Memo

To: VT PUC for Opinion Dynamics Draft TRM
Fr: CHS Technical Advisory Group
Re: Upstream Avoided Methane Emissions Impacts for Biofuels
Dt: 31 October 2024

The relevant statutory references, the options considered, and the pros and cons discussed for each option are summarized below. See the TAG's vote on these options at the end of the memo.

Question for TAG Consideration:

Should upstream avoided emissions impacts that occur during feedstock preparation or fuel production steps be recognized in the Clean Heat program's lifecycle analyses of eligible biofuels?

- **OPTION 1:** Upstream methane emission associated with biofuels should be included.
- **OPTION 2:** Upstream methane emissions associated with biofuels should be excluded.

Background:

The Vermont Clean Heat Standard (CHS) is required to include a framework for assessing the lifecycle greenhouse gas (GHG) impacts of the various resources which generate clean heat credits for program compliance. For biofuels, it is standard for such lifecycle assessments to include the upstream GHG impacts that occur during all aspects of energy production. This includes feedstock preparation, fuel production, and transport.

During the CHS development process there has been extensive consideration regarding the inclusion of the upstream emissions impacts—often referred to as "counterfactual" emissions impacts—as part of the program's lifecycle assessment framework. These impacts typically occur during the feedstock preparation or fuel production steps and are limited to certain feedstocks and technological pathways. The most common example is avoided methane emissions in the organic waste and livestock sectors that result from the capture and use of those emissions for productive purposes.

This document summarizes the main arguments in favor of and opposed to recognizing these upstream emissions impacts associated with biofuels within the CHS's lifecycle assessment framework. This document does not resolve any differences between the positions on matters of statutory interpretation, policy, analytical methods, and underlying facts.

Relevant Statutory Language:

30 V.S.A. § 8127 (g) Emissions Schedule.

> (2) For each fuel pathway, the schedule shall account for greenhouse gas emissions from biogenic and geologic sources, including fugitive emissions and loss of stored carbon. In determining the baseline emission rates for clean heat measures that are fuels, emissions baselines shall fully account for methane emissions reductions or captures already occurring, or expected to occur, for each fuel pathway as a result of local, State, or federal legal requirements that have been enacted or adopted that reduce greenhouse gas emissions."

30 V.S.A. § 8127 (j) Delivery in Vermont. Clean heat credits shall be earned only in proportion to the deemed or measured thermal sector greenhouse gas emission reductions achieved by a clean heat measure delivered in Vermont. Other emissions offsets, wherever located, shall not be eligible measures."

Option 1. Include upstream avoided methane emissions

Discussion

Arguments favoring recognition of upstream emissions associated with biofuels feedstock preparation or production steps impacts include the following:

- Anaerobic digestion of manure and organic waste consumes/destroys volatile solids that if stored/managed in an anerobic environment would otherwise produce methane. Therefore, production of biogas/RNG from manure/organic wastes avoids methane emissions when baseline management of those wastes produces methane.
- All other state-level portfolio standard-style programs which include lifecycle emissions assessments for biofuels also include counterfactual emissions impacts. With this in mind, exclusion of counterfactuals in Vermont would cause the CHS to lack the same price signals that attract the lowest carbon-intensity biofuel, potentially making Vermont less competitive as a destination for biofuels emissions reduction pathways.
- Reconciliation of program-based lifecycle carbon accounting and state-level inventories has been accomplished in other states for a number of years. Analogous precedent can be seen in California, Oregon, and Washington. Note that this must occur in Vermont regardless of whether counterfactuals are included.
- Program targets (i.e., the rate of decline of the cap) must be adjusted to preemptively account for expected lifecycle emissions from biofuels, which can include estimates for counterfactuals.
- Given the urgency of the climate crisis, a secondary goal to reducing emissions in the thermal sector should be to incentivize as many GHG reductions as possible. Doing so

is implied by the use of lifecycle carbon intensity scoring within the CHS. Including counterfactuals for methane avoidance is a significant lever for doing so.

- Providing value for upstream methane avoidance related to fuel production will provide an important pathway for Vermont dairy farmers to reduce their emissions. This should be an important consideration given the prominence of Vermont's dairy industry in the state and its vulnerability to climate change and out-of-state competition.
- Diversion of organic waste away from landfills as a feedstock for anaerobic digestion is a primary biogas/RNG production pathway with a volumetric and emissions reduction potential far greater than animal manure. This pathway is growing in prominence within North America and has allowed sustainability leaders like Denmark to achieve a landfill rate of less than 10% (some estimates show under 1%). Inclusion of the avoided methane benefits when assessing the lifecycle carbon intensity of such pathways will result in a carbon intensity score that values food waste diversion over landfilling. Exclusion of this counterfactual will treat landfilling and organic waste diversion the same. At this stage the act of landfilling remains less costly than organic waste diversion, meaning that the CHS will almost certainly select RNG derived from business-as-usual landfilling practices as the lowest hanging fruit, foregoing a significant opportunity to reduce methane emissions and improve the broader environmental impacts of organic waste disposal.
- Avoided methane emissions continue to remain a component of lifecycle assessment for RNG pathways in the GREET model according to updates by Argonne in 2024. Most recently, Argonne's September 2024 presentation[1] shows updated values for RNG after a year-long literature review of "state-level manure management data" (slide 10). R&D GREET values remain inclusive of avoided methane crediting (slide 13).
- State-level implementation of the Clean Water Act (including in Vermont) often results in large farms being required to have long term (e.g., >180 days) manure storage capacity, in order to remain in compliance with state level waste management permits. The primary purpose of these mandates is to mitigate adverse water quality impacts associated with manure spreading by requiring farms to spread manure at times that will not result in substantial run-off (e.g., when ground isn't frozen). As a result, large farms need large manure storage facilities (i.e., lagoons) to comply with permitting requirements and manure methane is often an in-direct consequence of otherwise well-intentioned state and federal policy. Like most businesses, farms need a business case to make substantial investments in sustainability improvements, including methane reduction. The financial incentives provided by clean and low-

[1] Ou, Logwen, Hao Cai, Michael Wang, "Life-Cycle Greenhous Gas Results of Fuels from Waste Streams and Biomass with the R&D GREET Model," Argonne National Laboratory, September 11, 2024, at chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.gti.energy/wp-content/uploads/2024/09/39-tcbiomass2024-Presentation-Longwen-Ou.pdf.

carbon fuel programs that include avoided methane crediting have proven effective at providing that business case to farms across the US, as evidenced by the growth of the number of anaerobic digesters on farms since implementation of such programs.

- As other jurisdictions have done, a CHS regulation could be written to cease crediting avoided methane emissions in the event that regulations are implemented in Vermont that require farms to reduce their manure methane emissions because such a regulation would make them no longer additional to business-as-usual. For example, the CARB LCFS regulation allows avoided methane crediting that is voluntary but in the event of a mandate the project would not be able to claim avoided methane reductions in subsequent crediting periods.[2]

Option 2: Exclude upstream avoided methane emissions

Arguments for excluding the upstream avoided methane emissions impacts of eligible fuels from the Clean Heat program's lifecycle analyses include the following:

- Act 18 explicitly requires that the CI phase-out account for the specific fuel pathway, which includes feedstock generation. However, as a matter of LCA boundary-setting, if the scope will recognize the benefits of avoided methane emissions, it should also account for other upstream emissions associated with the facilities and sources that produce the methane in the first place. For example, emissions from land-use changes (LUC), while sometimes indirect/induced, are caused by the existence of the biofuel: but for that biofuel, land use change would not have happened. Related to avoided methane, if the emissions from the manure lagoon are accounted for and credited to the CI, then it would also be appropriate to account for the other emissions associated with the agricultural operations. LCA standards would do this through the process of co-product credit accounting. Generally, the first step would be to consider whether the manure is a waste from the agricultural operation or a co-product. While LCA standards typically don't apply upstream emissions to recycled waste products, if the manure were considered a co-product, then LCA standards would allocate a portion of the upstream emissions to the manure. In the case of dairy manure the other primary co-products from the farm would likely be milk and meat. The appropriate portion of upstream emissions allocated to each would be determined through the process of co-product credit allocation.
- Including negative carbon-intensity scores could have a distortionary impact on the CHS program. If the CHS program credits emissions from avoided methane, including out-of-state (or at least out-of-sector) avoided methane, but those emissions reductions don't show up in Vermont's GHG inventory for the thermal sector, then the CHS program might need to compensate in some way for creating clean heat credits

[2] CARB LCFS regulation Section 95488.9(f). Pg. 143. Available at: https://ww2.arb.ca.gov/sites/default/files/2020-07/2020_lcfs_fro_oal-approved_unofficial_06302020.pdf.

that are not associated with Inventory emissions reductions. Requiring greater overall emissions reductions to compensate for some of those reductions not showing up in the Vermont GHG inventory could lead to higher costs for Vermont customers.

- Including negative carbon intensities for avoided methane could make electrification and weatherization pathways less competitive with RNG, even though those measures are more directly tied to Vermont's thermal sector emissions than avoided methane releases from agriculture.
- To the extent that the CHS program allows crediting for avoided emissions, the counterfactual case should be CO_2 rather than CH_4 emissions:
    - There is an active debate about whether it is appropriate to assume that animal management systems are allowed to vent methane to the atmosphere. If these systems were required to reduce their methane emissions (e.g. through covered lagoon digesters) and the resulting biogas was flared to destroy the methane, which is technically feasible where RNG production occurs, then the methane would be converted to CO_2 emissions, reducing its warming impact. In this case, the counterfactual scenario would be CO_2 rather than CH_4 emissions, resulting in less negative and potentially positive carbon intensities. A recent report from Argonne National Labs indicates that the GREET team is considering whether to change its assumptions about how to characterize counterfactual emissions from manure management systems to address this issue.[3]
    - Paying methane producers for their waste methane in effect pays polluters for producing pollution. As we think about aligning overall policy objectives with climate targets, it is likely that regulation will eventually be needed to require basic controls on pollution sources where it is technically feasible to do so, for example by requiring methane flaring at manure lagoons and landfills. However, if RNG facilities encode their right to emit methane in order to be paid for clean heat credits, they will have an incentive to oppose future methane regulations that would reduce their funding.

TAG Vote on 10/31/2024: 10 votes are considered a strong majority and "could live with" indicates support despite a preference for an alternate option. 14 members were present.

- **Include avoided methane emissions**: 7 votes
- **Exclude avoided methane emissions**: 5 votes (Michelle Keller, Emily Gruber, Emily Levin, Ken Jones, Brian Woods)
- **Abstain:** 2 votes (Jared Ulmer & Emily Roscoe)

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[3] Argonne National Laboratory, "Summary of Expansions and Updates in R&D GREET® 2023," Section 2.1.4, December 2023, pages 5-6, at https://www.osti.gov/servlets/purl/2278803.

MEMO

To: VT PUC for Opinon Dynamics draft TRM
Fr: CHS Technical Advisory Group
Re: **Step Down of Biofuel Carbon Intensities 2031-2050**
Dt: October 31, 2024

The.relevant.statutory.references?.the.options.considered?.and.the.pros.and.cons.discussed. for.each.option.are.summarized.below¡.See.the.TAG"s.Vote.on.these.options.at.the.end.of.the. memo¡

Question for TAG Consideration:

How should carbon intensity (CI) threshold values for liquid and gaseous biofuels decline from below 60 in 2030 to below 20 in 2050?

- **Option 1**: Linear annual decline in CIs from 2030 to 2050.
- **Option 2:** Step down in CIs from below 60 in 2030-2049 to below 20 in 2050.
- **Option 3:** The PUC publishes, not later than January 1, 2030, an alternative rate of decline whose trajectory (1) is determined with reference to the contributions to GWSA-mandated emissions reductions that these fuels should reasonably be expected to make and (2) is informed by other relevant factors, such as expectations of improvements in combustion efficiency. One alternative, for instance, is a step function defined by multiples of years (e.g., three, five, or seven).

The table below illustrates how the carbon intensity value relative to No. 2 fuel oil would decline from 2025 to 2050 under Options 1 and 2.

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Linear Decline (Option 1)	80	80	80	80	80	60	58	56	54	52	50	48	46	44	42	40	38	36	34	32	30	28	26	24	22	20
Step Down (Option 2)	80	80	80	80	80	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	20

Relevant Sections of CHS Statute for Reference:

30 V.S.A. § 8127(f) requires the Commission to establish and publish maximum allowable carbon intensity values (relative to No. 2 fuel oil in 2023) for eligible clean heat fuels. It reads in full as follows:

(f) Carbon intensity of fuels.

(1) To be eligible as a clean heat measure, a liquid or gaseous clean heat measure shall have a carbon intensity value as follows:

(A) below 80 in 2025;

(B) below 60 in 2030; and

(C) below 20 in 2050, provided the Commission may allow liquid and gaseous clean heat measures with a carbon intensity value greater than 20 if excluding them would be impracticable based on the characteristics of Vermont's buildings, the workforce available in Vermont to deliver lower carbon intensity clean heat measures, cost, or the effective administration of the Clean Heat Standard.

(2) The Commission shall establish and publish the rate at which carbon intensity values shall decrease annually for liquid and gaseous clean heat measures consistent with subdivision (1) of this subsection as follows:

(A) on or before January 1, 2025 for 2025 to 2030; and

(B) on or before January 1, 2030 for 2031 to 2050.

(3) For the purpose of this section, the carbon intensity values shall be understood relative to No. 2 fuel oil delivered into or in Vermont in 2023. Carbon intensity values shall be measured based on fuel pathways.

Background:

The May 29, 2024, PUC Straw Proposal on Pacing proposed that, on January 1, 2025, the Commission will adopt a step change in carbon intensity values – adopting the threshold limit of "below 80 in 2025" and "below 60 in 2030" with no rate of decline in in-between years. The PUC proposal did not take a position on how carbon intensity values for liquid and gaseous fuels should decline from 2031-2050: "In preparation for establishing carbon intensity values on January 1, 2030, for the years 2031-2050, the Commission will offer an opportunity for public input to help inform the step change or rate of decline proposed during that period."

On June 26, 2024, the TAG submitted comments on the May 29 PUC Staff Proposal on Pacing. The TAG supported the step change for declining carbon intensity from 2025 to 2030, noting that it "provides a simple and predictable target for the marketplace." The TAG did not take a position on how carbon intensity values for liquid and gaseous fuels should decline from 2031-2050.

Discussion:

A plain reading of the statutory language suggests that it calls for annual decreases in the maximum carbon intensities of eligible clean heat fuels and that, therefore, something along the lines of Option 1 is appropriate. However, given that improvements in technology are rarely gradual in nature, it's reasonable to conclude that the legislature did not intend to constrain the PUC's discretion in this fashion, but rather wants it to develop a long-term trajectory for reducing the carbon intensities of eligible fuels that will do most to induce technological improvement and minimize economic harm. A rate of change can be negative, positive, or zero and it can change from year to year.

In this light, Options 2 and 3 are also consistent with legislative intent. Option 2 is less complex, administratively, than Option 1 and likely to be less complex too than an as-yet unknown alternative under Option 3, but complexity is only one of many considerations that the PUC will need to juggle.

The choice of trajectory for reductions in target CIs could have a meaningful impact on which liquid and gaseous biofuels are eligible for clean heat credits in the 2031-2049 period. The filings of several interested parties to the rulemaking have catalogued a range of possible effects, from no disqualifications of eligible fuels until 2050 to a series of disqualifications in the second decade of the period. These depend, of course, on assumptions about the initial carbon intensities of the fuels, about which there is still debate.

Lastly, a relevant consideration to the choice of a CI trajectory for eligible clean heat fuels will be the contribution of emissions from the combustion of those fuels to Vermont's Greenhouse Gas Emissions Inventory—or, more accurately, their contribution to achievement of the emissions reduction targets of the Global Warming Solutions Act (GWSA). It was noted during TAG discussion that the second option appears to offer the least assistance to emissions reductions of the three.

TAG Vote on 10/31/2024: 10 votes are considered a strong majority and "could live with indicates support despite a preference for an alternate option. 13 members were present

- Option 1 – linear decline annually – 1 vote (NOTE: Patrick said he "could live with Option 3")
- Option 2 – step down from 2030 to 2049: 2 votes (NOTE: both Floyd & Matt said they "could live with" Option 3)
- Option 3 – PUC to decide appropriate incremental decline: 8 votes
- Abstain – 2 votes (Emily R. and Jared)

Memo

To: VT PUC
Fr: CHS Technical Advisory Group (TAG)
Re: **Draft CHS rule and companion memo**
Dt: Oct. 31, 2024

The TAG discussed the PUC's draft CHS rule and companion memo at the Oct. 24 and Oct. 31, 2024 meetings. We would like to share the following comments for the PUC's consideration.

1. The companion memo language on page 8 states:

   "*Our work over the past year and a half on the Clean Heat Standard demonstrates that it does not make sense for Vermont, as a lone small state, to develop a clean heat credit market and the associated clean heat credit trading system to register, sell, transfer, and trade credits.*"

   The use of the language "our work" could imply that the TAG addressed this question as part of our role in advising the PUC and came to the same conclusion. In fact, the TAG has not discussed and has not agreed to this characterization of the CHS. We request that this passage make it clear that this is solely the opinion of the PUC and has not been considered by the TAG.

2. Review of the draft rule uncovered some important missing elements:
   - **Clear and complete definitions of clean heat measures.** If these are not defined in the rule itself, the rule should point to the TRM as the definitive source of definitions for eligible clean heat measures.
   - **Review of consequences.** The draft rule should include a process to perform the biennial review of consequences as required by statute.
   - **TRM update process.** Part III of the draft rule "establishes a process for approval of additional clean heat measures that are not listed in 30 V.S.A. § 8127(d)." However, it does not appear to include a process for updating existing clean heat measures, such as incorporating new baselines or recent performance data. Also, it appears that only an obligated party, a default delivery agent, or the Department may propose potential clean heat measures to the TAG, that such proposals happen on a rolling basis, and that the proponent of the new measure has to provide supporting information to back up the savings. In contrast, the draft rule lays out a process to update the emissions table (carbon intensities of fuels) every three years.
     The TAG **recommends a similar process for installed measures, where there is a TRM update every three years and at that time a technical consultant is tasked with making appropriate updates to measure characterizations for both installed measures and fuels, as well as adding new measures as appropriate.** This would enable emerging technologies to be added to the TRM once they are market-ready.

TAG Vote on 10/31/2024: 10 votes are considered a strong majority and "could live with indicates support despite a preference for an alternate option. 13 members were present.

- **Support the above comments**: 10 votes
- **Do not support the above comments**: 1 vote (NOTE: Luce voted "No" re.# 1 above because she thought the TAG should consider the practicality of implementing the CHS and respond to PUC's statement, acknowledging that we haven't discussed this and could not meet tomorrow's deadline for comments.)
- **Abstain**: 2 votes (Brian and Jared)

Memo

To: VT PUC re Opinion Dynamics draft TRM
Fr: CHS Technical Advisory Group
Re: Treatment of Land Use Change in the CHS
Dt: 10/31/24

The relevant statutory references, the options considered, and the pros and cons discussed for each option are summarized below. See the TAG's vote on these options at the end of the memo.

Question Presented

How should land use change be considered, if at all, in the liquid biofuel lifecycle carbon intensity (CI) scores?

- **Option 1:** Exclude LUC initially (OD proposed approach), to be revisited through periodic reviews or when requested, pursuant to 8128(a)(3) and 8128(d).
- **Option 2:** Include LUC

Opinion Dynamics (OD) Proposed Approach[1]

- Assume there is no change in land use (either direct or indirect) associated with the biofuel that needs to be quantified in the emission rates
- Land use change (LUC)[2] from the CI scores and targets excluded for a number of reasons[3],[4]:

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[1] Draft Vermont Clean Heat Standard Lifecycle Emissions Rate Schedule, Aug. 29, 2024, at 7; OD Memo Response to Sept. 17, 2024, TAG Questions, Oct. 2, 2024, at 2.

[2] Note: ILUC modeling represents both direct and indirect LUC as an output – it's really induced land use change. The models cannot separate the two. Thus, for this discussion, we will refer to them collectively simply as "LUC."

[3] Draft CHS Emissions Rate Schedule, op cit. at 7:

> "For biofuels developed from purpose grown crops and animal waste, our emissions analysis assumes that there is no change in land use associated with the biofuel that needs to be quantified in our emissions rates.
>
> - Biofuels from purpose grown crops are currently predominately produced in the Midwestern United States. In our analysis, we assume that feedstock crops, such as soybeans, corn and canola, are grown on dedicated land for explicit use in the energy sector. This simplification, along with the uncertainty around the change in demand for these fuels nationally, and Vermont's contribution to that demand, leads to our decision to not quantify the implications of land use change on upstream emissions.
> - For biofuels from animal waste, our analysis assumes no change in land use as the feedstock is a byproduct and not the primary driver for animal farms."

[4] OD 10/2/24 response to the TAG's 9/17/24 questions at p. 2:

> "As we worked within GREET to account for LUCs, we determined that GREET is inconsistent how these impacts are accounted. For example, LUC impacts associated with soybeans include explicit input parameters, while other crop-based feedstocks do not. This resulted in additional challenges for proper accounting on top of issues like additionality. Lastly, our aim with the CHS is to produce a replicable and transparent resource that is easy to use. To achieve this, we made assumptions and simplifications to ensure that future revisions could replicate our numbers while also advancing its content. We appreciate the TAG's comments on LUCs; we don't

- GREET1 2023 is inconsistent in accounting of land use changes in fuel production and feedstock
- Simplified assumptions allow for a TRM that is an easy-to-use, replicable and transparent resource
- Crop-based biofuels[5] are currently produced predominately in the Midwest; they are assumed to be grown on dedicated land for explicit use in the energy sector, among their other uses (e.g., protein for animal feed)
- Uncertainty around change in demand for these fuels nationally and Vermont's contribution to that demand

Statutory Requirements

- **Express References to "land use change":** Act 18 mentions "land use change" twice:
  - 30 V.S.A. § 8128(a)(3) includes the following as one of the duties of the Technical Advisory Group (TAG): "periodically assessing and reporting to the [PUC] on the sustainability of the production of clean heat measures by considering factors including greenhouse gas emissions; carbon sequestration and storage; human health impacts; land use changes; ecological and biodiversity impacts; groundwater and surface water impacts; air, water, and soil pollution; and impacts on food costs." [emphasis added]
  - 30 V.S.A. § 8128(b) specifies a number of fields of expertise that should be represented among the TAG members selected by the PUC; these enumerated fields include expertise in "land use change" among the many fields identified.
- **Implied Reference to "land use change":**
  - **30 V.S.A** § 8127(h) ("Review of Consequences") directs the PUC to "biennially assess harmful consequences that may arise in Vermont or elsewhere from the implementation of specific types of clean heat measures and shall set standards or limits to prevent those consequences. Such consequences shall include environmental burdens as defined in 3 V.S.A. § 6002, public health, deforestation or forest degradation, conversion of grasslands, increased emissions of criteria pollutants, damage to watersheds, or the creation of new methane to meet fuel demand."
- **References to "verifiable" and "measured":**
  - 30 V.S.A. § 8127(c) requires that "[c]lean heat credits . . . be based on the accurate and verifiable lifecycle CO_2e emission reductions in Vermont's thermal sector . . .." [emphasis added]30 V.S.A. § 8127(g)(1) requires that the emissions schedule "be based on

believe that it is inappropriate to include LUCs, but at this time we don't see a pathway to including them in our carbon intensity values."

[5] OD's characterization of soybean and canola as "purpose grown" crops is factually inaccurate as it implies these crops are grown specifically for their oil content to be used for biofuel production. However, all biofuel crops generate a variety of fuel and non-fuel products. For example, 80% of the biomass in soybeans is protein, which is used in animal feed and other protein applications. Only 20% of the bean mass is oil, and only a fraction of that oil is converted to biofuel. The remaining oil is used for industrial, commercial, and personal care products, along with a host of other applications.

transparent, verifiable, and accurate emissions accounting adapting . . . GREET . . . or an alternative of comparable rigor to fit the Vermont thermal sector context, and the requirements of 10 V.S.A. § 578(a)(2) and (3).” [emphasis added]
    - 30 V.S.A. § 8127(f)(3) requires that “[c]arbon intensity values shall be measured based on fuel pathways. [emphasis added]
- **References to “fuel pathway”:**
    - 30 V.S.A. § 8127(f)(3) requires that, for purposes of this section, CI scores “be measured based on fuel pathways” and “fuel pathway” is defined in 30 V.S.A. § 8123(10) to include “feedstock generation.”
    - 30 V.S.A. § 8127(g)(2) requires that the emissions schedule, for each fuel pathway, account for, among other things, the “loss of stored carbon.”

Support for Option 1 (Exclude LUC)

As a starting point, indirect or induced LUC (ILUC) is based on the theory that land outside of the U.S. not already in use for biofuel production will be converted for agricultural purposes to backfill for the biomass converted into biofuel feedstock in the U.S. By definition, ILUC cannot be directly measured, but must be inferred from computer models that attempt to simulate global market responses to an external factor such as a major policy shift in one or more jurisdictions.

- *No explicit statutory requirement for upfront LUC incorporation.* As noted above, there is nothing in Act 18 that explicitly requires the CHS to incorporate a land use component to a fuel’s lifecycle CI score. Indeed, the wording in Section 8128(a)(3) suggests the Legislature intended land use change to be considered retrospectively as part of the TAG’s ongoing duties after the CHS is adopted (i.e., assisting the PUC with “ongoing management of the CHS,” including “periodically assessing and reporting…on the sustainability [of clean heat measures]”). This ongoing assessment includes looking at a variety of factors, with land use change being just one of many different factors identified, for potential impacts on the sustainability of clean heat measures being implemented. This “look back” intent is reinforced by Section 8127(h) [“Review of Consequences”], which directs the PUC to assess every two years the potential consequences of a clean heat measure, including but not limited to “deforestation or forest degradation” and “conversion of grasslands,” two typical types of land use change.
- *OD correctly identified sound and reasonable bases for excluding LUC.* As OD stated, LUC treatment (both direct LUC and indirect LUC) is inconsistent within the GREET model. Making the inputs and assumptions consistent among the various biofuels currently in or expected to be available to the region will require substantial additional expenditure of public resources for little or no gain:
    - ILUC modeling typically costs in the tens to hundreds of thousands of dollars, depending on the analyses requested. It requires specialized expertise in agroeconomics and is typically done by experienced academic institutions

- ILUC modeling is highly uncertain, controversial, heavily dependent on the inputs and assumptions used as well as the expertise of the modeler in interpreting the data, and by its nature, cannot be verified in the real world.[6]
- Nevertheless, the trend shows that as researchers have refined ILUC models to incorporate more nuance and understanding of agricultural and fuel markets, the resulting impacts have continuously declined. ILUC estimates for soybean oil have been reduced by over 95% since the initial estimates of soy ILUC at 300+ g/CO2e/MJ (early 2000s) to the current 2023 estimate by Purdue University, developer of the widely used Global Trade Analysis Project (GTAP) ILUC model. Purdue estimated an ILUC of about 9.1-9.7 g CO2e/MJ, estimated for a California-scale volume shock (3.22 billion gallons).[7] By contrast, the current CARB (2015) estimate for soy ILUC is 29.1 gCO2e/MJ, based on outdated data that is twenty years old and on a shock volume of 812 million gallons, whereas the most recent Purdue estimate (using the same GTAP model but updated with more recent data) shows 1/3 of the current CARB estimate (9.7 gCO2e/MJ) at four times the shock volume CARB used (3.22 billion gallons vs. 812 million gallons)
- The crops from which a small percentage of lipids would be used for this program are already grown sustainably on land that was in productive use before 2008 (a requirement for fuels to receive credit under the federal Renewable Fuel Standard). Therefore, no deforestation or other adverse change in land use would be expected to result from production of crop-based biofuels to meet the CHS requirements; the U.S. and Canada can easily absorb Vermont's demand for biofuel feedstock without converting additional acreage.
- Total U.S. consumption of biodiesel, renewable diesel, and renewable heating oil was 4.6-4.8 billion gallons in 2023.[8] Less than half that amount (48.3% by weight) was produced from soybean oil and canola oil, or about 2.2-2.3 billion[9] gallons of crop-based biodiesel and renewable diesel sustainably grown on land designated for this use since 2008.
- Vermont's heating oil consumption in the residential and commercial sectors was about 102 million gallons in 2020.[10] GTAP modeling of the ILUC that might occur from a policy like the CHS affecting such a small fraction of the overall U.S. consumption might be technically feasible, but it would be an expensive exercise that would most likely result in meaningless numbers, essentially within the "noise"

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[6] To illustrate, ILUC does not represent modeled changes in land use but a predetermined volume of increased biofuel production's hypothetical impact on the rate of afforestation and/or deforestation. E.g., Empirical ILUC modeling results show acres of cropland conversion in U.S. domestic models considering LUC impacts of the EPA's Renewable Fuel Standard, but U.S. cropland has not increased during the entire life of the policy.

[7] Purdue University analysis, June 2023

[8] Energy Information Administration, EPA Moderated Transaction System (EMTS)

[9] Ibid

[10] EIA, https://www.eia.gov/dnav/pet/PET_CONS_821USE_DCU_SVT_A.htm, visited 10/8/2024

- *Inclusion of ILUC conflicts with Section 8127.* Since ILUC is, by definition, not directly measurable, it is inherently unverifiable. Therefore, including it in the CI scores would conflict with Section 8127's requirement for verifiability.

Support for Option 2 (Include LUC)

- *Statutory requirement that clean heat measures be evaluated based on fuel pathway, which includes feedstock generation, and loss of stored carbon.* As noted above, Act 18 explicitly requires that the CI account for the specific fuel pathway, which includes feedstock generation. It is incomplete to evaluate a biofuel without also including how land would be used but for the feedstock generation.
- *OD noted that it is **not inappropriate** to include LUC emissions, while also noting the added complexities.* As can be seen from other jurisdictions, like with the California Air Resources Board's (CARB) Low Carbon Fuel Standard (LCFS), just because there is inconsistent treatment of LUC emissions in GREET and other challenges does not mean that it is not more complete to include LUC emissions.[11] OD opted to make certain assumptions and simplifications, but an option could be to use the accounting that has already been done by CARB for the LCFS to create default LUC emissions for use in determining CI scores.[12] It's also worth noting that the question of LUC impacts has been extensively discussed in the US EPA Renewable Fuel Standard. EPA includes LUC impacts for its national policies and has done extensive work to analyze the state of the literature. Excluding LUC would be inconsistent with the approach taken by US EPA, which has put more time into this question than any other agency in the US.
- *Inclusion of LUC emissions is consistent with statutory requirements that CI scores be based on verifiable lifecycle CO2 emissions*. Looking to other jurisdictions, such as CARB and the LCFS, it is common to require that greenhouse gas emissions reductions be "verifiable" even though it is technically preferred to refer to the separate components of "verification" and "validation."[13] Validation, as opposed to verification, needs to be used when there is not observable evidence that substantiates a claim (such as with a counterfactual of LUC emissions). Including LUC emissions in CI scores in Vermont, even when those CI scores need to be verified (but not explicitly validated), would be consistent with the approach that has been taken in other jurisdictions, such as with the LCFS.[14]
- *Other jurisdictions are considering increasing the LUC emissions that are incorporated into CI scores.* Despite the complexity of LUC emissions, other regulatory bodies, such as CARB, are

[11] *See* LCFS Regulation § 95488.3 Table 6 (Table 6) (includes LUC values for use in CI determination and cited authorities), visited 10/9/2024.
[12] *See* id.
[13] *See* CAL. HEALTH & SAFETY CODE § 38562(d)(1) (2017); International Organization for Standardization (ISO) 14064-3:2019 (Specification with guidance for the verification and validation of greenhouse gas statements).
[14] *See* Table 6.

considering increasing LUC emissions and giving greater flexibility to increase the LUC emissions that are factored into a CI score in certain situations.[15]

TAG Vote on 10/31/2024: 10 votes are considered a strong majority and "could live with indicates support despite a preference for an alternate option. 13 members were present.

- **Option 1:** Exclude LUCs initially (Opinion Dynamics' proposed approach), to be revisited through periodic reviews or when requested, pursuant to 8128(a)(3) and 8128(d). 9 votes
- **Option 2:** Include LUC – 2 votes (NOTE: Emily Grubert and Emily Levin said they could live with Option 1, although Option 2 is their preference)
- **Abstain -** 2 votes (Jared Ulmer and Emily Roscoe)

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[15] *See* Proposed Amendments to the LCFS Regulation, Aug. 12, 2024, at p. 128 ("The Executive Officer may determine that no value in Table 6 is conservatively representative and assign a more conservative [(higher)] LUC value."), visited 10/9/24.

Memo

To: The Vermont Public Utility Commission
From: Rick Weston, Chair, on behalf of the CHS Technical Advisory Group (TAG)
RE: Wood Measures in TRM & Carbon Intensity of Wood
Date: January 9, 2025

Questions for TAG Consideration

1. How should Advanced Wood Heating measures be characterized in the Technical Reference Manual (TRM)?
2. What is the appropriate methodology for evaluating the greenhouse gas (GHG) emissions and calculating the carbon intensity for wood biofuels?

Question 1: Issue Summary

The first and second draft TRMs include four wood heat installed measures:

- Advanced Wood Heating – Central Pellet Systems (Commercial & Industrial)
- Advanced Wood Heating – Pellet and Cordwood Stoves (Commercial & Industrial)
- Advanced Wood Heating – Central Pellet Systems (Residential)
- Advanced Wood Heating – Pellet and Cordwood Stoves (Residential)

The TAG offered the following feedback to Opinion Dynamics regarding the characterization of wood measures in the TRM:

1. The TRM should be updated to match the TAG's comments related to the definition of Advanced Wood Heating. (See TAG memo dated Nov 18, 2024).

2. Measure characterizations for Advanced Wood Heating measures should not assume only wood-to-wood replacements. The majority of installations are likely to involve fuel switching from fossil fuel to wood. If site-specific information on the existing fuel is not available, the TRM could assume a blended baseline based on a representative mix of oil, natural gas, propane, electricity, and wood.

3. Rather than separating out an installed measure and a fuel measure for wood-based systems, it makes more sense to lump them together so the fuel savings are folded into the measure characterization for Advanced Wood Heating installed measures. This would be similar to the approach for heat pump measures, in which the installed measure characterization accounts for the impact of fuel switching from fossil fuel to electricity.

Question 2: Issue Summary

As a first step to ensure a common understanding, the TAG confirmed that Opinion Dynamics used the following equation to calculate the lifecycle emissions rate for wood biofuels (as measured in grams of CO2 equivalent per megajoule (MJ)) in the TRM first and second drafts.

Upstream Emissions + Combustion Emissions of CH4 & N20 +
[CO2 Combustion Emissions x GWPbio] = Lifecycle Emissions Rate (gCO2e/MJ)

Determining an appropriate methodology for calculating the carbon intensity of wood therefore requires consideration of several different but related issues:

A. Assumptions for combustion emissions
B. Assumptions for upstream emissions, including the emissions from fuel processing
C. Assumptions for GWPbio, including the wood species used and whether the fuels are purpose-grown/harvested products or waste products

A. Assumptions for combustion emissions

In the draft TRM, Opinion Dynamics used combustion emissions rates for CO2, CH4, and N2O from the U.S. EPA Emission Factors Hub. The TAG did not have concerns with this approach.

B. Assumptions for upstream emissions

Opinion Dynamics used the GREET1 2023rev1 tool to calculate upstream emissions for wood biofuels. Upstream emissions for wood biofuels capture the emissions associated with steps in the lifecycle such as forest management, harvesting, lumber milling, fuel processing, and transporting the fuels to Vermont.

TAG members note that calculation of upstream emissions is sensitive to assumptions around the sourcing for wood biofuels (e.g., whether the fuels are purpose-grown/harvested products vs. waste products such as logging and mill residues). The Agency of Natural Resources (ANR) provided an issue briefing that offered detailed definitions for wood and timber products and residues, to ensure common terminology.[1] ANR's issue briefing also provided feedback that "wood pellets are primarily made from logging and mill residues." If pellets are considered a waste product, then it would follow that the upstream emissions associated with forest management, harvesting, and lumber milling should be set to zero to reflect that these products are not driving these activities. Some TAG members questioned the characterization of pellets as primarily a waste product or harvest residue with zero upstream emissions.

The assumptions around whether wood fuel feedstocks are waste products (logging and mill residues) should consistently apply to both GWPbio and upstream emissions. The issue of whether pellets should be considered waste/residue is therefore discussed further under "Issue C: Assumptions for GWPbio."

C. Assumptions for GWPbio

For wood fuels, Opinion Dynamics "considered CO2 released in combustion to be part of a longer biogenic carbon cycle than biofuels, in which it takes significant time for the regrowth of new trees to fully sequester the biogenic carbon emitted during combustion."[2] Accordingly, they "applied a GWPbio factor to CO2 combustion emissions from wood fuels to account for the regrowth period of the fuel." The higher the GWPbio, the higher the CO2 combustion emissions (e.g., the less

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[1] ANR, "Clean Heat Standard – Wood Fuel Carbon Intensities/Emission Factors and Other Issues," October 30, 2024.
[2] Opinion Dynamics, "Approach to Lifecycle Analysis for Wood Products," October 9, 2024.

emissions are discounted due to forest regrowth). Opinion Dynamics used the World Wildlife Fund (WWF) biogenic carbon footprint calculator to calculate GWPbio.

There are two supporting assumptions used by Opinion Dynamics that underpin calculation of GWPbio, both of which have been discussed by the TAG:

1. The WWF calculator relies on assumptions for the tree species in the forest stands where the wood fuels were sourced.
2. If the feedstock for wood biofuels is assumed to be 100% waste/residues, then none of the forest harvesting is due to the feedstock, and therefore, GWPbio will be set to zero. Therefore, like upstream emissions, GWPbio is sensitive to assumptions around the sourcing for wood biofuels (e.g., whether the fuels are purpose-grown/harvested products vs. waste products such as logging and mill residues).

On the first issue, tree species used in production of wood pellets, the TAG notes that the tree species assumptions should reflect the forests where the wood pellets are being sourced.[3] Opinion Dynamics identified a report indicating 70% of VT forests are maple/beech/birch and 7% are spruce/fir, resulting in a GWPbio of 0.75. ANR's issue brief raised several recommendations around the characterization of Vermont–sourced wood fuel to the extent it is used in the calculation of GWPbio for wood fuels.[4]

TAG members also suggested that GWPbio requires different assumptions for tree species mixes for pellets not sourced from Vermont forests. The TAG has not identified reliable data on where pellets burned in Vermont are sourced. Anecdotal information (NESCAUM communication with VT DEC) suggests that there is only one pellet producer in Vermont and most of its production is sold out of state, while most pellets used in Vermont are imported. As a result, it is more appropriate, especially in the early years of implementation of Vermont's credit system to reflect reasonable assumptions of forest species type for pellets sold in Vermont. Opinion Dynamics' second draft TRM proposed to update the eligibility criteria for pellets to require that they be imported from North America rather than from "the northeast." The TAG acknowledges that the pellet market is dynamic and will change over time and recommends that the wood species mix be determined based on the best available data or a close approximation of bulk and bagged pellet sales in Vermont and updated as more data becomes available.

[3] To the extent that they are part of the CHS program, wood chips and cordwood are likely to be sourced from Vermont forests.

[4] ANR's issue briefing offered the following recommendation: "Should the TAG and [Opinion Dynamics] move forward with the use of GWPbio for wood fuels, we recommend that the decision process to use it, and the evidence supporting that decision, be adequately explained in the technical and supporting documentation submitted to the PUC and/or used in the CHS. We also recommend that any use of the Calculator to estimate GWPbio factors be based on the available data for Vermont's forests, forest management, and wood utilization, and that any GWPbio estimates derived from the Calculator and used in the CHS be appropriately contextualized with respect to the limitations of the Calculator to account for Vermont-specific data." ANR also states that Forest Inventory & Analysis (FIA) data is available from the US Forest Service and recommends using Vermont-specific FIA data for this assessment, noting that "FPR is happy to facilitate access to FIA data upon request."

On the second issue, the TAG has not reached an agreement on whether, and to what extent, pellets are sourced from mill waste and harvest management residues. TAG members have identified several sources that could be useful to review to inform this determination:

- Buckholz, Thomas et al. "Wood Pellet Heat from Northeastern US Forests." *Energy*, vol. 141, December 15, 2017, pp. 483-491. https://doi.org/10.1016/j.energy.2017.09.062. Paper references "an industry-average feedstock mix consisting of equal parts of sawmill residues and pulpwood-quality wood." The paper further details: "Based on the survey results, pellet mills in the region [Maine, New Hampshire, Vermont, and New York] fall into three categories of feedstock inputs: 1) 100% pulpwood and small diameter trees; 2) 100% sawmill residue; and 3) some combination of pulpwood/small diameter trees and sawmill residue. While individual facilities vary in terms of feedstock inputs, 55.7% of total feedstock consumption by the nine facilities came from forest harvesting operations, 43.8% from sawmill residues (primary and secondary), and 0.5% from other sources such as municipal waste and landscaping/yard trimming.
- Rodriguez Franco, Carlos. "Forest Biomass Potential for Wood Pellets Production in the United States of America for Exportation." *Biofuels*, vol. 13, no. 8, 2022, pp. 983-94, https://www.fs.usda.gov/research/publications/jrnl/wo_2022_rodriguez-franco_001.pdf. This paper focuses on pellet production in the U.S. Southeast for export, noting, "wood pellets in the U.S. are mostly manufactured from forest residues or low-grade, low-quality logging and sawmill byproducts that would otherwise go to waste (i.e. tree tops and limbs, thinning treatments, mill residues such as sawdust or bark, low-quality wood)."
- Spelter, Henry et al. *North America's Wood Pellet Sector*. USDA, Forest Service, Forest Products Laboratory, 2009, https://doi.org/10.2737/FPL-RP-656. This 2009 paper says, "Over two-thirds of the fiber used in pellet manufacturing was sawmill residues (Fig. 5). Other secondary wood manufacturing facilities, such as furniture and millwork factories, supplied 14% of fiber, reflecting the large share of pellet plants located in predominantly hardwood-growing regions where furniture activity is greatest. Sixteen percent was green material sourced from pulpwood or logging residues." However, it also indicates that production of pellets using roundwood feedstock was growing as of 2009, noting "a number of new mills have been built to process chipped roundwood and have capacities three to four times as large."

Not taken up in this document is the question of how to calculate the GWPbio for pellets sourced from mill or forest harvest residues or the GWPbio for pellets sourced from other harvest management practices. The TAG discussed these questions at length, but, as yet, has not come to a broad shared understanding of the best approaches for doing so.

TAG vote to approve the content of this memo and forward to the PUC:

- 10 votes in favor (Rick Weston, Emily Levin, Alek Antczak, Brian Woods, Emily Roscoe, Luce Hillman, Ken Jones, Floyd Vergara, Michelle Keller, Emily Grubert)
- 2 abstentions (Jared Ulmer, Sam Lehr)
- 3 members absent during vote (Matt Cota, Patrick Wood, Casey Lamont)

Memo

To: The Vermont Public Utility Commission
From: Rick Weston, Chair, on behalf of the CHS Technical Advisory Group
RE: Health Impacts and Considerations for the Clean Heat Standard
Dt: January 9, 2025

Sections from the Vermont Clean Heat Standard Statute that relate to public health are copied below:

- § 8121. INTENT
  Pursuant to 2 V.S.A. § 205(a), it is the intent of the General Assembly that the Clean Heat Standard be designed and implemented in a manner that achieves Vermont's thermal sector greenhouse gas emissions reductions necessary to meet the requirements of 10 V.S.A. § 578(a)(2) and (3), minimizes costs to customers, protects public health, and recognizes that affordable heating is essential for Vermonters. It shall enhance social equity by prioritizing customers with low income and moderate income and those households with the highest energy burdens. The Clean Heat Standard shall, to the greatest extent possible, maximize the use of available federal funds to deliver clean heat measures.

- § 8127. TRADEABLE CLEAN HEAT CREDITS

  (h) Review of consequences: The Commission shall biennially assess harmful consequences that may arise in Vermont or elsewhere from the implementation of specific types of clean heat measures and shall set standards or limits to prevent those consequences. Such consequences shall include environmental burdens as defined in 3 V.S.A. § 6002, public health, deforestation or forest degradation, conversion of grasslands, increased emissions of criteria pollutants, damage to watersheds, or the creation of new methane to meet fuel demand.

- § 8128. CLEAN HEAT STANDARD TECHNICAL ADVISORY GROUP

  (a) The Commission shall establish the Clean Heat Standard Technical Advisory Group (TAG) to assist the Commission in the ongoing management of the Clean Heat Standard. Its duties shall include:

  (3) Periodically assessing and reporting to the Commission on the sustainability of the production of clean heat measures by considering factors including greenhouse gas emissions; carbon sequestration and storage; human health impacts; land use changes; ecological and biodiversity impacts; groundwater and surface water impacts; air, water, and soil pollution; and impacts on food costs.

  (8) calculating the savings associated with public health benefits due to clean heat measures.

Executive summary of health impacts and considerations for the Clean Heat Standard

This memo provides a high-level summary of potential human health impacts and considerations for individual measures or groupings of measures listed and defined in the draft Vermont Clean Heat Standard Technical Reference Manual (TRM). The focus of this analysis was on describing potential combustion-related health impacts and other health co-benefits or co-harms relating to end use of Clean Heat measures at a place of residence. Quantifying health impacts/costs and analyzing life cycle health impacts were both determined to require more time and resources than are available for this task at this time.

To best meet the intent of the Clean Heat Standard as described in Title 30, Chapter 94 to protect public health, the following summary statements can be made about potential TRM measures:

1. Public health benefits can most confidently be delivered through strategies supporting building envelope improvements and increased use of modern electric heating equipment and appliances, by reducing harmful combustion emissions while providing other health co-benefits.
2. Combustion emissions from liquid and gaseous biofuels included in the TRM may have a similar or slightly less harmful effect on health as compared to combustion emissions from fossil fuels in current use, though health effects vary by fuel type, feedstock, blend percentage, and other factors, as described in further detail in the body of this memo. There is some uncertainty about this conclusion, as liquid and gaseous biofuel emissions have not been well-studied in modern residential applications. Rather, this conclusion is derived primarily from findings of transportation engine studies that compared emissions of biofuels to emissions of fossil fuels of a similar composition to those used in residential heating applications today, and from the very small number of heating boiler studies that compared emissions from biofuels to fossil heating fuels of a similar composition to those used in heating applications today. The summary of evidence in this memo describes expected differences in emissions-related health effects between each biofuel included in the TRM and comparable fossil fuels, while also pointing out specific areas of uncertainty where research is lacking and/or scientific consensus has not been reached.
3. Wood heating produces combustion emissions that are more harmful to health than from other commonly-used fossil heating fuels. This is true even for the most modern, automated, central wood heating systems. Manually-operated cordwood stoves produce substantially more harmful emissions than automated wood heating systems.

For all potential TRM measures, it should also be considered that ensuring equitable and affordable access to home heating is essential for protecting Vermonters' health.

Recommended next steps

1) Establish a process for reviewing, summarizing, and considering the application of new scientific evidence on a biennial basis.
2) Consider dedicating resources to conduct a quantitative analysis of health impacts and monetizable costs or benefits of the measures listed in the Vermont Clean Heat Standard TRM.
3) Consider dedicating resources to conducting a life-cycle assessment of health impacts of the measures listed in the Vermont Clean Heat Standard TRM.

Initial Review of Public Health Impacts of Clean Heat Measures

This memo provides a high-level summary of potential human health impacts and considerations for individual measures or groupings of measures listed and defined in the draft Vermont Clean Heat Standard Technical Reference Manual (TRM). The focus of this analysis was on describing potential combustion-related health impacts and other health co-benefits or co-harms relating to end use of Clean Heat measures at a place of residence. Quantifying health impacts/costs and analyzing life cycle health impacts were both determined to require more time and resources than are available for this task at this time, though we recommend dedicating resources to such an effort in the future.

The discipline of public health uses an evidence-based approach to support decision-making.[1] Ideally, decisions about policy issues that impact public health should be informed by a rich and mature body of scientific evidence which has been synthesized into unbiased, peer-reviewed, systematic reviews that establish a clear consensus on the conclusions. Contradictory findings or simply a lack of directly relevant, high-quality studies reduce confidence in conclusions drawn from individual studies. The strength of individual studies can vary widely based on the source, research methods, whether scientific peer-review occurred before publication, and other factors. Additional resources describing how scientific evidence is evaluated and applied are provided.[2,3,4]

The scientific evidence is relatively mature and clear regarding health impacts relating to building envelope strategies, electric heating and appliances, and wood heating. These sections of the literature review were summarized at a high-level with only key resources noted in the list of references at the end of this memo. Wood heating received relatively more attention, highlighting potential harms associated with increased wood heating generally, and the different impacts of specific types of wood heating equipment and fuel characteristics.

In contrast, there is relatively little scientific evidence or consensus about the health impacts of biofuels used in residential applications, and almost none that compare emissions impacts from biofuels to emissions from fossil fuels currently used in residential settings. We identified and summarized relevant studies while also pointing out areas of concern and uncertainty that have not been definitively resolved. In an effort to be as clear and transparent as possible, the biofuels section of this memo is more detailed and includes specific citations.

For background relevant to all TRM measures, an overview of common air pollutants and their health effects can be found here.

Detailed findings organized by groupings of TRM measures

1. **Building envelope** – scientific evidence is clear that air sealing, building envelope insulation, and related home weatherization strategies result in generally positive health benefits from avoided combustion emissions, thermal comfort, and other indoor environment co-benefits.

    - Reduced combustion emissions; improved temperature control and indoor air quality; reduced humidity, mold, and pest intrusion; money saved on fuel often directly supports better health; opportunities for other health and safety improvements.
        - OEO estimated in 2024 an average household savings of $1,026 per year from reduced fuel demand.

    - VDH estimated in 2018 $1,302 per year in public health savings per year from reduced outdoor air emissions and reduced resident impacts from cold, heat, and asthma.
- Need to ensure sufficient ventilation and treatment of indoor air pollutants after weatherization.

2. **Electric heating and appliances** – scientific evidence is clear that switching from use of conventional fossil fueled heating and appliances to modern electric heating and appliances results in largely positive health benefits, primarily as a result of avoided combustion emissions.

    - Compared to conventional liquid or solid heating fuels: avoided combustion emissions; avoided indoor exposure to nitrogen dioxide and other air toxics (particularly from gas and propane cook stoves); avoided risk of carbon monoxide poisoning.
    - Heat pumps provide health co-benefits such as increasingly necessary air conditioning and dehumidification.

3. **Wood heating** – scientific evidence is clear that emissions from wood heating result in negative health impacts, though the magnitude of impact varies by heating device and fuel characteristics.

    - Residential wood heating emits substantially more fine particulate matter and air toxics than other non-woody residential fuels. Fine particulate matter ($PM_{2.5}$) is a critical pollutant of concern due to decades of research establishing significant associations with human mortality and morbidity.
        - This is true for all wood fuel types and heating equipment, though there is a spectrum from most -> least polluting per heat output (uncertified cordwood stove -> EPA-certified cordwood stove (noncatalytic) -> EPA certified cordwood stove (catalytic/hybrid) -> pellet stove or boiler). There is a wide range of other whole-house wood-fueled systems (boilers or furnaces using cordwood or wood chips) that are hard to place in this spectrum due to a lack of scientific emissions data.
    - Based on a 2022 VDH analysis using the EPA Co-Benefits Risk Assessment (COBRA) tool:
        - 97% of the monetizable health impact from residential heating emissions in Vermont is attributable to wood fuel combustion.
        - The monetizable health impact of residential wood heating in Vermont is $105M-$238M (about 30x greater than for all other residential fuels combined).
        - Pollution from wood heating is associated with 10-22 early deaths (about 20x greater that for all other residential fuels combined).
        - Cancer risk from wood heating pollution is 2.5 per million (about 20x greater than for all other residential fuels combined).
    - Replacing fossil fueled heating with wood heating, especially cordwood, would likely have a harmful impact on human health due to increased emissions of multiple air pollutants. The magnitude depends on what type of wood heating equipment and fuel is used and what is being replaced.
        - Replacing cordwood stoves and boilers with pellet stoves or boilers has the potential to provide a substantial public health benefit. Pellet stoves are very low emitting for most combustion emissions except trace metals of health concern (Pb, Cd, As). In general,

emissions from pellet heating systems are a much lower concern than cordwood emissions with respect to health impacts. Compared to cordwood emissions, pellet emissions have very low particulate matter, black carbon, volatile organics (including carcinogenic volatile organic compounds), and de minimus polycyclic aromatic hydrocarbons (PAHs).

- An important health consideration for those without alternative heat sources in the cold is that manually operated wood stoves can continue providing heat in the event of power loss.
- Increased fossil fuel prices may lead to increased wood heating as a more cost-effective option, which would have negative impacts on air quality and human health.

4. **Liquid and Gaseous Biofuels** - health impacts from biofuels are difficult to interpret due to very limited research about biofuels used in residential applications. Based mainly on studies of emissions from biofuel use in automotive engine applications, health impacts from biofuel combustion emissions are slightly improved or similar to emissions from conventional fossil fuels, with some variation by type of biofuel, feedstock, blend percentage, and other factors.

- Research on air quality and health impacts of liquid and gaseous biofuels is limited.
    - Most of that limited research is focused on the transportation sector, comparing biofuels (biodiesel or biomethane) to conventional transportation fuels (diesel, gasoline, or fossil gas). Very few peer-reviewed studies have been published about biofuels used for home heating or appliances. The review below prioritizes scientific findings about biofuels in this order:
        1) Peer-reviewed systematic literature reviews are always preferred to peer-reviewed individual studies.
        2) Home heating or appliance studies when the fossil fuel used for comparison was similar to fuels in real-world use today. Findings from these studies are the most directly relevant for residential uses today, but there have been very few published.
        3) Automotive engine studies when the fossil fuel used for comparison was similar to fuels in real-world use today – these findings may be helpful for understanding relative differences between emissions from biofuels compared to fossil fuels, while acknowledging this is an imperfect comparison. There are fundamental differences between combustion processes, operating conditions, and pollutant controls used in automotive engines versus home heating boilers that affect the composition and magnitude of emissions. However, evidence from transportation studies was often the best or only evidence available, so it was used in this assessment in a limited way. For example, evidence that switching from fossil fuels to biofuels in a transportation engine results in a change in emissions may suggest that similar emissions changes would occur if making a similar comparison in a residential heating application, but that assumption needs future validation. The composition and magnitude of emissions from transportation engines should not be generalized to residential applications.

4) Studies where the fossil fuel used for comparison is no longer in real-world use or was not clearly specified in the article, or the biofuel feedstock is not listed in the Vermont Clean Heat Standard TRM, were generally not considered. For example, since 2018, ultra-low sulfur diesel is the only diesel fuel allowed for residential heating use in Vermont, but most biodiesel studies in residential settings make comparisons to higher sulfur diesel fuels that are no longer used in residential settings (explained in further detail in the Biodiesel review below).

- Emissions impacts reported in the peer-reviewed literature differ by characteristics of the biofuel (e.g., feedstock, blend), type of combustion equipment used, consideration of part or all of the lifecycle impacts, and other factors.
- The evidence summarized below focuses on end use combustion impacts. Life cycle impacts should be considered but are outside of the scope of this review. Additional dedicated resources would likely be needed to explore life cycle health impacts.

- One of the concluding statements from EPA's 2022 Biofuels and the Environment: Third Triennial Report summarizes the uncertainty about health effects from biofuels:
  - "The understanding of the potential health effects of exposure to biofuels and emissions from vehicles using biofuels under real-world conditions, concentrations, and exposures including to susceptible human populations is limited. Recent literature that addresses cumulative impacts of upstream processes is limited. Much of the recent published literature focuses on impacts of individual sectors only."
- Abt Associates completed a literature review in 2022 for the New York State Energy Research and Development Authority (NYSERDA) summarizing the health impacts of liquid and gaseous biofuels. The findings below are largely consistent with the Abt Associates memo, which can be read in full here.

A. **Biodiesel**

- Compared to other biofuels, there is relatively more biodiesel research focused on emissions from home heating equipment, but most are older studies comparing biodiesel emissions to emissions from No. 2 fuel oil with a far higher sulfur content than what is allowed today (overview of the evolution of sulfur content standards). There are very few studies comparing emissions from biodiesel to ultra-low sulfur diesel (ULSD) in use today.
  - Vermont has required use of ULSD (sulfur content < 15ppm) for home heating oil since 2018. This replaced the low-sulfur diesel (LSD) standard (sulfur content <500ppm) implemented in 2014. The previous sulfur content standard was <20,000ppm, though home heating oil typically had a sulfur content in the 2000-2500ppm range.
  - Removing sulfur from fuel oil directly or indirectly reduces emissions of sulfur dioxide (SO_2), particulate matter (PM), nitrogen oxides (NO_X), polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), and other emissions. For any studies comparing biodiesel to conventional or low sulfur fuels no longer used today, it should be acknowledged that those fuels generated higher emissions than the ULSD in use today.
  - A report produced for NYSERDA summarized emissions differences comparing heating oils with varying sulfur content:

    - Switching from conventional heating oil (sulfur content = 2000ppm) to LSD (sulfur content = 500ppm) generally reduces emissions of SO_2 by 75-80%, PM by 75%, and NO_X by 5-10%.
    - Switching from conventional heating oil (sulfur content = 2000ppm) to ULSD (sulfur content = 15ppm) generally reduces emissions of SO_2 by 97%, PM by 90-95% (estimated from graph), and NO_X by 20-30%.
- Several literature reviews have summarized the health impacts of biodiesel primarily used in automotive applications, generally reporting reduced emissions of SO_2, PM, PAHs, and CO and increased emissions of NOx and aldehydes[5,6,7,8,9,10,11]. Some of this evidence is based on comparisons to diesel fuels with higher sulfur content than what is used in residential boilers today. Emissions differences are typically smaller or negligible when comparing biodiesel to ULSD since many emissions depend on sulfur content differences between fuels. Even the most recent reviews draw concluding statements about the lack of certainty and need for additional research about biofuel emissions impacts on human health, for example: "Currently there is no scientific consensus on the health effects associated with biodiesel exposure."[5]
- Few peer-reviewed studies of biodiesel used in home heating applications were identified, particularly comparing biodiesel to ULSD or similarly low-sulfur diesel fuel:
    - Biodiesel (from sunflower oil, S=2ppm) produced slightly higher CO emissions and reduced SO_2 compared to ULSD fuel oil (S=11ppm) used in a residential boiler.[12]
    - Biodiesel (unspecified feedstock, S=60ppm) produced lower CO, PM, and PAH emissions, higher SO_2 and formaldehyde emissions, and slightly higher NO_x emissions compared to LSD fuel oil (S=30ppm) used in a residential boiler.[13]
    - Biodiesel (from animal & vegetable fats, S=2) produced slightly higher CO and NOx emissions and similarly negligible SO2 emissions compared to ULSD fuel (S=5ppm) used in an industrial boiler.[14]
- Sulfur dioxide emissions largely depend on the sulfur content of the fuel. Both fossil diesel and biodiesel fuels must have sulfur content below 15ppm and biodiesel often has less sulfur content than fossil diesel. One exception was noted in our review, where the biodiesel used in a home heating fuel study was found to have a sulfur content of 60ppm.[13] This may be an outlier, though some articles noted that sulfur content can vary by feedstock and processing methods, with potentially higher sulfur content in fuels derived from waste oils.[15]
- Additional literature reviews focused solely on NO_x emissions from biodiesel are provided.[16,17] While there is some variation in NOx emissions reported, the general consensus is that NO_x emissions are higher from biodiesel compared to diesel fuel. Variation may be due to differences in feedstock, biodiesel blend percentage, equipment, operating characteristics, and application of specific NOx controls.
- The largest area of research uncertainty appears to be the overall toxicity and carcinogenicity of biodiesel emissions. One recent systematic review found that biodiesel emissions reduced particle toxicity in two-thirds of the comparisons reviewed, but that there were large differences between various biodiesels for five category-specific biomarkers (inflammation, oxidative stress, cytotoxicity, genotoxicity, and mutagenicity).[18] The review concluded that "[a]t present, we cannot say with certainty which fuels are more or less toxic than fossil diesel, however, the present analysis does demonstrate quantitatively that we cannot assume biodiesels are

interchangeable from a health perspective." Contradictory findings about biodiesel toxicity are also reviewed in articles cited above, and the additional literature reviews cited here. [19,20]

  - More recent studies have continued to find contradictory effects.[21,22] One found that blending biodiesel up to 20% had minimal impact on toxicity, but that B50-B100 blends were more toxic and carcinogenic than diesel fuel.[22]
  - Several articles noted that although total mass of PM emissions tends to decrease with biodiesel, there is a corresponding increase in emissions of ultrafine particle emissions with a different chemical composition compared to USLD emissions, which may contribute to greater biodiesel toxicity detected in some studies.[5,8,9]

B. **Renewable diesel**

- No peer-reviewed studies were identified regarding health impacts of renewable diesel used in residential boilers.
- Based on automotive engine studies, renewable diesel is expected to reduce emissions of PM, NO_x, and PAHs as compared to ULSD, though the differences may be small using modern engines, and some contrary findings have been published about both NO_x and PAHs.[23,24,25,26] SO_2 emissions should be similar between renewable diesel and ULSD.

C. **Biomethane/RNG** (not including biogas)

- No peer-reviewed studies were identified regarding health impacts of biomethane used in residential applications.
- Based on automotive engine studies, NO_x emissions from biomethane are generally lower as compared to fossil gas. Other emissions from biomethane are expected to be similar to or lower than emissions from fossil gas, though most outdoor air pollutant emissions from fossil gas are already relatively low.[23,27,28,29,30]
- Some recent studies have raised concerns about harmful indoor emissions from cook stoves fueled by conventional fossil gas and propane.[31,32] Using biomethane in place of fossil gas may produce similar or slightly less harmful emissions.

D. **Renewable propane**

- No peer-reviewed studies were identified comparing health impacts of renewable propane to fossil propane. Renewable propane is chemically identical to conventional propane so would be expected to produce similar emissions.
- Some recent studies have raised concerns about harmful indoor emissions from cook stoves fueled by conventional fossil gas and propane.[31,32] Using renewable propane in place of propane may produce similarly harmful emissions.

E. **Hydrogen**

- Combustion of hydrogen alone or hydrogen blended into fossil gas may generate more NO_x emissions than fossil gas under certain circumstances.[33,34,35,36,37,38] One article suggests that additional standards and controls may be needed to mitigate NO_x emissions from hydrogen fuel combustion.[39] Blending hydrogen into fossil gas should reduce SO_2 and PM emissions, though both are already low in fossil gas emissions.

Other considerations

- Equity and affordability considerations: Ensuring equitable access to heating fuels, health benefits, and protection from health harms.
- Lifecycle impacts: Extraction, production, transportation, etc. impacts on emissions, environmental health; impacts related with upstream electricity generation.
- Fuel/technology used for backup power: For example, battery backup versus fossil-fueled generator. Accidental CO poisoning has caused about 50 ED visits / year and 1-2 deaths / year in Vermont over the past 10 years. Common causes of accidental CO poisoning include improper generator use or the malfunction or improper use of heating equipment, cooking equipment, or other combustion-fueled appliances.
- Implementation and timing of benefits: It is possible that drop-in biofuels could provide more immediate but smaller benefits while weatherization and electrification may provide larger benefits that take longer to deploy. Consideration should be given to how overall benefits are affected by how fuel policies serve to complement or compete with each other.

Recommended next steps

1) Establish a process for reviewing, summarizing, and considering the application of new scientific evidence on a biennial basis.
2) Consider dedicating resources to conduct a quantitative analysis of health impacts and monetizable costs or benefits of the measures listed in the Vermont Clean Heat Standard TRM.
3) Consider dedicating resources to conducting a life-cycle assessment of health impacts of the measures listed in the Vermont Clean Heat Standard TRM.

TAG Vote to approve the content of this memo and forward to the PUC:

- 10 votes in favor (Rick Weston, Emily Levin, Matthew Bakerpoole on behalf of DPS, Brian Woods, Emily Roscoe, Luce Hillman, Ken Jones, Jared Ulmer, Michelle Keller, Emily Grubert)
- 3 votes objecting (Floyd Vergara, Sam Lehr, Matt Cota)
- 2 members absent during vote (Patrick Wood, Casey Lamont)

Key references

- Building envelope strategies
  - ENV_CH_WxHealthReport.pdf (healthvermont.gov) - 2018 Vermont Department of Health synthesis of scientific evidence describing health impacts of home weatherization. More recent studies below:
  - Cascading benefits of low-income weatherization upon health and household well-being - ScienceDirect
  - Saving lives by saving energy? Examining the health benefits of energy efficiency in multifamily buildings in the United States - ScienceDirect
  - Health and financial benefits of weatherizing low-income homes in the southeastern United States - ScienceDirect
  - A dollar well spent: Monetizing the societal benefits of low-income weatherization programs in the United States - ScienceDirect
- Electric heating and appliances
  - Heat pumps and our low-carbon future: A comprehensive review - ScienceDirect
  - Residential home heating: The potential for air source heat pump technologies as an alternative to solid and liquid fuels - ScienceDirect
  - US residential heat pumps: the private economic potential and its emissions, health, and grid impacts - IOPscience
  - Methane and NOx Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes | Environmental Science & Technology (acs.org)
  - Population Attributable Fraction of Gas Stoves and Childhood Asthma in the United States (mdpi.com)
  - Gas Stoves and Respiratory Health: Decades of Data, but Not Enough Progress | Annals of the American Thoracic Society (atsjournals.org)
- Wood heating
  - Criteria, Greenhouse Gas, and Hazardous Air Pollutant Emissions Factors from Residential Cordwood and Pellet Stoves Using an Integrated Duty Cycle Test Protocol | ACS ES&T Air
  - Particulate matter emission control from small residential boilers after biomass combustion. A review - ScienceDirect
  - Full article: Introduction to Special Issue on Residential Wood Combustion (tandfonline.com)
  - An overview of particulate emissions from residential biomass combustion - ScienceDirect
  - Full article: Residential wood heating: An overview of U.S. impacts and regulations (tandfonline.com)
  - Full article: Online measurement of PM from residential wood heaters in a dilution tunnel (tandfonline.com)
  - Full article: Impacts of wood species and moisture content on emissions from residential wood heaters (tandfonline.com)
  - Emission factors from small scale appliances burning wood and pellets - ScienceDirect
  - Toward the ultra-clean and highly efficient biomass-fired heaters. A review - ScienceDirect

  - Estimating State-Specific Contributions to PM2.5- and O3-Related Health Burden from Residential Combustion and Electricity Generating Unit Emissions in the United States - PubMed (nih.gov)
  - Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005 - ScienceDirect
  - Indoor wood-burning from stoves and fireplaces and incident lung cancer among Sister Study participants - ScienceDirect
  - Fine particulate air pollution and human mortality: 25+ years of cohort studies - ScienceDirect
  - Woodsmoke Health Effects: A Review: Inhalation Toxicology: Vol 19 , No 1 - Get Access (tandfonline.com)
  - Review: Woodsmoke and emerging issues - ScienceDirect
- Biofuels, broadly
  - Effect of Low-Carbon Fuels and Energy Technologies on Co-Pollutant Emissions (Abt Associates literature review)
  - Biofuels and the Environment: Third Triennial Report to Congress (External Review Draft) | Biofuels | US EPA
- Biodiesel
  - Biodiesel Emissions: A State-of-the-Art Review on Health and Environmental Impacts (mdpi.com)
  - Health impacts of liquid biofuel production and use: A review - ScienceDirect
  - Performance and emissions of biodiesel in a boiler for residential heating - ScienceDirect
  - Fuel effects on PAH formation, toxicity and regulated pollutants: Detailed comparison of biodiesel blends with propanol, butanol and pentanol - ScienceDirect
  - Technological, technical, economic, environmental, social, human health risk, toxicological and policy considerations of biodiesel production and use - ScienceDirect
  - Re-assessing the toxicity of particles from biodiesel combustion: A quantitative analysis of in vitro studies - ScienceDirect
  - Effect of biodiesel on engine performances and emissions - ScienceDirect
  - Biodiesel exhaust particle airway toxicity and the role of polycyclic aromatic hydrocarbons - ScienceDirect
  - Environmental sustainability of biofuels: a review | Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences (royalsocietypublishing.org)
  - Biodiesel fuels: A greener diesel? A review from a health perspective - ScienceDirect
  - A paler shade of green? The toxicology of biodiesel emissions: Recent findings from studies with this alternative fuel - ScienceDirect
  - Breathing easier? The known impacts of biodiesel on air quality. - Abstract - Europe PMC
  - Desulfurization of biodiesel produced from waste fats, oils and grease using β-cyclodextrin - ScienceDirect
  - Study of combustion process of biodiesel/gasoil mixture in a domestic heating boiler of 26.7 kW - ScienceDirect
  - Emissions and energy/exergy efficiency in an industrial boiler with biodiesel and other fuels - ScienceDirect
  - Biodiesel Multimedia Evaluation (California Environmental Protection Agency)

- Renewable diesel
  - Comprehensive review of combustion, performance and emissions characteristics of a compression ignition engine fueled with hydroprocessed renewable diesel - ScienceDirect
  - Low Emission Diesel (LED) Study: Biodiesel and Renewable Diesel Emissions in Legacy and New Technology Diesel Engines - Final Report
  - Assessment of carbonyl and PAH emissions in an automotive diesel engine fueled with butanol and renewable diesel fuel blends - ScienceDirect
  - Renewable Diesel Multimedia Evaluation (California Environmental Protection Agency)
- Biomethane/RNG
  - Chemical and Toxicological Properties of Emissions from a Light-Duty Compressed Natural Gas Vehicle Fueled with Renewable Natural Gas | Environmental Science & Technology
  - Ultrafine Particle Emissions from Natural Gas, Biogas, and Biomethane Combustion | Environmental Science & Technology
  - Assessment of the Environmental Impact of Using Methane Fuels to Supply Internal Combustion Engines
  - Environmental impact assessment of the production of biomethane from landfill biogas and its use as vehicle fuel - ScienceDirect
- Hydrogen
  - Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NO x emissions - Environmental Science: Atmospheres (RSC Publishing)
  - Analysis of NOx Formation in a Hydrogen-Fueled Gas Turbine Engine | J. Eng. Gas Turbines Power | ASME Digital Collection
  - Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels - ScienceDirect
  - Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance
  - The Impact of Hydrogen Admixture into Natural Gas on Residential and Commercial Gas Appliances
  - Combustion performance of low-NOx and conventional storage water heaters operated on hydrogen enriched natural gas - ScienceDirect
  - Ultra-low NOx emissions from catalytic hydrogen combustion - ScienceDirect

[1] Evidence-based public health: a fundamental concept for public health practice - PubMed
[2] Can science help people make decisions? | National Academies
[3] How to Evaluate Trustworthiness in Science | National Institutes of Health (NIH)
[4] Sources of Evidence - Evidence-Based Public Health - Research Guides at University of Alabama - Birmingham (uab.edu)
[5] Biodiesel fuels: A greener diesel? A review from a health perspective - ScienceDirect
[6] Effect of biodiesel on engine performances and emissions - ScienceDirect

[7] Biodiesel Emissions: A State-of-the-Art Review on Health and Environmental Impacts (mdpi.com)
[8] Environmental sustainability of biofuels: a review | Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences (royalsocietypublishing.org)
[9] Breathing easier? The known impacts of biodiesel on air quality. - Abstract - Europe PMC
[10] Health impacts of liquid biofuel production and use: A review - ScienceDirect
[11] Biodiesel Multimedia Evaluation (California Environmental Protection Agency)
[12] Study of combustion process of biodiesel/gasoil mixture in a domestic heating boiler of 26.7 kW - ScienceDirect
[13] Performance and emissions of biodiesel in a boiler for residential heating - ScienceDirect
[14] Emissions and energy/exergy efficiency in an industrial boiler with biodiesel and other fuels - ScienceDirect
[15] Desulfurization of biodiesel produced from waste fats, oils and grease using β-cyclodextrin - ScienceDirect
[16] Impacts of biodiesel combustion on NOx emissions and their reduction approaches - ScienceDirect
[17] Review of the effects of biodiesel on NOx emissions - ScienceDirect
[18] Re-assessing the toxicity of particles from biodiesel combustion: A quantitative analysis of in vitro studies - ScienceDirect
[19] A paler shade of green? The toxicology of biodiesel emissions: Recent findings from studies with this alternative fuel - ScienceDirect
[20] Technological, technical, economic, environmental, social, human health risk, toxicological and policy considerations of biodiesel production and use - ScienceDirect
[21] Biodiesel exhaust particle airway toxicity and the role of polycyclic aromatic hydrocarbons - ScienceDirect
[22] Fuel effects on PAH formation, toxicity and regulated pollutants: Detailed comparison of biodiesel blends with propanol, butanol and pentanol - ScienceDirect
[23] Effect of Low-Carbon Fuels and Energy Technologies on Co-Pollutant Emissions (Abt Associates literature review)
[24] Comprehensive review of combustion, performance and emissions characteristics of a compression ignition engine fueled with hydroprocessed renewable diesel - ScienceDirect
[25] Low Emission Diesel (LED) Study: Biodiesel and Renewable Diesel Emissions in Legacy and New Technology Diesel Engines - Final Report
[26] Assessment of carbonyl and PAH emissions in an automotive diesel engine fueled with butanol and renewable diesel fuel blends - ScienceDirect
[27] Assessment of the Environmental Impact of Using Methane Fuels to Supply Internal Combustion Engines
[28] Chemical and Toxicological Properties of Emissions from a Light-Duty Compressed Natural Gas Vehicle Fueled with Renewable Natural Gas | Environmental Science & Technology
[29] Ultrafine Particle Emissions from Natural Gas, Biogas, and Biomethane Combustion | Environmental Science & Technology
[30] Environmental impact assessment of the production of biomethane from landfill biogas and its use as vehicle fuel - ScienceDirect
[31] Clearing the Air: Gas Stove Emissions and Direct Health Effects - PMC
[32] Gas and Propane Combustion from Stoves Emits Benzene and Increases Indoor Air Pollution | Environmental Science & Technology
[33] Analysis of NOx Formation in a Hydrogen-Fueled Gas Turbine Engine | J. Eng. Gas Turbines Power | ASME Digital Collection
[34] Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels - ScienceDirect
[35] Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance
[36] The Impact of Hydrogen Admixture into Natural Gas on Residential and Commercial Gas Appliances
[37] Combustion performance of low-NOx and conventional storage water heaters operated on hydrogen enriched natural gas - ScienceDirect
[38] Ultra-low NOx emissions from catalytic hydrogen combustion - ScienceDirect
[39] Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NO x emissions - Environmental Science: Atmospheres (RSC Publishing)