# memorandum

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**To** Hillel Hammer (NYSERDA)

**From** David Cooley, Kait Siegel, and Elizabeth Shenaut (Abt Associates)

**Subject** Effect of Low-Carbon Fuels and Energy Technologies on Co-Pollutant Emissions

NYSERDA has asked Abt Associates to investigate the effect that certain low-carbon fuels and energy technologies have on direct emissions of air pollutants other than carbon dioxide ($CO_2$), including nitrogen oxides ($NO_x$), sulfur dioxide ($SO_2$), fine particulate matter ($PM_{2.5}$), volatile organic compounds (VOCs), and ammonia ($NH_3$). This memorandum summarizes our review of the current literature on these effects.

## Key Takeaways

| | |
|---|---|
| Renewable Diesel | Use of renewable diesel in older (uncontrolled) internal combustion **engines** (ICEs), largely non-road engines, may result in some decrease in $PM_{2.5}$ emissions, but no significant difference was found relevant to most on-road or newer non-road engines. $NO_x$ may increase or decrease relative to fossil diesel depending on the engine and use characteristics. There may be some reduction in toxic emissions (e.g., benzene), but this is not expected to result in substantial health benefits, as diesel is not a large source of air toxics in New York. |
| Biodiesel | Use of biodiesel in in older (uncontrolled) **ICEs**, largely non-road engines, might have some $PM_{2.5}$ benefits, but no significant difference was found relevant to most on-road or newer non-road engines. $NO_x$ emissions may increase relative to fossil diesel depending on the engine and use characteristics and needs to be further investigated. Similar to renewable diesel, there may be some reduction in toxic emissions (e.g., benzene) relative to fossil diesel. Use of biodiesel in **boilers** has not been well studied, but it may not provide substantial emission reduction benefits compared to ultra-low sulfur distillate fuel oil. |
| Renewable Natural Gas (RNG) | Emissions from RNG combustion are likely to be very similar to those from natural gas. |
| Biogas | Use of biogas in **ICEs** may result in little change in $NO_x$ emissions relative to natural gas. Effect on $PM_{2.5}$ emissions are unknown. Emissions of $SO_2$ may substantially increase due to higher sulfur content of gas. Emissions also depend on the feedstock used to produce the fuel. |
| Hydrogen Combustion | Use of hydrogen as a fuel likely reduces $SO_2$ and $PM_{2.5}$ compared to natural gas in all end uses. For **ICEs**, hydrogen may increase $NO_x$ compared with natural gas. Uncontrolled $NO_x$ emissions from hydrogen combustion **boilers and turbines** may be higher (compared with natural gas) but well-understood control technologies achieve almost negligible $NO_x$ emissions in demonstration-phase turbine applications. For **appliances**, such as stoves and grills, hydrogen combustion increases $NO_x$ compared to natural gas. |
| Hydrogen-enriched Natural Gas | Use of hydrogen-enriched natural gas (or RNG) is likely to increase $NO_x$ or leave it unchanged in **appliances** such as stoves and ovens compared with natural gas. It may decrease $NO_x$ in **ICEs** compared with natural gas. It does not substantially reduce $SO_2$ emissions, and its effect on $PM_{2.5}$ emissions has not been well studied. It may reduce $PM_{2.5}$ but increase ultrafine particulate matter with unknown net health effect. Similar to pure hydrogen, combustion of hydrogen-enriched natural gas has the potential to increase $NO_x$ emissions in boilers and turbines. |
| Carbon Capture and Storage (CCS) | Pollutant emission reductions depend on the type of CCS technology used. **Pre-combustion** CCS (applicable to coal only) reduces $NO_x$ and $SO_2$. **Oxy-combustion** reduces those pollutants and $PM_{2.5}$. **Post-combustion** (currently the most common technology) does not reduce pollutant emissions other than $CO_2$ but is typically paired with pollutant controls to increase CCS efficiency. Post combustion with amine scrubbing could increase ammonia ($NH_3$) emissions and increase secondary $PM_{2.5}$ formation. Emission reductions may be dependent on fuel type, such as larger $SO_2$ emission reductions for coal compared to natural gas. |

## Background

In 2019, New York State (NYS) passed the Climate Leadership and Community Protection Act (Climate Act), which set strict decarbonization goals for the state: a 40% reduction in annual greenhouse gas (GHG) emissions relative to 1990 levels by 2030, and 85% by 2050.[1]

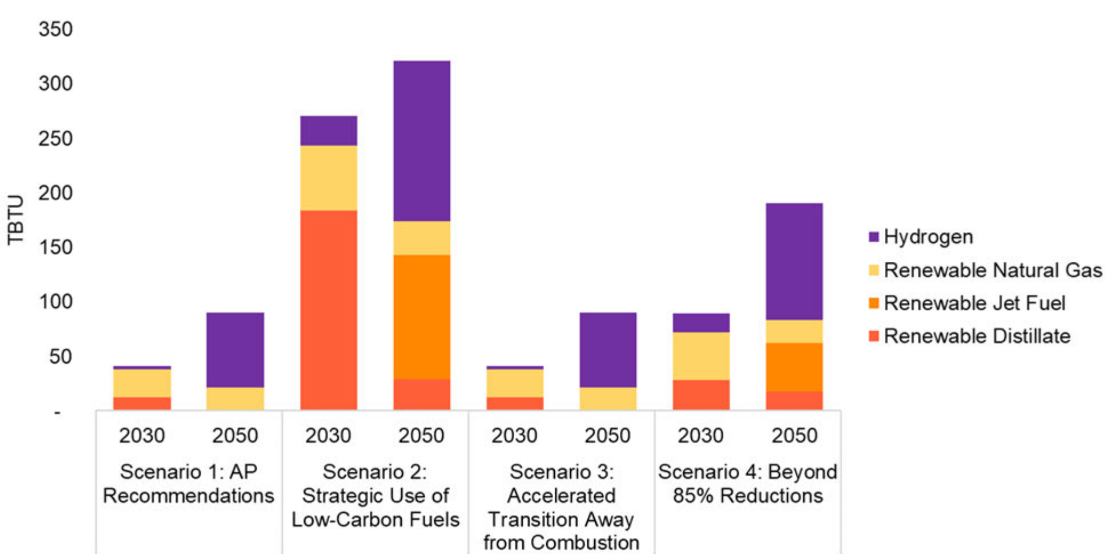
The Climate Act also requires—

- Reductions in emissions of toxic air contaminants and other air pollutants ("co-pollutants") in disadvantaged communities;
- That activities undertaken to comply with ensuing regulations do not result in a net increase in co--pollutant emissions or otherwise disproportionately burden disadvantaged communities; and
- The prioritization of measures to maximize net reductions of GHG emissions and co-pollutants in disadvantaged communities, and encourages early action to reduce GHG emissions and co-pollutants.

To understand ways in which it could meet the GHG targets, NYS conducted analyses looking at the State's current policies and additional measures it could implement. The *New York State Climate Action Council Draft Scoping Plan Integration Analysis Technical Supplement* outlines multiple scenarios that NYS could implement in the electricity, transportation, buildings, and industrial sectors to reach its decarbonization goals.[2]

Switching to low-carbon fuels (including electricity) and decarbonizing the electricity supply are key elements of this transformation. In addition to electrification, the analysis identified the potential need for increases in the use of alternative or low-carbon fuels, such as RNG, renewable diesel, and hydrogen (Figure 1), as well as the use of alternative energy technologies, including CCS. These measures would reduce emissions of carbon dioxide ($CO_2$), methane ($CH_4$), and other potent GHGs.

*Figure 1. Potential Bioenergy and Green Hydrogen Utilization*




**Note**: Includes hydrogen demand for transportation and industry but not electricity generation. Wood continues to be used across all scenarios (~30 TBtu in 2050).

**Source**: *New York State Climate Action Council Draft Scoping Plan Integration Analysis, 2021*

Pollutants, such as $NO_x$, $SO_2$, $PM_{2.5}$, VOCs, and $NH_3$, are another category of air pollutants that react to form ozone ($O_3$) and secondary $PM_{2.5}$ in the atmosphere. Exposure to increased ambient levels of $O_3$ and $PM_{2.5}$ have been linked to adverse health effects in numerous studies, and can exacerbate respiratory diseases, including asthma and bronchitis, lead to heart attacks and other cardiopulmonary issues, and result in premature mortality.[3,4,5,6,7] In some cases, reductions in $PM_{2.5}$ are also indicative of reductions in other toxic pollutants, especially in cases where combustion is eliminated.

Reductions in GHG emissions do not necessarily directly correspond to reductions in other pollutants, and some decarbonization measures may in fact increase some pollutant emissions relative to the reference case. It is therefore important for NYS to understand the effect of using low-carbon fuels and energy technologies on co-pollutant emissions to gain a better understanding of the full effects of potential actions.

This review of the scientific literature summarizes the effect of low-carbon fuels and energy technologies on various pollutant emissions, including biodiesel and renewable diesel, biogas and RNG, hydrogen and hydrogen-enriched natural gas, and CCS. In particular, the review focused on emissions of $NO_x$, $SO_2$, and $PM_{2.5}$. We identified some studies that included results for other pollutants, such as VOCs, $NH_3$, and carbon monoxide (CO), as well as hazardous air pollutants, which are also outlined below. On the whole, while the current literature offers some insight into the potential for health benefits (or lack thereof) by identifying increases or decreases in emissions of pollutants of concern resulting from the use of low-carbon fuels in lieu of fossil fuels and the use of energy technologies, this is still a growing field of research.

## Limitations

This memorandum reviews the existing literature on air pollutant emissions from the use of low-carbon fuels and technologies. This review generally does not examine the lifecycle emissions impacts of the low-carbon fuels or technologies, focusing instead on the local emissions from the use of the specific fuel or technology.

The focus of this review was on particulate matter (PM) and its precursors, but some other results are reported as well. Fossil fuel and low-carbon fuel combustion results in emissions of many air pollutants that are not discussed here, including metals, acid gases, and other hazardous air pollutants. The research into each of these fuels and technologies is ongoing and therefore the conclusions drawn in this memorandum could be updated as new research emerges.

In addition, it is important to note that the research reviewed here focuses on air pollutant emissions and not exposure to indoor and outdoor air pollution. Such an assessment of exposure would require air quality modeling to determine how changes in emissions from these low-carbon fuels and technologies result in changes in air quality and effect public health in the context of all sources, conditions, and underlying health data. This memorandum can help inform such analyses and evaluations.

## Renewable Diesel Fuels and Biodiesel

Biodiesel is a fuel that can be made from vegetable oils, animal fats, or waste grease from restaurants. Renewable diesel is a synthetic fuel that can also be made from biomass feedstocks, and is further processed to make it chemically similar to fossil diesel. In both cases, the use of these fuels may reduce GHG emissions. Biodiesel is currently blended into transportation fuels and heating oil in NYS. For example, heating oil in NYC currently includes 5% biodiesel, which will increase to up to 20% by 2030. Currently, renewable diesel is not broadly available and is relatively expensive.

Research suggests that there could be differences in pollutant emission rates between the different fuel types. This section summarizes the literature on emissions from renewable diesel used in ICEs and biodiesel used in ICEs and boilers. Note that the literature search did not reveal studies on renewable diesel use in boilers.

### *Renewable Diesel in Engines*

The literature is mixed on whether renewable diesel increases or decreases on-road engine $NO_x$ emissions. Two separate studies from the California Air Resources Board (CARB) compared renewable diesel to ultra-low sulfur diesel (ULSD), which has a maximum sulfur content of 15 ppm by volume and is usually lower. One of these studies found a decrease in $NO_x$ emissions of up to 18% from renewable diesel compared to ULSD,[8] while a later study (from 2021) found no significant difference in $NO_x$ emissions from renewable diesel.[9]

Another study showed an increase in $NO_x$ emissions of 26% from renewable diesel compared to fossil diesel, while a fourth study found little difference in $NO_x$ emissions between renewable diesel and fossil diesel (ranging from a 5% decrease for renewable diesel to no change).[10,11] Similarly, a recent article that reviewed over 60 studies found both increases and decreases in $NO_x$ emissions, ranging from a 30% decrease to a 26% increase.[12] This review article notes several possible explanations for the uncertainty surrounding whether renewable diesel increases or decreases $NO_x$ emissions, such as the type of engine (heavy duty or light duty), whether the engine is turbocharged or naturally aspirated, and the type of fuel injection system.

PM emissions from renewable diesel used in on-road engines are typically similar to or lower than those of fossil diesel. The two studies from CARB found no significant difference in PM emissions between renewable diesel and ULSD in newer heavy-duty engines equipped with diesel particle filters (DPFs). (Diesel particle filters are a necessary component of almost all new engines, required to meet emission standards, but are generally not included in older engines unless they have been retrofitted.) Both CARB studies found that in older engines not equipped with a DPF, there was a significant reduction in PM emissions of up to 38% from renewable diesel compared to ULSD. These results indicate that the use of DPFs reduces PM emissions from both fuel types to a degree that there are no discernible differences in emissions between renewable diesel and ULSD.

A separate study found that renewable diesel increases the regeneration efficiency of DPFs, reducing overall PM emissions by up to 40%.[10] However, another study found similar PM emissions between renewable diesel and ULSD when using a DPF.[13] A review article on emissions from renewable diesel found PM reductions of approximately 43% from renewable diesel compared to fossil diesel, although this review article included engines both with and without DPFs.[12]

Ultimately, it appears that renewable diesel does not have a strong impact on PM emissions in newer engines equipped with DPFs, which accounts for the vast majority of on-road heavy-duty engines. However, it could have a reduction of up to 40% in older engines not equipped with DPFs, some of which are still in use in nonroad applications.

We did not find studies examining the effect of renewable diesel on $SO_2$ emissions from on-road engines, but we do note that many of the studies of other pollutants stated that renewable diesel has a very low sulfur content, comparable to ULSD. Since NYS requires the use of ULSD, the $SO_2$ emissions from renewable diesel are likely to be similar to those of the fossil diesel currently in use in the state.

Although the literature search was focused on criteria pollutant emissions and their precursors, our research did identify some data suggesting that 20% renewable diesel mixed with fossil diesel could substantially decrease hazardous air pollutant emissions, including benzene (0.6-14%), toluene (24-27%), and xylene (23-36%) compared to 100% fossil diesel.[14] However, EPA's 2017 National Emissions Inventory shows that less than 5% of the emissions of these pollutants are from diesel vehicles; the majority of emissions of these pollutants are from gasoline combustion. Therefore, this potential benefit is not expected to be significant.

### *Biodiesel in Engines*

Similar to renewable diesel, biodiesel combustion typically results in either lower PM emissions or no significant difference compared with fossil diesel in ICEs (and reduces VOC and CO emissions, although both are already relatively low from diesel combustion).[15] The CARB analyses discussed above for renewable diesel also found no significant difference in PM emissions from biodiesel compared to ULSD in heavy-duty engines equipped with DPFs.[8,9] These studies did find a decrease in PM emissions of up to 25% for 20% blends of biodiesel (B20) and 60% from 100% biodiesel (B100) in older engines not equipped with a DPF. A separate meta-analysis comparing B20 to fossil diesel found slight decreases in total PM emissions by up to 6%.[16] However, when this meta-analysis limited their review to only more recent studies using ULSD, the authors found no significant difference in total PM emissions. One study looking at B20 found that biodiesel increases the regeneration potential of DPFs, resulting in up to a 67% decrease in PM emissions compared to fossil diesel from engines with DPFs, but only 25% in engines without DPFs (note that in absolute terms, the reduction in engines without DPF would be much larger as DPFs reduce PM emissions on the order of 92-98%).[17] In addition, a study of different blends of biodiesel showed that blends with higher percentages of biodiesel (up to B100) resulted in faster regeneration times for the DPFs and lower PM emissions.[18] There may also be differences in PM emissions due to the feedstocks used to produce the biodiesel, with studies using biodiesel produced from animal fats resulting in lower PM emissions on average compared to biodiesel produced from soybeans or rapeseed.[12]

As with renewable diesel, the studies have found both increases and decreases in $NO_x$ emissions from biodiesel use in engines. One of the CARB analyses found increases in $NO_x$ emissions of approximately 4-6% for B20 and up to 47% for B100.[8] Other studies have found both higher and lower $NO_x$ emissions from biodiesel of +/-10%, depending on the blend, vehicle speeds/load, and the feedstock used to produce the biodiesel.[19,20,21] The majority of studies appear to find that biodiesel increases $NO_x$ emissions, although the studies do not agree on the magnitude of the increase, with differences ranging on average between 2 and 10% compared to fossil diesel,[22,23] with one study finding an increase of up to 77%.[10] The recent meta-analysis comparing B20 to fossil diesel found an increase in $NO_x$ emissions from biodiesel of 2-4%.[16] Moreover, the differences are heavily dependent on vehicle speeds and engine loads, with one study finding that biodiesel slightly decreases $NO_x$ emissions in engines at low and medium speeds compared to fossil diesel, but increases emissions by 15% or more at higher speeds, leading to an overall increase in $NO_x$ emissions.[24]

Biodiesel also has a lower sulfur content than fossil diesel,[25] and therefore likely has comparable $SO_2$ emissions to those of renewable diesel and ULSD.[26]

Additionally, B20 biodiesel could increase benzene emissions by up to 60% and decrease toluene by 15-77% and xylene by 20-63%.[14] As discussed above, less than 5% of the emissions of these pollutants are from diesel vehicles; the majority are from gasoline combustion. Therefore, similar to renewable diesel, this potential benefit from biodiesel is not expected to be significant.

***Biodiesel in Boilers***

We found no studies that directly compared biodiesel to ULSD in boilers. There are several studies that compared biodiesel to fossil diesel with higher sulfur contents, which have typically found that biodiesel results in lower emissions. For example, one study compared biodiesel to #6 fuel oil with a very high sulfur content (3%) in boilers, finding lower $NO_x$ emissions of 20% (for B20) to 50% (for B100) compared to #6 fuel oil.[27] This study also found lower $PM_{2.5}$ and $SO_2$ emissions from biodiesel; however, the comparison fuel was #6 fuel oil with 3% sulfur content, which has significantly more sulfur than currently allowed in NYS.

Another study that compared #2 fuel oil (but not ULSD) to B20 found an average decrease of 15.7% for PM, 19.7% for $SO_2$, and no change for $NO_x$.[28]

A separate study that compared fossil-based ULSD to fossil-based higher-sulfur #2 fuel oil (up to 0.5% sulfur content) in boilers found that $PM_{2.5}$ emissions from boilers decline linearly with declines in sulfur content in fuel oil.[29]

There is one study that compared #2 fuel oil with a sulfur content of 30 ppm to B100 with an even higher sulfur content (60 ppm), and still found that biodiesel in boilers reduced PM emissions by nearly 60% and no significant change for $NO_x$.[30]

The literature appears to indicate that biodiesel does not have a large change in $NO_x$ emissions, while there can be a reduction in $SO_2$ and PM emissions that is likely due to differences in sulfur content of fuels. However, the question of the impact on emissions when compared to ULSD—the fuel currently used in NYS—cannot be answered directly without additional research.

## Biogas and Renewable Natural Gas

Biogas is generated via a process known as anaerobic digestion, in which organic matter, typically agricultural waste, municipal organic waste, or wastewater, breaks down in an oxygen-free environment. Biogas is usually composed of 50-70% methane and 40-50% carbon dioxide, along with other trace gases. Biogas can be processed to remove non-methane components, creating RNG (also known as biomethane), which can be injected into traditional natural gas pipelines.

The literature on emissions from biogas and RNG focuses mainly on emissions of $CO_2$ and $CH_4$. However, our research identified a limited number of studies that compare pollutant emissions from biogas and RNG to those of fossil natural gas in ICEs, which are summarized below. We did not find studies on RNG or biogas use in boilers.

### *Renewable Natural Gas in Engines*

We identified relatively few studies that compared pollutant emissions from RNG to fossil natural gas. One study we identified suggests that RNG has similar or slightly lower $NO_x$ emissions compared to fossil natural gas in passenger vehicle engines.[31] Because RNG has been processed to be chemically similar to fossil natural gas, there is no reason to assume that emissions would be significantly different.[32]

Similarly, RNG has been processed to remove impurities such as hydrogen sulfide, and therefore has a similar sulfur content as natural gas.[32] Sulfur in natural gas is mainly due to the odorant (mercaptan) added to the gas to help detect leaks. For this reason, the $SO_2$ emissions from RNG are likely similar to those from natural gas, unless the odorant used is different. In general, $SO_2$ emissions from natural gas are very low.

We did not find specific studies on $PM_{2.5}$ emissions, but the literature suggests that there is no clear relationship between emissions of ultrafine PM (UFP) and RNG or natural gas combustion.[33] Emissions of UFP from motor vehicles fueled with compressed natural gas (CNG), RNG, and biogas were not found to be significantly different. While ultrafine particles are not regulated like $PM_{2.5}$ and $PM_{10}$, a 2013 study found these particles of diameter equal to or less than 0.1 micrometers can be more toxic due to their large surface area relative to volume and increased reactivity. The study found that these particles can travel beyond the lungs into the bloodstream and other organs.[34]

### *Other Uses of Renewable Natural Gas*

We did not find research on RNG combustion in boilers or turbines, but based on the limited research on engines, we suspect there is no substantial difference in emissions between RNG and natural gas in these applications.

The study cited above that investigated UFP emissions from RNG combustion also looked at RNG use in cooking stoves and water heaters.[33] UFP emissions rates from these appliances were similar for RNG and natural gas. The cooking stove (GE, Model # JGBS10DEKWW) tests showed significantly higher emission rates for RNG from one facility (of three types of RNG tested from different facilities), which the authors linked with higher sulfur content in that specific fuel (RNG sulfur = 2.8 ppm and CNG sulfur = 0.5ppm). Emissions of UFP from water heaters (Rheem, Model #XG40T06EC36U1) were not significantly different between CNG and the different types of RNG tested.

### *Biogas in Engines*

Emissions of $NO_x$ from biogas, like those from RNG, do not differ significantly from emissions from natural gas. One study found that $NO_x$ exhaust concentrations from the same ICE used to generate electricity were 38 parts per million by volume (ppmv) when fueled with natural gas and 37 ppmv from biogas.[35] The same study found that emissions of CO and $SO_2$ from biogas may be slightly higher than emissions from natural gas. Higher $SO_2$ concentrations are likely due to incomplete removal of hydrogen sulfide ($H_2S$) and other reduced sulfur compounds from biogas during the pre-treatment stage; $H_2S$ is a byproduct of sulfur compounds in biogas feedstocks undergoing anaerobic digestion.

Combustion of biogas may have a different emissions profile depending on the feedstocks used to produce the gas, as well as the end use of the gas. One study found that CO, $NO_x$, $SO_2$, and PM emissions from biogas produced from different types of organic waste varied widely when combusted for heating and electricity generation (Table 1).[36] The same study also compared different end uses of biogas, and found that emissions from heating and electricity were generally lower than emissions from light- and heavy-duty transportation. However, this study did not compare biogas emissions to natural gas emissions.

*Table 1. Fuel Cycle Emissions from a Large-Scale Heat and Electricity System, Fueled Using Biogas Generated from Various Feedstocks.*

| Feedstock | Emissions (mg/MJ) | | | |
|---|---|---|---|---|
| | CO | $NO_x$ | $SO_2$ | PM |
| Ley crops | 38 | 240 | 22 | 7.8 |
| Straw | 34 | 160 | 6.4 | 4.0 |
| Tops and leaves of sugar beet | 31 | 160 | 7.3 | 3.8 |
| Liquid manure | 29 | 130 | 5.3 | 3.6 |
| Food industry waste | 24 | 99 | 4.2 | 2.8 |
| Municipal organic waste | 36 | 160 | 6.3 | 3.7 |

**Source**: Borjesson and Berglund, 2006.

## Hydrogen and Hydrogen-Enriched Pipeline Gas

Combustion of pure hydrogen fuel does not produce most pollutants, but can produce $NO_x$ in substantial quantities depending on the end use of the fuel. Renewably produced hydrogen can also be blended into natural gas pipelines to reduce the GHG emissions intensity of pipeline-delivered fuel.

Literature on combustion of hydrogen and hydrogen-enriched natural gas focuses primarily on implications for GHG emissions, not for other pollutants. This literature review found some studies that examined emissions of $NO_x$ and $PM_{2.5}$, but did not find information on $SO_2$ emissions.

### *Hydrogen Combustion*

Most studies on hydrogen fuel are in the context of vehicle engines. One study showed that hydrogen ICEs produce slightly less $NO_x$ than fossil fuel-powered alternatives, including CNG, gasoline, and diesel.[37] The same study showed that total lifecycle $NO_x$ emissions can be higher than fossil alternatives, depending on how the hydrogen is produced. Note that hydrogen fuel cells are an electricity source that does not include combustion and is therefore a clean alternative for vehicles. This literature review focuses on combustion fuels, and therefore we did not include any studies on fuel cells.

A limited number of studies tested emissions from stoves and other equipment where combustion occurs in the open air rather than an enclosed chamber. A 1994 study tested a hydrogen-fueled barbecue at the cooking surface and found $NO_x$ at concentrations between 80 to 160 ppm, compared to 15 to 25 ppm for natural gas.[38] A 2005 study that modeled emissions of a small burner found that hydrogen as a fuel resulted in $NO_x$ concentrations of 537 ppm at the point of combustion, whereas methane as a fuel produced $NO_x$ concentrations of 28 ppm.[39] The study concluded that the increase in $NO_x$ from burning hydrogen was due to the fuel's high combustion temperature, which forms more nitric oxide (NO) than lower temperature combustion.

Hydrogen contains no sulfur, and therefore has no $SO_2$ emissions. The $SO_2$ emissions from natural gas are small and are mostly due to the sulfur-containing odorant added to the fuel to help detect leaks. If hydrogen fuel uses mercaptan or another similar sulfur-based odorant to help detect leaks, the $SO_2$ emissions could be similar to those of natural gas.

We did not find significant research into combustion of hydrogen in gas turbines or boilers. One study conducted a modeling exercise estimating that $NO_x$ emissions from hydrogen combustion in one boiler type without adjustment of combustion or emission controls can be up to seven times higher than $NO_x$ emissions from natural gas combustion.[40] For turbines, one report from an industry group indicates that $NO_x$ emissions from hydrogen combustion can be up to twice as high as those from natural gas combustion in turbines, due to the higher combustion temperature of hydrogen.[41] A separate report states that the $NO_x$ emissions could be at least as high from turbines that use gaseous fuel that is partially or (theoretically) fully hydrogen compared with turbines that use natural gas.[42] The report does not quantify the emissions difference, but ongoing demonstration projects with dry low-$NO_x$ technology have shown the potential to reduce or eliminate $NO_x$ emissions from turbines by mixing the hydrogen fuel with an excess of air during combustion to reduce combustion temperatures.[43] Other $NO_x$ control options for hydrogen turbines mentioned in the industry report include injecting water or steam diluents into the turbine.[42]

Although we did not find research on oxy-combustion for hydrogen turbines, this could be another approach to suppress $NO_x$ formation from hydrogen turbines. A 2015 U.S. Department of Energy report indicated that demonstration-phase projects have been able to operate a hydrogen turbine that reduces $NO_x$ to single-digit parts per million, although the report did not specify whether this turbine was operated with pure hydrogen or which $NO_x$-reduction method was used.[44]

#### *Hydrogen-Enriched Natural Gas*

The literature does not indicate a consensus on whether $NO_x$ emissions increase or decrease as a result of adding hydrogen to natural gas or RNG. Experiments published in 2019 and 2020 with a commercial oven and room furnace found that $NO_x$ emissions were unaffected on an energy input basis when hydrogen was added to natural gas.[45,46] An experiment published in 1998 with residential cooking devices and boilers found that $NO_x$ emissions stayed the same or decreased slightly with hydrogen-enriched natural gas.[47] A 2005 study found that $NO_x$ levels increased as the amount of hydrogen in the fuel increased, from 96 ppm with 10% hydrogen and 90% methane, to 228 ppm with a 50% blend of each fuel, to 375 ppm with 70% hydrogen and 30% methane.[39] In this study, the temperature increased as the hydrogen proportion of the fuel increased, causing more thermal NO formation and leading to more $NO_x$. Another experiment on emissions from domestic boilers published in 2020 notes that hydrogen-enriched natural gas tends to have higher combustion temperatures, leading to increase $NO_x$ emissions. However, the same study found that the air-fuel ratio could be managed to reduce $NO_x$ production.[48]

The literature review did not identify any information on the implications of hydrogen-enriched natural gas on $PM_{2.5}$ emissions. However, a 2016 study added hydrogen to CNG in vehicle engines and found reductions in $PM_{2.5}$ emissions compared with traditional CNG. The study also found that while the overall PM mass decreased, adding hydrogen resulted in a larger proportion of the PM appearing as extremely small ultrafine particles.[49]

The literature search found no information on the change in $SO_2$ emissions due to hydrogen enrichment of pipeline gas. However, as with hydrogen combustion, if the same sulfur-containing odorants are used in the gas, the $SO_2$ emissions will likely not change significantly.

Similar to hydrogen combustion, use of hydrogen-enriched natural gas in turbines results in $NO_x$ emissions at least as high as those of natural gas, although control technologies, such as dry low-$NO_x$ technology, are in development.

## Carbon Capture and Storage

In the Pathways Integration Analysis, NYS uses CCS as a control strategy for GHG emissions only in the industrial sector. Note that the focus in this review is on the fuels and technologies themselves; CCS does require power, and additional emissions would therefore occur from the power source if power is provided from combustion sources (whether on- or off-site). While CCS technologies reduce $CO_2$ emissions, they do not necessarily capture other air pollutants.[50] In many cases, CCS technologies can be paired with  pollutant controls, such as electrostatic precipitators for $PM_{2.5}$ and flue gas desulfurization units for $SO_2$, to increase the efficiency of the $CO_2$ capture.[51] Because these technologies are not yet in widespread use, there are uncertainties about their effect on  pollutant emissions. Most research on the co-pollutant impact of CCS have focused on the electricity generation sector, with less focus on the use of CCS in industrial settings.

The electricity generation sector uses three main types of CCS technologies: pre-combustion, post-combustion, and oxy-combustion. Pre-combustion involves using high pressure to turn a solid fuel such as coal into its components in gas form. Subsequently, the $CO_2$ in the gasified fuel is separated and removed prior to combustion of the remaining gaseous fuel components, which are mostly hydrogen. (Note that coal is no longer used for electricity generation in New York State.) Post-combustion involves capturing $CO_2$ from the exhaust of the combustion process, and it is currently the most commonly used CCS approach in power plants. Oxy-combustion involves burning fuel in an environment of nearly pure $O_2$ in order to increase the efficiency of the removal of $CO_2$ from the flue gas emissions after combustion. The flue gas from with oxy-combustion has minimal nitrogen content, so the $CO_2$ is captured by condensation of the water from the flue gas.[52]

The industrial sector can use the same CCS technologies as the electricity sector, although some industries can implement CCS more easily than others, and the specific approach to CCS may vary by subsector.[53] The chemicals subsector already separates $CO_2$ as part of many chemical production processes, such as ethanol production.[54] Additionally, CCS in the industrial sector can be more complex than in the electricity sector because $CO_2$ emissions can result from non-combustion processes. Cement production facilities, for example, tend to emit more “process emissions” of $CO_2$ than combustion emissions.[53] The literature does not address the way these nuances would affect co-pollutant emissions from facilities with different CCS technologies and different fuel types. As with the power sector, studies of CCS in the industrial sector have focused on coal more than other fuels.

### *Pre-Combustion*

Pre-combustion CCS technologies (used only for solid fuels like coal) can alter the amount of some co-pollutants produced per unit of fuel input. In pre-combustion CCS, $NH_3$ and $SO_2$ are almost completely removed prior to combustion and therefore greatly reduced from emissions created during combustion. There appears to be little to no change in $PM_{2.5}$ emissions from pre-combustion CCS, but $SO_2$ emissions can be reduced by 40-50% and $NO_x$ by 70-80% in coal-fired units.[55,56]

### *Oxy-Combustion*

In oxy-combustion, virtually no nitrogen is present during fuel combustion, reducing $NO_x$ emissions by 50% or more. Emissions of $SO_2$ and $PM_{2.5}$ can be reduced by 90% or more compared to systems without CCS.[55,57,58] The literature indicates that these reductions apply to both coal and natural gas combined cycle systems. However, because natural gas has much lower $SO_2$ and $PM_{2.5}$ emissions compared to coal, the absolute emission reductions (in tons) would be much lower for natural gas systems. In addition, flue gas from oxy-combustion is smaller in volume due to the absence of nitrogen, making the exhaust more concentrated with pollutants. In these conditions, pollution control technologies for removal of $SO_2$, $NO_x$, and $PM_{2.5}$ are more effective.[59]

### *Post-Combustion*

In post-combustion $CO_2$ capture, the chemistry of the fuel and its combustion remain unchanged from systems without CCS, so co-pollutants are created in the same amount per unit of input energy as in a facility without CCS. Post-combustion $CO_2$ capture technology is the easiest to add as a retrofit to an existing facility, and is therefore currently the most common approach to CCS.[60]

One type of post-combustion CCS technology that is currently at commercial scale, amine scrubbing, requires that $SO_2$ concentrations be minimized before the scrubber can effectively capture $CO_2$.[51,55] The literature on the use of CCS in the electric power sector reports that plants with this type of control technology must employ improved $SO_2$ removal systems to operate efficiently, and thus these plants emit less $SO_2$ into the atmosphere per unit of input energy than plants without CCS. For coal power plants retrofitted with post-combustion CCS, $SO_2$ could be reduced by more than 90%.[55,56] These controls would also reduce $SO_2$ emission at natural gas combined cycle plants, but the absolute emissions reductions would be much lower compared to coal plants due to the very low sulfur content of natural gas.

Amine scrubbing can also increase $NH_3$ emissions, as the amine solvent can oxidize to $NH_3$ in the atmosphere.[61] $NH_3$ reacts with $SO_2$ and $NO_x$ in the atmosphere to form ammonium sulfate and ammonium nitrate, which are key components of secondary $PM_{2.5}$ formation. An increase in $NH_3$ emissions could therefore lead to increases in secondary $PM_{2.5}$ if excess $SO_2$ and $NO_x$ are present to react with the $NH_3$.

Pre-treatment of exhaust gases, including removal of $PM_{2.5}$ and $NO_x$ prior to $CO_2$ capture, can further increase the efficiency of $CO_2$ control but are not a requirement of the technology.[56] CCS plants that include such measures could emit less $PM_{2.5}$ and $NO_x$ per unit of input energy than non-CCS plants.[51] Additionally, some post-combustion $CO_2$ capture technologies remove $NO_x$ or $SO_2$ simultaneously with $CO_2$ removal.[56] Finally, while traditional desulfurization technologies only remove $SO_2$ from exhaust gases, researchers are looking into single-technology solutions that would also capture $NO_x$.[62]

There is little literature on the effect of CCS on VOCs, and so these effects are uncertain. One study that analyzed VOCs indicates that VOC emissions per unit of input energy are likely to remain the same or decrease with the addition of CCS.[55]

There is also the potential for post-combustion CCS to alter the dispersion of air pollution emissions from exhaust stacks, due to reductions in emissions flow rates and stack temperatures following the diversion of the exhaust gas into the carbon capture process.[63] However, the only source we found on this issue raised it as a theoretical concern that could result in higher concentrations nearer to the emissions source, but it did not quantify the effects. More research is needed to understand these effects. Note that plume rise can also be adjusted using stack design and flow control.

## Conclusions

This literature review investigated the effect of the use of low-carbon fuels and energy technologies air pollutant emissions other than $CO_2$. Our review identified a number of studies that explore these effects. Our findings are summarized in Table 2, which shows that some fuels and technologies result in net emission reductions of $NO_x$, $SO_2$, and $PM_{2.5}$ relative to fossil fuels or standard technologies. However, in some cases we identified studies that showed both increases and decreases in emissions of some pollutants, particularly $NO_x$. Overall, we note that research into the effect of these fuels and technologies on co-pollutant emissions is ongoing, and more studies are needed to draw any definite conclusions.

For low-carbon fuels, co-pollutant emissions are heavily dependent upon the fuel type, the end use or application of the fuel, and in some cases the feedstock(s) used to generate the fuel. Renewable diesel and hydrogen use in engines may both result in net emission reductions and ensuing health benefits. Research on biodiesel use was not conclusive. Most studies indicate a reduction in $SO_2$ and $PM_{2.5}$ emissions, but some studies indicate a potential increase in $NO_x$ emissions. Biogas was the only low-carbon fuel type that appeared to result in disbenefits due to higher $SO_2$ emissions. However, biogas can be processed to produce RNG by removing sulfur, which will result in no additional emissions compared to fossil natural gas.

The effect of CCS technologies on emissions of co-pollutants depends on the type of CCS technology. Pre-combustion and oxy-combustion technologies result in $NO_x$ and $SO_2$ emission reductions due to pre-removal of nitrogen and/or sulfur from the combustion gas. Post-combustion CCS technology, which is currently the most common technology, results in air pollution emission reductions only if additional pollution control measures are implemented in conjunction with CCS.

In many cases, these low-carbon fuels and power generation technologies are not yet in widespread commercial use. Additional research should be conducted into the co-pollutant impacts of these fuels and technologies as they become more widely used.

*Table 2. Reported effect of Low-Carbon Fuels and Energy Technologies on Pollutant Emissions Relative to Equivalent Fossil Fuels.*

| Alternative Fuel or Technology | Fossil Fuel or Technology Compared | Application | $NO_x$ | $SO_2$ | $PM_{2.5}$ |
|---|---|---|---|---|---|
| Renewable diesel | Diesel* | Internal combustion engine (R100, pre-2007) | 22% decrease to 25% increase | Possible decrease, but likely not a large change if both are ULSD | Up to 40% decrease |
| | | Internal combustion engine (R100, post-2007) | 22% decrease to 25% increase | Possible decrease, but likely not a large change if both are ULSD | Little to no change |
| Biodiesel | Diesel* | Boiler | Little to no change | Possible decrease, but likely not a large change if both are ULSD | Possible decrease, but potentially not a large change if both are ULSD |
| | | Internal combustion engine (B20, pre-2007) | Likely +/- 10% change (up to 20% increase for B100) | Possible decrease, but likely not a large change if both are ULSD | 20-25% decrease (up to 60% decrease for B100) |
| | | Internal combustion engine (B20, post-2007) | Likely +/- 10% change (up to 47% increase for B100) | Possible decrease, but likely not a large change if both are ULSD | Little to no change |
| Renewable natural gas | Natural gas | Internal combustion engine | Little to no change | Little to no change | Little to no change |
| | | Boilers, other combustion | Unknown | | |
| Biogas | Natural gas | Internal combustion engine | Little to no change | 75% average increase for biogas | Unknown |
| Hydrogen | Natural gas | Internal combustion engine /other | Potential to double emissions | 100% decrease ($H_2$ has no $SO_2$ emissions) but very small benefit | Unknown, but potentially up to 100% decrease, although may increase ultrafine |
| Hydrogen-enriched natural gas | Natural gas | Internal combustion engine | Slight decrease to slight increase | Unknown, but likely not a large change | Unknown |
| | | Appliances (e.g., stoves, ovens, furnaces) | 20% decrease to 15% increase | Unknown, but likely not a large change | Unknown |
| Carbon capture and storage | System w/o CCS | Pre-combustion | 70-80% decrease | 40-50% decrease | Little to no change |
| | | Oxy-combustion | ~50% decrease | ~75% decrease | 80-90% decrease |
| | | Post-combustion | <5% decrease | 40-80% decrease (higher end assumes additional $SO_2$ controls to increase CCS efficiency; absolute effect depends on fuel) | Little to no change |

* Renewable diesel and biodiesel were compared to fossil diesel (D100) in the studies; however, most diesel available today is B5. Therefore, the benefits of renewable diesel and biodiesel may be slightly lower when compared to B5. Note also that studies have found that biodiesel in engines can improve the performance of diesel particle filters, potentially improving the benefits from PM reductions.

*Table 3. Assessment of Overall Net Benefit or Disbenefit from each Fuel or Technology Type and Application.*

| Alternative Fuel or Technology | Fossil Fuel or Technology Compared | Application | Overall Net Benefit or Disbenefit |
|---|---|---|---|
| Renewable diesel (R100) | Diesel* | Internal combustion engine (pre-2007, mostly non-road) | Likely a net benefit due to decreased PM emissions |
| | | Internal combustion engine (post-2007) | Unclear; potential for increased $NO_x$ emissions with no significant change in PM emissions |
| Biodiesel (B20) | Diesel* | Boiler | Unclear; this application has not been studied for ULSD |
| | | Internal combustion engine (pre-2007, mostly non-road) | Likely a net benefit due to decreased PM emissions |
| | | Internal combustion engine (post-2007) | Unclear; potential for increased $NO_x$ emissions with no significant change in PM emissions |
| Renewable natural gas | Natural gas | Internal combustion engine | No substantial difference |
| | | Boilers, other combustion | Unknown; not well studied |
| Biogas | Natural gas | Internal combustion engine | Possibly a net disbenefit for biogas because of higher $SO_2$ emissions |
| Hydrogen | Natural gas | Internal combustion engine /other | Likely a net benefit, depending on the $NO_x$ emissions |
| Hydrogen-enriched natural gas | Natural gas | Internal combustion engine | Unknown; depends on $NO_x$ emissions |
| | | Appliances (e.g., stoves, ovens, furnaces) | Unknown; depends on $NO_x$ emissions |
| Carbon capture and storage | System w/o CCS | Pre-combustion | Net benefit |
| | | Oxy-combustion | Net benefit |
| | | Post-combustion | Possibly a net benefit, assuming use of $SO_2$ controls and fuels such as coal with higher $SO_2$ emissions. Amine scrubbing will increase $NH_3$ |

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