Vermont Energy Sector Life Cycle Assessment
Draft

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LIST OF ABBREVIATIONS & ACRONYMS

ANL	Argonne National Laboratory
CAP	Vermont Climate Action Plan
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon dioxide equivalents
DEC	Vermont Department of Environmental Conservation
EF	Emission factor
GHG	Greenhouse Gas
G-res	GHG Reservoir Model
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GWP	Global Warming Potential
GWSA	Vermont Global Warming Solutions Act
IPCC	Intergovernmental Panel on Climate Change
ISO-NE	New England Independent System Operator
LCA	Life Cycle Assessment
MMT	Million metric tonnes
N_2O	Nitrous Oxide
RCI	Residential / Commercial / Industrial
REC	Renewable Energy Credit
VCC	Vermont Climate Council
VT GHG EI	Vermont Greenhouse Gas Emissions Inventory
WTW	Well-To-Wheel

GLOSSARY

To be added

1. INTRODUCTION

The *Vermont Global Warming Solutions Act* (GWSA) set emission reduction requirements through the 2020 to 2050 period. Emissions abatement thresholds are as follows: 26% below 2005 levels by 2025, 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050. Benchmarking progress for these requirements is officially evaluated using the *Vermont Greenhouse Gas Emissions Inventory* (VT GHG EI), which was developed by the Vermont Agency of Natural Resources (ANR). The annually published VT GHG EI quantifies baseline greenhouse gas (GHG) emissions levels for 1990 and 2005, and additionally tracks time series changes in those emissions for the 1990 to 2020 period in accordance with Intergovernmental Panel on Climate Change (IPCC) guidelines. The VT GHG EI is an in-boundary, sector-based analysis (Vermont ANR, 2023). This means that it characterizes emissions associated with the use phase of energy commodities consumed within Vermont (e.g., fuel combusted in vehicles or at facilities) and emissions associated with upstream activities (e.g., raw material extraction, processing, transportation, etc.) to the extent they occur within the state. Additionally, the VT GHG EI includes emissions from non-energy sectors such as agriculture, industrial processes, waste, and the fossil fuel industry.[1] The emissions associated with electricity consumption account for the direct emissions from generating electricity from outside of the state. However, for all other energy sectors, upstream emissions occurring outside of the state borders are not included. Additionally, the upstream emissions from extraction and processing of fuel consumed for electricity generation are similarly not included.

The GWSA furthermore mandates the development of the *Vermont Climate Action Plan* (CAP) under the guidance of the established Vermont Climate Council (VCC). The GWSA requires that the CAP is to be updated at four-year intervals, with the first iteration drafted and released in 2021. It called for further research and data gathering around life cycle emissions related to the use of energy pathways in Vermont, where energy pathways reflect the combination of fuel types and end-use sectors. This project supplements the VT GHG EI by developing upstream emissions factors (EFs) and upstream emissions estimates for energy pathways used in Vermont. This report then combines the existing VT GHG EI with the upstream emission estimates to determine total VT energy sector life cycle emissions.

This project included the following objectives:

1) Identification of energy pathways used in Vermont and life cycle stages represented in the VT GHG EI.
2) Determination of life cycle assessment (LCA) data, methods, and tools to best characterize each energy pathway's upstream emissions.
3) Calculation of upstream emission factors for each energy pathway.
4) Calculating total upstream energy pathway emissions based on VT GHG EI activity data.
5) Combine total upstream energy pathway emissions with the existing in-state VT GHG EI.

The outcomes of this effort are an Excel workbook and this report. The Excel workbook includes (1) a dataset of upstream EFs for the energy pathways included in the VT GHG EI, and discussed herein for the time series 1990-2020, and (2) an upstream emissions inventory for VT that includes both upstream and in-state emissions for energy sectors for the time series 1990-2020.

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[1] That is, emissions from these sectors that do not result from energy use.

1.1 Intended Use

The results from this project include upstream emission factors, by major GHG species, for each VT energy pathway and total energy sector emissions estimates based on activity data for 1990-2020. The emission factors can be used in any applications which seek to either compare upstream emissions on a per unit energy basis between pathway options, or for supply chain footprinting based on quantities of energy pathway consumption data. The upstream emissions totals can be paired with emissions estimates from the VT GHG EI to provide full life cycle emissions accounting for VT energy pathways. This effort provides key information that will support the VCC in its decision-making as it moves forward with implementing and updating the CAP, such as the identification of additional GHG emission sources, where to focus strategic next steps in emission GHG impacts reductions, and how best to prioritize funding for needed programs and technical analyses.

2. PATHWAY METHODS

Relevant energy pathways for examination were identified through use of the VT GHG EI and the CAP. Each document was evaluated for energy pathways which are currently established, or quickly emerging, in Vermont. The list of energy pathways assessed are shown in Table 1, with the relevant sectors indicated.

For a consistent and comprehensive approach, emissions modeling of most energy pathways was performed using the Greenhouse Gases, Regulated Emissions, and Energy Used in Technologies (GREET) model from Argonne National Laboratory (ANL) (Argonne National Laboratory, 2023). GREET is a highly parameterized life cycle model which includes many of the most common U.S. fuels and energy pathways. GREET also provides full time series estimates back to 1990. As documented for each pathway, where appropriate we configure GREET to reflect conditions specific to Vermont.

Table 1: List of Vermont Energy Pathways and Relevant Sectors

Fuel	Relevant Sectors
Asphalt	RCI
Biodiesel	Transport
Bioelectricity	Electricity
Compressed Natural Gas	Transport
Corn Ethanol	Electricity; RCI
Coal	Transport
Diesel	Transport
Firewood, Commercial	RCI - Residential
Firewood, Non-Commercial	RCI - Residential
Gasoline Blendstock (E0)	Transport
Gasoline, E10	Transport
Heating Oil	RCI
Hydro, Quebec	Electricity
Hydro, Reservoir	Electricity
Hydro, Run-of-River	Electricity
Jet/Kerosene	RCI; Transport

Fuel	Relevant Sectors
Natural Gas	Electricity; RCI
Nuclear	Electricity
Petroleum	Transportation
Propane, from crude petroleum	RCI
Propane, from natural gas liquids	RCI
Renewable Natural Gas, from animal waste	Electricity; RCI
Renewable Natural Gas, from landfill gas	Electricity; RCI
Solar Photovoltaic, Residential	Electricity
Solar Photovoltaic, Commercial	Electricity
Wind, Offshore	Electricity
Wind, Onshore	Electricity
Wood, Chips	RCI - Commercial, Industrial
Wood, Pellets	RCI - Residential

Table Acronym: RCI – Residential/Commercial/Industrial

For each of the energy pathways shown above, we identified the appropriate data sources required to evaluate the upstream GHG emissions. Together with the in-state emissions provided in the VT GHG EI, these emissions will enable the evaluation of the full life cycle for each. A simplified system diagram is shown in Figure 1. Included in the evaluation are emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). For each pathway, we describe the data sources used to characterize the GHG emissions for the production and distribution of the energy source below.

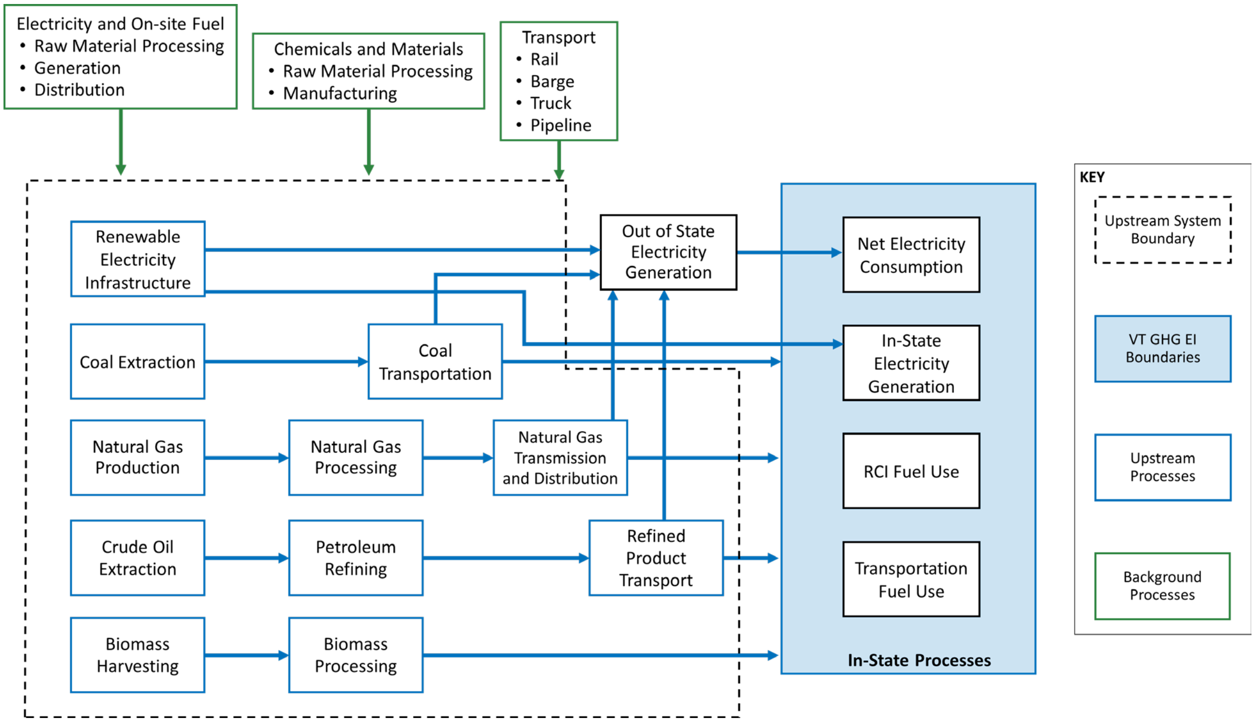

Figure 1. Simplified system diagram highlighting stages for upstream emissions for energy pathways.

The EFs generated for this assessment are included in a companion Excel workbook. Within the workbook, users can adjust the global warming potential (GWP) characterization factors used to convert emissions of GHGs to units of carbon dioxide equivalents (CO_2e). Characterization factors are available from the 4th, 5th, and 6th Assessment Reports produced by the IPCC, at both 20-year and 100-year time horizons. Users can also toggle whether biogenic CO_2 is included in any GHG assessment. The accounting of biogenic CO_2 for any pathway is discussed for each in subsequent sections.

The upstream EFs for each energy source may differ depending on their end use. For example, natural gas consumed by the Residential/Commercial/Industrial (RCI) sectors uses a different distribution network than that consumed by the electricity sector. As such, the EFs for each energy pathway reflects the combination of fuel types and end-use sector.

After developing EFs for each energy pathway, annual emissions totals are calculated consistent with the activities defined in the VT GHG EI. Activity data (e.g., natural gas consumed by the residential sector)—by year, sector, and pathway—are derived from the VT GHG EI. Annual emissions are calculated by multiplying the activity data by the appropriate EFs (Table 2).

Table 2: Emissions Activities and Assigned Energy Pathways

Activity	Energy Pathway
Electricity; Coal	[Electricity] Coal
Electricity; Natural Gas	[Electricity] Natural Gas
Electricity; Oil/Diesel/Jet	[Electricity] Petroleum
Electricity; LPG (propane)	[Electricity] Petroleum
Electricity; Wood/Biomass	[Electricity] Wood Residues
Electricity; Nuclear	[Electricity] Nuclear
Electricity; Hydro (VT)	[Electricity] Hydro, Run-of-River
Electricity; Hydro (US non-VT)	[Electricity] Hydro, Reservoir
Electricity; Hydro (US non-VT)	[Electricity] Hydro, Run-of-River
Electricity; Hydro (Quebec)	[Electricity] Hydro Quebec
Electricity; Wind	[Electricity] Wind, Onshore
Electricity; Solar PV (utility)	[Electricity] Solar PV, Commercial/Utility, Fleet Average
Electricity; Landfill Gas	[Electricity] RNG, Landfill
Electricity; Other Renewable	n/a
Electricity; Anaerobic Digester	[Electricity] RNG, Animal Waste
Electricity; MSW/Trash/Waste	n/a
RCI Fuel - Residential; Coal	[RCI] Coal
RCI Fuel - Residential; Distillate Fuel	[Transport] Diesel
RCI Fuel - Residential; Kerosene	[RCI, Transport] Jet/Kerosene
RCI Fuel - Residential; Hydrocarbon Gas Liquids	[RCI] Propane, from NGL
RCI Fuel - Residential; Fossil Natural Gas	[RCI] Natural Gas
RCI Fuel - Residential; Renewable Natural Gas	[RCI] RNG, Animal Waste
RCI Fuel - Residential; Renewable Natural Gas	[RCI] RNG, Landfill
RCI Fuel - Residential; Wood, Pellets	[RCI] Wood Pellets

Activity	Energy Pathway
RCI Fuel - Residential; Wood, Cord	[RCI] Firewood, Commercial
RCI Fuel - Commercial; Coal	[RCI] Coal
RCI Fuel - Commercial; Distillate Fuel	[Transport] Diesel
RCI Fuel - Commercial; Kerosene	[RCI, Transport] Jet/Kerosene
RCI Fuel - Commercial; Hydrocarbon Gas Liquids	[RCI] Propane, from NGL
RCI Fuel - Commercial; Motor Gasoline	[Transport] Gasoline, E10
RCI Fuel - Commercial; Residual Fuel	[RCI] Heating Oil
RCI Fuel - Commercial; Fossil Natural Gas	[RCI] Natural Gas
RCI Fuel - Commercial; Renewable Natural Gas	[RCI] RNG, Animal Waste
RCI Fuel - Commercial; Wood	[RCI] Wood Chips
RCI Fuel - Industrial; Coking Coal	[RCI] Coal
RCI Fuel - Industrial; Other Coal	[RCI] Coal
RCI Fuel - Industrial; Asphalt and Road Oil	[RCI] Asphalt
RCI Fuel - Industrial; Distillate Fuel	[Transport] Diesel
RCI Fuel - Industrial; Kerosene	[RCI, Transport] Jet/Kerosene
RCI Fuel - Industrial; Hydrocarbon Gas Liquids	[RCI] Propane, from NGL
RCI Fuel - Industrial; Lubricants	[RCI] Heating Oil
RCI Fuel - Industrial; Motor Gasoline	[Transport] Gasoline, E10
RCI Fuel - Industrial; Residual Fuel	[RCI] Heating Oil
RCI Fuel - Industrial; Special Naphthas	[RCI] Heating Oil
RCI Fuel - Industrial; Waxes	[RCI] Heating Oil
RCI Fuel - Industrial; Fossil Natural Gas	[RCI] Natural Gas
RCI Fuel - Industrial; Renewable Natural Gas	[RCI] RNG, Animal Waste
RCI Fuel - Industrial; Wood	[RCI] Wood Chips
Transportation; Ethanol	[Transport] Corn Ethanol
Transportation; Fossil Motor Gasoline	[Transport] Gasoline Blendstock (E0)
Transportation; Fossil Diesel	[Transport] Diesel
Transportation; Bio Diesel	[Transport] Biodiesel
Transportation; Natural Gas	[Transport] CNG
Transportation; Jet Fuel	[RCI, Transport] Jet/Kerosene
Transportation; Aviation Gasoline	[RCI, Transport] Jet/Kerosene

Table Acronyms: CNG – Compressed Natural Gas, LPG – Liquified Petroleum Gas, MSW – Municipal Solid Waste, NGL , PV – Photovoltaics, RCI – Residential/Commercial/Industrial, RNG – Renewable Natural Gas

2.1 Coal

GREET was used to generate EFs associated with the supply chain of coal consumed in Vermont. The scope of activities represented in the coal models include coal mining, fugitive coal mine methane, cleaning, and transportation of coal to power plants or other facility. The model also uses default, or user specified, transportation data detailing mode, mode shares, and transportation distance of coal.

2.2 Natural Gas

GREET was used to generate EFs associated with the supply chains of various natural gas products consumed in Vermont. The scope of activities represented in the natural gas models include shale or conventional natural gas recovery, processing, transmission, transportation, and distribution. GREET also models processes involved in liquefication and compression, where appropriate. EFs for the following natural gas end-uses are available in GREET: stationary fuel, electricity generation, compressed natural gas, and liquefied natural gas as transportation fuel. GREET models natural gas extraction using a weighted average approach based on the national split in conventional and shale natural gas recovery. GREET models transportation using average transmission distance and mode data for natural gas products in the U.S. GREET results for natural gas products reflect the average mix of shale and conventional gas produced in the U.S. For the purposes of this project, default transmissions parameters for natural gas in GREET were used. GREET does not differentiate emissions by natural gas basin, but rather uses a national average.

2.3 Petroleum Products

GREET was used to generate EFs associated with the supply chains of various petroleum products consumed in Vermont. The scope of activities represented includes the extraction of crude oil, transportation of oil to refiners, refining into petroleum products, and distribution of petroleum products. GREET models crude oil extraction using a weighted average approach for conventional crude and shale oil. GREET models transportation using average transmission distance and mode data for imported crudes and petroleum products in the U.S. GREET results for petroleum products reflect the average mix of foreign and domestic crudes processed by U.S. refineries. For the purposes of this project, default transportation parameters for crude oil in GREET were used.

2.4 Biofuels

GREET was used to generate EFs associated with the supply chains of fuel ethanol and biodiesel. The scope of activities represented includes the farming and harvest of biomass feedstocks (corn and soybeans, respectively based on current U.S. conditions), the processing of feedstocks and refining to fuels, and the transportation between activities and delivery to distributors. GREET models transportation segments using average distance and mode data for biofuels distributed throughout the United States. The majority of the feedstock pathways in GREET assume agricultural production in the U.S. Midwest. GREET does not model biogenic CO_2 uptake during plant growth nor differentiate fossil from biogenic GHG emissions within the life cycle phases used to compile the upstream EFs generated here.

2.5 Solar

GREET was used to estimate GHG emissions associated with the production of solar panels. The model provides EFs from materials and energy inputs consumed in the manufacturing of both residential and utility solar PV systems. The scope of activities that these factors represent includes raw material extraction, intermediate materials production; silicon and solar PV panel production, solar PV transportation, solar PV system installation, and end-of-life treatment. GREET models solar PV production using an assortment of default, or user-defined, supply chain parameters, alongside various assumptions for transportation between production geographies. Moreover, GREET provides default solar PV system parameters pertaining to installation type; lifespan; performance ratio; annual average irradiation on tilted panels; average yield; average degradation rate per year; lifetime average degradation; and average yield including degradation. Key material inventories are provided for each installation type. End-of-life emissions are only representative of energy consumption during treatment.

2.6 Wind

GREET was used to estimate GHG emissions associated with the manufacturing of wind turbines. The model provides EFs from materials and energy inputs consumed in the manufacturing of both onshore and offshore wind turbines in the U.S. Due to the low penetration of offshore wind projects, all wind energy currently consumed in VT was modeled using onshore emission estimates. GREET provides emissions embodied in material comprising modeled turbines. The model does not provide emissions data on maintenance, end-of-life, or land use change.

2.7 Hydroelectricity

Hydroelectric power falls into two categories as it relates to the VT GHG EI. The first comes in the form of renewable energy credits (RECs) and direct consumption from the Canadian public utility Hydro-Quebec. The second is electricity generated from hydroelectric sites within Vermont, and more broadly imported from the New England Independent System Operator (ISO-NE), which primarily rely on run-of-river assets.

2.7.1 Hydro Quebec Mix

Levasseur et al. (2021) models Hydro-Quebec hydropower plants through various estimation methods, which differ by the types of emissions they represent (diffusion, bubbling, or degassing through various emission vectors); whether they are gross or net emissions; if they are reservoir-specific; if they are geography-specific; the number of impoundments they represent; and if they use direct measurements, modeling, or a generic approach. Net emissions (100 years) from the GHG Reservoir (G-res) model EFs produced by Levasseur et al. (2021) for average GHG emissions associated with hydropower in the Hydro-Quebec mix were used to model the CO_2 and CH_4 emissions resulting from both run-of-river and boreal reservoir hydroelectric assets. Nitrous oxide emissions were excluded from the Levasseur et al. (2021) study as other research found no net nitrous oxide emissions change between pre- and post-impoundment periods.

The G-res model factors were selected because the emissions this method addresses includes net diffusion of CO_2 and CH_4; net bubbling of CH_4; and net degassing of CH_4. The Levasseur et al. (2021) factors are aggregated life cycle EFs, and do not delineate EFs by the flux type or hydroelectric asset from which a GHG flux occurs. The G-res estimates are generated using the publicly available G-res model developed by the International Hydropower Association in collaboration with the UNESCO Chair in Global Environmental Change. Using sites-specific parameters, the model estimated GHG fluxes associated with hydropower resources in the Hydro-Quebec mix. While other methods use direct measurements, none offer this level of granularity or spectrum of emission fluxes.

Levasseur et al. (2021) only characterizes use-phase and biogenic emissions that are a consequence of installing infrastructure. Construction emissions associated with the building of the hydroelectric dams were developed using GREET and Ecoinvent 3.7 (ecoinvent, 2021). GREET provides an abbreviated construction inventory for reservoir-based plants, and

Ecoinvent 3.7 process LCI data allows for calculation of run-of-the-river facility construction. These are weighted using available Hydro-Quebec data. GREET reservoir construction data represent average conditions in the U.S. Ecoinvent 3.7 infrastructure data for run-of-the-river plants were constructed using a mix of plants constructed during the period defined in the dataset.

EFs produced using the G-res model are calculated using data from 2017 and represent average emissions over a 100-year time horizon. Levasseur et al. (2021) 100-year G-Res emissions resulting from hydroelectric impoundments are temporally sensitive. Therefore, through use of these factors, it is assumed that 2017 modeled emissions estimates are representative of current and historical conditions. Run-of-the-river infrastructure data are representative of plants constructed between 1930 and 2011.

2.7.2 Regional Hydroelectric

Vermont hydroelectric resources are largely comprised of run-of-river assets. In the absence of robust life cycle emissions data for Vermont, and U.S. contexts more broadly, data were used from Levasseur et al. (2021) from Hydro Quebec. However, those emission factors relate to the average production split of various impoundment and run-of-river sites within the Hydro Quebec network. To isolate average emission factors only for run-of-river assets, Appendix A.1. and Table A.4. of the publication were used. Appendix A.1. lists the type (run-of-river or reservoir) and electricity production for the 2011-2015 period ($GWh \cdot yr^{-1}$), by site. Table A.4. lists the Net 100-year emissions calculated using the G-Res model, by GHG species, for all sites within Hydro Quebec. To develop average emissions from run-of-river facilities, contribution coefficients to total run-of-river electricity production were calculated. These contribution coefficients were then multiplied by the sites' corresponding CO_2 and CH_4 emission factors. Results were then summed by gas. Emissions from ISO-NE hydroelectric facilities were calculated using the average emission factor between run-of-river and reservoir technologies.

2.8 Woody Biomass

The GREET Bio-Electricity Generation module was used to model the life cycle inventories and GHG emissions of most woody biomass pathways, including both solid fuels and electricity. This module contains unit processes that model the entire upstream supply chains of many forms of wood commodities including processes before transport to and combustion in a bio-electricity plant. For example, wood pellet production from an array of feedstocks (e.g., mill residues, logging residues, or pulp logs) is characterized at a resolution where EFs by life cycle stage, from cradle to pellet plant gate, are all available. GREET provides these EFs for all wood commodities except non-commercial firewood, which is instead constructed from CORRIM data (itself derived from Oniel et al., 2010) from the Federal LCA Commons (CORRIM, 2019; Oneil et al., 2010). Additionally, representative hardwood (HW) and softwood (SW) tree species consumed in VT were chosen and used throughout the pathway modeling: eastern white pine (*pinus strobus*) for SW and sugar maple (*acer saccharum*) for HW. Average physical properties for these representative tree species were obtained from USDA Forest Service estimates, and used to parameterize GREET and construct the non-commercial firewood unit processes (Miles & Smith, 2009).

Biogenic CO_2 sequestration by forests and biogenic GHG emissions from woody biomass decomposition and combustion are excluded from this analysis due to GREET's focus on short-rotation, carefully managed wood crops. These limitations, along with broader perspectives and visions for improved forest carbon modeling, are further discussed below in section 3.5 on Woody Biogenic Emissions.

2.8.1 Woody Biomass for Electricity Generation

Electricity derived from an array of woody biomass feedstocks was characterized using GREET's Bio-Electricity module. Feedstock categories included HW and SW logging residues, HW and SW mill residues, SW mill chips (as a proxy for waste wood), and <1% fractions of HW and SW logs (i.e., reserve fuel for mud season).

Each of these feedstocks underwent some or all of the following life cycle stages which are included in the analysis: tree harvest and residue collection, biomass processing (loading, grinding, chipping), transportation (origin and destination round-trip). Residue feedstocks (e.g., milling residues) may only experience a subset of those stages, depending on the allocation parameters specified within GREET. Residues can either be (a) treated as a co-product of logging and milling operations and be attributed to some fraction of upstream impacts via mass-based or economic allocation, or (b) assumed to be obtained as a burden-free waste product. By default, GREET performs economic allocation and so includes upstream emissions from the residues. Additionally, the "lumber mill operations, shared" stage will appear as an additional life cycle stage for pathways incorporating mill residues when a mass or economic allocation method is selected.

GREET inventory data and results are typically derived from nationally or regionally averaged data. However, GREET can also accept average transportation distances and modes as parameters in order to better reflect sub-regional activity (i.e., in-state or imported energy products). For the purposes of this project, ERG estimated transportation distances to bio-electricity plants via the maximum typical harvest radius around the McNiel plant: per Burlington Electric's website, "wood used is harvested primarily in Vermont and upstate New York within a 60-70 mile radius of the plant" (Burlington Electric Department, 2023).

2.8.2 Woody Biomass for RCI Fuel Use

A combination of the GREET Bio-Electricity Generation module and CORRIM data were used to model the life cycle inventories and GHG emissions of woody biomass solid fuel commodities consumed in VT, including firewood (commercial and non-commercial), pellets, and wood chips. Firewood and pellets are assumed to only correspond to residential consumption as an RCI fuel, whereas chips are consumed by commercial and industrial entities.

Wood pellets undergo the following life cycle stages: lumber milling, mill residue collection, mill residue drying, pellet production, and transport. Wood chips' stages include lumber milling, mill residue collection, and transport. And firewood commodities, both commercial and non-commercial, are modeled as having just two stages: harvest/collection and transport.
Again, "lumber mill operations, shared" can appear as an additional life cycle stage for feedstocks derived from mill residues if a mass-based or economic allocation method is selected—as opposed to assuming that mill residues are obtained as a burden-free waste product.

2.9 Nuclear

GREET was used to estimate GHG emissions associated with nuclear power. The model provides EFs for materials and energy inputs involved in the construction and operation of a nuclear power plant. Results from this tool were applied to the historical in-state nuclear and ISO-NE residual mix pathways. GREET models the average emissions attributable to infrastructure for a variety of nuclear power plant designs. For this model, Generation II Pressurized Water Reactor (PWR) data were selected. This is the reactor type operated by the Seabrook Nuclear Power Station and are assumed for the now-retired Yankee Nuclear Power Plant. Default parameter values were used for both infrastructure and uranium supply chains. All background fossil fuel consumption data are modeled using the same parameter values applied when collecting upstream EFs for the fossil fuels consumed in Vermont. Emissions for infrastructure are allocated on a per kWh basis according to key assumption parameters for the modeled plant. For uranium fuel, GREET models emissions associated with mining; enrichment; conversion; fabrication & waste storage; and uranium fuel transportation. Power plant emissions for the nuclear power plant are representative of PWR conditions, while uranium procurement, processing and management are only representative of Light Water Reactor conditions; to which PWRs are a subset. The GREET model provides average data for nuclear power fuel and infrastructure under U.S. conditions. All mining of uranium is modeled as occurring in the United States. All background fossil fuel consumption applied for infrastructure or fuel processes are representative of average U.S. conditions.

2.10 Renewable Natural Gas (RNG)

GREET was used to generate an array of EFs associated with the supply chains of both landfill gas (LFG) and animal waste (AW) RNG consumed as a gaseous RCI fuel and as a source of electricity in Vermont. The GREET RNG and Waste tabs allow users to model the life cycle inventory and GHG emissions of RNG derived from both captured LFG methane and AW processed by an anaerobic digester. EFs by GHG species were produced for each RNG type across two end-uses: (1) capture-to-element RCI fuel use, and (2) capture-to-plant-gate supply of RNG for the electricity sector. EFs are provided in aggregate for the life cycle of each RNG product, alongside their stage-level EFs. RNG-LFG stages include biogas production and pipeline transport. RNG-AW's stages include waste collection, biogas production, and biogas upgrading for all end-uses. A pipeline transport stage is modeled for animal waste RNG consumed as an RCI fuel, but excluded when used to generate electricity, as most of this RNG is consumed on-site in combined heat and power (CHP) generators.

By default, GREET assigns counterfactual emissions credits to both RNG pathways: landfill RNG is credited with avoided landfill gas flaring emissions, and animal waste RNG is credited with avoiding emissions from traditional manure treatment. ERG excludes these counterfactual credits from the baseline EFs, since these shifts in emissions sources should be already counted within the VT GHG EI in the Waste sector. Furthermore, these credits implicitly rely upon a status quo where RNG is typically not captured and LFG flaring and animal manure emissions occur unabated, which does not conform to the stated goals of the GWSA. Separately, in order to facilitate isolated, *current* comparisons of RNG to fossil natural gas, separate emission factors are provided that reincorporate these counterfactual emissions credits.

Within the animal waste RNG pathway, GREET assigns a negative emissions credit where carbon is permanently "sequestrated" when applying AD residues or conventionally treated animal waste as soil amendments. However, GREET's assumption of permanent sequestration is not supported by citation nor soil organic carbon (SOC) modeling. Following application of AD digestate and treated manure to farmland, re-emission of sequestered soil carbon can occur, depending largely on how farming practices disturb the soil (Sanderman et al., 2017). Additionally, GREET does not consider any counterfactual source reduction scenarios (i.e., avoiding livestock production, converting pasture to other land uses, etc.) which could potentially achieve higher SOC storage than raising livestock on pasture. For these reasons we exclude all negative emissions credits assigned due to "C Sequestration" across GREET's RNG and Waste tabs.

When scaling RNG pathway upstream emission factors to total upstream emissions, a collection of assumptions were made (in lieu of sufficient high-resolution data) in order to distribute RNG-LNG and RNG-AW consumption across the RCI sub-sectors. The latest VT GHG EI only contains a total, state-wide time-series estimate of RNG consumption. We assume this RNG is half RNG-AW and half RNG-LF, and is also uniformly distributed across residential, commercial, and industrial sub-sectors.

3. RESULTS AND DISCUSSION

Results are shown for the time series 1990-2020 by sector. Figures reflect the use of AR5-100yr characterization factors (GWPs) and include biogenic CO_2 emissions unless otherwise stated. Where In-state emissions are shown, these emissions reflect those emissions published in the latest VT GHG EI.[2]

3.1 Energy Sector: Total emissions by sector

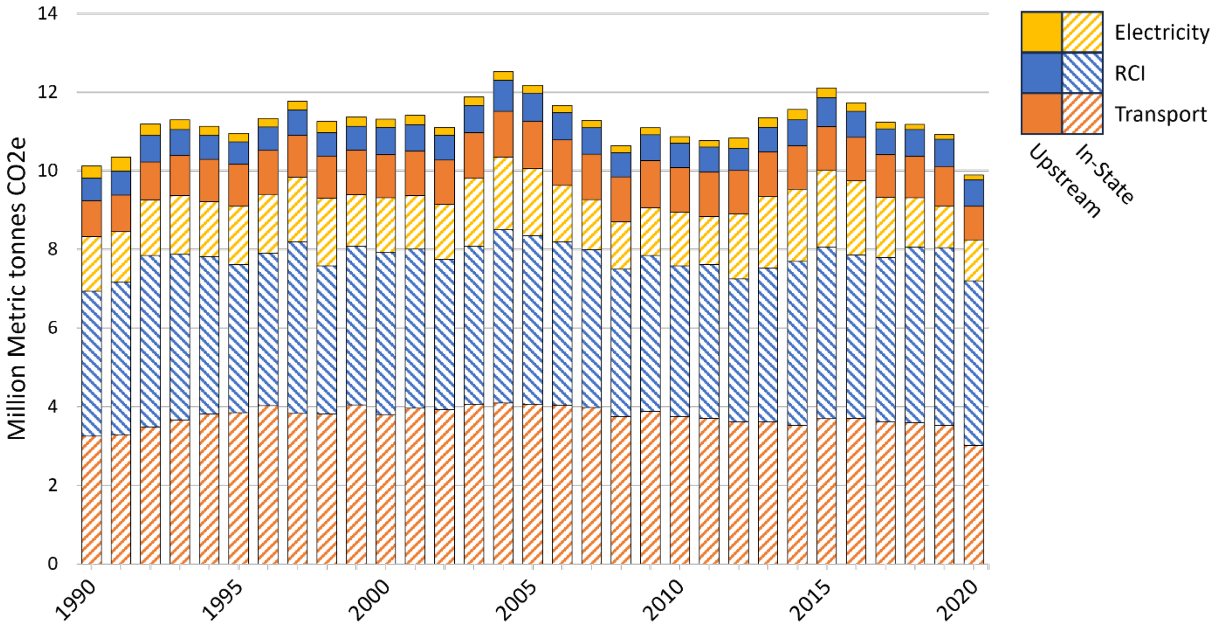

Figure 2. Upstream and In-state emissions by sector, including biogenic CO_2.

Figure 2 depicts total life cycle emissions by all Vermont energy sectors with the upstream and in-state contributions represented in filled and striped bar segment patterns, respectively. The upstream portion of these emissions are consistently small contributors to the full life cycle totals. This is likely attributable to high overall combustion emissions and proportionately lower supply chain emissions for fossil and bio-based energy feedstocks. Along the entire 1990-2020 time series, low overall emissions are observed across all energy pathways consumed in the electricity sector relative to total energy-driven emissions in the state. This is due to the state's historical reliance on low-emitting or renewable sources of electricity such as hydroelectric and nuclear power. Conversely, the transport and RCI sectors historically consume high quantities of fossil-based energy. Lastly, total emissions across all three sectors have remained relatively stable between 10 and 12 million metric tonnes CO_2e ($MMTCO_2e$) throughout the time period, until 2020 when they dropped to 9.9 $MMTCO_2e$. Total emissions by sector, including a comparison to non-energy sectors, is included in Table 3.

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[2] For consistency to the latest published estimates, in-state emissions should be sourced directly from the VT GHG EI instead of from values included here.

Table 3. Upstream and In-state emissions for VT (MMTCO$_2$e), including biogenic CO$_2$

	1990	2000	2010	2015	2018	2019	2020
Electricity - In-state	1.39	1.38	1.37	1.95	1.26	1.05	1.04
Electricity - Upstream	0.30	0.21	0.17	0.26	0.13	0.12	0.12
RCI - In-state	3.69	4.13	3.83	4.37	4.46	4.51	4.19
RCI - Upstream	0.58	0.69	0.62	0.73	0.68	0.69	0.67
Transport - In-state	3.25	3.80	3.75	3.69	3.59	3.53	3.01
Transport - Upstream	0.92	1.10	1.14	1.12	1.05	1.02	0.86
Energy - Total	**10.12**	**11.32**	**10.87**	**12.11**	**11.18**	**10.92**	**9.89**
Other* - In-state	1.84	2.30	2.18	2.33	2.26	2.29	2.18
Gross - In-state	10.17	11.61	11.13	12.34	11.57	11.38	10.42
Gross - Upstream	1.79	2.01	1.92	2.10	1.87	1.82	1.65
Total	**11.96**	**13.62**	**13.05**	**14.44**	**13.44**	**13.21**	**12.07**

* Other includes the additional sectors captured in the VT GHG EI: Fossil Fuel Industry, Industrial Processes, Waste Management, and Agriculture.

Results are shown excluding biogenic CO$_2$ emissions in Figure 3. Biogenic CO$_2$ emissions primarily result from combustion of wood in the electricity and RCI sectors, and to a lesser extent from combustion of ethanol and biodiesel in the transportation sectors. As a result, in-state emissions from these sectors drop approximately 2.4 MMTCO$_2$e in 2020 (for a total of 7.5 MMTCO$_2$e) when biogenic CO$_2$ is excluded. Upstream emissions are less sensitive to the inclusion of biogenic CO$_2$. Hydroelectricity is the primary source of biogenic CO$_2$ emissions in the upstream supply chain for energy sectors. See the section on Woody Biogenic Emissions for a more complete discussion of accounting for biogenic emissions in the biomass supply chain. Total emissions by sector, excluding biogenic CO$_2$, including a comparison to non-energy sectors, is included in Table 4.

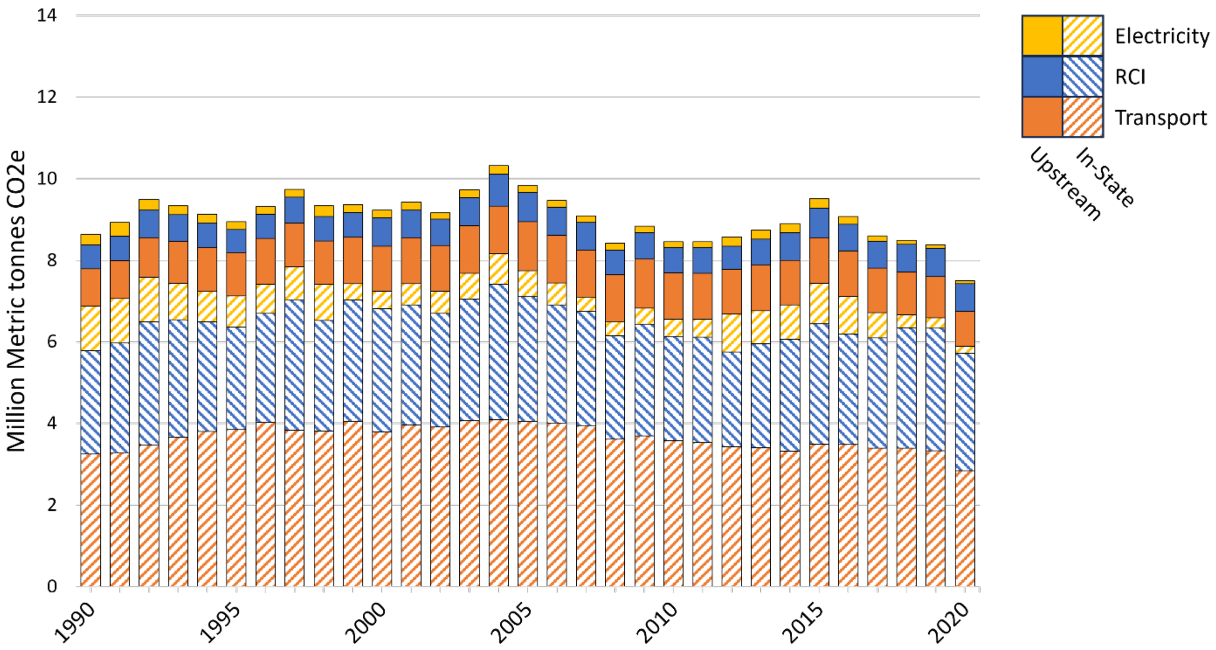

Figure 3. Upstream and In-state emissions by sector, excluding biogenic CO$_2$.

Table 4. Upstream and In-state emissions for VT (MMTCO_2e), excluding biogenic CO_2

	1990	2000	2010	2015	2018	2019	2020
Electricity - In-state	1.09	0.43	0.43	1.00	0.31	0.25	0.18
Electricity - Upstream	0.26	0.18	0.14	0.23	0.09	0.09	0.08
RCI - In-state	2.54	3.02	2.56	2.94	2.94	3.00	2.87
RCI - Upstream	0.58	0.69	0.62	0.73	0.68	0.69	0.67
Transport - In-state	3.25	3.80	3.58	3.50	3.40	3.34	2.85
Transport - Upstream	0.92	1.10	1.14	1.12	1.05	1.02	0.86
Energy - Total	**8.64**	**9.23**	**8.45**	**9.52**	**8.49**	**8.38**	**7.51**
Other* - In-state	1.73	2.14	2.06	2.23	2.17	2.20	2.10
Gross - In-state	8.61	9.39	8.62	9.66	8.83	8.79	7.99
Gross - Upstream	1.76	1.97	1.90	2.08	1.83	1.79	1.61
Total	**10.37**	**11.37**	**10.51**	**11.74**	**10.67**	**10.58**	**9.60**

* Other includes the additional sectors captured in the VT GHG EI: Fossil Fuel Industry, Industrial Processes, Waste Management, and Agriculture.

3.2 Upstream Emissions: Electricity

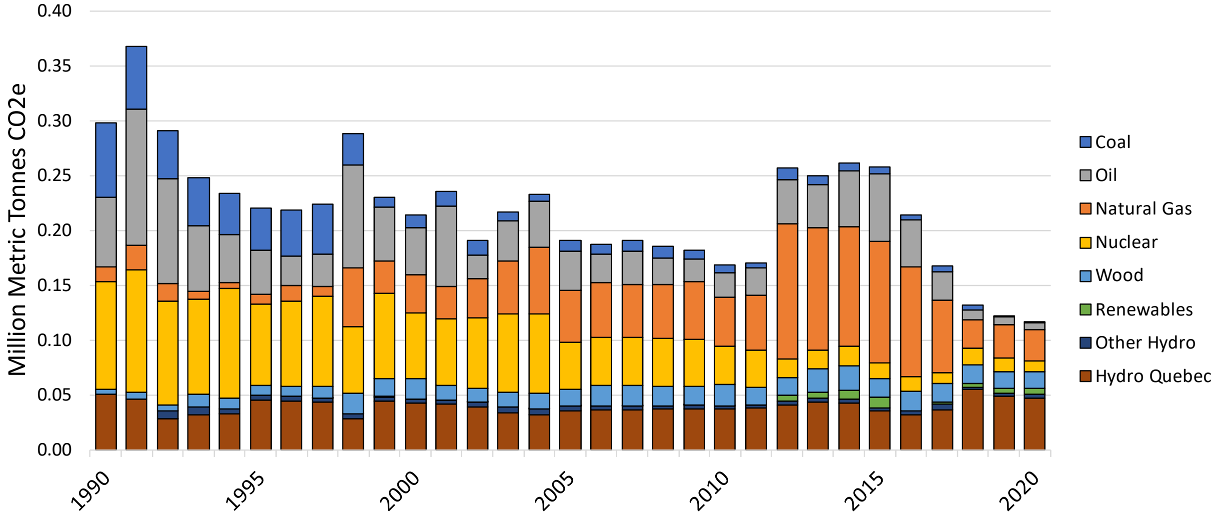

Figure 4. Upstream emissions for Electricity sector.

Figure 4 disaggregates upstream electricity sector emissions, by energy pathway from 1990 to 2020. The contribution from coal, oil, and nuclear is high at the beginning of the period. Improvements in processing of uranium over time have resulted in lower upstream emissions from nuclear, despite a relatively stable contribution to the power grid from 1990-2011. The overall level of emissions from Hydro Quebec remains around or below 0.05 MMTCO_2e throughout the time period due to stable quantities of procured electricity and static emission factors (see Hydro Quebec Mix modeling methods for more details). Emissions from Coal and Oil in the electricity sector exhibit a steady decline as those fuel sources have become less prominent in the VT energy mix, replaced largely by natural gas and renewables. Despite renewable pathways like ‘Solar’ exhibiting increases in overall supply of energy in the last decade, upstream emissions for ‘Renewables’ are negligible throughout the later years of the time series.

3.3 Upstream Emissions: Residential, Commercial, Industrial (RCI)

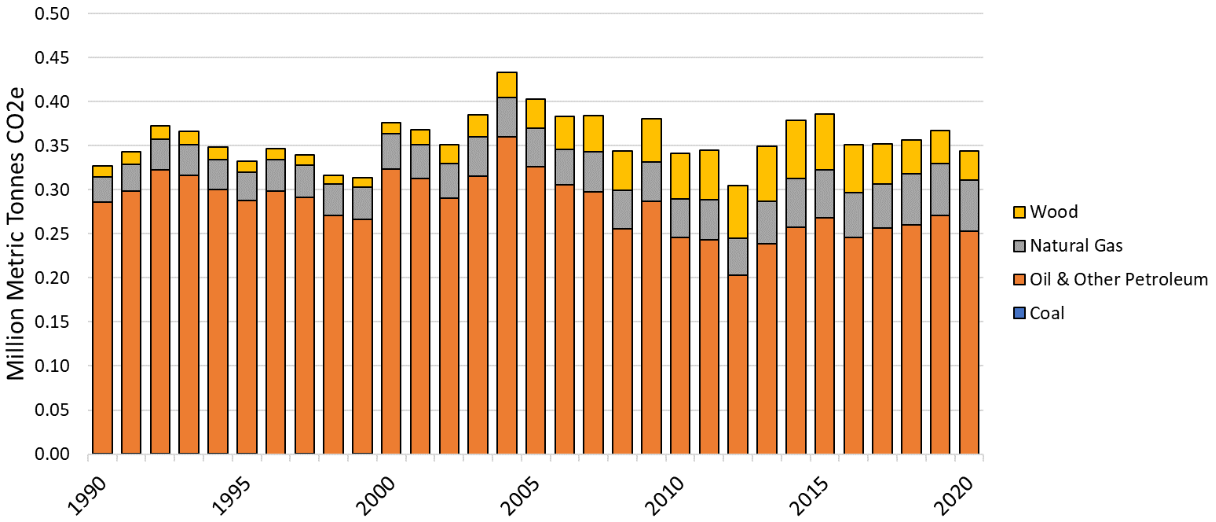

Figure 5. Upstream emissions for Residential sector.

Figure 5 similarly breaks down upstream emissions of the residential subsector of RCI, by energy pathway category, for the 1990-2020 time series. While from 2002-onwards energy pathways for Wood and Natural Gas see higher contributions to yearly totals due to increased consumption, fuels within the Oil & Other Petroleum category such as Propane and Distillate Fuel Oil drive an outsized majority of emissions within the subsector.

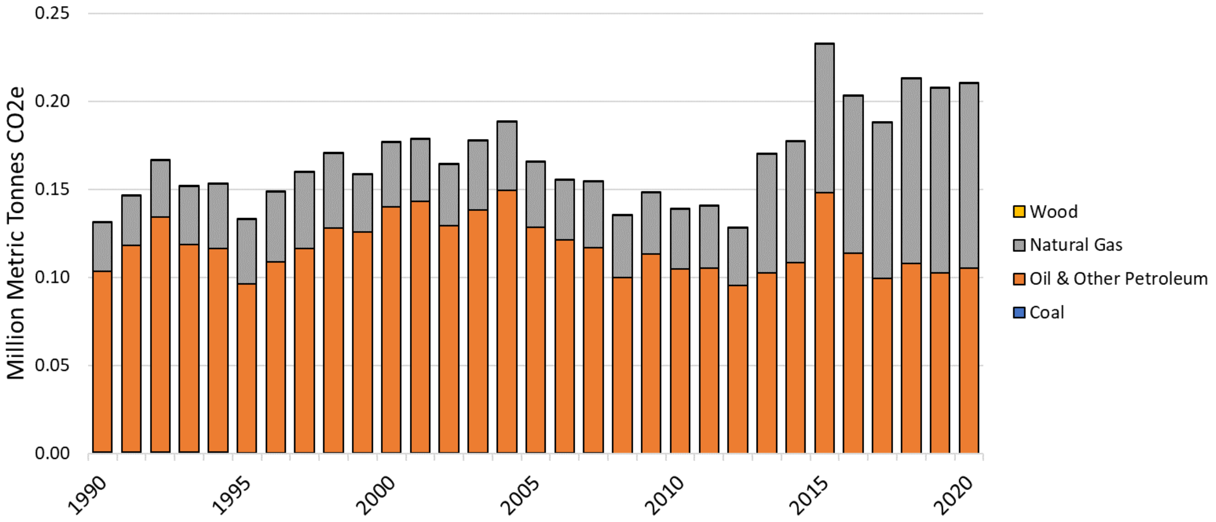

Figure 6. Upstream emissions for Commercial sector.

Figure 6 disaggregates the commercial subsector’s upstream emissions totals by energy pathway category for the 1990 to 2020 time period. Like with the residential sector, particular Oil & Other Petroleum fuels like Distillate Fuel Oil and Kerosene contribute the majority of emissions from 1990-2017 due to high consumption quantities. However, starting in 2018, upstream Natural Gas emissions approximately match those of Oil & Other Petroleum pathways, likely due to fuel switching. Recent years steadily trend towards the highest levels of upstream commercial subsector emissions in the time series.

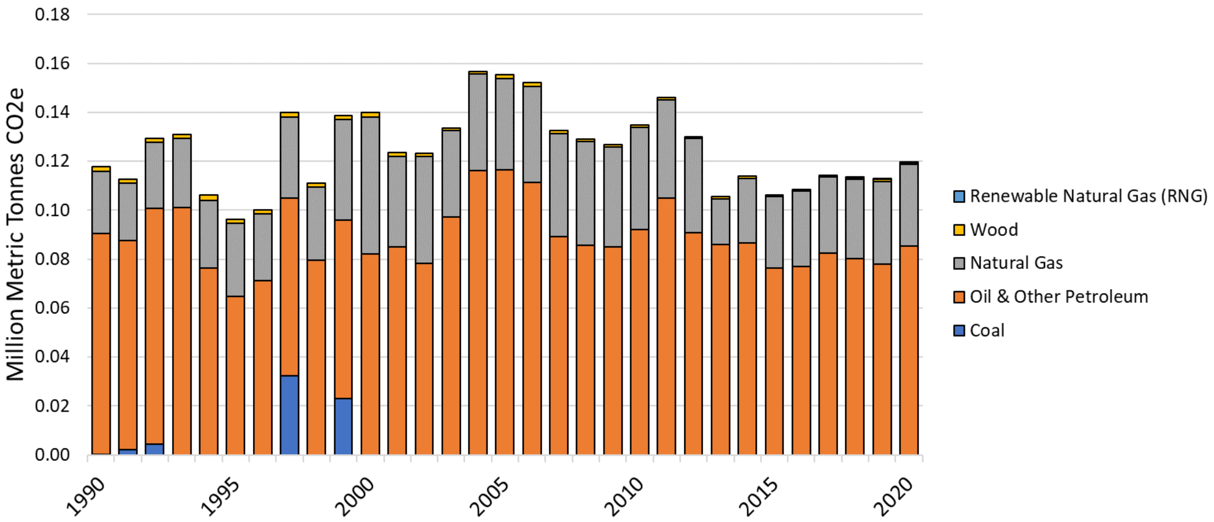

Figure 7. Upstream emissions for Industrial sector.

Upstream emissions for the industrial subsector of RCI, by energy pathway category, for the 1990 to 2020 time period are displayed in Figure 7. Natural Gas contributions to yearly upstream industrial emissions have remained steady for the entire time series. Low levels of 'Wood' and 'Renewable Natural Gas' consumed by the subsector throughout the time series are reflected with proportionately small levels of upstream emissions.

3.4 Upstream Emissions: Transportation / Mobile

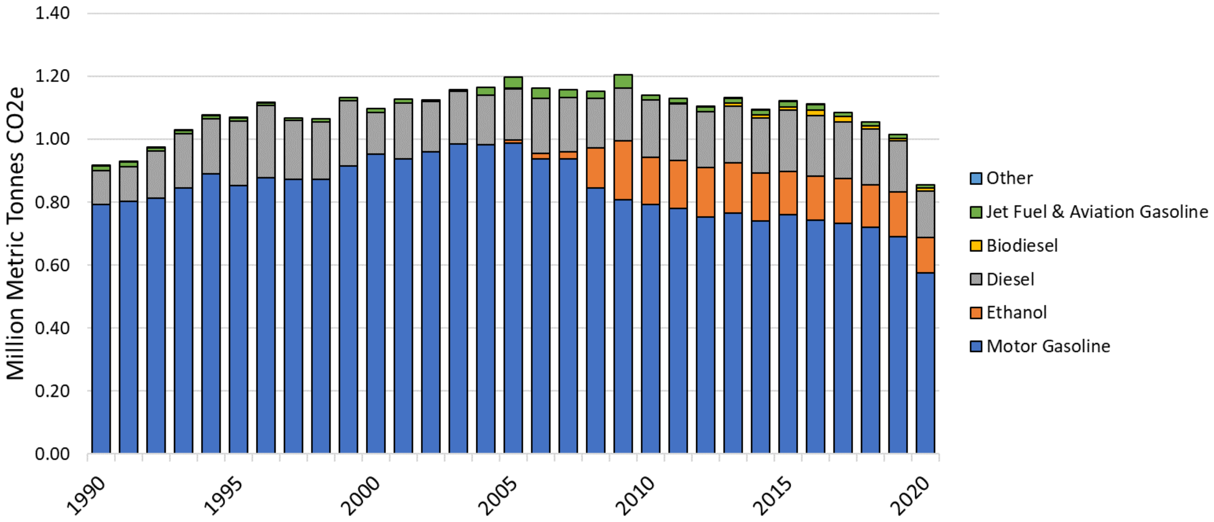

Figure 8. Upstream emissions from Transportation / Mobile sector.

Transportation sector upstream emissions, by energy pathway category, are shown in Figure 8 for the 1990-2020 time period. Due to high quantities of consumption, Motor Gasoline comprises the majority of emissions for all years in the time series. Since the mid-1990s, Diesel has seen consistent contributions to total upstream emissions for transportation due to steady levels of consumption across all years. Starting in 2005 with the passing of the *Energy Policy*

Act, Ethanol has been mixed into some of the fuels consumed by the VT transportation sector, and increases in their consumption are reflected by progressively more notable amounts of emissions attributable to this energy pathway. The remaining energy sources (Jet Fuel & Aviation Gasoline and Other) consistently see low overall upstream emissions due to their small levels of consumption.

3.5 Woody Biogenic Emissions

Woody biomass growth, and its associated biogenic carbon sequestration, are specifically modeled on GREET's Woody tab to best represent short-rotation woody crops (SRWC) grown on dedicated energy plantations. In Vermont however, most harvested wood is obtained from unmanaged plots after much longer periods of growth than SRWCs. For this reason, ERG did not incorporate the biogenic CO_2 uptake modeling from GREET's Woody tab in this analysis.

Aside from GREET, many other popular LCA tools—such as the WWF and Quantis Biogenic Carbon Footprint Calculator for harvested wood products (Quantis et al., 2020)—perform a similar type of biogenic carbon stock-and-flow modeling but also include broader arrays of tree species, harvest periods, and end-of-life processes. However, similar to GREET, these tools typically model forest carbon dynamics at the individual tree- or stand-level, which is needed to estimate CO_2 sequestration during tree growth under various scenarios (e.g., no harvest versus an array of harvest patterns) and time-series emission of GHGs (i.e., decay and combustion emit all major GHG species). As discussed extensively in Cowie et al. (2021), and most directly in Section 7, individual tree- and stand-level forest carbon models inevitably rely on temporal scope assumptions that significantly, arbitrarily affect LCA results. At these levels, LCA model developers must choose to represent forest bioenergy pathways as a sequence of (a) growth, harvest, then combustion, or (b) harvest, combustion, then regrowth. This decision, typically relying on value judgments and additional, separate arguments on the temporal effects of GHG emissions— leads to inconsistent results across the LCA literature, as best demonstrated by Peñaloza et al.'s dynamic LCA modeling of a single product system adopting different temporal and spatial boundaries (Peñaloza et al., 2019).

To avoid these pitfalls, Cowie et al. recommend performing landscape-level assessments of forest carbon dynamics, using the types of integrated assessment models (IAM) commonly relied upon in IPCC reports. We at ERG agree with this suggestion, and urge the broader LCA community to help compose a forest product LCI model that integrates the outputs of forest carbon IAMs—such as the recent VT-specific work by Dugan et al. (2021)—with existing LCA background data. A similar bridging of LCA and IAM models was recently completed by Sacchi et al. (2022) in order to connect a prospective LCA model to future grid projections.

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APPENDIX A: RECOMMENDATIONS FOR NEXT STEPS

This section describes recommendation for future work based on learning that occurred from the implementation of the Greenhouse Gas (GHG) life cycle analysis (LCA). More specifically, this section discusses two primary topics: 1) efforts made to incorporate traditional ecological knowledge (TEK) into the analysis, and 2) a future multi-attribute analysis that describes how the data used in this initial effort could be used in a future multi-indicator LCA that incorporates a suite of impacts related to TEK. Each of these topics is described in further detail below.

Integrating Traditional Ecological Knowledge

TEK, also referred to as Indigenous Knowledge and Native Science, has a variety of definitions, including:

> "The cumulative body of knowledge, practice, and belief concerning the relationship of living beings to one another and the physical environment that evolved by adaptive processes and handed down through generations by cultural transmission. It is an attribute of societies with historical continuity in resource use practice" (Berkes (1993) as cited in Kimmerer (2020)).

Native people have also described TEK in the following ways (Alaska Native Science Commission, n.d.):

- "It is holistic. It cannot be compartmentalized and cannot be separated from the people who hold it. It is rooted in the spiritual health, culture and language of the people. It is a way of life."
- "Traditional knowledge is an authority system. It sets out the rules governing the use of resources - respect, an obligation to share. It is dynamic, cumulative and stable. It is truth."
- "Traditional knowledge is a way of life -wisdom is using traditional knowledge in good ways. It is using the heart and the head together. It comes from the spirit in order to survive."

Given that the results of GHG LCA will be used as a decision-making tool for the Vermont Climate Council (VCC) and possible other state entities moving forward, ERG and the Vermont state team[3] planned to integrate TEK into the analysis. At the project outset, ERG and the Vermont state team agreed to incorporate TEK stakeholder perspectives into the analysis by conducting stakeholder engagement meetings and also developing recommended future analyses based on information learned throughout the project and engagement efforts. For purposes of this report, the recommended future analyses are described in the multi-attribute analysis section below, and this section focuses on the TEK stakeholder engagement.

The sections that follow describe the methods used to try to incorporate TEK into the GHG LCA through stakeholder engagement, lessons learned from that process, and suggested next steps for being able to integrate it into future work.

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[3] The VT state team refers to the representatives from the state of Vermont who comprise the project team.

Methods

The stakeholder engagement was designed to revolve around two online TEK stakeholder meetings. The first meeting would aim to collect feedback from stakeholders on the energy pathways selected for the analysis and the second would elicit feedback on study results, including the interpretation of those results and implications of those findings when considering how information form the analysis would be utilized moving forward.

When discussing the stakeholder engagement approach with the Vermont state team and select members of the LCA task group[4], the issue was raised that holding two stakeholder online meetings may not be the most appropriate way to engage TEK stakeholders and that the project team should consult with one to two TEK experts to better understand what type of engagement might be preferable. Based on this feedback, ERG met with the Vermont state team and LCA task group members to determine an approach to stakeholder engagement. The resulting approach is shown in Figure 9 and includes:

- Identify one to two TEK experts to inform stakeholder engagement efforts. The aim was to identify individuals who have experience working at the intersection of traditional/Western science and TEK, as preliminary research indicated no known individuals with experience integrating TEK with GHG LCAs. While an understanding of LCA or GHG could be beneficial, it was not considered a pre-requisite for participating in engagement efforts. Consideration was given to the tribal affiliation of the potential expert (e.g., Are they Abenaki?) as well as their geographical location (e.g., Are they located near Vermont or the northeastern portion of the United States?) as these factors may impact participant perceptions and experiences as they relate to the GHG LCA information being generated by the project.

  To identify potential experts, ERG conducted an online search for potential candidates, the VT state team reached out to professional contacts for recommendations, and one LCA task group member leveraged her existing tribal and organizations connections to help identify appropriate individuals.

- Conduct outreach to potential experts to secure their participation in providing input on engagement efforts. Outreach efforts were primarily conducted by an LCA task group and Abenaki Tribe member who attempted to leverage existing connections to help facilitate participation. VT state team members also attempted outreach to individuals or organizations, where there was a known contact, and ERG conducted outreach efforts where no project team member connection existed. Outreach efforts were conducted between May and July 2023.

Figure 9: Overview of TEK Stakeholder Engagement Process

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[4] The LCA task group is comprised of members from the Vermont Climate Council who provide input on the GHG project, as directed by the Vermont state team.

- Conduct conversations with the initially-identified experts to discuss the TEK engagement process. Through these conversations, the project team could develop a better understanding of how best to engage TEK stakeholders, what that engagement might look like, and what type of individuals might be helpful to include in the process.
- Develop a TEK engagement process based on expert input.
- Identify and conduct outreach to TEK engagement participants
- Conduct TEK engagement.

Findings

While the combined project team (ERG, VT state team, LCA task group members) identified a number of potential candidates for initial expert interviews, the team was not able to secure participation from these individuals within allotted two-month project timeframe. The project team found the following:

- It was challenging to identify individuals with the desired expertise and experience. The project team began with identifying who they deemed to be the most appropriate candidates (e.g., experienced working at the intersection of TEK and western scientific analysis, understands local tribal communities, culture, and environment) and then worked outward to individuals who might be able to provide helpful expertise in some capacity but might be less specific to Vermont and the GHG LCA (e.g., not familiar with Vermont, its native populations, environment, and/or energy pathways).
- Of those individuals identified as having the desired expertise, some self-identified as not being a good fit for the project while others were not willing to participate or were unable to do to so within the project timeframe due to scheduling/workload conflicts.

Given that no identified experts were able to participate within the project timeframe, the VT state team determined that TEK stakeholder engagement would conclude and that information learned through the identification and outreach experience be captured and used to inform future efforts to integrate TEK into LCA and other technical analyses.

Lessons Learned and Recommendations for Future Work

Lessons learned from attempting to incorporate TEK in the GHG LCA include:

- The project team is not aware of other instances of TEK being integrated into GHG LCAs that are focused solely on GHGs, and determining the best way(s) to integrate these two ways of knowing is a learning process for all involved.
- Individuals with TEK experience and/or expertise should be involved in shaping what TEK engagement or input looks like where no previous example of a similar effort is identified. Individuals with TEK experience and/or expertise are best positioned to provide insight on the type of topics or information that should be gathered, the types of methods and processes that are most appropriate to capture information of interest, and the types of TEK stakeholders that should be invited to participate. The project schedule should consider the time needed to conduct this preliminary engagement, or engagement

could, potentially, occur before the project start to inform what activities should be conducted once the project begins.

- Identifying individuals to inform TEK engagement or methods for incorporating TEK into a technical analysis, such as the GHG LCA, can be challenging and requires schedule and resource considerations. Should an overarching expert(s) be sought under future projects, it could be helpful to:
  - Develop a list of potential TEK expert contacts. If the list of criteria for identifying experts is similar to this project, a helpful starting point could be to use the list of experts contacted under the current project and identify those that were relevant but unavailable due to scheduling constraints and those that should not be contacted again.
  - Determine who will review and determine if the experts on the list are considered to have relevant/in-scope experience prior to contacting.
  - Designate which team members will be responsible for given contacts and track outreach efforts in a single location (e.g., spreadsheet).
  - Develop an outreach email and/or phone script to be used by all team members conducting outreach to help ensure project messaging and requests are consistent.
  - Consider that outreach efforts may require considerable time (e.g., 1-2 months rather than 1-2 weeks), and the expert may need to schedule a conversation far in advance.
  - Being able to provide the expert an honorarium for their time (e.g., $200 - $500) could help increase willingness to participate.
- Expanding the LCA analysis beyond only GHGs would create additional opportunities to integrate information informed by TEK. For example, inventory data used in LCAs often track environmental flows such as air emissions that can lead to local human health effects as well as land use considerations. See also the Multi-Attribute Analysis in the following section.

Multi-Attribute Analysis

The VT GHG EI and this investigation are singularly focused on assessing GHG emissions and their impacts resulting from the supply chains or consumption of energy pathways in the state. Many methods for estimating these emissions across both projects rely on LCA tools and resources, which themselves can offer data on a variety of other environmental burdens beyond GHGs across pathway supply chain stages. A study which expands consideration to other impact assessment categories is called a multi-attribute analysis. This investigation sought only to characterize the GHG emissions for three major GHG species: carbon dioxide, methane, and nitrous oxide. This involved identifying the quantity of these emissions released at each stage of energy pathway supply chains using available life cycle inventory (LCI) data. LCIs are developed through other research projects focused on understanding the inputs (ex. raw materials, processed materials, fuels, etc.) and outputs (ex. further processed materials, emissions, wastes, etc.) resulting from processes in defined systems (ex. raw material extraction, processing, disposal, etc.). In many cases, these LCIs will often capture non-GHG emissions to the environment which impact human and non-human systems. Moreover, some GHGs may have impact in other categories beyond global warming such as human health. Identical to how any given quantity of methane or nitrous oxide can be connected to a certain level of global warming potential (GWP), other emissions to the environment can be associated with their impact in other human and environmental categories. Several domestic and international research groups have developed an assortment of impact assessment methods which readily tie environmental releases to impact. One example is maintained by the U.S. EPA called *Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts* (TRACI) (Bare, 2011), which is capable of characterizing and quantifying potential impacts to the categories shown in Table 5.

Table 5. Life cycle impact categories available in EPA's TRACI.

Impact Category	Description
Climate Change	"Climate change is a long-term change in the average weather patterns that have come to define Earth's local, regional and global climates. These changes have a broad range of observed effects that are synonymous with the term. Changes observed in Earth's climate since the mid-20th century are driven by human activities, particularly fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere, raising Earth's average surface temperature. Natural processes, which have been overwhelmed by human activities, can also contribute to climate change, including internal variability (e.g., cyclical ocean patterns like El Niño, La Niña and the Pacific Decadal Oscillation) and external forcings (e.g., volcanic activity, changes in the Sun's energy output, variations in Earth's orbit)." (NASA, n.d.)
Ozone Depletion	"The ozone layer in the stratosphere absorbs a portion of the radiation from the sun, preventing it from reaching the planet's surface. Most importantly, it absorbs the portion of UV light called UVB. UVB has been linked to many harmful effects, including skin cancers, cataracts, and harm to some crops and marine life… Some compounds release chlorine or bromine when they are exposed to intense UV light in the stratosphere. These compounds contribute to ozone depletion, and are

	called ozone-depleting substances (ODS). ODS that release chlorine include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), carbon tetrachloride, and methyl chloroform. ODS that release bromine include halons and methyl bromide. Although ODS are emitted at the Earth's surface, they are eventually carried into the stratosphere in a process that can take as long as two to five years." (US EPA, 2017)
Acidification	"Acidification is the increasing concentration of hydrogen ion (H+) within a local environment. This can be the result of the addition of acids (e.g., nitric acid and sulfuric acid) into the environment, or by the addition of other substances (e.g., ammonia) which increase the acidity of the environment due to various chemical reactions and/or biological activity, or by natural circumstances such as the change in soil concentrations because of the growth of local plant species." (US EPA, 2012)
Eutrophication	"Within the past 50 years, eutrophication — the over-enrichment of water by nutrients such as nitrogen phosphorus — has emerged as one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms, which among other things can destroy aquatic life in affected areas. The rise in eutrophic and hypoxic events has been attributed to the rapid increase in intensive agricultural practices, industrial activities, and population growth which together have increased nitrogen and phosphorus flows in the environment." (WRI, n.d.)
Smog Formation	"Ground-level ozone is formed by a chemical reaction between VOCs and oxides of nitrogen (NOx) in the presence of sunlight. Ozone concentrations can reach unhealthful levels when the weather is hot and sunny with little or no wind." (US EPA, n.d.)
Human Health Impacts & Ecotoxicity	The human health category of TRACI represents three subcategories: 1) Human Health Particulate: "Particulate matter contains microscopic solids or liquid droplets that are so small that they can be inhaled and cause serious health problems. Some particles less than 10 micrometers in diameter can get deep into [human and animal tissues]. Of these, particles less than 2.5 micrometers in diameter, also known as fine particles or PM2.5, pose the greatest risk to health." (US EPA, 2016) 2) Human health Cancer, Noncancer, and Ecotoxicity: In addition to particulate impacts, TRACI also provides characterization factors for emissions contributing to cancer and noncancer human health impacts, as well as ecotoxicity.

In this project, methods for calculating upstream life cycle stage emissions for energy pathways used in Vermont were largely centered around tools or resources which focused on GHG and other criteria emissions. GREET was selected to generate most emission factors, but it only specifies data for a subset of emissions released during upstream processes of pathways. If a multi-attribute analysis was the goal of future work, alternative sources of data would be required to fill inventory gaps and in turn enable assessment of impact in other categories.

Resources like the United States Life Cycle Inventory (USLCI) database compile inventory data for a variety of industrial processes. However, unlike GREET which can be manipulated to account for changes in time and technology, LCIs are static snapshots of processes as they exist at the time of their data collection. Therefore, a broader assessment of impact attributable to energy pathways would require that data be both comprehensive and representative of modeled conditions.

By approaching these projects under the framework of multi-attribute analysis, fuller pictures of impact along energy pathway supply chains and at the point of consumption can be developed. Results from these studies can then be leveraged to expand understanding of impact beyond climate change and to balance tradeoffs between options during decision-making processes.

APPENDIX B: EMISSIONS BY SECTOR

Table 6: Upstream Emissions by Sector (MMTCO2e).

Sector	1990	2000	2010	2015	2018	2019	2020
Electricity - Total Upstream	**0.30**	**0.21**	**0.17**	**0.26**	**0.13**	**0.12**	**0.12**
Coal	0.07	0.01	0.01	0.01	0.00	0.00	0.00
Natural Gas	0.01	0.03	0.04	0.11	0.03	0.03	0.03
Oil	0.06	0.04	0.02	0.06	0.01	0.01	0.01
Nuclear	0.10	0.06	0.03	0.01	0.02	0.01	0.01
Wood	0.00	0.02	0.02	0.02	0.02	0.01	0.02
Renewables	-	0.00	0.00	0.01	0.00	0.00	0.01
Other Hydro	-	0.00	0.00	0.00	0.00	0.00	0.00
Hydro Quebec	0.05	0.04	0.04	0.04	0.05	0.05	0.05
RCI - Total Upstream	**0.58**	**0.69**	**0.62**	**0.73**	**0.68**	**0.69**	**0.67**
Residential - Coal	0.00	0.00	-	-	-	-	-
Residential - Oil, Propane, & Other Petroleum	0.29	0.32	0.25	0.27	0.26	0.27	0.25
Residential - Natural Gas	0.03	0.04	0.04	0.05	0.06	0.06	0.06
Residential - Wood	0.01	0.01	0.05	0.06	0.04	0.04	0.03
Commercial - Coal	0.00	0.00	-	-	-	-	-
Commercial - Oil, Propane, & Other Petroleum	0.10	0.14	0.10	0.15	0.11	0.10	0.11
Commercial - Natural Gas	0.03	0.04	0.03	0.08	0.10	0.10	0.10
Commercial - Wood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Industrial - Coal	0.00	-	-	-	-	-	-
Industrial - Oil, Propane, & Other Petroleum	0.09	0.08	0.09	0.08	0.08	0.08	0.09
Industrial - Natural Gas	0.03	0.06	0.04	0.03	0.03	0.03	0.03
Industrial - Wood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Renewable Natural Gas (RNG)	-	-	-	-	0.00	0.00	0.00
Transportation/Mobile - Total Upstream	**0.92**	**1.10**	**1.14**	**1.12**	**1.05**	**1.02**	**0.86**
Motor Gasoline (Onroad and Nonroad)	0.79	0.95	0.79	0.76	0.72	0.69	0.57
Diesel (Onroad and Nonroad)	0.11	0.13	0.18	0.19	0.18	0.16	0.15
Hydrocarbon Gas Liquids, Residual Fuel, Natural Gas	0.00	-	-	0.00	-	-	-
Jet Fuel & Aviation Gasoline	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Ethanol - Transportation	-	-	0.15	0.14	0.13	0.14	0.11
Biodiesel - Transportation	-	-	0.00	0.01	0.01	0.01	0.01
Total Upstream	**1.79**	**2.01**	**1.92**	**2.10**	**1.87**	**1.82**	**1.65**

GWP calculated using AR5-100yr characterization factors. Includes Biogenic CO_2.