions compared to fossil diesel (~60%). Fleets in California, where a Low Carbon Fuel Standard is in place, have been quick to adopt RD. It is not clear that there is any NOx reduction relative to conventional diesel. There is, however a particulate reduction of 40% associated with RD compared to diesel. To date, challenges here include fuel availability, limited domestic production, and higher fuel costs.

- **Hydrogen fuel**, also long seen as a true "fuel of the future," has so far not become a commercial option. 95% of the hydrogen made today is produced by splitting hydrogen atoms from natural gas (CH4), in an energy-intensive process called steam methane reforming.[14] Just 5% is made by splitting hydrogen atoms from water (H2O) using renewable energy. While 22 hydrogen refuse trucks are being demonstrated in Europe, there are none presently in the US, although several companies are innovating in this arena, especially in California (see Case Studies).

**Four other technologies and fuels analyzed in this report offer moderate improvements over diesel.** Two of them, diesel hybrid-electric and hydraulic hybrids, seemed to have some real promise when they were launched, but they have not lived up to that potential of greatly increasing the efficiency of fuel use. A third, biodiesel, cuts reliance on petroleum diesel by 5-20% on average, but is more of a stopgap solution that offers short-term benefits. And fourth, dimethyl ether (DME) has promising characteristics, but to date, its adoption has been severely limited due to minimal production capacity and a general lack of vehicles equipped to use it. For these reasons, we do not consider DME to be a commercial option in the refuse sector today.

- **Hybrid-electric vehicles (HEVs)** have lost some of the excitement that they first attracted a decade ago, when they were introduced with the promise of greater fuel efficiency compensating for their higher cost. Hybrid refuse trucks emit fewer greenhouse gases than diesel vehicles, but they emit the same level of criteria pollutants. And while they cost approximately 20% more than diesel models, they offer only moderate fuel efficiency improvements (20-30%). Their market penetration in the refuse sector is unclear, but new technologies are emerging.

- **Hydraulic hybrids (HHVs)** also earned some acceptance in the refuse truck class, promising greater fuel efficiency and lower GHG emissions than diesel models. But they have not performed as well as hybrid electric trucks, and their air emissions are the same as for diesel and hybrid electric. Their market penetration appears to have been hampered mainly by a fall in oil prices that slowed their adoption, to the degree that two major hydraulic systems suppliers stopped production.

- **Biodiesel**, used in conventional diesel trucks, is relatively inexpensive, widely available, and easy to use. When blended with fossil diesel, biodiesel cuts petroleum use by 5-20%. It produces no reduction in NOx emissions but cuts PM2.5 emissions by 40%. "First generation" biodiesel made from food crops, or from crops that could compete with food crops for land and water, does not constitute a long-term, sustainable option. It is a stopgap solution on route to the total replacement of petroleum-based diesel trucks. Biodiesel is also a useful fuel for achieving some level of emissions reduction in conventional diesel trucks up to their end of life, but it is not a choice that can enable a full switch away from diesel when buying a new truck today.

- **Dimethyl Ether (DME)** is a synthetic fuel alternative to diesel. It can be produced from biomass and methanol, but natural gas is the "feedstock of choice" in the US.[15] DME has been explored as an attractive substitute for diesel because it ignites relatively easily, has energy efficiency and power ratings similar to diesel, and its use generates no particulates. However, its limitations have hampered adoption. It has a relatively low energy density, requiring a larger tank than diesel. It also requires pressurization to remain a liquid, and necessitates the need for a specially built engine and fuel system. In 2017, the NYC Sanitation Department ran a short pilot on DME, but pursued the fuel no further. The sole US producer, Oberon Fuels, is demonstrating DME in California.

# Diesel Refuse Trucks: A Technology/Fuel Combination of the Past

## Lifecycle Emissions of Greenhouse Gases from Diesel-Fueled Refuse Trucks

The combustion of fossil fuels like petroleum diesel or gasoline releases significant amounts of carbon dioxide (CO2), a greenhouse gas (GHG) that traps heat in the atmosphere, contributing to climate change.

Based on industry estimates, the average refuse truck consumes approximately 9,000 gallons of diesel per year, which means that diesel-burning refuse trucks consume close to 1.4 billion gallons of fuel annually. Each gallon of diesel consumed generates approximately 22.4 pounds of CO2, according to the US Energy Information Administration.[16] So the average refuse truck generates about 179,000 pounds (89.5 tons) of CO2 per year. While this is a relatively small subset of the overall on-road sector, the challenges and opportunities that exist are indicative of the broader transportation sector, and all of these operations must be decarbonized.

*In discussing diesel fuel as well as alternative fuels, GHG impacts are framed in terms of "lifecycle analysis" – all of the emissions associated with a fuel, having to do with its extraction and production, its refining, its transportation to the vehicles using it and its combustion by those vehicles. (This is also called a "well-to-wheels" analysis.) When fuels are made from crops, the lifecycle analysis also includes land use impacts. For fuel comparisons, GHGs are quantified in grams of CO2 equivalent per mile traveled by the vehicle (gCO2e/mile).*

## The Air Pollution and Health Impacts of Diesel-Fueled Refuse Trucks

Because of their adverse impacts on both the climate and human health, this report looks at emissions of harmful compounds from the combustion of fuel in a vehicle, as well as from indirect sources like wear on tires and brakes.

While the diesel trucks of today are considerably cleaner than those of the early twenty first century, that is less about improvements in diesel fuel than about the addition of sophisticated "aftertreatment systems" which clean up the exhaust post-combustion. These systems include **diesel particulate filters (DPFs)** which, as the name suggests, filter particulates or soot from the exhaust stream[17]; **oxidation catalysts** which convert exhaust hydrocarbons and carbon monoxide to carbon dioxide and water[18]; and **selective catalytic reduction (SCR) mechanisms** that convert nitrogen oxides into nitrogen and, depending on the catalyst, water or CO2.[19]

Aftertreatment systems add considerable complexity and cost to the operation of diesel trucks. With selective catalytic reduction systems, improper introduction of the catalyst (often urea) can limit system efficiency and create deposits of unevaporated catalyst that cause backpressure in the exhaust system. DPFs require periodic "regeneration," or the combustion of accumulated soot to clean the filter. Raised exhaust temperatures in vehicles traveling at high speeds over distance can burn away the soot for a "passive regeneration," but this option isn't available to refuse trucks with their stop-start duty cycle. If (frequently automatic) "active regeneration" that injects a catalyst or fuel into the DPF doesn't do the job, a vehicle may have to be pulled off the road by the driver for a time-consuming "forced regeneration," with a risk of damage to the DPF or engine if the driver misses or ignores the dashboard indicator.[20,21,22,23] In short, post-combustion treatment of emissions, rather than their reduction or prevention through the use of cleaner fuels, creates costs and complications for maintenance crews and drivers alike.

The "criteria pollutants" described below are among the most common byproducts of diesel fuel combustion and the most damaging to human health.

**Nitrogen Oxides (NOx)**: "NOx" generally refers to nitric oxide (NO) and nitrogen dioxide (NO2), gases which are primary contributors to smog formation, acid rain, and ozone layer depletion. Short-term exposure to NOx can aggravate existing respiratory conditions, including asthma; longer-term exposure can cause asthma attacks and greater vulnerability to respiratory infections.

Combining NOx with moisture, ammonia or other chemical compounds found in air can form nitric acid, which can cause breathing to become difficult and damage lung tissue; it can also worsen existing heart conditions. People with respiratory conditions, children, and the elderly are at particular risk from NOx pollution.[24,25] The US Environmental Protection Agency (EPA) considers NOx to be a precursor to the formation of "secondary" fine particulate matter formed in the air through the chemical reaction of primary emissions or PM2.5; see below).[26]

**Particulate Matter 2.5 (PM2.5)**: PM2.5 is one of the most harmful air pollutants to human health. It refers to particles of pollutants in the air that are 2.5 microns or less in size. Molecules of this size are able to penetrate deeply into the respiratory system, aggravating existing heart and lung disease (potentially fatally), triggering irregular heartbeats and heart attacks, restricting lung function, worsening asthma and causing general breathing difficulties.[27]

High levels of exposure to small-particle air pollution have also been linked to impaired cognitive development in children, and to brain atrophy and memory decline in the elderly.[28] Particulate matter is estimated to account for 63% of deaths from "environmental causes" in the US, and about 95% of air pollution health impacts globally.[29]

While PM2.5 is one of the most harmful air pollutants to human health, it has also been among the most difficult to study.[30] Unlike CO2 or NOx, PM is a catch-all term for a diverse set of liquid and solid compounds produced by many different vehicle processes.[31] As such, rates of PM emissions from heavy-duty engines vary across model year, engine mileage, and emissions control system, not to mention across speed and load within a single vehicle's duty cycle. Very little research has been published addressing the interaction of these factors and how they impact PM emissions from refuse collection vehicles. However, research is beginning to show that many low-carbon fuel alternatives suitable for heavy-duty vocational vehicles also provide consistent reductions in particulate matter emissions when compared to petroleum diesel.[32]

In general, lower-income communities of color in urban areas are far more likely to be exposed to all of these pollutants, as they are more likely to be living or working in areas with high levels of heavy-duty (diesel) vehicle traffic – near warehouses, heavy-duty vehicle depots, landfills, transfer stations, commercial and industrial zones, and highways.[33]

Public health officials have long been in agreement on the damage done by diesel emissions. Dr. Philip J. Landrigan, a global expert on children's health at Boston University, put it most succinctly:

> *"Diesel exhaust is nasty stuff. It's a complex mix of gases and particulates, potent respiratory irritants and metabolic toxins. These include proven human carcinogens such as formaldehyde and soot. Exposure to diesel exhaust leads to more asthma, more respiratory tract infections, more missed school days for children, and more heart attacks and lung disease for adults. Recent studies have linked it to chronic kidney disease, diabetes and preterm births for pregnant women. One new study posits an increased risk for Alzheimer's disease. These chemicals waft through the urban air and make us all sick. There is no place in our environment with children and other living things for diesel. Getting rid of it is the right thing to do."*[34]
>
> — **Dr. Philip J. Landrigan**

## Introduction to Alternative Fuels and Technologies

### Biodiesel

Biodiesel was first introduced in the 1970's to reduce U.S. dependence on foreign oil. It is most often produced from vegetable or seed oils or animal fats through a process called "transesterification."[35],[36] This produces a liquid fuel that is commonly mixed with petroleum diesel in a "biodiesel blend" generally containing 5-20% biodiesel.[37] 100% biodiesel is rarely used, as the manufacturing process introduces oxygen into the fuel, making it prone to freezing, separation during storage and even algae growth.[38] (Even blends above B5 – e.g. B20 – are more susceptible to freezing and "gelling."[39])

Biodiesel and other biofuels are often referred to by "generation." "First generation" biofuels are commonly made with oils from food crops such as canola, palm, and (most commonly in the US) soy.[40],[41] Concerns about negative impacts on food prices, production, and land and water use – "food vs. fuel" – led to "second generation" biofuels, marked by use of tougher-to-break down "lignocellulosic" biomass, like non-food crops (often grown on poor-quality land), agricultural residues (stems, husks, leaves), and wood, as well as feedstocks like food waste and cooking oil.[42],[43] Biofuels made from engineered crops – specifically algae – are commonly called "third generation."[44]

In its infancy, biodiesel was criticized for being corrosive of certain engine parts, particularly polymers, and for clogging injectors or filters.[45] More recently, the National Biodiesel Board has claimed that roughly 90% of medium- and heavy-duty truck manufacturers approve the use of up to B20 in their engines, and all approve B5 blends under factory warranty.[46] Biodiesel blends are now in such widespread use that American Society for Testing and Materials (ASTM) International specifications for conventional diesel allow for up to a 5% blend without separate labeling.[47]

### Renewable Diesel

Renewable diesel (RD) is a cousin to traditional biodiesel, most commonly made by reacting the same kinds of feedstocks[48] with hydrogen instead of with alcohols ("hydrotreating"). RD has the same chemical structure as petroleum diesel, and can be used in diesel engines with no blending required,[49] making it a "drop-in" diesel substitute. Producers maintain that it lacks the corrosive and injector-plugging qualities attributed to biodiesel.[50] Containing no oxygen, it does not freeze or separate, and it also burns more cleanly; it is often described as a "second-generation biofuel."[51],[52]

Renewable diesel, which can be directly substituted for petroleum diesel without engine modifications, has generated considerable interest and has been well-reviewed by the municipal agencies piloting its use.[53],[54] However, it faces supply and cost hurdles (see discussion of "Cost & Practicality"). Renewable diesel is currently being used by refuse trucks in Oakland,[55] San Diego,[56] Sacramento, and New York City; after a successful pilot, the latter has issued an RFP for suppliers.[57],[58] (A case study released by New York City in July 2020 indicated that the adoption of renewable diesel, which is more expensive than conventional diesel, was being hampered by the lack of a low-carbon fuel standard in New York State,[59] which would create an economic incentive for low-carbon fuels.)

### Battery Electric

Battery electric vehicles show promise for two primary reasons: 1) for the efficiency of their power source; and 2) for eliminating tailpipe emissions of greenhouse gases and health-threatening pollutants. According to the US Department of Energy (US DOE), all-electric vehicles are more efficient than their fossil fuel counterparts, converting over 77% of their charge into power at the wheels, compared to 12-30% efficiency for vehicles powered by internal combustion engines.[60]

A battery electric vehicle (BEV) has no internal combustion engine; instead, electricity stored in an onboard battery pack powers an electric motor and its control systems.[61] The batteries used in BEVs are called "deep cycle," which means that they are designed to provide a steady supply of current over a long period of time, regularly using 80% or more of their charge.[62],[63] Depleted batteries in heavy vehicles are recharged with grid electricity from a dedicated charging unit.[64] Charge can also be maintained in

BEVs through regenerative braking, in which braking energy that would normally be lost as heat is returned to the battery as electricity.[65] The stop-start nature of refuse truck operations has been cited as making these vehicles ideal for electrification with regenerative braking.[66]

The weight of battery packs, however, can be an obstacle for BEVs in the heavy-duty sector. The heavier the vehicle, the larger the battery needs to be, which adds to the weight of the vehicle, creating a loop that requires weight reductions elsewhere or payload limitations that reduce the operational and economic viability of BEVs.

Battery electric refuse trucks have been sold by the California-based electric drivetrain manufacturer Motiv Power Systems[67],[68] to Chicago and Sacramento and by BYD, a Chinese producer, to Los Angeles, Palo Alto, and Seattle.[69],[70],[71] New York City's Department of Sanitation (DSNY) road-tested an electric model from Mack in the first quarter of 2020.[72] Additional demonstrations are underway across the country, from Boise, ID to Hickory, NC. Nonetheless, Energy Vision estimates that there are less than 50 battery electric refuse trucks operating in the United States and Canada as of summer 2021, making this still an experimental technology with limited real-world operational data. A number of economic and environmental obstacles to adoption of heavy-duty BEV trucks are discussed elsewhere in this report.

## Diesel Hybrid

Hybrid vehicle technologies come in three main forms. While they don't involve a fuel switch away from diesel,[73] their benefit is to effectively cut emissions by extending the range of each gallon of fuel by storing/using otherwise wasted energy. The adoption of hybrid technologies in refuse trucks by manufacturers and customers has been broad enough to lead to its inclusion here.[74] However, the penetration of the refuse market by these vehicles is unclear.

A **hybrid electric vehicle (HEV)** combines a conventional fossil-fuel (typically gasoline or diesel) internal combustion engine with the electric motor of a battery electric vehicle (hybrid vehicle drivetrain).[75] Generally speaking, at low speeds the vehicle runs on the electric motor. When cruising at higher speeds, the vehicle switches over to the internal combustion engine. During heavy acceleration, both systems work together to maximize the power going to the wheels.[76]

"Conventional" or "grid independent" hybrids use regenerative braking technology to recharge their batteries, and cannot be recharged externally. "Plug-in" hybrids (PHEVs) can be recharged using grid electricity.[77],[78] Argonne National Laboratory's AFLEET and GREET databases both omit plug-in hybrids as a heavy-duty vehicle technology, and they are not evaluated here, as heavy-duty PHEVs aren't a commercial option.

In **hydraulic hybrids (HHVs)**, rather than charging a battery, braking energy is used to pressurize a fluid kept in the reservoir of a hydraulic system. The kinetic energy stored in this pressurized fluid is then applied to one or more pumps or motors to aid acceleration by an internal combustion engine.[79] HHVs are more efficient at energy recovery than HEVs, and can improve fuel economy by 15-50%, depending on the configuration of the system. They also significantly extend brake life by 200-400% in certain applications.[80]

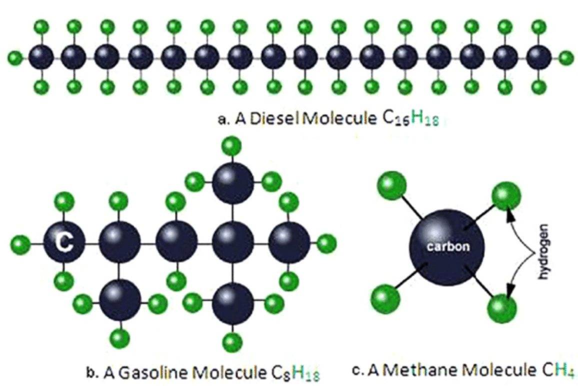
***Is it electric? Is it a hybrid?*** In their approach to hybrids, **Wrightspeed Powertrains** produces a battery-electric powertrain with a turbine for on-the-go recharging; the turbine can be fueled with diesel, CNG, LNG, liquid propane or RNG.[81] Wrightspeed has described its system as a "range-extended electric vehicle powertrain," which offers improved mileage and a 54% reduction in fuel consumption; however, the all-electric range for their refuse truck application is only 24 miles.[82] For that reason, this report places the system within hybrid technology, rather than battery-electric technology.[83]

In a recent variation on the supplemental electric drivetrain, Texas-based **Hyliion** provides a "brand and engine agnostic" after-market powertrain package for Class 8 tractor-trailers. Diesel, CNG or RNG in dedicated behind-cab storage fuels a generator that is installed alongside the engine. The generator charges batteries that power a motor, which provides additional power to the rear axles for hill-climbing and other high-demand activities. Because this system supplements a diesel or CNG engine, it too is considered a hybrid technology rather than a battery-electric technology, but initial testimonials have been quite positive and a number of high-profile fleets including Anheuser-Busch, Penske, Ryder, and Ruan have committed to piloting the technology.[84],[85] As of summer 2021, Energy Vision had not found any publicly available information indicating that Hyliion is looking at refuse truck applications for its technology.

**Efficiency improving technologies**: "Stop-start" technology – in which an electrical system takes over non-propulsion functions from the internal combustion engine during braking, and the engine re-engages when the brake is released – is also counted as a hybrid technology. Electricity generated by braking is stored and used to get the vehicle moving again.[86],[87] While such systems can significantly reduce emissions from vehicles that stop and start frequently, the vehicles aren't switching between propulsion systems, so we consider this an efficiency-improving technology and will not address it further in this report.

## Fossil Natural Gas

Natural gas vehicle engines were first developed in the 1980's to take advantage of a fuel that was significantly cleaner burning than gasoline or diesel at the time. The diesel molecule is a complex, long-chain hydrocarbon containing 16 carbon atoms and 34 hydrogen atoms. Fossil natural gas is composed primarily of methane (CH4, one carbon atom and four hydrogen atoms).




*Molecules of diesel, gasoline and methane*

Fossil natural gas is extracted from dedicated wells or recovered in conjunction with crude oil extraction.[88] It can be used as a vehicle fuel either in compressed (CNG) or liquid (LNG) form; both require fuel storage, delivery and ignition systems specifically built for a gaseous fuel. Natural gas can be used to displace gasoline or diesel fuel and emits fewer GHGs than petroleum-based fuels.[89]

Natural gas engines in use in the United States are adapted from existing diesel engine technology (not specifically designed from the ground up for a gaseous fuel), with some changes to the ignition and air-intake systems, although the valves are the same. According to some experts, this helps account for why particulate emissions from natural gas engines are not even lower.[90]

According to industry reports, there are nearly 18,000 natural gas-fueled refuse trucks in the US, and 60% of new refuse trucks ordered since 2017 have been natural gas models.[91] All new natural gas vehicles are now equipped with "near-zero" NOx natural gas engines, which significantly reduce health-threatening air pollutants. They reduce emissions of nitrogen oxides by 90% or more relative to the current Environmental Protection Agency standard for these pollutants (see endnote for explanation of EPA standard). [92] Similar to older natural gas vehicle technology, the newer "near zero" engines keep emissions of particulate matter at or below the EPA standard, and beat the Federal Phase 1 GHG emissions standards for heavy-duty engines by approximately 8%.[93] As noted earlier, natural gas engines can also be up to 50% quieter than trucks with diesel engines.

## Renewable Natural Gas (RNG)

RNG, also called biomethane, is chemically similar to fossil gas but is not a fossil fuel. Obtaining it requires no fracking or drilling. It is made from a renewable resource – from food wastes, agricultural manures, wastewater, and other sources organic material long-considered "waste."

The fuel is produced by capturing the methane-rich biogases that are released as organic materials decompose in oxygen-free environments; these gases can be captured from the wastes in landfills, or from organics that are put into airless tanks called anaerobic digesters. The biogases can then be "upgraded" by removing moisture, CO2, siloxanes, and other impurities. This process produces a pipeline-quality gas that is 95%-plus methane. Since it is then sufficiently pure, it can be used in all the ways that fossil natural gas is used today. It can be transported in natural gas pipelines, stored in the same tanks, and used to generate power, heat buildings or, arguably its highest and best use, propel heavy-duty vehicles.

RNG production has the climate benefit of trapping methane biogases that would otherwise escape into the air as potent GHGs, including from landfills — the third largest source of human-caused methane emissions in the US. Its other GHG benefit is that the fuel's use can then replace high-carbon diesel in heavy-duty trucks once they are equipped with commercially available natural gas engines. RNG use, like that of fossil natural gas, reduces particulate matter compared to diesel and reduces nitrogen oxide emissions by over 90% compared to the EPA standard when used in new natural gas engines (model year 2016 or newer).[94] It is a drop-in option for any vehicle with a natural gas engine, requiring no alteration to vehicles or dispensing equipment.

## Hydrogen Fuel Cells

Hydrogen has long been the holy grail of renewable technologies, for good reason, but it has been plagued with economic and technical challenges. Hydrogen (H2) is naturally abundant in water (H2O), methane (CH4) and other organic materials, but it takes a significant amount of energy to separate the strong bond within these molecules.[95] Today, more than 95% of hydrogen production in the US[96] is based on a process known as **steam-methane reforming**, in which natural gas molecules are blasted with steam to separate out the hydrogen atoms.

This is an energy-intensive process and produces significant lifecycle GHG emissions.[97,98] The production of "green" hydrogen by **electrolysis**, which uses electricity (generated from renewables) to split water into its components is now emerging, and would enable hydrogen to become both carbon-neutral and zero-emissions, although costs are still high and production capacity remains low.[99,100]

A hydrogen fuel cell, rather than using combustion, generates energy through an electrochemical reaction between hydrogen and a catalyzing agent;[101] the electrons released by the reaction create an electric current.[102] A fuel cell vehicle then works much like a BEV, and must periodically be refueled with hydrogen to maintain the electrochemical reaction. Byproducts of the reaction are water and heat.[103]

According to the US DOE, as of September 2021 there are 48 hydrogen fueling stations in the US; 47 are in California, and there is one in Hawaii.[104] In June 2020, DOE announced a 5-year, $100 million investment in hydrogen vehicle technology, focusing on the development of "large-scale, affordable electrolyzers," and heavy-duty fuel cell trucks.[105] However, DOE has also called hydrogen production by electrolysis suboptimal in many parts of the United States, given the high emissions generated by some regional electrical grids.[106]

In August 2020, private refuse hauler Republic Services signed a deal with Nikola Motor Company for 2,500 fuel-cell trucks, to be delivered starting in 2023 and with Republic participating in the design process. The deal was apparently met with some skepticism, as Nikola had "yet to deliver a volume production vehicle to date."[107] Since the announcement, Nikola has been accused of fraud, including that it faked product demos.[108] Shortly after the announced partnership, both entities agreed to discontinue the collaboration to develop and deploy fuel cell refuse trucks.[109]

Under two separate projects, 22 hydrogen-fueled refuse trucks have recently been piloted in 15 European cities, including a pilot in Glasgow, Scotland with Ballard Power Systems.[110] Engine manufacturer Cummins is contributing to the development of hydrogen refuse trucks there, providing fuel cell modules to multiple European truck manufacturers, and recently announced a similar effort in California.[111] In the US, a partnership between fuel cell truck manufacturer Hyzon and distributed hydrogen producer Raven SR was announced in April 2021. The two companies "plan to build 100 'hydrogen hubs' that will power fuel cell garbage trucks with hydrogen generated from the very refuse they haul."[112] The city of Anchorage, Alaska used DOE funding to purchase a Peterbilt 520EV fuel-cell electric refuse truck, which it expects to receive in 2021.[113]

While Energy Vision's research found that hydrogen-fueled refuse truck demonstrations had been funded in the US,[114] we found no information about such trucks in use on American roads as of December 2020. **Hydrogen technology should be watched closely in the coming years, but due to lack of commercial deployments in the U.S. refuse sector it will not be discussed further in this report**.

**TABLE 1: Estimated Market Penetration of Available Refuse Truck Technologies**

| Diesel | | | Natural Gas | | Electric |
|---|---|---|---|---|---|
| Ultra-Low Sulfur Diesel | Biodiesel (B5 or more) | Renewable Diesel | Fossil Natural Gas | Renewable Natural Gas | Battery Electric |
| ~160,000[298] | ~160,000[299] | ~2,000 | ~8,000 | ~10,000 | <50 |

### Dimethyl Ether

Dimethyl Ether (DME) is a synthetic alternative to diesel. It can be produced from biomass, methanol, or fossil fuels, with natural gas being the "feedstock of choice" in the US.[115] Producing DME is a multistage process, starting with production of a "synthesis gas" that is converted to methanol, which is then converted to DME.[116]

DME has been explored as an attractive substitute for diesel or propane because it ignites relatively easily and has energy efficiency and power ratings similar to diesel. Its chemical structure means that its combustion produces virtually no particulate matter, potentially eliminating the need for particulate filters. However, a relatively low energy density requires a larger tank than diesel, and DME, like propane, must be kept pressurized to remain in liquid form.[117] It also requires a purpose-built engine and fuel system, further complicating its adoption.[118,119]

After a 2017 trial by the New York City Department of Sanitation failed to produce a contract, DME proponent Volvo abandoned the fuel in the US market. The sole US producer, Oberon Fuels, refocused its efforts on its home state of California. In 2019, the company received a $2.9 million grant from the California Energy Commission to upgrade its existing plant from pilot to demonstration scale and to test DME in modified diesel trucks.[120] Legislation in 2020 aligned the taxes on DME with other alternative fuels (effective July 2021), for DME used as a diesel replacement or blended with propane.[121] However, **it does not represent a commercial alternative to diesel in the United States at this time and is not further addressed in this report**.

In commercial terms, only four alternatives to conventional diesel are viable choices today: biodiesel, renewable diesel, fossil natural gas, and renewable natural gas. Battery-powered and hydrogen are still in the pilot testing phase, but there are no hydrogren refuse trucks on the road today, as summarized in the table above.

## Comparing Impacts of Alternative Fuels on Climate, Public Health and Noise

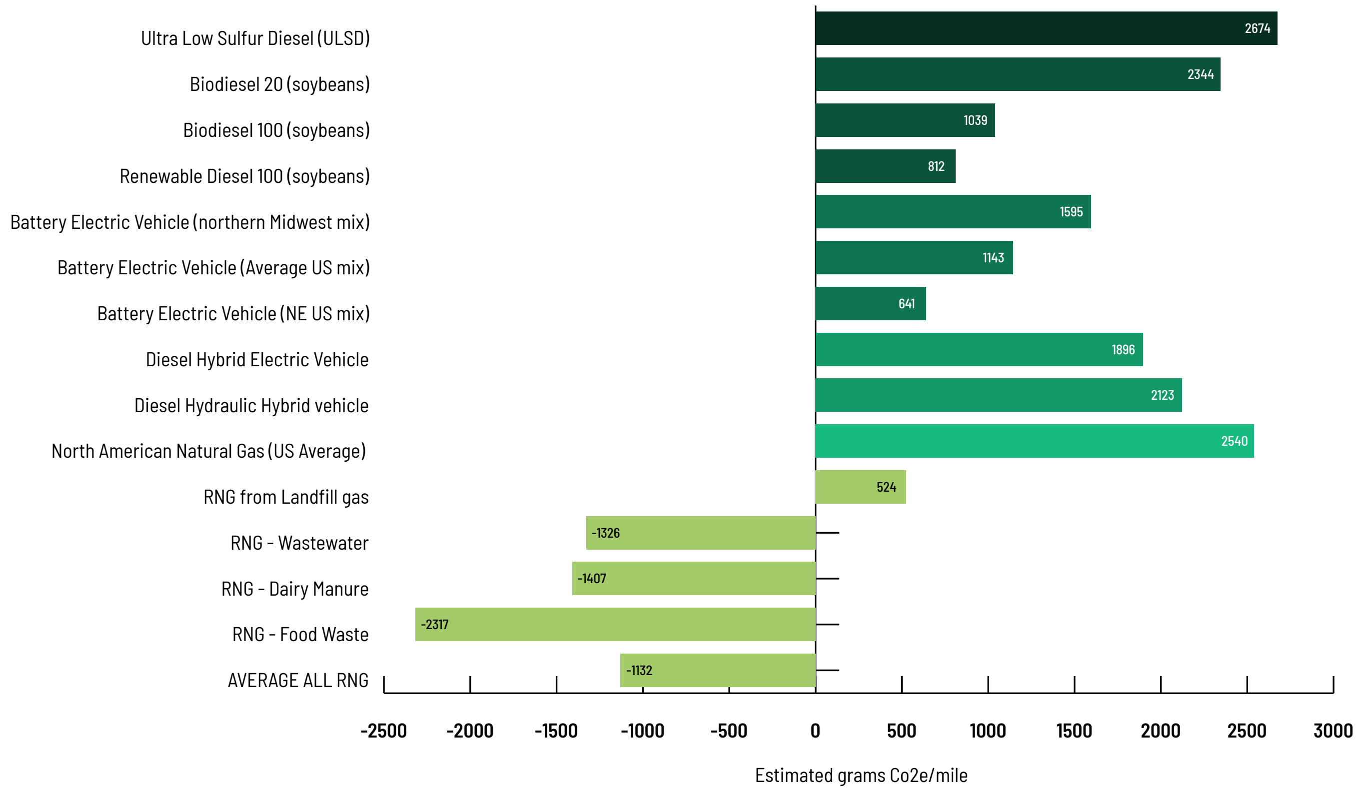
### The Lifecycle Greenhouse Gas Emissions of Alternative Fuels (Chart 1)

The range of GHG emissions for trucks burning alternative fuels compared to trucks burning ultra-low-sulfur diesel fuel is striking. Lifecycle GHG modeling is essential to assessing the total climate impacts (and benefits) of a particular fuel/technology combination. Emissions vary widely depending on the "feedstocks" and technology(s) used to produce a fuel.

Chart 1 (below) shows the lifecycle greenhouse gas emissions of 13 alternative fuels compared to ultra-low-sulfur petroleum diesel, based on the Argonne National Laboratory GREET model, the gold standard for assessing the combined climate impacts of a fuel's entire lifecycle. The comparisons are made on the basis of grams of CO2 equivalent (CO2e) emitted per mile traveled, and they take into account the emissions from all stages of a fuel's lifespan – including production, transportation, and consumption, as well as land-use impacts (if crops are the source of fuel production). Following the chart is a discussion of the factors considered in these fuel evaluations.

## CHART 1: Comparative Lifecycle Greenhouse Gas Emissions of Various Fuels

Grouped by Type




**Renewable Natural Gas (RNG)**: RNG made from four different feedstocks achieved by far the greatest greenhouse gas reductions. Using landfill gas results in an 80% reduction of emissions (CO2e). But organic wastes processed in anaerobic digesters from wastewater, dairy manure and food waste all achieve net-carbon-negative results – results achieved by no other fuel. According to Argonne GREET, the lowest emissions were attributed to food waste. (The California Air Resources Board, however, has attributed the greatest emissions reduction to RNG made from livestock manure in the "carbon intensity" tables[122] it developed to give credits to fuel producers selling low-carbon fuels in the state.)

*According to Argonne National Lab (ANL), average emissions for RNG made from different feedstocks (landfill gas, wastewater, animal manure and food waste), are approximately 150% lower than ULSD and 145% lower than fossil natural gas. ANL shows the greatest emissions reductions coming from RNG made from food waste, at 196% and 191% lower than ULSD and fossil natural gas, respectively.*

**Compressed Natural Gas (CNG)**: Compressed natural gas (CNG) in North America has lifecycle emissions just 5% lower than diesel, according to ANL GREET mainly because of the emissions related to fracking. Natural gas also has a lower energy content than diesel, meaning that traveling the same mile requires more fuel; if the two fuels are compared on the basis of emissions per unit of energy, natural gas has about 19% lower emissions.

**Battery Electric (BEV)**: An operating BEV has no tailpipe emissions. However, its lifecycle emissions depend on the fuel powering the electric grid charging its batteries. In the US, this often includes natural gas and coal. The above chart provides three examples: Battery electric vehicles charged on an upper Midwest grid (which uses 43% coal) have lifecycle GHG emissions that are about 40% lower than petroleum diesel; those charged on an "average US mix" (which uses nearly 25% coal) have emissions 57% lower than diesel; and vehicles using a Northeastern grid (which relies less than 3% on coal and much more on natural gas, nuclear and hydroelectric power) have lifecycle emissions that are 76% lower.

**Renewable Diesel**: The chart includes emissions for RD made from soybeans, the most common oil crop, although RD can also be made from switchgrass; other cellulosic materials like crop residues, wood and sawdust; agricultural waste; and rendered animal fats.[123] It evaluates RD made with no blending ("R100"), which has 70% lower GHG emissions than diesel, according to ANL GREET.

**Two types of Biodiesel**: The chart compares the emissions of vehicles using 100% biodiesel (B100) and 20% biodiesel (B20). Both are made from soybeans, the most common US feedstock for biodiesel. According to ANL GREET, B100, which totally replaces petroleum diesel, achieves a 61% reduction compared to diesel. (B100 is rarely used in practice, as it requires a later-model engine with biodiesel-compatible parts to avoid degradation of some engine components;[124] as discussed above, it is also subject to gelling, freezing, and separation.) B20, one of the most common blends (20% biodiesel and 80% petroleum diesel) achieves a 12.3% reduction in GHGs.[125]

**Hybrid-Electric**: Grid-independent hybrid diesel-electric refuse vehicles have about 29% lower emissions than ULSD, according to ANL GREET 2020. As noted above, hybrid technology extends the range of a gallon of fuel, so that these emissions represent a greater distance traveled – approximately 20% greater, compared to diesel.[126]

According to Argonne National Laboratory, the local electric grid impacts multiple aspects of a vehicle's total lifecycle emissions, even if its batteries are not being charged from that grid;[127] however, based on GREET, these variations for grid-independent hybrid electrics come in at less than 1%, and Chart 1 shows only the average US mix.

**Hydraulic Hybrid**: Hydraulic hybrid vehicles (HHVs) have GHG emissions that are almost 21% lower than diesel, according to GREET 2020. Argonne estimates that HHVs get approximately 21% greater fuel economy than diesel vehicles, although HHV drivetrain manufacturer Parker Hannifin claimed up to 43% (see Case Studies).

## The Emissions of Criteria Pollutants: Nitrogen Oxides and Particulate Matter (Chart 2)

Battery Electric Vehicles emit no NOx emissions at all, while vehicles using fossil or renewable natural gas cut NOx by 90% or more. (Please see endnote 89 for an explanation of the EPA's current NOx standard.) NOx tailpipe emissions for chemically similar conventional ultra-low-sulfur diesel, biodiesel, renewable diesel, and hybrid technologies using diesel fuel all came in at the same level.

## Particulate matter, 2.5 microns or smaller (PM2.5)

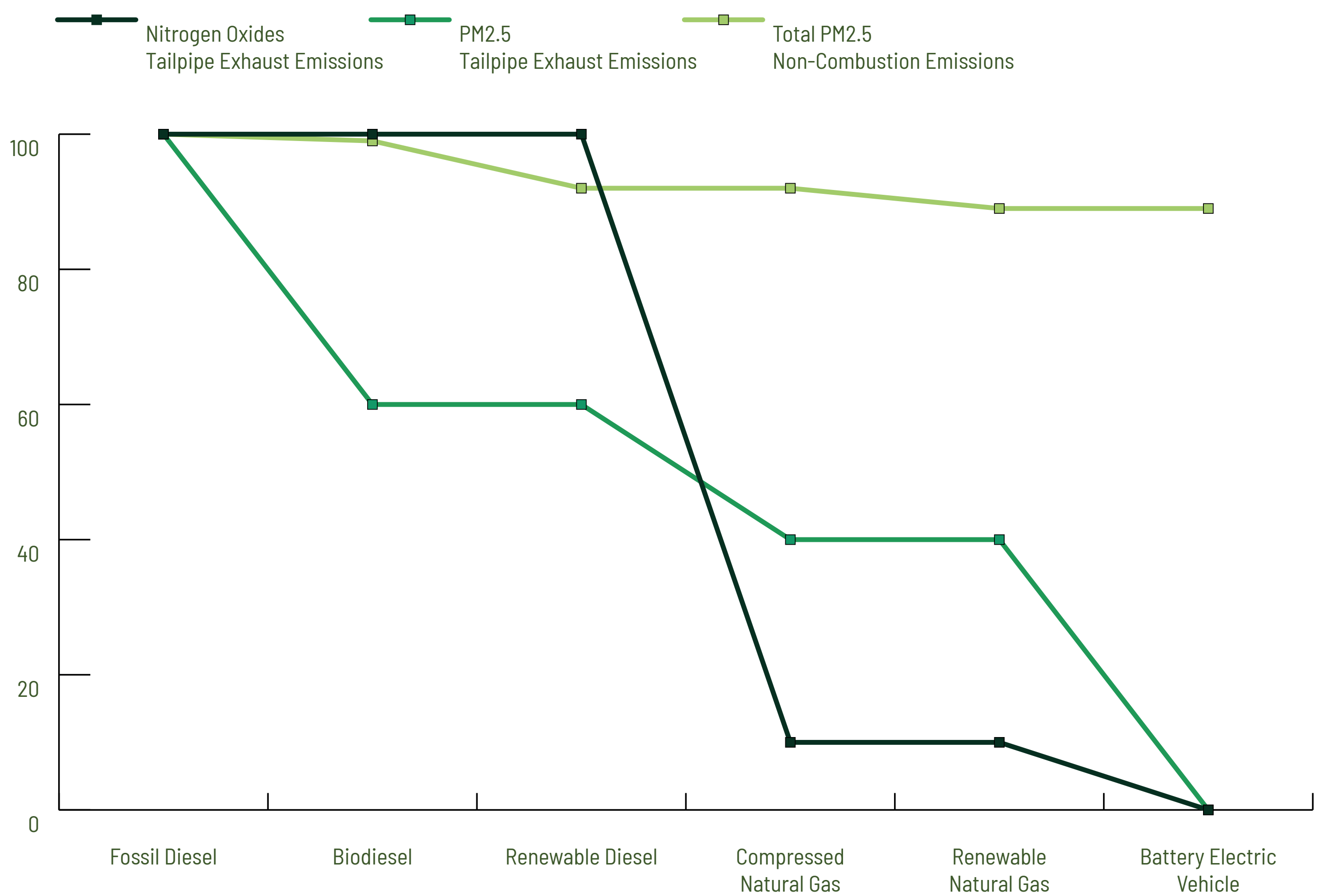
PM2.5 is known to have serious life-shortening impacts on human health, but there is a lot we do not understand about its behavior in heavy-duty refuse trucks.[128] Fuel, technology, vehicle weight, model year, engine mileage, maintenance compliance, payload, speed, outdoor temperature, and emissions control system all impact rates of PM emissions. Little work has been published addressing the interaction of these factors and how they impact PM emissions from refuse collection vehicles.

However, research is beginning to show that many low-carbon fuel technologies suitable for heavy-duty vocational vehicles provide consistent reductions in particulate matter emissions when compared to petroleum diesel.[129] This report looks at particulate matter related to combustion and to non-combustion emissions (Chart 2).[130]

## Combustion-related PM2.5:

With no tailpipe, battery electric vehicles have zero exhaust emissions. Combustion of natural gas (primarily CH4), whether from a fossil or organic waste source, produces little-to-no particulate matter; PM2.5 emissions from natural gas engines come primarily from lubricating oil burned in the combustion chamber.[131] PM2.5 emissions from natural gas refuse truck engines consistently come in lower than emissions from their diesel counterparts, about 0.01 grams of PM2.5 every mile.[132] This is 60% lower than a modern diesel engine with industry-standard emissions controls systems.[133]

**CHART 2: Emissions from Alternative Fuels as a Percentage of Average Ultra-Low-Sulfur Diesel Exhaust (Source: ANL GREET 2020)**




That reduction can have significant health benefits: based on data released by the EPA, we calculate that replacing just five diesel refuse trucks with natural gas-fueled vehicles would prevent one case of acute respiratory illness in the communities they serve, from the avoided PM2.5 alone.[134]

Biodiesel burned in a traditional heavy-duty diesel engine also seems to provide measurable reductions in PM emissions. Biodiesels tend to have a higher oxygen content than fossil or renewable diesel and burn more completely, and thus avoid releasing unburned particles of fuel into the atmosphere.[135] However, most heavy-duty engine manufacturers only approve low-biodiesel blends in their engines – 5% or 20% at the most.[136] This significantly mitigates the PM reduction benefits of using the bio-based fuel. A B20 blend in a diesel engine will see average PM reductions[137] around 40% less than traditional diesel.[138] Renewable diesel also reduces PM to a lesser degree, but unlike biodiesel, RD can be used in diesel engines unblended. All told, R100 also delivers a 40% reduction in PM on average, no better than B20.[139]

## Non-Combustion PM2.5:

Particulate matter is also produced by wear and tear on tires and brakes, and even the surface of the road during normal operation. In addition, trucks kick up dust as they pass and these "resuspended" particles are often included in total PM2.5 emissions inventories. Combustion-engine refuse trucks (diesel and natural gas alike) typically release around 0.08 grams of PM2.5 per mile from tires and brakes.[140] Road wear and resuspended dust are harder to measure, but these sources tend to produce about 5 times more PM2.5 than tire wear from the same vehicle.[141] Thus we estimate that an average fuel-powered refuse truck produces around 0.045 g PM2.5/mi.

The on-road operation of BEV's aren't truly zero emission. While battery electric vehicles have no tailpipe emissions, these vehicles do emit meaningful amounts of PM. Their heavy batteries are known to increase tire wear because the extra weight increases the friction between tire and road, and between brake pad and wheel.[142] Mounting evidence from studies on a diverse set of electric and combustion-engine vehicles shows that BEVs may in fact produce more dust and wear on tires and roads than their combustion engine cousins – enough that net reductions in PM2.5 compared to internal combustion vehicles may be negligible.[143] One study suggested that electric vehicles may generate up to 8% more PM than their conventional counterparts.[144]


*A Mack LR Electric truck. While the vehicle has no tailpipe, it does produce non-combustion emissions.*

## The Health Impacts of Noise Pollution

A common complaint about refuse collection trucks is noise – not just the noise of the compactor, but of the diesel engine itself. That noise can disturb communities during nighttime waste collection, and it can also damage the hearing of drivers or others who work with diesel trucks.[145] How much difference does an alternative fuel or drivetrain technology make? Information on noise levels of alternative technologies is actually limited. But diesel and renewable diesel produce similar noise levels while natural gas and renewable natural gas engines are up to 50% quieter, and battery electric vehicles are virtually free of engine noise.

**Battery Electric and Hybrid Electric**: At low speeds, electric and hybrid-electric vehicles almost completely eliminate engine noise (at lower speeds hybrids run on their electric motor), and the noise that the drivetrains produce doesn't travel like that from an internal combustion engine.[146] Until the vehicles are moving at about 20 miles per hour and generating tire and wind noise, they can actually be so quiet that they are potentially hazardous to unsuspecting pedestrians. Legislation that went into effect in fall 2019 requires such vehicles to make enough noise to enable "blind and other pedestrians to reasonably detect a nearby electric or hybrid vehicle"; however, that legislation does not apply to vehicles over 10,000 pounds, exempting refuse trucks.[147]

**Natural Gas**: Trucks running on CNG are regularly described as much quieter than diesel vehicles. A US DOE Clean Cities report on CNG refuse trucks specifically references a fleet conversion by Illinois hauler Groot Industries that was made in part to achieve noise reductions.[148] According to truck maker Freightliner, natural gas engines run up to 10 decibels (dB) quieter than their diesel counterparts.[149] The same noise reduction is cited by fueling station operators,[150] and according to ANL's AFLEET tool, a CNG refuse truck produces between 5 and 12 decibels less noise, depending on the listener's position relative to the truck.[151]

Since decibels are measured on a logarithmic scale, the difference of 10dB can actually mean a 50% noise reduction; 60dB is considered half as loud as 70dB.[152] Having essentially the same characteristics as conventional natural gas, and being used in the same vehicle engines, RNG runs just as quietly as its fossil counterpart.

**Renewable Diesel (RD)**: The largest producer of renewable diesel in the world (Neste) states that use of RD does not increase noise levels relative to conventional diesel fuel, but also that the high cetane number of RD "ensures quicker cold starts, less noise and better throttle response."[153]

According to the fleet manager for the City of Oakland, which uses RD in its fleets, there is no noticeable noise difference between RD and conventional diesel.[154] Similarly, the director of fleet services for Knoxville Tennessee, which tested RD, said that truck crews reported less eye irritation and coughing (their duties required time outside the cab and exposure to exhaust), but did not mention noise reductions.[155]

**Hydraulic Hybrid**: It is unclear from a literature re-


*A driver refueling at a biodiesel station in India. A drop-in substitute, biodiesel achives moderate GHG/PM reductions.*

view what the noise impacts of hydraulic hybrid technology are. Articles written or updated in 2004, 2014 and 2020 describe noise as "a technical challenge" for HHVs.[156] However, a 2011 article quotes a refuse truck driver in Miami Dade County describing his new HHV as "a whole lot quieter" than what he was used to driving.[157]

## Comparing the Impacts of Alternative Fuels Related to Their Fuel Extraction & Production

### Renewable Natural Gas

RNG is not a fossil fuel and therefore avoids the potential impacts related to fracking or other forms of drilling. Instead of generating waste or pollution, its production can transform organic wastes into a feedstock for making two products that are essential for sustainable economies: RNG and nutrient-rich effluent (see next page).

The methane gases emitted by organic materials are captured and put to use, rather than being left to rise into the air as potent climate warmers. They are 50-60% methane, but when they are refined by removing moisture, $CO_2$, siloxanes, and other impurities, the result is a pipeline-quality gas that is 95%-plus methane. It is sufficiently pure and similar to fossil natural gas that it can be distributed via the existing gas grid and can be used in all the same applications as fossil gas.

Based on ANL GREET, RNG's lifecycle GHG emissions – taking into account all aspects of production, transport and combustion – range from 80% lower than diesel fuel to significantly carbon negative. This reflects the fact that RNG is capturing fugitive methane that is above ground and would – were it not captured – escape, whether from landfills, manure ponds or wastewater treatment processes. These above ground methane biogases account for nearly a third of all anthropogenic methane emissions in the US[158] and they must be captured to meet our climate commitments moving forward. (By contrast, fossil natural gas is extracted from deep underground and used or released into the air. Left underground, it would do no environmental harm.) The remaining biosolids – or "digestate" – left in anaerobic digesters after the gases are captured can be used as high-quality, nutrient-rich compost or liquid fertilizer which can enrich depleting soils.

As with fossil natural gas, there are downstream leakage concerns with RNG that are important to address. There may be leakage from the anaerobic digesters where organic wastes are processed or from the pipeline networks that are used to transport RNG. But like fossil natural gas, there is a direct economic incentive with major climate benefits to minimize leakage throughout the system – from production to end-use.

## Biodiesel and Renewable Diesel

The US EPA sees biofuel production potentially causing "changes to land use patterns that may increase GHG emissions, pressure on water resources, air and water pollution, and increased food costs."[159] Biofuels are often referred to in terms of "generations," based on the feedstocks from which they're made. "First generation" biofuels are commonly made using food crops such as canola, palm, and soy. Concerns about negative impacts on food prices, production, and land use – "food vs. fuel" – led to "second generation" biodiesels, made from non-food crops (often grown on poor-quality land), agricultural residues (stems, husks, leaves) and wood, as well as feedstocks like food waste and cooking oil.

A 2016 report by the UN Food and Agriculture Organization (FAO) expressed concern about a lack of coordination between different policy areas that touch on biofuels: agriculture, energy, transport, environment, and trade. The report saw production of biofuel feedstocks competing with food production, leading to food insecurity and volatile prices. Noting that biofuel production economics are a function of oil prices, the report also highlighted the potential for volatility in energy markets to be "transmitted to agricultural markets and on to food prices."[160]

Biodiesel groups have countered that the soybean oil that is the main source of the fuel in the US is just a byproduct of producing soybeans for food, and does not lead to food crops being sacrificed for fuel.[161] The industry also argues that biodiesel creates a market for animal and other fats that were once waste products.[162] A past industry position that biodiesel helped keep food prices down by creating an additional market for soybean oil[163] seems to have fallen out of favor, as fuel use has been shown to drive the cost of soybeans up.[164]

## Battery Electric / Hybrid Vehicles

Labor, health, and pollution issues of concern are related to both the production and disposal of batteries. According to a study of passenger vehicles by the Union of Concerned Scientists, the material and energy requirements for manufacturing a battery electric vehicle are 15-68% higher than for manufacturing an internal combustion vehicle. However, the report concluded that the higher vehicle "manufacturing emissions are offset within 6 to 16 months of normal driving," depending on the source of the electricity charging the vehicle.[165] While Energy Vision was unable to identify similar studies specifically related to electric heavy-duty vehicles, it seems likely that even with larger battery requirements similar "paybacks" would apply, depending on the duty cycle of the vehicle.

*A large cobalt mining operation in the DRC, where geopolitics and labor practices are cause for concern.*

The batteries in BEVs and HEVs generally use lithium-ion technology, and include in their composition cobalt, graphite, manganese, and nickel.[166,167,168] Of these, cobalt is the least abundant, and over half of the world's supply comes from the Democratic

*A large "direct lithium mining" operation requires almost no water. To meet growing BEV demand, extraction of critical elements necessary for battery production is expected to grow exponentially. Minimizing the environmental impact(s) of these operations will be critical to ensuring that BEVs are a truly sustainable alternative for the refuse sector.*

Republic of Congo (DRC), where exploitative labor practices in mining have drawn international condemnation.[169,170] Amnesty International has reported children as young as seven "working in life-threatening conditions and subjected to violence, extortion and intimidation."[171] With up to 65% of the global supply coming from the DRC, concerns about over-centralization of supply, refining, and processing are also an issue for manufacturers.[172]

Another concern with hybrid and electric vehicles are rare earth metals, used in components like magnets that help turn electric drivetrains.[173,174,175] Once mined, rare earth metals must be separated from other minerals; this can require multiple applications of toxic chemicals, with residues being "dumped back into the environment."[176,177]

China has dominated rare earth metal markets for years, outproducing its nearest competitor, Australia, by a factor of six, and the third-place finisher, the United States, by a factor of eight.[178] Supply will likely fall and prices rise as China now focuses on cleaning up environmental damage and closing down illegal mines. It has been proposed that countries including the US and Australia gear up their own rare-earth minerals production.[179,180]

However, one of the first large lithium mines in the US (Thacker Pass, NV) now applying for permits has been met with passionate opposition from environmentalists concerned with potential land-use and water impacts, as well as from Native Americans who consider the land sacred—highlighting early challenges associated with increased domestic production of elements critical to producing BEVs.[181]

Larger vehicle batteries bring specific end-of-life issues. According to the International Energy Agency, a boom in all-electric vehicles caused by countries trying to meet climate goals could mean that by 2030 there will be 140 million BEVs on the world's roads – and 11 million metric tons of lithium ion batteries to be dealt with.[182]

Recycling these batteries is also a critical environmental issue. Batteries that get damaged (as might happen in a landfill) can leak over 100 toxic gases;[183] ones that overheat and combust release poisonous fluoride gases.[184] Heavy metal leakage can pollute soil and water. As noted above, key ingredients like cobalt and lithium are hard to come by and have their own environmental consequences, making recycling all the more important.

Recycling technologies exist, and new ones are being developed, but significant hurdles remain – there are, for example, as many chemical formulations for batteries as there are manufacturers, making standardization difficult.

This challenge is birthing new startups, and car manufacturers are entering the space, prodded by anticipated government regulation; China and the EU already hold electric vehicle makers responsible for battery recycling,[185] although recycling rates in the EU may still be as low as 5%.[186] Improving that number may be hampered by the reluctance of car manufacturers to use recycled materials out of reliability concerns, even though lead-acid batteries are largely recycled.[187]


*Thacker Pass is home to a proposed open-pit lithium mine. Some conservation groups oppose the project.*

BEVs' large lithium ion batteries can be repurposed before being recycled. Such batteries retain significant charge capacity even if they're no longer suitable for vehicles, and so can be used in applications like powering streetlights or providing back up power for elevators or data centers.[188,189]

For hybrid-electric vehicles, the issues are similar but on a smaller scale. Batteries for HEVs are commonly nickel-metal hydride technology, although lithium ion batteries are also used.[190] Hybrid batteries are much smaller than those in all-electric vehicles; for passenger cars, a BEV battery can weigh up to 1,200 pounds, while an HEV battery may only be about 100 pounds.[191,192] Smaller HEV batteries do not contain the same amount of reclaimable resources, but there are rare earth elements and valuable metals to be recovered,[193] and similar environmental and health hazards from landfill disposal, as with BEV batteries.[194,195]

## Compressed Natural Gas

**The Fracking Dilemma**. Production of conventional natural gas in the US has increased greatly with the widespread adoption of hydraulic fracturing, or "fracking." Fracked gas represented 67% of the US natural gas supply in 2015, according to the US Energy Information Administration.[196] However, fracking is a highly contentious issue that has affected the entire view of the benefits of fossil natural gas as a lower-carbon alternative to other fossil fuels. The technique involves drilling vertical "boreholes" that are then cased in cement and steel, often in combination with horizontal drilling deep underground.

High-pressure water, chemicals and a granular substance like sand are then injected into the gas wells to fracture rock formations, allowing oil and/or gas to escape.[197,198] 60% of the water injected into the wells comes back up containing the chemicals as well as metals, radionuclides, and hydrocarbons which have to be disposed of or reused.

Innovations in horizontal drilling led to the increased use of fracking to extract oil and gas deposits held in shale formations ("shale gas"), putting the method in the public spotlight.[199,200] Fracking has been linked to contamination of drinking water,[201] increased release of methane into the atmosphere because of higher venting and more leakage than normal extraction,[202] and even earthquakes.[203] In 2014, New York State banned fracking,[204] a move praised by environmentalists. Their criticism was renewed, however, when New York continued to import fracked gas from Pennsylvania.[205,206,207]

Claims about water pollution have been attacked as parlaying what *could* happen into what *has hap-*


*A large "fracking" operation extracts oil and gas by blasting rock formations with a high-pressure mixture of water and chemicals. Like other mining/drilling operations, "fracking" can threaten human health and the local environment.*

*pened*, and for equating complaints about *possible* pollution with *proven incidents* of pollution.[208,209] A 2016 EPA study acknowledged that fracking operations could "impact drinking water resources under some circumstances,"[210] but did not draw conclusions on frequency or severity because of "data gaps."[211] However, resistance to fracking by many environmental and environmental justice groups has persisted across the country, citing water quality concerns, destruction of ecological formations and animal habitat, carving of roadways for heavy truck traffic, and trucking- and drilling-related pollution.[212]

The notion that increased emissions from fracking offset the climate advantages of using fossil natural gas instead of other fossil fuels has gained traction, as has the idea that the EPA's emissions estimates for natural gas leakage are too low.[213]

The Natural Resources Defense Council (NRDC) has called for both tighter regulation of natural gas extraction and gradually reducing dependence on the fuel.[214,215] The Environmental Defense Fund (EDF) calls for natural gas to be produced more responsibly and regulated at the state and federal levels.[216]

However, many other grassroots environmental organizations called for the complete prohibition of any fracking in New York State. Energy Vision's research concludes that leakage across natural gas systems is a legitimate and important concern.
Argonne GREET puts combined leakage and venting from shale gas recovery approximately 6.8% higher than from conventionally drilled gas.[217] Even so, GREET puts lifecycle GHG emissions for natural gas 5% below those of diesel fuel on a per-mile basis, and approximately 19% lower per unit of energy (MMBTU). The California Air Resources Board considers North American compressed natural gas to have emissions roughly 20% lower than diesel fuel per unit of energy.[218]

# Comparing the Practicality and Cost of Alternative Fuels & Case Studies

## Biodiesel

**Practicality**: As noted above, the use of biodiesel has become so standard that most vehicle manufacturers approve the use of B20 in the United States. It is an established fuel produced by a robust domestic industry. In 2018, 1.8 billion gallons of B100 was produced; in 2019, production fell off by about 7%, to 1.7 billion gallons, but regained ground to close 2020 at more than 1.8 billion gallons.[219] As noted above, the use of biodiesel has become so standard that most vehicle manufacturers have approved the use of B20 in their vehicles in the US.

**Cost**: There is no additional vehicle capital cost involved for biodiesel since these blends can be used in standard diesel engines. A B20 blend has 1-2% less energy content than petroleum diesel.[220] According to the US DOE's Alternative Fuels Data center, during 2020 the price of B20 closely shadowed that of conventional diesel, selling for between $0.06 and $0.20 less. As of late-summer 2021, B20 sold for $0.21 less than conventional diesel (based on the national average).[221]

### **Case Studies**:

**New York City**: New York City began piloting biodiesel in 2005. Today, its municipal fleets, which include over 1,200 diesel-fueled refuse trucks, use biodiesel extensively. Historically, they ran on B20 from April through November, before freezing and gelling were recognized as serious concerns, and B5 from December through March. However, blending B20 with "winterized fuels" containing kerosene was so successful that some parts of the fleet started using B20 year-round – 2 million gallons in the winters of 2017 and 2018.[222] As noted above, however, the City has successfully tested lower-emissions renewable diesel and plans to transition all of its diesel trucks to run on it.

**Madison, Wisconsin**: In October 2019, the City of Madison announced to residents that over the summer it had moved its entire diesel fleet to B20 biodiesel, making it the second city in Wisconsin to do so (after Milwaukee). Given Wisconsin's climate, the fleet will use B5 in the winter months, and revert to conventional diesel when the temperature approaches 0°F.[223]

## Renewable Diesel

**Practicality**: Renewable Diesel is a drop-in replacement for petroleum diesel made primarily from animal fat and other agricultural waste streams. Despite its potential to displace petroleum in refuse trucks, domestic supply remains limited. A significant portion of the renewable diesel used in the US is now imported, and domestic production remains regionally concentrated. Of 57 samples of RD referenced in the California Air Resources Board's Pathway Certified Carbon Intensities, 19 were imported, coming from Singapore (the majority), Finland, and Canada. Of the 38 samples produced domestically, 22 were from Louisiana, 10 were from California, and the remainder came from Kansas, Mississippi, North Dakota, Washington, and Wyoming.[224]

Neste, the world's largest producer of renewable diesel, produces a maximum of 21.3 million barrels per year (~895 million gallons) from facilities in Finland, The Netherlands and Singapore.[225] One market analysis sees US domestic RD production increasing from ~353 million gallons in 2018 to ~1 billion in 2020 and over 2.2 billion gallons in 2022.[226] By comparison, on-road diesel fuel consumption in the US in 2018 totaled more than 40 billion gallons.[227]

**Cost**: There is no additional vehicle capital cost involved in using RD, as it is a drop-in substitute for conventional diesel fuel. However, RD is typically more expensive to produce and the price of the fuel has varied widely. Its use to date has been largely limited to California. Under the state's Low Carbon Fuel Standard, support for production of renewable diesel means that it has been able to sell at a cost competitive to conventional diesel.[228]

In 2016, renewable diesel in Oregon sold for about the same as a B20 blend, a premium of $0.15 per gallon over standard diesel.[229] The Eugene Water and Electric Board in Oregon saw the price differential that it paid for RD spike to over $1/gallon in 2018 before falling to $0.19 in 2019, with the reduction attributed to the launch of Oregon's Clean Fuel Standard.[230]

However, for its 2017 trial of renewable diesel, the City of Knoxville, Tennessee was paying $2.80/gallon for RD, compared to $1.53 for conventional diesel – a 45% increase.[231] For New York's pilot of RD, the City was paying a premium of $1.50 per gallon over conventional diesel – again, about a 45% mark up.[232]

**Case Studies**:

**Turlock, California**: In 2018, Turlock Scavenger began switching its fleet of refuse trucks to renewable diesel. This waste collection and recycling company in central California serves the city of Turlock and Stanislaus County. The switch "was easy," according to the company's maintenance shop supervisor, and has brought improvements in engine performance, as well as fewer routine maintenance costs from a reduced need for after-filter replacement.[233]

*A portion of Turlock Scavenger's diesel refuse fleet, which has been using Renewable Diesel since 2015.*

**Oakland, California**: The City of Oakland was an early adopter of renewable diesel, switching over all 366 of its diesel vehicles, including refuse trucks, in 2015. Other than limited availability in some areas, the Oakland fleet manager maintained that the transition had "not a single downside." The Oakland fleet uses about 250,000 gallons of RD per year.[234]

## Battery Electric

The executive director of the California Transit Association has called electrification of heavy-duty vehicles – in reference to transit buses – a "complex and expensive proposition," given higher vehicle costs, infrastructure requirements, and the high and variable costs of power around the state.[235]

**Practicality**: Battery electric refuse truck options have been extremely limited and have received mixed reviews. Motiv Power Systems rollouts in Chicago and Los Angeles were plagued by troubles or delayed, while a successful test by Chinese producer BYD in Los Angeles was for a single, smaller Class 6 vehicle (see case studies below). A Class 8 BEV refuse truck delivered to Seattle waste contractor Recology in 2019 has performed well on light duty applications. Several additional BEV refuse truck demonstrations are in the early stages now (see case studies).

Battery electric vehicles must contend with a singular factor that does not affect other fuels in such a significant way: the size and weight of the energy source. The batteries used by heavy-duty BEVs are large and heavy, and become larger and heavier the more power the vehicle requires. This creates a sort of self-negating cycle: the more power required, the heavier the battery pack, requiring more power to compensate, which adds more weight to the battery pack, etc. This can lead to a crucial "trade-off between battery weight and payload" that may result in the need for additional vehicles to complete routes traditionally serviced by a single truck.[236]

**Cost**: Electric vehicles are considerably more expensive than their diesel counterparts. Argonne's AFLEET tool puts the cost of a BEV refuse truck 66% higher than that of diesel model— $500,000 as opposed to $300,000.[237]

A municipal fleet using electric refuse trucks would also need to install appropriate charging infrastructure. The kind of direct current (DC) fast-charge point appropriate for a Class 8 refuse truck can run an estimated $25,000 or more per charging station.[238] The additional on-site electricity requirements are significant, and may require additional generating capacity; one study found that a "representative utility, depending on charging patterns, will need to invest between $1,700 and $5,800 in grid upgrades per electric vehicle through 2030", going on to note that most of this cost would be passed on to the utility's customer base.[239]

While the cost of charging electric vehicles is dependent on the price of grid electricity, it remains low overall, once the necessary infrastructure has been developed. For instance, a BYD Class 8 refuse truck of the type delivered to Seattle in 2019 has a maximum battery capacity of 435 kWh, and a range of about 145 miles.[240] If the batteries are drawn down by 80% between charges, each recharge is roughly 350 kWh. If the vehicle is recharged at night by an entity paying a commercial rate for electricity, such a charge would cost approximately $22.61 in Seattle as of September 2021.[241] Based on the 145-mile range, the fueling cost is about $0.156 (15.6 cents) per mile.

**Case Studies**:

**Motiv Power Systems, Chicago**. In 2014, Motiv Power Systems delivered an electric refuse truck to the City of Chicago. The truck had a Crane Carrier chassis with a 200 kWh-capacity Motiv powertrain and a Loadmaster 20 rear-loader body.[242]

According to the manager of fleet services, the truck's trial was trouble-plagued from the start. Initially attributed to cold weather, problems continued into summer. Issues with the hydraulics, battery and brakes ultimately led to it being pulled off the road. The truck did about 20 days total service over two years, and now sits unused in a maintenance depot; the city is seeking a financial remedy from Motiv. The experience has soured the entire conversation about electric heavy-duty vehicles in Chicago. The 526 trucks in the refuse fleet are almost exclusively diesel, with a small CNG contingent of seven vehicles.[243]

**Motiv Power Systems, Los Angeles Sanitation Department (LASAN)**: In a press release on October 9, 2017, Motiv Power Systems announced the pending delivery to LASAN of two Class 8 (heavy-duty) refuse trucks based on its electric powertrain and a Crane chassis. In September 2018, a LASAN official told Energy Vision that the trucks had not yet been delivered and that the project was experiencing "some delay."[244]

In May 2020, a Motiv representative told Energy Vision that that the company had ultimately canceled the LASAN deal when a partner providing refuse-truck-specific parts went out of business. After re-evaluating the market's potential and the challenges specific to refuse trucks, the company has moved away from the sector and shifted its focus to vehicles in Classes 4-6.[245]

**BYD, LASAN**: In January 2017, LASAN started a four-month trial of a Class 6 (medium-duty) battery-electric refuse truck developed by BYD and refuse-industry equipment manufacturer Wayne Engineering. (It is estimated that Class 6 trucks represent about one third of the roughly 180,000 refuse trucks in service daily in the US.)[246] The demonstration vehicle drove an average of 99 miles per day and clocked 5,200 miles "with no major mechanical or performance issues."[247,248] A LASAN official confirmed by email that "the test was successful," and referred further inquiries to BYD.[249] It is unclear whether LASAN intends to purchase more BEV trucks.


*Recology ordered two BYD Class-8 trucks in 2018 for its Seattle operations. They appear to be performing well.*

**BYD, Seattle**: Seattle waste-hauling contractor Recology took delivery of a BYD Class 8 electric refuse truck in summer 2019, and took delivery of a second vehicle in 2020. According to the city's manager of solid waste contracts, the BYD truck has performed well so far, although that is based on relatively light duty usage. The unit is not running a full shift, and is only being used on lighter, shorter and less-hilly routes; this is not because of any problems, but rather Recology's "comfort level" in using the truck. The official also noted that, because of the extra space required for the unit's large batteries, the payload capacity appears to be slightly smaller than for comparable diesel or CNG models.

The Seattle official acknowledged that the refuse collection application is challenging for electric vehicles, and did not foresee a rush to transform the fleet to electric any time soon. Currently, Seattle's contracted fleet is about 50% trucks running on RNG (from Waste Management), and about 45% on renewable diesel (from Recology). As vehicles are retired there may be an opportunity to further electrify, but the official expects a slow transition.[250]

**Mack, New York City**: New York City's Sanitation Department (DSNY) ran a Mack electric refuse truck through a six-hour road test in the first quarter of 2020. The vehicle was returned to Mack on the grounds that the two-hour charging window it required was too long; DSNY refuse trucks are also responsible for snow-plowing, and during snow events they may be out for 12 hours at a time. Mack agreed to return the vehicle to DSNY with a larger battery for further testing,[251,252] and DSNY received the new "LR Electric" truck for "rigorous, real world trials" in September 2020.[253] In June 2021 Mack announced that DSNY had ordered seven more of the trucks.[254]


*In 2020, DSNY piloted a Mack LR Electric truck. In 2021, the agency ordered seven more BEV refuse trucks.*

**Mack, Republic Services, North Carolina**: In October 2020, Mack also delivered a pre-production LR Electric model to private waste hauler Republic Services, for testing on a residential route in Hickory, North Carolina.[255] The results of this demonstration have not yet been made public.

## Hybrid Electric

**Practicality**: It is unclear whether the higher costs can be justified based on fuel savings and performance over the life of a hybrid electric refuse truck. Like battery electric models, hybrid electric refuse trucks have had problematic rollouts, as highlighted in the brief case studies below.

**Cost**: Hybrid electric trucks tested by DSNY beginning in 2009 were twice as expensive as a diesel truck, at $500,000 compared to $300,000. A 30% reduction in fuel costs and federal subsidies were expected to bridge the gap.[256] The price gap has narrowed since then, and the AFLEET 2020 tool puts the price of a hybrid electric refuse truck at $350,000, compared to $300,000 for a diesel model – approximately 14% higher.[257]

**Case Studies:**

**DSNY**: Between 2009 and 2011, DSNY tested eight diesel-electric hybrid refuse trucks, five from Mack and three from Crane Carrier; the Crane vehicles were built around a BAE powertrain. All tested satisfactorily for general performance, but neither model achieved the promised fuel efficiency. Meanwhile, diesel prices had fallen from a peak of over $4.50/gallon,[258] weakening the case for the hybrid vehicles. The prototype vehicles were returned after the trials, with no orders placed. A 2017 Department of Citywide Administrative Services fact sheet indicated that DSNY had 32 diesel hybrid flatbeds but no diesel hybrid refuse trucks.[259]

**Private waste hauler, Bay Area**: In November 2016, Wrightspeed and California hauler The Ratto Group announced that over the following 12 months, Ratto would put 15 or more refuse trucks built on Wrightspeed's extended-range electric technology on the road.[260] In January 2017, The Ratto Group announced its sale to local competitor Recology.[261] By summer 2018, Recology had abandoned the deal on the grounds that a pilot vehicle that had been in development for Ratto was long overdue.[262] (Reflecting these early challenges, in a May 2021 article a Wrightspeed executive was quoted as saying that the company has recently been keeping a low profile while "getting the product ready to go to market".[263])


*An early Wrightspeed hybrid-electric system prototype in 2016, using a Freightliner Condor truck chassis.*

## Hydraulic Hybrid

**Practicality**: It is unclear to date whether the higher costs can be justified based on fuel savings and performance over the life of a hydraulic hybrid refuse truck. DSNY tested the first generation of Bosch Rexroth's hydraulic hybrid drive, which went into production in late 2010.[264] According to a representative of DSNY's Bureau of Motor Equipment, there were multiple technical issues with the system. By the time these bugs were worked out, the price of diesel had fallen and the return-on-investment for the vehicles (about $100,000 more than a standard diesel vehicle at the time[265]) no longer worked; DSNY's main truck supplier gave up on the technology shortly thereafter.[266]

**Cost**: According to AFLEET 2020, a diesel hydraulic hybrid refuse truck costs $340,000 as opposed to $300,000 for a diesel model, a premium of roughly 12%.[267] It is worth noting here that DSNY's Bureau of Motor Equipment believes that hydraulic hybrids are simply no longer available in refuse models.[268]

**Case Studies**:

Parker Hannafin: As previously noted, the US EPA was closely involved in the development of hydraulic hybrids and had a cooperative relationship with manufacturer Parker Hannafin, which introduced its heavy-duty RunWise Hydraulic Hybrid Drive system in 2010.[269] According to the HHV technologies contact at EPA's Office of Transportation and Air Quality, while HHVs did gain traction – including in the refuse sector – they were hit hard by the aforementioned fall in the price of diesel, which was concurrent with more abundant and cheaper natural gas supplies.[270] Thus, while Parker Hannafin referred in a 2015 press release to more than 200 refuse trucks using 43% less fuel with the RunWise system,[271] in 2020 a company representative said in an email that they had ceased RunWise production "a few years ago,"[272] although the company still maintains its hydraulic products.

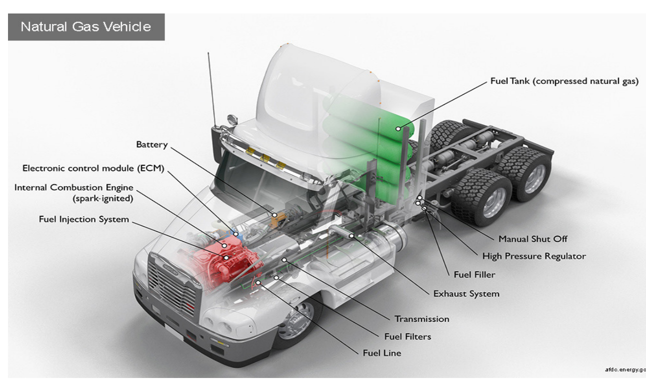
In another sign of the retreat of HHVs, in 2017 a Parker Hannifin competitor changed its name from Lightning Hybrids to Lightning Systems, and has since switched to converting "familiar commercial vehicle platforms" to electric drivetrains.[273] A background document on the company website attributes the move away from hydraulic hybrid systems to slow "market adoption."[274]

## Compressed Natural Gas (CNG)

**Practicality**: From the technology and deployment perspective, compressed natural gas refuse trucks have been a success, with approximately 8,000 CNG refuse trucks on the roads and half of the refuse trucks presently on order being for natural gas models. Recently, over 60% of new refuse truck sales have been natural gas models.[275]

**Cost**: According to AFLEET, the incremental cost of a CNG refuse truck is about $35,000 more than a diesel model: $335,000 as opposed to $300,000. However, the lower costs of vehicle maintenance and fuel has meant that this higher sales price is recovered during the lifespan of the trucks. Still, the cost for installation of a dedicated, time-fill CNG fueling station runs roughly $700,000, assuming 10 dual hose stations dispensing 440 to 700 diesel gallon equivalents (DGEs)/day. A comparable fast-fill station may exceed $1.5 million.[276]

According to the US DOE's Alternative Fuels Data Center, in July 2021 the average national retail cost of CNG was about 22% less than diesel fuel, on an energy equivalent basis.[277] But price volatility in the oil markets is always a factor; in spring 2020, oil prices slid dramatically, with the average price of ultra-low-sulfur diesel falling by an average of 17% nationwide from January to April.[278] As indicated by the hybrid case studies above, such price events can adversely impact the adoption of alternative technologies. Since then, diesel and gasoline prices have risen quickly due to global supply shortages.




*Typical components in a heavy-duty (Class 8) compressed natural gas (CNG) truck, including fuel storage.*

**Case Studies**:

**The City of Chicago**: Chicago's refuse fleet has seven natural gas refuse trucks. According to the manager of fleet services for Chicago, all are performing well. In 2018, he described an expansion of the CNG portion of the fleet as impractical, as Chicago's CNG refueling infrastructure was limited, dated to the 1990s, and had deteriorated at some locations. Nonetheless, a possible future outsourcing of the city's CNG fueling was seen as making such an expansion more realistic.[279,280]

In a follow-up conversation in 2020, the manager of fleet services said that the contemplated outsourcing had in fact happened, the City having reached an agreement with ready-mix concrete supplier and CNG station builder Ozinga. That agreement gave the City access to CNG fueling infrastructure at one of Ozinga's depots; with only one "reliable" CNG fueling station of its own, this effectively doubles the City's capacity. As a result of the arrangement, the manager of fleet services foresees buying additional CNG refuse trucks, and some CNG street sweepers, in the near future.[281]


*One of approximately 68 operation CNG collection trucks in the City of Milwaukee's municipal fleet. The vehicles have performed well, including to plow snow in the winter.*

**The City of Milwaukee**: In 2015, Milwaukee acquired 22 CNG refuse trucks, bringing the city's total up to 45 CNG trucks out of a fleet of 121. At approximately $271,000 a piece, each of those trucks costs $39,300 more than comparable diesel models. Milwaukee's director of fleet operations was quoted at the time as saying that he would like to convert the entire fleet, and as of 2020 the total number of CNG trucks has risen to 68 operational vehicles, with 11 additional chassis waiting installation of compactors. The trucks are used to plow snow in winter, and the two fueling stations that service them are open to the public.[282,283]

**The City of Chesapeake, Virginia**: Chesapeake has gone from 6 CNG refuse trucks in 2012 to 50 in 2019, and has one fast-fill and one time-fill fueling station to service them. It generates revenue by allowing other area CNG fleets to use the station.[284]

**WastePro**: This hauling company, which operates in 9 states in the southeastern US, had added over 300 CNG trucks to its fleet and built seven fueling stations for them as of late 2018.[285]

**Waste Management**: The country's largest waste hauler has over 8,900 natural gas trucks in its fleet of 17,000. Waste Management also operates 145 natural gas refueling stations, 25 of which are open to the public.[286]

**New York City's Department of Sanitation (DSNY)**: DSNY is the largest municipal refuse fleet in the country with a long history of piloting new technology. As of early 2021, DSNY had 39 CNG refuse trucks.[287] These vehicles all work well, including in their secondary – but critical – responsibility of plowing snow. However, DSNY has closed its one CNG-dispensing garage, citing its age, opting instead to rely on public-access refueling stations, which may limit the ultimate size of the CNG fleet.[288] An analysis by Energy Vision concluded that existing public access stations could provide fuel for several hundred additional natural gas refuse trucks.

## Renewable Natural Gas (RNG)

**Practicality**: RNG is nearly identical chemically to fossil CNG, and therefore can be used in any vehicle equipped with a natural gas engine. Its primary advantage is that the fuel is produced from the organic portion of the waste these trucks handle daily, providing a unique opportunity to implement a circular economic solution.

**Cost**: RNG from any source (landfills, wastewater, agricultural residues, food waste) is generally more expensive to produce than low-cost fossil natural gas. However, existing federal and state programs, namely the Renewable Fuel Standard and California's Low Carbon Fuel Standard, incentivize the production and use of low-carbon biofuels to such an extent that RNG is available at parity, or even at a discount, to fossil natural gas.

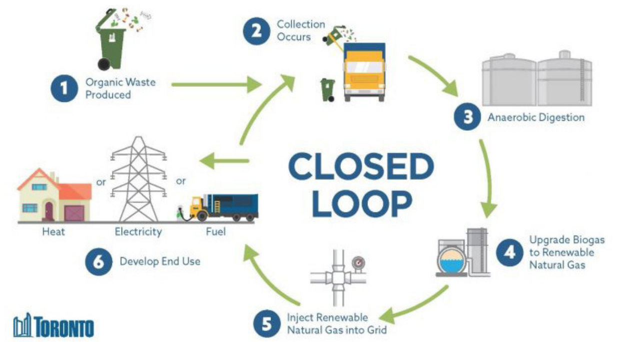
**Case Studies**:

**Waste Management**: Waste Management now operates more than half of its collection fleet – the largest in the US – on natural gas. Over a third of these natural gas trucks (3,500 out of 8,900) run on RNG fuel made from landfill gas.[289] The company also sells RNG produced at several of its own landfills to the market. All of its trucks in California, Oregon and Washington are RNG-fueled. Since much of the fuel for the Waste Management trucks is produced at the company's own landfills, the garbage collected daily in these vehicles is transformed into the fuel that powers them.[290]


*A Waste Management RNG truck in West Seattle.*

**Republic Services**: Republic, the second-largest private hauler operating throughout the United States, uses exclusively RNG in its fleet of natural gas vehicles (~3,100 trucks) across 21 states, buying gas that is often produced at its own landfills.[291] Republic began collaborating with Aria Energy, one of the country's largest developers of RNG from landfill gas, and BP, to develop projects. BP is marketing the gas, most of it to Clean Energy Fuels for use across its 500+ natural gas fueling stations.[292]

**CR&R**: Refuse hauler CR&R in Perris, California, converts the food waste that it collects for the city into RNG at a dedicated anaerobic digestion facility, and uses it to fuel some of its 900 trucks.[293] The company has plans to convert the entire fleet to natural gas and fuel all of its trucks on RNG. These trucks provide waste collection services to the City of Perris, California as well as to 40 other communi-




*The City of Toronto collects ~170,000 metric tons of "green bin" organics annually, which are processed in two municipally owned anaerobic digestion facilities. A portion of the RNG produced at these facilities will soon power natural gas vehicles that collect this material.*

ties in the L.A. Basin in southern California.

**Long Beach, California**: Long Beach currently fuels 77 vehicles, including 35 refuse trucks,[294] with RNG, and has said that it intends to convert all 98 of its refuse trucks and street sweepers to use RNG.[295]

**City of Toronto, Canada:** The City of Toronto (City) collects source-separated organic waste from residents and businesses and takes it to two municipally owned Organics Processing Facilities (OPF), (with anaerobic digestion). The City initiated a project commissioned in the fall of 2021 with Enbridge Gas Inc., whereby the biogas produced at its Dufferin OPF is upgraded to RNG and used to decarbonize its natural gas supply. Incorporating RNG into the mix will allow the City to create a low-carbon fuel blend that will not only be used to fuel City vehicles but also heat City facilities.

By creating a low-carbon RNG/NG fuel blend, a portion of Toronto's waste collection fleet, which now includes 145 natural gas refuse trucks out of 186, allows the City to lower the overall emissions of the solid waste collection fleet, Class 7 and 8 vehicles.

Toronto's ambitious climate action strategy, which includes converting its diesel waste collection fleet to RNG/NG, also includes short and long-term actions to meet the City's greenhouse gas reduction targets of 65 percent by 2030, and net zero by 2050, or sooner. Mayor John Tory recently announced plans to expand the City's digestion and RNG production capacity based on the success of the Green Bin organics recycling program.[296]

| | | Lifecycle Emissions Compared to Diesel | "Tailpipe" Emissions Compared to Diesel | | | |
|---|---|---|---|---|---|---|
| **Technology** | **Level of Use in Refuse Trucks** | **Greenhouse Gas Reduction** | **Nitrogen Oxides Reduction** | **Particulate (PM 2.5) Reduction** | **Special Requirements** | **Cost** |
| **ULSD** | Commercial Standard | N/A | N/A | N/A | None | **Vehicles**: ~$300,000<br>**Fuel cost**: ~$2.60/gallon |
| **Biodiesel (B20)** | Commercial Standard | ~12.5% for B20<br>~61% for B100 | Same as diesel | 40% | None | **Vehicles**: ~$300,000;<br>**Fuel cost**: similar to diesel for 5% blend, more expensive for 20% or higher blends |
| **Renewable Diesel** | 2,000 | ~72% | Same as diesel | 40% | None | **Vehicles**: ~$300,000<br>**Fuel cost**: 1.5-3x the price of diesel |
| **Battery Electric** | Pilot phase Less than 50 | Varies by grid: ~37% upper Midwest ~57% US Average ~76% Northeast | 100% NOx reduction | 100% (~50% including brake and tire wear) | New vehicle, charging infrastructure | **Vehicles**: ~$500,000 (66% more than for diesel)<br>**Fuel cost**: very inexpensive<br>**Refueling**: charging pedestals: $25,000 and up for 1 or 2 trucks |
| **Hybrid Electric** | Legacy + New Tech | ~30% in form of extended mileage per gallon fuel | Same as diesel | Same as diesel | Vehicle | **Vehicle**: ~$350,000 (17% mark up on diesel) |
| **Hybrid Hydraulic** | Legacy | ~30% in form of extended mileage per gallon fuel | Same as diesel | Same as diesel | Vehicle | **Vehicles**: ~$340,000 (12% mark up on diesel) |
| **CNG** | Commercial ~18,000; 60% of trucks on order are for CNG/RNG | ~6% | 90%+ | 60% | New vehicle, fueling infrastructure and depot ventilation | **Vehicles**: ~$335,000 (10.5% markup relative to diesel)<br>**Fuel cost**: ~20% less than diesel<br>**Refueling**: station is ~$1-2 million to service 50-100 trucks (fuels vehicles in 5-10 minutes).<br>**Other**: depots may need new ventilation equipment and/or retrofits |
| **RNG** | Commercial More than 10,000 in use | ~80% landfill gas; Net carbon negative: **120-188% food waste or animal manure processed in ADs** | 90%+ | 60% | New vehicle, fueling infrastructure and depot ventilation | **Vehicles**: ~$335,000 (10.5% markup on diesel)<br>**Fuel cost**: ~20-40% less than diesel<br>**Refueling**: station is ~$1-2 million to service 50-100 trucks (fuels vehicles in 5-10 minutes).<br>**Other**: depots may need new ventilation equipment and/or retrofits |

## Glossary of Terms/Abbreviations

**AFLEET**: A database tool developed by Argonne National Laboratory (see below) which is used to calculate costs, paybacks and environmental footprints for fleets of vehicles. A module of the GREET database (see below).

**Argonne National Laboratory (ANL)**: Argonne is a multidisciplinary science and engineering research center of the US Department of Energy. It works in concert with universities, industry, and other national laboratories on questions and experiments too large for any one institution to do by itself.

**Battery Electric Vehicle (BEV)**: A BEV has no internal combustion engine, instead using electricity stored in an on-board battery pack to power an electric motor and the vehicle's control systems.

**Biodiesel**: A vegetable oil or animal-fat based diesel fuel, generally used in a blend with fossil diesel fuel to reduce emissions, less commonly used on its own.

**Biogas**: Gaseous fuel, especially methane, produced by the fermentation of organic matter.

**California Air Resources Board (CARB)**: CARB is charged with protecting the public from the harmful effects of air pollution and developing programs and actions to fight climate change. CARB administers California's Low Carbon Fuel Standard (LCFS), and has done extensive work in measuring comparative emissions for different fuels.

**Cetane number**: A rating of the ignition properties of diesel fuel in terms of combustion speed and required compression.

**Class 6 vehicle**: A vehicle weighing between 19,501 and 26,000 pounds; classified as "medium-duty."

**Class 8 vehicle**: A vehicle weighing more than 33,000 pounds; classified as "heavy-duty."

**Criteria pollutants**: Common air pollutants for which the US EPA has set National Ambient Air Quality Standards. In the context of this report, these include nitrogen oxides (NOx); particulate matter that is 2.5 microns in size or less (PM2.5), capable of getting deeper into the lungs than larger particulate matter, and so considered by the US EPA to pose a greater risk to health;[296] and black carbon (BC), a component of particulate matter linked to respiratory and cardiovascular disease, cancer and birth defects, and which aggravates climate change by decreasing the reflectiveness of e.g. snow and ice, so trapping heat in the atmosphere.[297]

**Diesel gallon equivalent (DGE)**: A quantity of an alternative fuel that contains the same amount of energy as a gallon of diesel fuel, measured in terms of energy content (BTUs).

**Drop in (substitute) fuel**: A fuel that can be used by an existing vehicle technology without changes to vehicle.

**DSNY**: New York City Department of Sanitation.

**FAME**: Fatty acid methyl ester, a first-generation biofuel. "Biodiesel" is commonly a FAME fuel.

**Feedstock**: The material from which a fuel is made. For instance, biodiesel can be made from various food crops, including soybean oil or rapeseed oil, or from algae. Biogas can be collected from landfills, wastewater or animal manure. The source feedstock affects the energy content of a fuel.

**Gasoline gallon equivalent (GGE)**: A quantity of an alternative fuel that contains the same amount of energy as a gallon of gasoline, measured in BTUs.

**(ANL) GREET**: Greenhouse gases, Regulated Emissions and Energy use in Transportation. A database tool used to evaluate the emissions of various fuels on a well-to-pump, pump-to-wheels and well-to-wheels basis (see below). GREET was developed by the US Department of Energy's Argonne National Laboratory, and has been adapted and expanded by the California Air Resources Board (CARB) to meet the requirements of that state's Low Carbon Fuel Standard. This document references 1) Argonne's GREET1 2020, Fuel Cycle Model, and 2) Argonne's AFLEET tool, which is based on GREET and is used to calculate costs, paybacks and environmental footprints for fleets of vehicles.

**Hybrid Electric Vehicle (HEV)**: HEVs have both an internal combustion engine and a large battery which are alternated or combined to energize the vehicle drivetrain at different stages of acceleration.

**Hydraulic Hybrid Vehicle (HHV)**: HHVs have both an internal combustion engine and a built-in hydraulic system which are alternated or combined to energize the vehicle drivetrain at different stages of acceleration.

**Hydrotreating**: Oil refining process in which hydrogen is used to remove impurities such as oxygen, sulfur, nitrogen, or unsaturated hydrocarbons.

**Hydrogenation**: To combine or treat with hydrogen, especially to add hydrogen to an organic (carbon-based) compound, typically in the presence of a catalyst.

**Lifecycle emissions**: Assessment of the environmental impacts of all stages of a product's life, including raw material extraction, processing, manufacturing, distribution, use, and disposal or recycling. With vehicles, also called well-to-wheels (see below). With vehicles, a lifecycle analysis tends to focus on GHG emissions.

**Pump-to-wheels emissions (PTW)**: A measure of emissions from combustion of fuel by the vehicle. Effectively, tailpipe emissions. A PTW analysis will look at both GHG emissions and criteria pollutants such as particulate matter, nitrogen oxides and sulfur oxides.

**Regenerative braking**: A vehicle braking system in which the kinetic energy of the vehicle is captured and 1) converted to electricity to recharge the vehicle's battery or run other vehicle systems, or 2) used to pressurize a fluid for use in hydraulic systems.

**Renewable diesel**: An "advanced biofuel" made from waste fats and residue. Similar to biodiesel, it is derived form a different process, burns more cleanly and can be used on its own, without blending with conventional diesel.

**Renewable Natural Gas**: Biogas (see above) that has been upgraded to pipeline/vehicle quality by removing CO2, moisture and other impurities. It can be substituted for conventional natural gas in a natural gas vehicle.

**Transfer station**: A facility at which refuse trucks dump their contents for transfer to an ultimate disposal location, such as a landfill. Final transfer may take place via road, railroad or waterway.

**Ultra-low-sulfur diesel (ULSD)**: A diesel fuel containing 15ppm of sulfur or less, as opposed to 500ppm for once-standard highway diesel. Almost all petroleum-based diesel is now of the ULSD type.

**Well-to-pump emissions (WTP)**: Emissions associated with upstream extraction, processing and transportation of a fuel before it gets to the vehicle.

**Well-to-wheel emissions (WTW)**: All emissions associated with the extraction, processing and transportation of a fuel, as well as its combustion in a vehicle. A combination of well-to-pump and pump-to-wheels, effectively referring to lifecycle emissions.

# References


1 Values are for 2019. US EPA, "Overview of Greenhouse Gases," https://www.epa.gov/ghgemissions/overview-greenhouse-gases. Accessed July 2021.

2 "Cut methane emissions to avert global temperature rise, UN-backed study urges," UN News. https://news.un.org/en/story/2021/05/1091402

3 "Real-world activity, fuel use, and emissions of heavy-duty compressed natural gas refuse trucks," Gurdas S. Sandhu,.H. Christopher Frey, Shannon Bartelt-Hunt and Elizabeth Jones. https://www.sciencedirect.com/science/article/abs/pii/S0048969720368546

4 Based on US EIA, "Petroleum Consumption: Transportation and Electric Power Sectors," 2019 values for average annual transportation consumption of motor gasoline (137.439 billion gallons) and distillate fuel (47.356 billion gallons). Uses EIA 42 gallons per barrel. US EIA, "Monthly Energy Review" webpage, Table 3.7c, https://www.eia.gov/totalenergy/data/monthly/index.php#consumption.

5 David Z. Morris, "Today's Cars Are Parked 95% of the Time." Fortune Magazine, 3/13/2016, via Yahoo Finance, https://finance.yahoo.com/news/today-cars-parked-95-time-210616765.html

6 Based on a comparison of emissions from vehicle operations in Argonne National Laboratory's GREET tool (Greenhouse Gases, Regulated Emissions and Energy Use in Technologies), 2020 edition.

7 "Renewable Natural Gas Database," Argonne National Laboratory. https://www.anl.gov/es/reference/renewable-natural-gas-database

8 MJ Bradley & Associates, "Renewable Natural Gas: Potential Supply and Benefits," July 2019. https://www.mjbradley.com/sites/default/files/RNGSupplyandBenefits07152019.pdf

9 Presentation by Clean Energy Fuels, https://energy-vision.org/pdf/EV-NWNatural-CER_Henn.pdf. Slide 6 – Refuse Trucks, Transit Buses and Airport Vehicles alone consume approximately 5.5 billion gallons of diesel per year.

10 NGV America, https://www.ngvamerica.org/vehicles/refuse/. Accessed April 2020.

11 NGVAmerica Fact Sheet. https://ngvamerica.org/vehicles/refuse/#:~:text=Over%2017%2C000%20refuse%20trucks%20run%20on%20natural%20gas&text=Today%2C%20over%2017%2C000%20natural%20gas,are%20powered%20by%20natural%20gas.

12 There are multiple references to CNG trucks being about 10dB quieter than diesel models. Since decibels are measured on a logarithmic scale, the difference of 10dB can actually mean a 50% noise reduction; 60dB is considered half as loud as 70dB. See "Comparison of Health Impacts of Noise Pollution" on page 19.

13 Comparative cost based on AFLEET 2020, Background Data tab.

14 US Department of Energy, "Hydrogen Production: Natural Gas Reforming." https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

15 Alternative Fuels Data Center https://www.afdc.energy.gov/fuels/emerging_dme.html

16 US EIA, "Carbon Dioxide Emissions Coefficients," https://www.eia.gov/environment/emissions/co2_vol_mass.php. Accessed July 2021.

17 Wikipedia, "Diesel particulate filter," https://en.wikipedia.org/wiki/Diesel_particulate_filter. Accessed July 2021.

18 DieselNet Technology Guide, Diesel Catlysts, "Diesle Oxydation Catalyst," https://dieselnet.com/tech/cat_doc.php. Accessed July 2021. A "DOC" is best used with low-sulfur fuels; with higher sulfur content, it will break down sulfur dioxide gas into additional parrticulate matter. US EPA, "Diesel Oxydation Catalyst General Information," https://www.epa.gov/sites/default/files/2016-03/documents/420f10031.pdf; accessed July 2021.

19 Wikipedia, "Selective caltalytic reduction," https://en.wikipedia.org/wiki/Selective_catalytic_reduction. Accessed July 2021.

20 Alex Crissey, "Dealing with Aftertreatment Issues," Fleet Equipment 11/27/2017, https://www.fleetequipmentmag.com/dealing-aftertreatment-issues/. Accessed July 2021.

21 Fullbay, "Diesel Particulate Filter (DPF) Regen and Repair," undated, https://www.fullbay.com/blog/diesel-particulate-filter-dpf-regen/. Accessed July 2021.

22 Ron Jessen, "How to Reduce Fordced Regen Hassles," Cenex, undated, https://www.cenex.com/about/cenex-information/cenexperts-blog-page/fuel-efficiency/how-to-reduce-forced-regen-hassles. Accessed July 2021.

23 James Booth, "Maintenance issues in aftertreatment systems: the causes and costs," Chevron Lubricants, undated, https://www.chevronlubricants.com/en_us/home/learning/from-chevron/heavy-duty-diesel-vehicles-and-equipment/maintenance-issues-in-aftertreatment-systems-the-causes-and-the-costs.html. Accessed July 2021.

24 US EPA, "Basic information about NO2," https://www.epa.gov/no2-pollution/basic-information-about-no2. Accessed April 2020.

25 US EPA, "NOx: how nitrogen oxides affect the way we live and breathe." https://web.archive.org/web/20080716063437/

http://www.epa.gov/air/urbanair/nox/noxfldr.pdf. Accessed April 2020.

26 US EPA, "Particulate Matter Emissions," https://cfpub.epa.gov/roe/indicator_pdf.cfm?i=19. 2018? Accessed May 2020. Also US EPA "Final Rule: Fine Particulate Matter National Ambient Air Quality Standards…." 2016? Accessed May 2020.

27 US EPA, "Health and Environmental Effects of Particulate Matter (PM)." https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

28 PM 2.5 and cognitive development in children, "How Pollution Affects the Brain," Neuroscience News, 8/6/2020, https://neurosciencenews.com/ brain-pollution-16785/. Impacts on the elderly, "Exposure to PM2.5 pollution linked to brain atrophy and memory decline," Neurosicence News.com, 11/21/2019, https://neurosciencenews.com/exposure-to-pm-2-5-pollution-linked-to-brain-atrophy-and-memory-decline/, accessed December 2020. Both articles relate to studies at USC.

29 Pinto de Moura, Reichmuth and Gatti, "Inequitable Exposure to Air Pollution from Vehicles in the

Northeast and Mid-Atlantic." Union of Concerned Scientists, June 2019, www.ucsusa.org/sites/default/files/attach/2019/06/Inequitable-Exposure-to-Vehicle-Pollution-Northeast-Mid-Atlantic-Region.pdf

30 Personal communication with Kent Johnson of UC Riverside Ctr. for Environmental Research and Technology on PM2.5 emissions from natural gas, biodiesel and renewable diesel refuse trucks, May 11, 2021.

31 US EPA, "Particulate Matter (PM) Basics."

32 To date, no emissions study has been published that directly compares recent-model diesel and natural gas refuse collection vehicles with similar mileages over the same duty cycle and under the same conditions. The comparisons made here are based on averages of findings from multiple studies, model outputs, and interviews with experts. They are intended to give a ballpark idea of the emissions rates that can be expected from these technologies. New and better data is expected to be published in 2022 from a large study conducted by teams at the University of California Riverside and West Virginia University for California's South Coast Air Quality Management District.

33 De Moura, Reichmuth and Gatti, op. cit.; Clauia Boyd-Barrett, "People of color and the poor disproportionately exposed to air pollution, study finds." California Health Report, February 2019, https://www.calhealthreport.org/2019/02/08/people-of-color-and-the-poor-disproportionately-exposed-to-air-pollution-study-finds/. Accessed June 2020.

34 Dr. Philip Landrigan, award acceptance speech at Energy Vision annual year end event, October 12, 2018.

35 This chemical reaction produces a "fatty-acid-methyl-ester," which is why first generation biodiesel is sometimes called FAME biodiesel. Wikipedia https://en.wikipedia.org/wiki/Biodiesel. Accessed June 2020.

36 Oregon State University, College of Agricultural Science, "Generations of Biofuels," https://agsci.oregonstate.edu/sites/agsci.oregonstate.edu/files/ bioenergy/generations-of-biofuels-v1.3.pdf. Accessed December 2020.

37 Shelley Ernst in Government Fleet, "What You Need to Know About Renewable Diesel." https://www.government-fleet.com/156621/what-you-need-to-know-about-renewable-diesel. Accessed June 2020.

38 100% biodiesel has a lower energy content than petroleum diesel, and also has solvent properties that can affect engine parts as well as releasing deposits from fuel systems that end up clogging filters. US DOE, Alternative Fuels Data Center, "Biodiesel blends." https://www.afdc.energy.gov/fuels/biodiesel_blends.html. Accessed June 2020.

39 "Biodiesel cloud point and cold weather issues," Farm Energy, April 2019, https://farm-energy.extension.org/biodiesel-cloud-point-and-cold-weather-issues/.

40 Lee and Lavoie, "From first-to third-generation biofuels: Challenges of producing a commodity from a biomass of increased complexity." Animal Frontiers, April 2013, https://academic.oup.com/af/article/3/2/6/4638639, Accessed December 2020.

41 Soy most commonly used in US, Caitlin Marquis, "This is advanced Energy: First Generation Biofuels (Ethanol and Biodiesel)." Advanced Energy Economy, 4/12/2016, https://blog.aee.net/this-is-advanced-energy-first-generation-biofuels-ethanol-and-biodiesel. Accessed December 2020.

42 Oregon State University, op.cit;. also "Second Generation biofuels," Wikipedia, https://en.wikipedia.org/wiki/Second-generation_biofuels, accessed December 2020.

43 "Bhuiya, Rasul, Khan, Ashwath, Azad and Hazrat, Second Generation Biodiesel: Potential Alternative to Edible Oil Derived Biodiesel," https://core.ac.uk/download/pdf/82572581.pdf

44 Oregon State University, op. cit; Caitlin Marquis, op. cit.; Lee and Lavoie, op. cit.

45 See for instance Penn State Extension, "Using Biodiesel Fuel in Your Engine." June 2016, https://extension.psu.edu/using-biodiesel-fuel-in-your-engine; or "Compatibility of biodiesel with petroleum diesel engines," Dieselnet, https://dieselnet.com/tech/fuel_biodiesel_comp.php (publicatin date not specified). Accessed December 2020.

46 National Biodiesel Board, "Why Biodiesel?" https://www.biodiesel.org/what-is-biodiesel/why-biodiesel Accessed April 2020. Researchers at WVU inducated that this claim may be exaggerated and that only Cummins has approved B20 for their diesel engines. Other suppliers have never approved anything over B5. Personal communication with Dr. Arvind Thiruvengadam Padmavathy of West Virginia University on PM2.5 in natural gas and diesel refuse vehicles, April 9, 2021.

47 US DOE, Alternative Fuels Data Center, "Biodiesel blends." https://www.afdc.energy.gov/fuels/biodiesel_blends.html. Accessed June 2020.

48 Argonne National Laboratory GREET tool.

49 Government Fleet "What You Need to Know About Renewable Diesel" https://www.government-fleet.com/156621/what-you-need-to-know-about-renewable-diesel. Accessed June 2020.

50 Neste, "What is the difference between renewable diesel and traditional biodiesel—if any?" September 20, 2016. https://www.neste.com/what-difference-between-renewable-diesel-and-traditional-biodiesel-if-any. Accessed June 2020.

51 Ibid.

52 Advanced Energy Economy Advanced Energy Perspectives, "This is advanced energy: second and third generation biofuels," https://blog.aee.net/second-and-third-generation-biofuels, accessed June 2020.

53 City of Knoxville Fleet Services, "Renewable Diesel Test," 2017, http://tngreenfleets.org/tncleanfuels.org/docs/Renewable-Diesel-Report_City-of-Knoxville_6-15-17.pdf. Accessed June 2020.

54 Rich Piellisch in NGT News, "Oakland and renewable diesel: 'Not a single downside.'" March 26, 2018. https://ngtnews.com/oakland-and-renewable-diesel-not-a-single-downside. Accessed June 2020.

55 Neste, Oakland Case Study, "Can French Fries Power Fleets?" https://www.neste.us/sites/neste.com/files/oakland_case_study.pdf. Accessed 6/18/21.

56 Government Fleet, "San Diego Adopts Renewable Diesel," November 18, 2016, https://www.government-fleet.com/137498/san-diego-adopts-renewable-diesel. Accessed 6/18/21

57 Government Fleet, "New York City Says Renewable Diesel Pilot met It's Goals," May 21, 2019, https://www.government-fleet.com/332292/new-york-city-says-renewable-diesel-pilot-met-its-goals Accessed 6/18/21.

58 NYC RFP for renewable diesel, NYC City Record Online, 10/22/2020, https://a856-cityrecord.nyc.gov/RequestDetail/20200904101

59 NYC Department of Citywide Administrative Services (DCAS), "Case Study Renewable Diesel, a Potential Replacement for All Fossil Fuel for New York City's Trucking Fleet and Buildings," July 2020, https://www1.nyc.gov/assets/dcas/downloads/pdf/fleet/NYC-Fleet-Case-Study-Renewable-Diesel-7-16-2020.pdf

60 US Department of Energy, Office of Energy Efficiency and Renewable Energy, "All-electric vehicles." https://www.fueleconomy.gov/feg/evtech.shtml. Accessed May 2020.

61 Wikipedia "Battery Electric Vehicle" https://en.wikipedia.org/wiki/Battery_electric_vehicle. Accessed June 2020.

62 Michael Mobbs Sustainable Projects, "Lead acid vs. lithium ion battery comparison," https://static1.squarespace.com/static/55d039b5e4b061baebe46d36/t/56284a92e4b0629aedbb0874/1445481106401/Fact+sheet_Lead+acid+vs+lithium+ion.pdf. Accessed June 2020.

63 HowStuffWorks, "What is the difference between a normal lead-acid car battery and a deep cycle battery?" https://auto.howstuffworks.com/ question219.htm. Accessed June 2020.

64 Union of Concerned Scientists "How Do Battery Electric Cars Work" https://www.ucsusa.org/clean-vehicles/electric-vehicles/how-do-battery-electric-cars-work#.W0jJ1q2ZM_U. Accessed June 2020.

65 Wikipedia, "Regenerative brake." https://en.wikipedia.org/wiki/Regenerative_brake. Accessed June 2020.

66 James Ayre, "Electric semi-trucks and heavy duty trucks—available models and planned models," Clean Technica, December 16, 2017. https://cleantechnica.com/2017/12/16/electric-semi-trucks-heavy-duty-trucks-available-models-planned-models/. Accessed June 2020. A review of an electric refuse model references its ability to "recapture energy from the hundreds of stops refuse trucks make per day," Greencarcongress.com, "Mack LR Elewctric refuse truck to enter production in 2021," 9/17/2020, https://www.greencarcongress.com/2020/09/20200917-mack.html

67 Kyla Gardner, "Quiet Trash Pickup? Chicago Has Continent's Only All-Electric Garbage Truck." DNAinfo, 9/26/14, https://www.dnainfo.com/chicago/20140926/little-village/quiet-trash-pickup-chicago-has-continents-only-all-electric-garbage-truck/. Accessed July 2020.

68 Motiv Power Systems Press Release, "California's first all-electric garbage truck headed to Sacramento." June 13, 2017. https://www.capradio.org/articles/2017/06/13/sacramento-buying-californias-first-all-electric-garbage-truck/. Accessed June 2020.

69 Heavy Duty Trucking, "Los Angeles completes battery-electric refuse truck demo," June 7, 2017. https://www.truckinginfo.com/140793/los-angeles-completes-battery-electric-refuse-truck-demo. Accessed April 2020.

70 James Ayre in Clean Technica, "BYD Delivers 1st All-Electric Automated Side-Loader Garbage Truck To City Of Palo Alto & GreenWaste." https://cleantechnica.com/2017/11/21/byd-delivers-1st-electric-automated-side-loader-garbage-truck-city-palo-alto-greenwaste/. Accessed June 2020.

71 BYD press release, "Seattle's first electric refuse trucks to be delivered by BYD." July 17, 2018. http://en.byd.com/usa/news-posts/press-release-seattles-first-electric-refuse-trucks-to-be-delivered-by-byd/. Accessed June 2020.

72 Cole Rosengren, "Electric refuse trucks on the road or on the way in rising number of states." Waste Dive, March 2020, www.wastedive.com/ news/electric-refuse-trucks-byd-lion-mack-dsny-ecomaine/573352/

73 See for instance James Riswick, "What is a Hybrid Car?" Car and Driver, February 22, 2019. www.caranddriver.com/features/a26390899/what-is-hybrid-car/

74 See for instance: Anthony Ingram in Green Car Reports, 8/15/14, "Hybrid garbage truck now on sale in U.S.: saving fuel while hauling trash," https://www.greencarreports.com/news/1093892_hybrid-garbage-truck-now-on-sale-in-u-s-saving-fuel-while-hauling-trash; Jim Mele in Fleet Owner, 5/1/06, "Autocar shows hybrid," https://www.fleetowner.com/equipment/nutsbolts/fleet_autocar_shows_hybrid; Wikipedia, "Hydraulic hybrid vehicle," https://en.wikipedia.org/wiki/Hydraulic_hybrid_vehicle. All accessed June 2020.

75 Wikipedia "Hybrid Electric Vehicle" https://en.wikipedia.org/wiki/Hybrid_electric_vehicle

76 The Atlantic, "Infographic: How does a hybrid car engine actually work?" https://www.theatlantic.com/technology/archive/2011/06/infographic-how-does-a-hybrid-car-engine-actually-work/241021/. Accessed June 2020.

77 Grid independent hybrids: Jared Sagoff, Argonne National Laboratory, "Different energy mixes will fuel plug-in hybrid cars," 8/7/2010,. https://www.anl.gov/article/different-energy-mixes-will-fuel-plugin-hybrid-cars. Accessed June 2020.

78 Union of Concerned Scientists, "Comparing electric vehicles: Hybrid vs. BEV vs. PHEV vs. FCEV." https://blog.ucsusa.org/josh-goldman/comparing-electric-vehicles-hybrid-vs-bev-vs-phev-vs-fcev-411. Accessed June 2020.

79 Wikipedia, "Hydraulic hybrid vehicle," https://en.wikipedia.org/wiki/Hydraulic_hybrid_vehicle; also, "Are hydraulic hybrid vehicles the future of driving?," Mobile Hydraulic Tips, January 2014, www.mobilehydraulictips.com/hydraulic-hybrid-vehicles-future-driving/. Accessed April 2020.

80 "Engineering Hydraulic Hybrid Vehicles," CZero Solutions, https://czero-solutions.com/projects/hydraulic-hybrid-vehicles/. Accessed April 2020.

81 Wrightspeed website, The Route Powertrain," https://www.wrightspeed.com/the-route-powertrain, accessed November 2021.

82 Ibid.

83 The Wrightspeed technology is also referred to as "hybrid" in David Palmer's "Tesla cofounder plays Frankenstein with hybrid electric garbage truck," Digital Trends, June 12, 2016, https://www.digitaltrends.com/cars/tesla-cofounder-teams-with-mac-trucks-on-hybrid-garbage-truck/, accessed November 2021.

84 Hyliion website, https://www.hyliion.com/

85 Freight Waves, "Hyliion gathers fleets to test natural gas-electric hybrid truck." https://www.freightwaves.com/news/hyliion-gathers-fleets-to-test-natural-gas-electric-hybrid-truck. Accessed April 2021.

86 Wikipedia, "Stop-start system." https://en.wikipedia.org/wiki/Start-stop_system. Acessed June 2020.

87 Effenco Hybrid Solutions, "Effenco delivers 30% fuel savings in NYC" (video). https://www.youtube.com/watch?v=wad064CgLCk Accessed June 2020.

88 Wikipedia "Natural Gas" https://en.wikipedia.org/wiki/Natural_gas

89 Wikipedia, "Natural gas." https://en.wikipedia.org/wiki/Natural_gas. Accessed June 2020.

90 Personal communication, Dr. Kent Johnson, Uniersity of California Riverside, Center for Environmental Research and Technology.

91 NGV America, https://www.ngvamerica.org/vehicles/refuse/. Accessed April 2020.

92 The current EPA standard for NOx emissions from heavy-duty highway compression-ignition engines and urban buses is .2 grams per brake horsepower hour (g/bhp-hr). The standard for particulate matter is .01 g/bhp-hr. G/bhp-hr is an index for which Energy Vision was unable to find any conversion formula (e.g. to grams per mile), despite outreach to multiple experts; during one conversation, it was referred to as "archaic."

93 NOx and GHG emissions reduction based on Cummins Westport 11.9 liter natural gas engine, www.cum-minswestport.com/content/841/ISX12N_5544037_0418.pdf; for NOx also CARB emissions-testing certificates for Cummins NG engine, https://ww3.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2020/2020.php; particulate matter reductions below the EPA standard based on CARB certificate Supplemental Emissions Testing reading.

94 Based on California Air Resources Board (CARB) "LCFS Pathway Certifed Carbon Intensities: Current Fuel Pathways Table," https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx. An average of the "carbon intensity" scores (grams of CO2 equivalent per megajoule of energy, or g/CO2e/mj) for landfill-gas-generated RNG comes in at 37, compared to diesel's 100.

95 Alternative Fuels Data Center "Hydrogen Basics" https://www.afdc.energy.gov/fuels/hydrogen_basics.html, accessed July 2018.

96 Robert Rapier, "Life Cycle Emissions of Hydrogen," 5/26/2020, The Fourth Generation: News and Per-spectives on the Future of Energy, https://4thgeneration.energy/life-cycles-emissions-of-hydrogen/.

97 Office of Energy Efficiency & Renewable Energy. "Hydrogen Production: Natural Gas Reforming." https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. Accessed December 2020.

98 Sun, Young, Elgowainy et al., "Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities." Argonne National Laboratory, 4/30/2019, https://www.osti.gov/pages/biblio/1546962

99 US DOE Office of Energy Effiency and Renewable Energy, "Hydrogen Production: Electrolysis." https://www.energy.gov/eere/fuelcells/ hydrogen-production-electrolysis#:. Accessed December 2020.

100 Ibid.

101 Wikipedia "Fuel Cell" https://en.wikipedia.org/wiki/Fuel_cell

102 US DOE, "Fuel Cells." Energy.gov, https://www.energy.gov/eere/fuelcells/fuel-cells. Accessed December 2020.

103 Ibid.

104 US DOE Alternative Fuels Data Center, "Alternative Fueling Station Countes by State," https://www.afdc.energy.gov/stations/states. Accessed September 2021.

105 US DOE, "DOE announces new lab consortia to advance hydrogen and fuel cell R&D." Energy.gov, 6/23/20, https://www.energy.gov/articles/doe-announces-new-lab-consortia-advance-hydrogen-and-fuel-cell-rd

106 Office of Energy Efficiency & Renewable Energy. "Hydrogen Production: Electrolysis." https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis. Accessed December 2020.

107 Bridie Schmidt, "Nikola stock jumps on news of 2,500 feul-cell garbage truck order." The Driven, 8/11/2020, https://thedriven.io/2020/08/11/nikola-stock-jumps-on-news-of-2500-fuel-cell-garbage-truck-order/

108 Daniel Howley, "Investors wanted Nikola to be the next Tesla. It's not." Yahoo! Finance, 12/2/2020, https://www.yahoo.com/entertainment/investors-wanted-nikola-to-be-tesla-its-not-204150259.html

109 "Republic Services and Nikola cancel major electric truck order," Waste Dive. https://www.wastedive.com/news/republic-services-nikola-electric-refuse-truck-waste-recycling/582647/. Accessed April 2021.

110 The HECTOR Project has 7 demo trucks in 7 northern European cities, https://www.nweurope.eu/projects/project-search/hector-hydrogen-waste-collection-vehicles-in-north-west-europe/; and the REVIVE Project has 15 trucks in 8 cities in Belgium, Italy and the Netherlands, https://h2revive.eu/. Accessed December 2020.

111 "Cummins Delivers Fuel Cells for Refuse Trucks in Europe," FuelCellsWorks, 6/24/2020, https://fuelcellsworks.com/news/cummins-delivers-fuel-cells-for-refuse-trucks-in-europe/

112 Green Car Reports, "Venture hatches 'hydrogen hubs' to power fuel-cell garbage trucks—from waste." https://www.greencarreports.com/news/1132071_venture-hatches-hydrogen-hubs-to-power-fuel-cell-garbage-trucks-from-waste

113 FleetOwner, "Paccar tests more zero-emission trucks ahead of 2021 production." https://www.fleetowner.com/running-green/article/21137951/paccar-tests-more-zeroemission-trucks-ahead-of-2021-production

114 See for example US DOE hydrogen and fuel cells program, https://www.hydrogen.energy.gov/pdfs/progress15/x_5_goodarzi_2015.pdf , and Small Business Innovation Research Program and Small Business Technology Transfer program, https://www.sbir.gov/sbirsearch/detail/686900.

115 Alternative Fuels Data Center https://www.afdc.energy.gov/fuels/emerging_dme.html

116 Ibid.

117 Ibid.

118 Ibid.

119 Technology Collaboration Programme on Advanced Motor Fuels, "Dimethyl Ether (DME)." http://www.iea-amf.org/content/fuel_information/dme. Accessed July 2018.

120 "Oberon Fuels Secures $2.9 Million Grant from State of California for First-Ever Production of Renewable Dimethyl Ether (rDME) in United States," 6/13/2019. Oberon Fuels press release, http://oberonfuels.com/2019/06/13/oberon-fuels-secures-2-9-million-grant-from-state-of-california-for-first-ever-production-of-renewable-dimethyl-ether-rdme-in-united-states/. Accessed December 2019.

121 "Oberon Fuels Hails passing of California Assmebly Bill 2663," 9/28/2020. Oberon Fuels press release, https://www.globenewswire.com/news-release/2020/09/28/2100016/0/en/Oberon-Fuels-Hails-Passing-of-California-Assembly-Bill-2663.html. Accessed December 2020. In September 2019 Suburban Propane Partners acquired a 39% stake in Oberon.

122 California Air Resources Board, "Pathway Certified Carbon Intensity Values," https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm and https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx

123 US EIA, "Biomass-based diesel fuels," https://www.eia.gov/energyexplained/biofuels/biodiesel-in-depth.php. Accessed December 2020.

124 "B100 will degrade, soften, or seep through some hoses, gaskets, seals, elastomers, glues, and plastics with prolonged exposure. Nitrile rubber compounds, polypropylene, polyvinyl, and Tygon materials are particularly vulnerable to B100." US DOE Office of Energy Efficiency and Renewaqble Energy, "Biodiesel Handling and Use Guide," 5th edition, November 2016. https://afdc.energy.gov/files/u/publication/ biodiesel_handling_use_guide.pdf. Accessed December 2020.

125 BD 100, Argonne AFLEET, 2020; BD 20, Argonne GREET 2020.

126 Energy Vision calculation based on ANL AFLEET, Background Data tab, "Average fuel economy," refuse truck.

127 Email communication with GREET database team, April 2020.

128 Personal communication with Kent Johnson of UC Riverside Ctr. for Environmental Research and Technology on PM2.5 emissions from natural gas, biodiesel and renewable diesel refuse trucks.

129 To date, no emissions study has been published that directly compares recent-model diesel and natural gas refuse collection vehicles with similar mileages over the same duty cycle and under the same conditions. The comparisons made here are based on averages of findings from multiple studies, model outputs, and interviews with experts. They are intended to give a ballpark idea of the emissions rates that can be expected from these technologies. New and better data is expected to be published in fall 2021 from a large study conducted by teams at the University of California Riverside and West Virginia University for California's South Coast Air Quality Management District.

130 References include:

Argonne National Laboratory. "ANL GREET, Heavy Duty Vehicles Tab and Inputs Tab." Emissions Model Output, n.d.

California Air Resources Board. "EMFAC Run for New Model SWCV Class 8 Vehicles Powered by Diesel and Natural Gas," May 2021.

Gren, Louise, Vilhelm B. Malmborg, John Falk, Lassi Markula, Maja Novakovic, Sam Shamun, Axel C. Eriksson, et al. "Effects of Renewable Fuel and Exhaust Aftertreatment on Primary/Secondary Emissions from a Modern Heavy-Duty Diesel Engine." Journal of Aerosol Science 156 (August 2021): 105781. https://doi.org/10.1016/j.jaerosci.2021.105781

Hesterberg, Thomas W., Charles A. Lapin, and William B. Bunn. "A Comparison of Emissions from Vehicles Fueled with Diesel or Compressed Natural Gas." Environmental Science & Technology 42, no. 17 (September 1, 2008): 6437–45. https://doi.org/10.1021/es071718i.

Na, Kwangsam, Subhasis Biswas, William Robertson, Keshav Sahay, Robert Okamoto, Alexander Mitchell, and Sharon Lemieux. "Impact of Biodiesel and Renewable Diesel on Emissions of Regulated Pollutants and Greenhouse Gases on a 2000 Heavy Duty Diesel Truck." Atmospheric Environment 107 (April 2015): 307–14. https://doi.org/10.1016/j.atmosenv.2015.02.054.

Nabi, Md. Nurun. "Reductions in Diesel Emissions Including PM and PN Emissions with Diesel-Biodiesel Blends." Journal of Cleaner Production 166 (November 10, 2017): 860–68. https://doi.org/10.1016/j.jclepro.2017.08.096.

Personal communication with Kent Johnson of UC Riverside Ctr. for Environmental Research and Technology on PM2.5 emissions from natural gas, biodiesel and renewable diesel refuse trucks, May 11, 2021.

Personal communication with Marc Besche from West Virginia University's Center for Alternative Fuels Engines and Emissions about PM2.5 from refuse vehicles, April 9, 2021.

Sandhu, Gurdas S., H. Christopher Frey, Shannon Bartelt-Hunt, and Elizabeth Jones. "In-Use Measurement of the Activity, Fuel Use, and Emissions of Front-Loader Refuse Trucks." Atmospheric Environment 92 (August 2014): 557–65. https://doi.org/10.1016/j.atmosenv.2014.04.036.

Sandhu, Gurdas S., H. Christopher Frey, Shannon Bartelt-Hunt, and Elizabeth Jones. "Real-World Activity, Fuel Use, and Emissions of Diesel Side-Loader Refuse Trucks." Atmospheric Environment 129 (March 2016): 98–104. https://doi.org/10.1016/j.atmosenv.2016.01.014.

Sandhu, Gurdas S., H. Christopher Frey, Shannon Bartelt-Hunt, and Elizabeth Jones. "Real-World Activity, Fuel Use, and Emissions of Heavy-Duty Compressed Natural Gas Refuse Trucks." Science of the Total Environment 761 (March 20, 2021): 143323. https://doi.org/10.1016/j.scitotenv.2020.143323.

Singh, Devendra, K. A. Subramanian, and S. K. Singal. "Emissions and Fuel Consumption Characteristics of a Heavy Duty Diesel Engine Fueled with Hydroprocessed Renewable Diesel and Biodiesel." Applied Energy 155 (October 1, 2015): 440–46. https://doi.org/10.1016/j.apenergy.2015.06.020.

Timmers, Victor R.J.H., and Peter A.J. Achten. "Non-Exhaust PM Emissions from Electric Vehicles." Atmospheric Environment 134 (June 2016): 10–17. https://doi.org/10.1016/j.atmosenv.2016.03.017.

131 Personal communication with Dr. Arvind Thiruvengadam Padmavathy of West Virginia University on PM2.5 in natural gas and diesel refuse vehicles; Thiruvengadam et al., "Natural Gas Vehicles in Heavy-Duty Transportation-A Review"; personal communication with Kent Johnson of UC Riverside Ctr. for Environmental Research and Technology.

132 Calculated natural gas PM emissions rate of 0.01 g/mi by averaging values from one government modeling tool, two scholarly sources and two interviews with emissions testing experts: personal communication with Marc Besche from West Virginia University about PM2.5 from refuse vehicles; California Air Resources Board, "EMFAC Run for New Model SWCV Class 8 Vehicles Powered by Diesel and Natural Gas"; Sandhu et al., "Real-World Activity, Fuel Use, and Emissions of Heavy-Duty Compressed Natural Gas Refuse Trucks"; Hesterberg, Lapin, and Bunn, "A Comparison of Emissions from Vehicles Fueled with Diesel or Compressed Natural Gas"; Personal communication with Kent Johnson of UC Riverside Ctr. for Environmental Research and Technology.

133 Calculated diesel emissions rate of 0.03 g/mi by averaging values from two government modeling tools and three scholarly sources on refuse vehicles. Sandhu et al., "In-Use Measurement of the Activity, Fuel Use, and Emissions of Front-Loader Refuse Trucks"; Sandhu et al., "Real-World Activity, Fuel Use, and Emissions of Diesel Side-Loader Refuse Trucks"; Hesterberg, Lapin, and Bunn, "A Comparison of Emissions from Vehicles Fueled with Diesel or Compressed Natural Gas." California Air Resources Board, "EMFAC Run for New Model SWCV Class 8 Vehicles Powered by Diesel and Natural Gas."; Argonne National Laboratory, "ANL GREET, Heavy Duty Vehicles Tab and Inputs Tab."

134 M J Bradley & Associates. "New York City Commercial Refuse Truck Age-out Analysis." New York City Business Integrity Commission, September 2013, https://mjbradley.com/sites/default/files/EDF-BIC-Refuse-Truck-Report-2013.pdf. 43.2 cases of acute respiratory illness prevented per ton of PM2.5 reduction. Conversion assumes a 240,000 mile lifespan for a refuse vehicle. Wolfe et al., "Updated Mobile Source Benefit-per-Ton Values: 2020-2045."; M J Bradley & Associates, "New York City Commercial Refuse Truck Age-out Analysis."

135 Nabi, "Reductions in Diesel Emissions Including PM and PN Emissions with Diesel-Biodiesel Blends."

136 Personal communication with Dr. Arvind Thiruvengadam Padmavathy of West Virginia University on PM2.5 in natural gas and diesel refuse vehicles.

137 To date, no studies have been published tracking the particulate matter in refuse vehicles using the most common biodiesel blends, so its behavior is poorly understood. Thus, we have to depend on work done on heavy-duty engines in general, and use the broader metric of particulate matter (PM) as a proxy for the more specific pollutant PM2.5. Unlike biodiesel, renewable diesel can be used in diesel engines unblended. However, all told, R100 delivers a 40% reduction in PM on average, no better than B20.

138 Averaged percent reductions from two studies on B20. Nabi, "Reductions in Diesel Emissions Including PM and PN Emissions with Diesel-Biodiesel Blends"; Na et al., "Impact of Biodiesel and Renewable Diesel on Emissions of Regulated Pollutants and Greenhouse Gases on a 2000 Heavy Duty Diesel Truck."

139 Averaged percent reductions from three studies and one conversation with emissions expert. Gren et al., "Effects of Renewable Fuel and Exhaust Aftertreatment on Primary and Secondary Emissions from a Modern Heavy-Duty Diesel Engine"; Personal communication with Marc Besche from West Virginia University about PM2.5 from refuse vehicles; Na et al., "Impact of Biodiesel and Renewable Diesel on Emissions of Regulated Pollutants and Greenhouse Gases on a 2000 Heavy Duty Diesel Truck"; Singh, Subramanian, and Singal, "Emissions and Fuel Consumption Characteristics of a Heavy Duty Diesel Engine Fueled with Hydroprocessed Renewable Diesel and Biodiesel."

140 California Air Resources Board, "EMFAC Run for New Model SWCV Class 8 Vehicles Powered by Diesel and Natural Gas."

141 Timmers and Achten, "Non-Exhaust PM Emissions from Electric Vehicles."

142 Ibid.

143 Ibid.

144 Farrow, Katherine, and Walid Oueslati. "Non-Exhaust Emissions from Road Transport: Causes, Consequences and Policy Responses." Organisation for Economic Co-operation and Development, June 25, 2020, https://www.oecd.org/environment/non-exhaust-parcticulate-emissions-from-road-transport-4a4dc6ca-en.htm

145 "In Harm's Way: How Waste Management, Inc. Endangers the Sanitation Workers Who Protect the Public's Health," A report by the National Commission of Inquiry into the Worker Health and Safety Crisis in the Solid Waste Management Industry, 2008. https://www.labornotes.org/files/pdfs/Waste_In_Harms_Way.pdf

146 Clean Technica, "Will Electric Cars Make Traffic Quieter? Yes & No." https://cleantechnica.com/2016/06/05/will-electric-cars-make-traffic-quieter-yes-no/. Accessed July 2018.

147 Text of Senate Pedestrian Safety Enhancement Act of 2010, https://www.congress.gov/bill/111th-congress/senate-bill/841/text. Accessed July 2018. The Act refers to vehicles making "an alert noise," but what form the "alert" will take still seems unclear. Because of delays in rulemaking, enforcement of the law began on September

1, 2019, after which 50% of all new hybrid and electric vehicles weighing less than 10,000 pounds must comply, the requirement extending to 100% of such vehicles produced after September 1, 2020. See The Drive, "Hybrid and Electric Cars Must Make Noise by 2020." http://www.thedrive.com/news/18820/hybrid-and-electric-cars-must-make-noise-by-2020 and John Pare, "Progress on the Pedestrian Safety Enhancement Act: the regulations, the law and what they will mean for the blind." National Federation for the Blind, April 2017, https://www.nfb.org/sites/www.nfb.org/files/images/nfb/publications/bm/bm17/bm1704/bm170403.htm

148 "Case Study: compressed natural gas refuse fleets." US Department of Energy, Clean Cities Program, https://afdc.energy.gov/uploads/publication/casestudy_cng_refuse_feb2014.pdf. Accessed February 2018.

149 Freightliner, "The benefits of compressed natural gas vs. diesel." November 17, 2017, https://freightliner.com/blog-and-newsletters/the-benefits-of-compressed-natural-gas-vs-diesel/. Accessed August 2018.

150 American Natural Gas, "Why choose CNG?" http://americannaturalgas.com/why-choose-cng/. Accessed August 2018.

151 ANL AFLEET 2020, Background Data tab, "Average Noise Level (dBA)."

152 IAC Acoustics, "Comparative examples of noise levels," http://www.industrialnoisecontrol.com/comparative-noise-examples.htm, accessed April 2020.

153 Neste, "Performance meets sustainability. The choice in diesel is clear." https://www.nestemy.com/ Accessed July 2018.

154 E-mail exchange with Richard Battersby, Oakland Fleet Manager, June 24th, 2018.

155 E-mail exchange with Keith Shields, Director of Fleet Services for Knoxville, July 26, 2018.

156 US EPA, "Hydraulic Hybrid Technology—a proven approach," 2004, https://nepis.epa.gov then search title, accessed April 2020; Mobile Hydraulic Tips, "Are hydraulic hybrid vehciles the future of driving?', January 2014, https://www.mobilehydraulictips.com/hydraulic-hybrid-vehicles-future-driving/; Wikipedia, "Hydraulic Hybrid Vehcle," https://en.wikipedia.org/wiki/Hydraulic_hybrid_vehicle, updated March 2020, accessed April 2020.

157 Nicole Danna, "Hybrid garbage trucks saving Miami-Dade big money." Government Technology, April 5, 2011, https://www.govtech.com/transportation/Hybrid-Garbage-Miami-Dade-040511.html. Accessed May 2020.

158 US EPA, "Inventory of US Greenhouse Gas Emissions and Sinks," 1990-2019. https://www.epa.gov/sites/production/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf

159 US EPA, "Economics of Biofuels." https://www.epa.gov/environmental-economics/economics-biofuels. Accessed April 2020. Land changes in land use patterns could increase GHG emissions by increasing release of terrestrial carbon stocks; additional air and water pollution would be associated with additional fertilizer and pesticide use.

160 United Nations Food and Agriculture Organization, "The State of Food and Agriculture 2016," page 97, http://www.fao.org/3/a-i6030e.pdf. Accessed April 2020. Increasing land demands for bioenergy production were also referenced in the 2019 edition, http://www.fao.org/3/ca6030en/ca6030en.pdf

161 National Biodiesel Board, "Biodiesel Industry Overview & Technical Update," September 2020. https://www.biodiesel.org/docs/default-source/fact-sheets/biodiesel-industry-and-technical-overview.pdf

162 National Biodiesel Board, "As food waste concerns rise, biodiesel plays active role in reduction." 4/30/2019, https://www.nbb.org/news-resources/press-releases/2019/04/30/As-Food-Waste-Concerns-Rise-Biodiesel-Plays-Active-Role-in-Reduction. Accessed December 2020.

163 See for instance Fuels Market News, "Food prices merrier as biodiesel production grows." December 27, 2016. https://fuelsmarketnews.com/ food-prices-merrier-as-biodiesel-production-grows/. Accessed December 2020.

164 Jane Byrnem "COVID-19: US corn prices linked to health of clean fuel industry says [sic] US governors in funding call." Feednavigator.com, 4/22/2020, https://www.feednavigator.com/Article/2020/04/22/USDA-warned-corn-prices-linked-to-health-of-biofuel-sector

165 Union of Concerned Scientists, "Cleaner Cars form Cradle to Grave (2015)." https://www.ucsusa.org/clean-vehicles/electric-vehicles/life-cycle-ev-emissions#.W1o_vNJKjIW. Accessed December 2020.

166 Battery University, "Is Li-ion the solution for the electric vehicle?" http://batteryuniversity.com/learn/archive/ is_li_ion_the_solution_for_the_electric_vehicle. Accessed July 2018.

167 Wikipedia, "Electric truck," https://en.wikipedia.org/wiki/Electric_truck. Accessed April 2020.

168 Union of Concerned Scientists, "Electric vehicle battery: materials, cost, lifespan." https://www.ucsusa.org/clean-vehicles/electric-vehicles/electric-cars-battery-life-materials-cost#.W4hUoc5KjIU. Accessed August 2018.

169 Union of Concerned Scientists, https://www.ucsusa.org/clean-vehicles/electric-vehicles/electric-cars-battery-life-materials-cost#.W0jMeK2ZM_U

170 Mike Mwenda, "Tech giants sued over child lanbour, deaths and infuries in cobalt mining in the DRC." Lifegate, January 2020, https://www.lifegate.com/people/news/cobalt-mining-congo-tech-lawsuit

171 The Guardian, "Children as young as seven mining cobalt used in smartphones, says Amnesty." January 18, 2016. https://www.theguardian.com/global-development/2016/jan/19/children-as-young-as-seven-mining-cobalt-for-use-in-smartphones-says-amnesty. Accessed July 2018.

172 The Guardian, "Carmakers' electric dreams depend on supplies of rare minerals." July 29, 2017. www.theguardian.com/environment/2017/jul/29/electric-cars-battery-manufacturing-cobalt-mining. Accessed July 2018.

173 The Guardian, "Rare earth metals: tech manufacturers must think again, and so must users." March 26, 2014. https://www.theguardian.com/sustainable-business/rare-earth-metals-upgrade-recycle-ethical-china. Accessed July 2018.

174 Reuters, Tesla's electric motor shift to spur demand for rare earth neodymium." March 12, 2018. https://www.reuters.com/article/us-metals-autos-neodymium-analysis/teslas-electric-motor-shift-to-spur-demand-for-rare-earth-neodymium-idUSKCN1GO28I. Accessed July 2018.

175 IEEE Spectrum, "Shut up about the batteries: the key to a better electric car is a lighter motor." June 22, 2017. https://spectrum.ieee.org/transportation/advanced-cars/shut-up-about-the-batteries-the-key-to-a-better-electric-car-is-a-lighter-motor. Accessed July 2018.

176 Lizzie Wade in Wired, "Tesla's electric cars aren't as green as you might think." https://www.wired.

com/2016/03/teslas-electric-cars-might-not-green-think/. Accessed July 2018.

177 Cecile Bontron in The Guardian, "Rare earth mining in China comes at a heavy cost for local villages." August 7, 2012. Accessed July 2018.

178 Charlotte McLeod, "10 top countries for rate earth metal production." Investing News, May 2019. https://investingnews.com/daily/resource-investing/critical-metals-investing/rare-earth-investing/rare-earth-producing-countries/ Accessed April 2020.

179 Hongqiao Liu in New Security Beat, "As China adjusts for 'true cost' of rare earths, what does it mean for decarbonization?" March 21, 2017. https://www.newsecuritybeat.org/2017/03/china-begins-adjusting-true-cost-rare-earths-decarbonization/

180 Keith Bradsher, New York Times, "China tries to clean up toxic legacy of its rare earth riches." October 22, 2013. https://www.nytimes.com/2013/10/23/business/international/china-tries-to-clean-up-toxic-legacy-of-its-rare-earth-riches.html

181 See, for instance, NPR, "These Tribal Activists Want Biden to stop a Planned Lithium Mine on Their Sacred Land," September 2, 2021, https://www.npr.org/2021/09/02/1031726626/these-tribal-activists-want-biden-to-stop-a-planned-lithium-mine-on-their-sacred; New York Times, "The Lithium Gold Rush: Inside the Race to Power Electric Vehicles," May 6, 2021, https://www.nytimes.com/2021/05/06/business/lithium-mining-race.html; KTVN News, "Tribal Lawyers Asking Judge Not To Build Lithium Mine Near Thacker Pass Due To Sacred Site," https://www.ktvn.com/story/43576810/activists-camp-at-thacker-pass-to-prevent-lithium-mine-from-opening

182 Joey Gardiner, "The rise of electric cars could leave us with a big battery problem." The Guardian, August 10, 2017. https://www.theguardian.com/sustainable-business/2017/aug/10/electric-cars-big-battery-waste-problem-lithium-recycling. Accessed September, 2018.

183 Jack Loughran "Lithium ion batteries found to produce toxic gases," Engineering & Technology, October 24, 2016, https://eandt.theiet.org/content/articles/2016/10/lithium-ion-batteries-found-to-produce-toxic-gases/. Accessed September 2018.

184 Larrson, Andersson, Blomqvist and Mellander, "Toxic fluoride gases emissions from lithium ion battery fires," 2017, nature.com, https://www.nature.com/articles/s41598-017-09784-z. Accessed September 2018.

185 Financial Times "Rise of Electric Cars Poses Battery Recycling Challenge." https://www.ft.com/content/c489382e-6b06-11e7-bfeb-33fe0c5b7eaa

186 The Guardian "The Rise of Electric Cars Could Leave us with a Big Battery Waste Problem" https://www.theguardian.com/sustainable-business/2017/aug/10/electric-cars-big-battery-waste-problem-lithium-recycling

187 Financial Times, "Rise of Electric Cars…"

188 Institute for Energy Research, "The Afterlife of Electric Vehicles: Battery Recycling and Repurposing." May 2019. https://www.instituteforenergyresearch.org/renewable/the-afterlife-of-electric-vehicles-battery-recycling-and-repurposing/. Accessed May 2020.

189 Fleetcarma.com, "How Electric Vehicle Batteries are Reused or Recycled." July 2018. https://www.fleetcarma.com/electric-vehicle-batteries-reused-recycled/. Accessed May 2020.

190 Alternative Fuels Data Center, "Batteries for Hybrid and Plug-In Electric Vehicles." See also Hybrid Geek,

"3 Types of Hybrid Batteries," https://www.thehybridgeek.com/3-types-of-hybrid-batteries/. January 28, 2019. Accessed May 2020.

191 Ecocycle, "Recycling electic car batteries: How to recycle EV, HEV, PHEV and eBike batteries." May 2, 2017. https://ecocycle.com.au/batteries/recycling-electric-car-batteries-recycle-ev-hev-phev-ebike-batteries/. Accessed May 2020. See also "Influence of Batteries Weight on Electric Automobile Performance," Engineering for Rural Development, www.tf.llu.lv/conference/proceedings2017/ Papers/N316.pdf, which gives passenger car batteries a weight range of 385-544 kilograms (847-1,197 pounds). Accessed May 2020.

192 According to 2016 a "Car and Driver" article, the battery for the hybrid Chevy Mailu weighed 95 pounds; for the hybrid Chevy Volt, 403 pounds; and for the all electric Chevy Bolt, 948 pounds. "Battery Taxonomy: The Difference between Hybrid and EV Batteries." October 2016. https://www.caranddriver.com/news/a15345397/battery-taxonomy-the-differences-between-hybrid-and-ev-batteries/. Accessed May 2020.

193 Porvali et. al., "Nickel Metal Hydride Battery Waste: Mechano-hydrometallurgical Experimental Study on Recycling Aspects." January 2020. Springer Link, https://link.springer.com/article/10.1007/s40831-019-00258-2. Accessed May 2020.

194 Environmental issues with disposal of lithium ion batteries, see Loughran, above; and Larrson, Andersson, Blomqvist & Mellander, above. Disposal issues with disposal of nickel-metal-hydride batteries, Mahmud et. al, "Comparative Life Cycle Environmental Impacts Analysis of Lithium Ion and Nickel-Metal Hydride Batteries." Macquarie University, 2019. https://www.mdpi.com/2313-0105/5/1/22. Accessed May 2020.

195 Metheys et. al, "Comparison of the Enironmental Impact of 5 Electric Vehicle Battery Technologies Using LCA." Conference Paper, 2006. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.421.8032&rep=rep1&type=pdf. Accessed May 2020.

196 US EIA, "Hydraulically fractured weill provide two-thirds of US natual gas production," 5/5/2016, https://www.eia.gov/todayinenergy/detail.php?id=26112. Argnonne National Labora

197 "What is hydraulic fracturing?," US Geological Survey (USGS), https://www.usgs.gov/faqs/what-hydraulic-fracturing?qt-news_science_products=0#qt-news_science_products. Accessed April 2020.

198 Wikipedia, "Hydraulic fracturing," https://en.wikipedia.org/wiki/Hydraulic_fracturing. Accessed April 2020.

199 Horizontal drilling: Robert Rapier in Forbes, "No, the EPA has not actually changed its conclusion on risks of fracking to drinking water." December 15, 2016. https://www.forbes.com/sites/rrapier/2016/12/15/yes-direct-injection-of-fracking-fluid-into-groundwater-causes-contamination/#147f3b2c19d3. Accessed April 2020.

200 Robert Howarth in Energy and Emissions Control Technologies, "Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy." October 8, 2015. https://www.eeb.cornell.edu/howarth/publications/f_EECT-61539-perspectives-on-air-emissions-of-methane-and-climatic-warmin_100815_27470.pdf Accessed December 2020.

201 NRDC, "We could do a lot more to regulate fracking," 7/18/2018, https://www.nrdc.org/stories/we-could-do-lot-more-regulate-fracking. Accessed December 2020.

202 Howarth et. al., "Should Fracking Stop?." Nature, 9/14/2011, https://www.nature.com/articles/477271a. Accessed December 2020.

203 Earthworks, "Fracking related earthquakes." https://www.earthworks.org/issues/fracking_earthquakes/.

Accessed December 2020.

204 Thomas Kaplan in The New York Times, "Citing health risks, Cuomo bans fracking in New York State." December 17, 2014. https://www.nytimes.com/2014/12/18/nyregion/cuomo-to-ban-fracking-in-new-york-state-citing-health-risks.html

205 Kristen Lombardi in State Impact, "New York's heralded fracking ban isn't all it's cracked up to be." https://stateimpact.npr.org/pennsylvania/2017/12/08/new-yorks-heralded-fracking-ban-isnt-all-its-cracked-up-to-be/. Accessed April 2020.

206 Justine Calma, "This proposed pipeline is fracturing New York's green new image." Grist, April 2019, https://grist.org/article/this-proposed-pipeline-is-fracturing-new-yorks-green-new-image/. Accessed April 2020.

207 US EIA profile for New York State, https://www.eia.gov/state/analysis.php?sid=NY#87

208 What could happen vs. what has happened: Rapier in Forbes, op. cit.

209 Complaints vs. proven incidents: David Ropeik on Big Think, "Fracked up news coverage of fracking." https://bigthink.com/risk-reason-and-reality/fracked-up-news-coverage-of-fracking. Accessed July 2018.

210 US EPA, "Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States." Executive Summary, page 1. Dec. 2016. https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=332990. Accessed December 2018.

211 Ibid, page 2.

212 Natural Resources Defense Council, "Fracking 101." https://www.nrdc.org/stories/fracking-101

213 Steven Mufson, "Methane leaks offset much of the climate change benefits of natural gas, study says." Washington Post, 6/24/2018, https://www.washingtonpost.com/business/economy/methane-leaks-offset-much-of-the-benefits-of-natural-gas-new-study-says/2018/06/21/e381654a-7590-11e8-b4b7-308400242c2e_story.html. Accessed December 2020.

214 NRDC, "We can do a lot more to regualte fracking." 7/18/2018, https://www.nrdc.org/stories/we-could-do-lot-more-regulate-fracking

215 Carter & McEnaney, "The Climate crisis requires that we move away from gas." NRDC, 7/26/2019, https://www.nrdc.org/experts/sheryl-carter/climate-crisis-requires-we-move-away-gas. Accessed December 2020.

216 Environmental Defense Fund, "Oil and gas: how we're reducing harmful impacts." https://www.edf.org/climate/oil-and-gas. Accessed December 2020.

217 Energy Vision calculation based on ANL GREET 1 (2020), Inputs Tab, Section 4: Natural Gas, values for CH4 leakage and venting for conventional natural gas recovery and shale gas recovery (grams of methane per MMBTU natural gas).

218 California Air Resources Board, "LCFS Pathway Certified Carbon Intensities," https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities; download Current Fuel Pathways spreadsheet. Accessed December 2020.

219 US Energy Information Administration, "Monthly Biodiesel Production Report," data table 1, https://www.eia.gov/biofuels/biodiesel/production/. Accessed September 2021.

220 Alternative Fuels Data Center, "Biodiesel blends." https://afdc.energy.gov/fuels/biodiesel_blends.html. Accessed April 2020.

221 US DOE, Alternative Fuels Data Center, "Fuel Prices," https://afdc.energy.gov/fuels/prices.html. Accessed June 2021.

222 Biodiesel Magazine, "NYC is Heating Up with America's Advanced Biofuel," http://www.biodieselmagazine.com/articles/2516876/nyc-is-heating-up-with-americaundefineds-advanced-biofuel, 1/3/2020, Accessed June 2021.

223 City of Madison, "Madison's Fleet Goes to B20 Across the Board – the Second Public Fleet in Wisconsin History," October 2019, https://www.cityofmadison.com/fleet-service/blog/madisons-fleet-goes-to-b20-across-the-board-the-second-public-fleet-in-wisconsin. Accessed June 2021.

224 California Air Resources Board, "LCFS Pathway Certified Carbon Intensities." Accessed September 2021.

225 Energy Vision estimate. According to Neste's Q3 2020 quarterly report presentation (link at https://www.neste.com/for-media/material), the company produced 2.846 million tons of "renewable products" in 2019. Assuming these to be metric tons (Neste is a Finnish company), and that the entire production is renewable diesel (that Neste also makes renewable aviation fuel), this equates to about 7.5 barrels per ton, for a total of 21.345 million barrels; CME Group Conversion Calculator, https://www.cmegroup.com/tools-information/calc_refined.html.

226 Energy Vision calculation based on daily capacities in Exhibit 1, "Regulations to drive US renewable diesel capacity growth through 2025." ADI Analytics, February 2020, https://adi-analytics.com/2020/02/10/regulations-to-drive-u-s-renewable-diesel-capacity-growth-through-2025/. Calculations assume production 365 days/year and 42 gallons per barrel. Accessed December 2020.

227 US EIA, "Adjusted Sales of Distillate Fuel Oil by End Use." Based on on-highway use, assumes 42 gallons per barrel. https://www.eia.gov/dnav/pet/pet_cons_821dsta_dcu_nus_a.htm. Accessed December 2020.

228 Jon Leonard and Patrick Crouch, "The potential—and challenges—of renewable diesel fuel for heavy duty vehicles." January 2017(?). Gladstein, Neandross & Associates, https://www.gladstein.org/the-potential-and-challenges-of-renewable-diesel-fuel-for-heavy-duty-vehicles/. Accessed December 2020.

229 Ernst, "What you need to know about renewable diesel."

230 Shelley Ernst, "Is renewable diesel still a 'miracle fuel'?" Government Fleet, January 2020, https://www.government-fleet.com/348069/is-renewable-diesel-still-a-miracle-fuel. Accessed April 2020.

231 City of Knoxville Fleet Services, "Renewable Diesel Test: testing an alternative fuel in the City of Knoxville fleet." http://tngreenfleets.org/tncleanfuels.org/docs/Renewable-Diesel-Report_City-of-Knoxville_6-15-17.pdf. Accessed July 2018.

232 Based on personal communications with NYC Department of Citywide Administrative Services Fleet Management office, Spring 2018.

233 NGT News, "California's Turlock Scavenger Tours "Easy Switch" to Renewable Diesel," Ocotber 2018, https://ngtnews.com/californias-turlock-scavenger-touts-easy-switch-to-renewable-diesel. Accessed June 2021.

234 NGT News, "Oakland and renewable diesel: 'Not a single downside.'" March 26, 2018. https://ngtnews.com/oakland-and-renewable-diesel-not-a-single-downside. Accessed June 2021.

235 Joshua W. Shaw, California Transit Association, "Setting the record straight on bus electrification." https://caltransit.org/news-publications/our-newsroom/press-releases/setting-the-record-straight-on-bus-electrification/#.WnSCRbMYjjI.linkedin. February 2018. Accessed May 2020.

236 Hovi et al., "Experiences from Battery Electric truck users in Norway." World Electric Vehicle Journal, 10/11/2019, https://www.mdpi.com/2032-6653/11/1/5/pdf

237 Argonne AFLEET 2020, "Background Data" tab.

238 Based on Gladstein, Neandross and Associates, "Electric Vehicle Charging Guidebook for Medium and Heavy Duty Commercial Fleets," 2019, https://www.gladstein.org/gna_whitepapers/electric-vehicle-charging-guidebook-for-medium-and-heavy-duty-commercial-fleets/. Based on GNA's Guidebook, Class 8 refuse trucks would probably call for a charge rate of 20+ kW to cover day to day variation, which enters the realm of DC fast charging, as opposed to regular AC charging. Individual charging statioins of this type cost from $10,000 to $40,000, and we have used $25,000 as the midpoint.

239 Boston Consulting Group, "The Costs of Revving Up the Grid for Electric Vehicles," Dec. 20 2019, https://www.bcg.com/publications/2019/ costs-revving-up-the-grid-for-electric-vehicles. Accessed November 2021.

240 BYD Brochure for Class 8 truck, http://en.byd.com/usa/wp-content/uploads/2018/07/8tt_redesign6-23-18.pdf. 145 miles is the average of the fully loaded range and the half loaded range. Accessed August 2018, unavailable as of April 2020.

241 Based on Seattle City Light, "Business Rates," http://www.seattle.gov/city-light/business-solutions/business-billing-and-account-information/business-rates#seattlebusinesses,as of September 2021. Assumes off peak fueling at off peak rate of $.0646 per kWh, an average of the "Large City of Seattle" and "Large Downtown Network" rates.

242 MOTIV press release, "First all-electric garbage truck in North America, developed by Motiv Power Systems, hits the road in Chicago." http://www.motivps.com/motivps/pressreleases/first-all-electric-garbage-truck-in-north-america-developed-by-motiv-power-systems-hits-the-road-in-chicago/. Accessed August 2018.

243 Information from telephone interview with Manager of Fleet Services for City of Chicago, 8/3/18.

244 Personal communication, LASAN, September 2018.

245 Personal communication, MOTIV Power System sales, May 2020.

246 Personal communication, VP of Sales and Marketing for a national refuse truck manufacturer (see footnote 1).

247 Heavy Duty Trucking, "Los Angeles completes battery-electric refuse truck demo," June 7, 2017. https://www.truckinginfo.com/140793/los-angeles-completes-battery-electric-refuse-truck-demo. Accessed April 2020.

248 John O'Dell, "BYD Launches new electric garbage truck, but what's next?" Trucks.com, November 21st, 2016. https://www.trucks.com/2016/11/21/byd-electric-garbage-truck/. Accessed September 2018.

249 E-mail exchange with Kim Tran, Solid Resources Manager at LASAN, September 2018.

250 Personal communication, February 2020.

251 Cole Rosengren, "Electric refuse trucks on the road or on the way in rising number of states."

252 Personal communication, DSNY Bureau of Motor Equipment, May 2020.

253 "First Mack LR electric model begins service with New York City Department of Sanitation." Mack press release, Spetember 23, 2020. https://www.macktrucks.com/mack-news/2020/first-mack-lr-electric-model-begins-service-with-new-york-city-department-of-sanitation/

254 "New York City Department of Sanitation to purchase seven Mack LR Electric models," Cision PR Newswire, 6/30/2021, https://www.prnewswire.com/news-releases/new-york-city-department-of-sanitation-to-purchase-seven-mack-lr-electric-models-301322822.html. Accessed September 2021.

255 "Mack delivers LR Electric model to Republic Services to begin real-world trials." Mack press release, 10/06/2020, https://www.macktrucks.com/mack-news/2020/mack-delivers-lr-electric-model-to-republic-services-to-begin-real-world-trials/

256 Jenifer Lee, "Sanitation Department unveils hybrid garbage trucks." NY Times, 8/25/2009. https://cityroom.blogs.nytimes.com/ 2009/08/25/sanitation-dept-unveils-hybrid-garbage-trucks/

257 AFLEET 2020, Background Data tab.

258 Diesel $4.50 per gallon, US EIA, "Petroleum and Other Liquids: US No. 2 Diesel Retail Prices," https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMD_EPD2D_PTE_R10_DPG&f=M. Accessed Septemeber 2018.

259 NYC Department of Citywide Services, "Fleet Sustainability, Citywide Fact Sheet." http://www.nyc.gov/html/dcas/downloads/pdf/ fleet/nyc_fleet_sustainability_facts.pdf. Accessed August 2018.

260 Wrightspeed press release, November 2, 2016: "Wrightspeed and the Ratto Group deploy first Route enabled refuse truck." https://www.wrightspeed.com/releases/wrightspeed-ratto-group-deploy-first-route-enabled-refuse-truck. Accessed August 2018.

261 Kevin McCallum, "Santa Rosa-based Ratto Group selling North Bay garbage empire to Recology of San Francisco." The Press Democrat, January 28, 2017. https://www.pressdemocrat.com/news/6600779-181/santa-rosa-based-ratto-group-selling. Accessed August 2018.

262 Kevin McCallum, "Santa Rosa-based Ratto Group selling North Bay garbage empire to Recology of San Francisco." The Press Democrat, January 28, 2017. https://www.pressdemocrat.com/news/6600779-181/santa-rosa-based-ratto-group-selling. Accessed August 2018.

263 "Stealthy Wrightspeed ready to make noise in refuse," Fleet Owner, May 19, 2021, https://www.fleetowner.com/emissions-efficiency/article/21164594/stealthy-wrightspeed-ready-to-make-noise-in-refuse. Accessed November 2021.

264 Eric Linzus, "HRB- Hydrostatic regenreative braking system: the hudraulic hybrid drive from Bosch Rexroth." https://www.iswa.org/fileadmin/galleries/General%20Assembly%20and%20WC%202010%2011%20Ham-

burg/Presentations/Lindzus.pdf. 2011? Accessed May 2020.

265 Nicole Danna, "Hybrid garbage trucks saving Miami-Dade big money."

266 Personal communication, DSNY Bureau of Motor Equipment, May 2020.

267 AFLEET 2020, Background Data tab.

268 Personal communication, DSNY Bureau of Motor Equipment, May 2020.

269 RunWise launched in 2010, "Parker Hannifin gaining traction with RunWise HD hydraulic hybrid," Green Car Congress, October 2014. https://www.greencarcongress.com/2014/10/20141009-runwise.html. Accessed May 2020.

270 Personal communication, May 2020.

271 Parker Hannifin, "Parker Hannifin Hydraulic Transmission Outperforms Proposed EPA Emissions Regulations for Heavy-duty Trucks." September 2015, https://www.parker.com/portal/site/PARKER/menuitem.7322a3ce19c3a730b5170b9d237ad1ca/?vgnextoid=761d42f0a7a6e210 VgnVCM10000048021dacRCRD&vgnextfmt=EN&vgnextitem=96b8c90375584510VgnVCM100000e6651dacRCRD&newsroom=Y&vgnextcat=News%20Release%20Details. Accessed May 2020.

272 Personal communication, Parker Hannifin Hydraulic Pump and Power Systems, May 2020.

273 Lightning Hybrids name change, "Lightning Hybrids renames itself Lightning Systems; rollout of new lineup of fleet efficiency products," Green Car Congress, May 2017, https://www.greencarcongress.com/2017/05/20170503-lightning.html; Lightning Systems doing electric drivetrain conversions, Lightning Systems website, https://lightningsystems.com/. Both accessed May 2020.

274 "Lightning Systems Company Background," https://lightningsystems.com/wp-content/uploads/2020/01/Lightning_Systems_company_ background_Jan2020.pdf. Accessed May 2020.

275 NGV America, https://www.ngvamerica.org/vehicles/refuse/. Accessed April 2020.

276 AFLEET 2020, Background Data tab. AFLEET provides a range of $550,000 to $850,000 — $700,000 is the midpoint. AFLEET measures fuel flow in gasoline gallon equivalents (GGE), Energy Vision has applied a conversion factor of 1.14 GGE per DGE.

277 Alternative Fuels Data Center, "Fuel Prices, National Average Price between July 1and July 15, 2021." https://afdc.energy.gov/fuels/prices.html ..

Energy-equivalent basis: AFDC denominates the price of CNG in gasoline gallon equivalents (GGEs). There are 1.14 GGEs to the diesel gallon equivalent (DGE), and Energy Vision has multiplied AFDC's GGE price for CNG by 1.14 to make the price comparison on the basis of a DGE.

278 US EIA, "US On-Highway Diesel Fuel Prices," full history, https://www.eia.gov/petroleum/gasdiesel/. May 2020.

279 Ibid.

280 Personal communication, Kevin Campbell, Manager of Fleet Services, Chicago, August 2018.

281 Personal communication, Kevin Campbell, May 2020.

282 Thi Dao, "Milwaukee Rolls Out Last of 22 CNG Refuse Trucks." Government Fleet, May 20, 2015. https://www.government-fleet.com/129561/milwaukee-rolls-out-last-of-22-cng-refuse-trucks. Accessed May 2020. $271,000 each, Energy Vision calculation based on reported total cost of $5.97 million for 22 trucks.

283 Now have 68 trucks, 11 chassis delivered, fueling stations open to public, personal communication with Fleet Operations Manager, May 2020.

284 NGV Journal, "City in Virginia refuels its millionth gallon of CNG," January 2019, http://www.ngvjournal.com/s1-news/c4-stations/city-in-virginia-refuels-its-millionth-gallon-of-cng/

285 Waste Pro, "Waste Pro recognized for eco-friendly operations," November 2018, https://www.wasteprousa.com/waste-pro-recognized-for-eco-friendly-operations/

286 Waste Management media room, https://mediaroom.wm.com/waste-management-opens-100th-natural-gas-fueling-station/

287 NYC Department of Sanitation, "2020 Annual Report on Alternative Fuel Vehicle Programs." February 2021. https://a860-gpp.nyc.gov/downloads/d791sj08f?locale=en. Accessed September 2021.

288 Personal communication with DSNY Bureau of Motor Equipment, July 2021.

289 Waste Management press release, "Waste Management unveils $30 million renewable natural gas (RNG) facility in Louisville, Kentucky." June 5, 2018. http://mediaroom.wm.com/waste-management-unveils-30-million-renewable-natural-gas-rng-facility-in-louisville-kentucky/. Accessed June 2020.

290 Cole Rosengren, "Waste Management CEO projects fleet could be 75% CNG in 2021." Waste Dive, 2.3.20, https://www.wastedive.com/news/waste-management-ceo-projects-75-percent-cng-fleet-2021/571273/

291 "Republic Services Strengthens Commitment To Reduce Fleet Emissions With Expanded Adoption Of Redeem™ Renewable Natural Gas (RNG)," Clean Energy Fuels, https://www.cleanenergyfuels.com/press-room/republic-services-strengthens-commitment-to-reduce-fleet-emissions-with-expanded-adoption-of-redeem-renewable-natural-gas-rng, February 2019.

292 "How Republic Services is fueling the future through its landfill gas to RNG projects," Waste Today. https://www.wastetodaymagazine.com/article/republic-services-aria-energy-bp-landfill-gas-rng/

293 Energy Vision, "The Latest Anaerobic Digester in the United States sets the Green Pace in Perris, California." https://energy-vision.org/ pdf/CR&R_Project_Profile.pdf. Accessed July 2018.

294 Waste 360, "California refuse vehicles go full circle with Redeem RNG," March 2019, https://www.waste360.com/fuel/california-refuse-vehicles-go-full-circle-redeem-rng

295 Government Fleet, "Calif. City switches to renewable natural gas," August 2017, https://www.government-fleet.com/141937/calif-city-switches-to-renewable-natural-gas

296 US EPA, "Particulate Matter (PM) Basics," https://www.epa.gov/pm-pollution/particulate-matter-pm-basics. Accessed May 2020.

297 US EPA, "Black Carbon Research," https://www.epa.gov/air-research/black-carbon-research. Accessed May 2020.

298 Calculated by subtracting non-ULSD refuse trucks from 180,000 total refuse trucks, "Real-world activity, fuel use, and emissions of heavy-duty compressed natural gas refuse trucks," Gurdas S. Sandhu,.H. Christopher Frey, Shannon Bartelt-Hunt and Elizabeth Jones. https://www.sciencedirect.com/science/article/abs/pii/S0048969720368546

299 Based on assumption that practically all diesel fuel on the market is a biodiesel blend, Hearst Autos Research "Biodiesel vs. Diesel: Everything You Need to Know," Car and Driver, April 22, 2020, https://www.caranddriver.com/research/a31883731/biodiesel-vs-diesel/