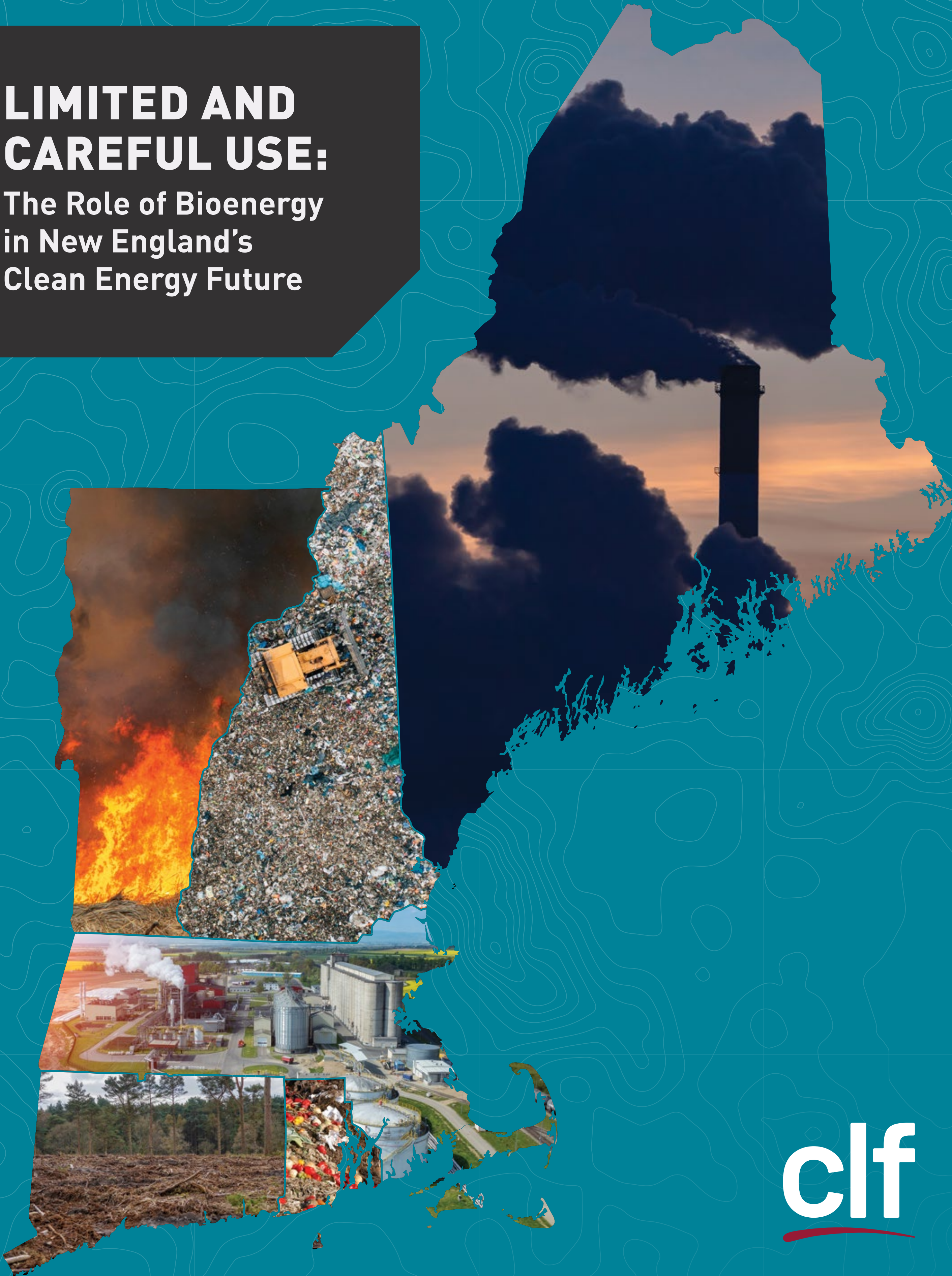
LIMITED AND CAREFUL USE:

The Role of Bioenergy in New England's Clean Energy Future



PROJECT MANAGERS
Chase Whiting
Caitlin Peale Sloan

RESEARCHERS
Michael J. Walsh, Ph.D.
Jonathan S. Krones, Ph.D.

ABOUT CLF

Conservation Law Foundation (CLF) creates comprehensive long-term solutions to environmental challenges. CLF is a critical mover in building a new energy infrastructure, restoring the health of our oceans, countering climate change, and safeguarding the health, quality of life, and economic prosperity of our families and neighbors for generations to come. CLF protects New England's environment for the benefit of all people. We use the law, science, and the market to create solutions that preserve our natural resources, build healthy communities, and sustain a vibrant economy.

Contents

EXECUTIVE SUMMARY 1

1. NEW ENGLAND'S CLIMATE LAWS AND POLICIES 3

Non-Combustion Strategies 4

Managing Residual Combustion Uses in Pursuit of Net Zero 6

Summary for Policymakers 7

2. FROM FIELDS AND FORESTS TO USABLE FUELS: BIOENERGY PRODUCTION 8

Bioenergy Feedstocks 9

Conversion of Feedstocks into Usable Energy 10

3. CURRENT APPLICATIONS OF BIORESOURCES AND BIOENERGY IN NEW ENGLAND 12

Forest Carbon Sequestration 12

Wood Bioenergy 13

Crop Biofuels 14

Bioenergy from Waste Treatment 15

4. BIOENERGY AND EMISSIONS: LIFE-CYCLE ASSESSMENT OF GREENHOUSE GAS ACCOUNTING OF BIOENERGY PATHWAYS 18

The Greenhouse Gas Impacts of Bioenergy Are Often Underestimated and Misunderstood 18

Life-Cycle Assessment Is One Way to Calculate Accurate Greenhouse Gas Emissions from Bioenergy 24

Life-Cycle Accounting Can Be Manipulated to Greenwash Bioenergy 34

Conclusions 35

5. COST AND ECONOMIC CONSIDERATIONS 36

Production and Use Costs 36

Broader Environmental and Socioeconomic Impacts 38

6. GUIDELINES FOR THE STRATEGIC CONSIDERATION OF BIOENERGY FOR NET ZERO 40

Example Application of Guidelines to Pending Bioenergy Strategies in New England 42

REFERENCES 45

EXECUTIVE SUMMARY

What role will our natural resources and waste systems play in the energy system as New England moves toward 2050?

From blistering heat that aggravates air pollution and respiratory illnesses to mild winters devoid of the classic snow New England economies depend so heavily on – climate change is affecting us here and now. **The good news is our region has made its voice clear: We want climate action.** That is why nearly every New England state has passed mandatory climate laws and policies to slash polluting emissions, with targets for 2025 all the way to 2050. We need to end our reliance on fossil fuels, and that presents a pressing question: what role will our natural resources and waste systems play in the energy system as New England moves toward 2050?

As each state implements its climate law, it is critical that government and business leaders invest in the policies and strategies that will drive down climate-damaging emissions the fastest and the cheapest. They must also ensure an energy transition that accommodates vulnerable and already burdened communities and individuals. Foundational to all such strategies will be a heavy investment in energy efficiency and clean energy.

As such investment is pursued, states, communities, and institutions will need to be vigilant about avoiding misguided and ineffective solutions that may conflict with these broadly defined decarbonization goals. Such discipline is particularly needed around the application of alternatives to fossil fuels that enable the continuation of entrenched industries and activities that conflict with the region's codified emissions and social goals. Generally referred to as "bioenergy," these alternative resources are produced from organic matter such as agricultural crops, wood, sewage sludge, food waste, and animal waste.

Fossil fuels are not the only source of climate-causing emissions: agriculture and land use currently contribute to a quarter of the planet's warming.

While bioenergy resources are not of fossil origin, their use has significant potential for climate damage. Fossil fuels are not the only source of climate-causing emissions: agriculture and land use currently contribute to a quarter of the planet's warming. Likewise, large-scale bioenergy cultivation and processing have the potential to exacerbate climate change through various mechanisms.

It is common sense that directly replacing all of our current fossil energy systems with those derived from forests or from energy crops would create unbearable economic, ecological, and climate costs. Such costs are one of the many reasons why New England's, and the world's, clean energy goals focus on rapidly scaling wind and solar electricity generation to power electric end-uses. Despite this direction, questions remain about the modest application of bioenergy that need answers.

In this report, we analyze bioenergy's role in New England's clean energy future and provide guidance to decisionmakers who are considering bioenergy to meet their mandatory climate targets. The appropriate role of bioenergy is a limited and targeted one. Indiscriminate use of bioenergy in the electricity and heating sectors can undermine efforts to decarbonize and in some cases results in emissions that are more climate-damaging than fossil fuels. Particularly when it comes to fuels that might replace natural gas in end-uses that will be electrified, it could be both cheaper and cleaner to continue using fossil fuels until the use can be electrified, instead of temporarily adopting a bioenergy strategy.

But, of course, we must end our use of fossil fuels as quickly as possible by transitioning to clean electric alternatives.

Bioenergy may have a role to play in industries and transportation that are hard to electrify, such as aviation or shipping. But even in these limited scenarios, policymakers and investors must use a holistic lens beyond life-cycle analysis to scrutinize the climate-damaging emissions and other impacts from the fuels' production, transportation, and ultimate use.

When implemented with the appropriate safeguards, the production of bioenergy from waste resources delivers some modest climate benefits. However, we must avoid depending on intentionally cultivated sources (such as corn, soybeans, or wood) whose overuse of agricultural lands can impact food production or result in the clearing of forests and reduction in forests' inherent ability to soak up carbon. We also should be careful to use currently abundant waste materials in an efficient way without creating demand for waste streams, like food waste, that could be eliminated by better waste policies.

We are in the process of fighting climate change and securing a livable and healthy future for New England. We don't have time or resources to waste on costly and ineffective solutions. The economic, environmental, and public health of our communities and businesses demands that we invest substantially in energy efficiency and clean energy resources while moving with caution and care on bioenergy resources.

1. NEW ENGLAND'S CLIMATE LAWS AND POLICIES

As New England looks to fulfill the mandates of its climate laws and the global climate policy consensus, the role of bioenergy has become a key issue. The last several years have seen the emergence of plans and studies for how the region should evolve to achieve its net-zero goals, including cutting gross emissions as deeply as possible and strategic continued use of emitting technologies only where it is not possible to eliminate the emissions. Table 1 summarizes these actions using examples of key strategies.

Table 1.

COMMON NET-ZERO ACTIONS AND EXAMPLES OF SUCH ACTION THAT APPEAR IN VARIOUS NEW ENGLAND-FOCUSED DECARBONIZATION STUDIES [1–6]

NET-ZERO ACTION	EXAMPLE
CLEAN ELECTRICITY	• Deploy wind and solar as aggressively as possible.
ENERGY EFFICIENCY AND CONSERVATION OF RESOURCES	• Reduce energy losses across all energy uses. • Reduce demand for energy by smart dense growth while reducing reliance on personal vehicles.
ELECTRIFICATION	• Electrify fuel-consuming end-uses in buildings, transportation, and industry. • Deploy electric heat pumps to capture and use renewable ambient heat from the air, earth, and water.
INTEGRATION	• Build transmission to share renewable energy resources between regions. • Construct local integrated energy systems, such as microgrids and thermal networks, to better share energy resources across space and time for efficiency and resiliency. • Pursue systems emissions reductions rather than relying on credit or offset programs.
LIMITED USE OF ALTERNATIVE FUELS IN HARD-TO-ELECTRIFY SECTORS	• Prioritize green hydrogen use for chemical feedstocks and high-temperature heat demands. • Use bioenergy from wastes and residues in aviation, shipping, high heat industry, and chemical feedstocks.
MODEST USE OF FOSSIL FUELS WHERE ALTERNATIVE FUELS ARE NOT PRACTICAL	• Rightsize and leak-manage pipeline gas systems to support energy system reliability. • Wind down existing paid-for fossil infrastructure rather than building temporary alternative fuel infrastructure.
CARBON DIOXIDE REMOVAL	• Preserve and enhance natural carbon stocks. • Engineer removal of carbon dioxide via direct air capture or bioenergy carbon capture and storage.

It is important to emphasize that the actions listed above are complementary – not competitive – actions that play a role at different scales and in specific ways. However, the need to deploy a diverse solution set to meet ambitious emissions reduction goals does not mean that these strategies achieve equal scales: **combustion of alternative fuel is not a substitute for clean electrification.**

Non-Combustion Strategies

Integrating the strategies of renewable electricity, efficiency, and electrification reduces the region's reliance on imported fuels, replacing them with locally available energy resources like wind, solar, and ambient heat. This transition delivers remarkable benefits by replacing the combustion of fuels with clean local energy resources. Instead of being spent on volatile out-of-state energy imports, such as imported biofuels and fossil fuels, money is invested locally in energy-producing assets, more-efficient vehicles, and healthier and better buildings. Improvements in air quality from reduced air pollutants are realized across the energy system, from inside the home to environmental justice communities adjacent to dirty power plants.

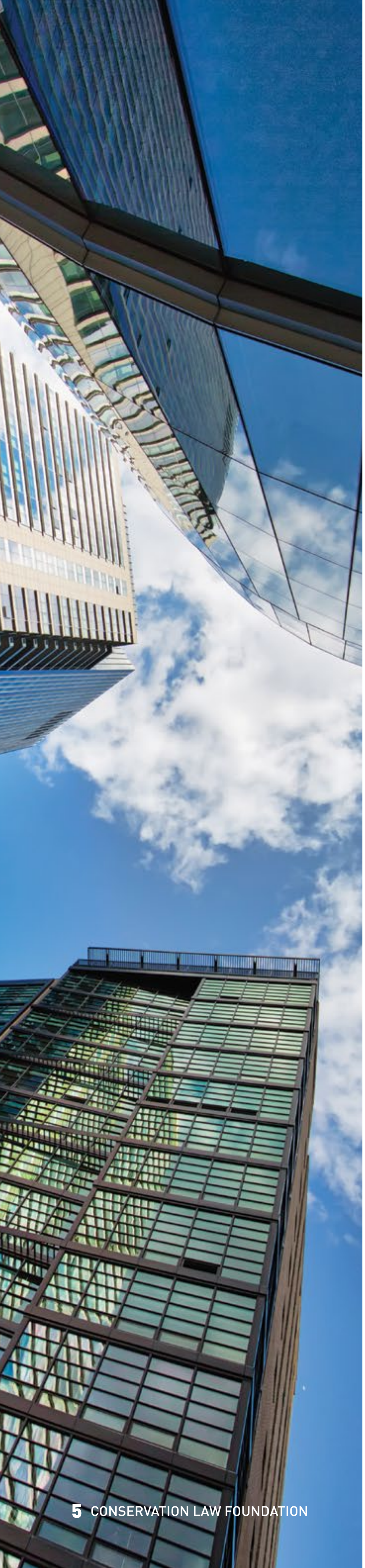
While these benefits will be achieved across all sectors, the mechanics and the pace of how this deployment proceeds will vary by sector.

LOW-CARBON CLEAN ELECTRICITY

New England's coastline is rich with wind energy resources and the region has ample solar potential.[7] Wind and solar electricity are on track to be cost-competitive with fossil fuel-based power and can meet the bulk of the region's current and future electric demands. However, the electricity sector faces challenges in *eliminating* emissions because of the region's large winter heating demand and the variable nature of wind and solar generation. Where storage, demand shifting, and imported electricity from other regions cannot cover the full scope of our electricity generation needs, the best available modeling acknowledges a minor role for maintained combustion-based electricity generation[8,9] at a fraction of today's use – at least until cleaner technological options emerge. Such technologies could include green hydrogen combustion, hydrogen fuel cells, enhanced geothermal, small modular nuclear, and carbon capture and storage, all of which currently face significant cost and practical barriers in the region. Woody biomass electricity generation faces long-term challenges due to its inefficiency,[10] inflexibility, lack of sustainable scalability,[11,12] and relatively high generation of harmful air pollutants.[13]

ELECTRIFICATION AND EFFICIENCY IN THE TRANSPORTATION SECTOR

Electrification of the light-duty vehicle sector has become all but certain as policy incentives,[14] regulations, and manufacturers[15] are aligning on a phase-out of new internal combustion engine vehicle sales by the 2030s. All New England states except New Hampshire are in the process of adopting[16] California's Zero Emissions Vehicle Mandate.[17] The electrification of larger vehicles is also gaining traction on these fronts. While electrification slashes fossil fuel consumption and demand for corn ethanol and biodiesel,[6,8] the current limits of electrification in some heavy-duty vehicles, aviation, and shipping leave open the need for targeted uses of combustible fuels for the foreseeable future. Overall, transportation system efficiency will benefit from a focus on minimizing the use of personal vehicles where possible.



ELECTRIFICATION AND EFFICIENCY IN THE BUILDINGS SECTOR

Electrifying building heat and appliances has emerged as the consensus strategy for eliminating emissions from the building sector. The ability of heat pumps to capture renewable ambient heat from the nearby air, water, and earth offers significant efficiency advantages over combustion fuel technologies. Modern heat pump technology provides more energy than it consumes the majority of the time and thus *reduces* fuel consumption. This reduction occurs even when relatively inefficient combustion-based power plants supply the heat pump's electricity. As the grid becomes more renewable as new wind and solar generation facilities come online, the trio of wind, solar, and ambient heat can displace most fuel consumption for heat. Even partial electrification of most building heat has been recognized by regional gas utilities as necessary for achieving the region's decarbonization goals, given the challenges associated with scaling strategies for decarbonizing pipeline gas such as renewable natural gas (RNG) or green hydrogen.[18]

With currently available technologies, there would likely remain a residual amount of non-electrified heat demand in 2050. While heat pumps operate at the coldest temperatures, they require more electricity to do so at very cold temperatures when heat demand is high. And some buildings (e.g., hospitals) and processes require a backup or high-temperature heat source for which electricity may not be sufficient. As such, and while it is in decline, a limited amount of combustion may play an important role in the clean energy transition by supporting thermal reliability at the building scale and electric reliability at the grid scale.

It is important to move beyond conversations that equate electrification and RNG as future building heat options. Electrification of heat and other end uses have the potential to benefit New Englanders with improved comfort and air quality. Despite a supporting transitional role for combustion, it is also clear that even a modest degree of electrification will severely challenge the long-term financial viability of the gas system.[1,19,20] Transitioning away from gas use in a coordinated way will be important to avoid utility death spirals, in which an unmanaged transition results in fixed gas system costs being borne by the few likely-lower-income consumers who are unable to migrate to clean technologies. Managing the implications of such a transition is beyond the scope of this report, but it is being actively explored in Massachusetts[21] and Rhode Island.

This transition will need to proceed on three fronts. First, given the emerging cost-effectiveness[22] of all-electric, high-performing buildings, it is clear that continued expansion of the gas system is misguided and could lock in combustion infrastructure that will be costly to convert in the future. Second, New England states currently accelerating the process of replacing leak-prone pipes should seek out opportunities to avoid reinvestment in gas distribution systems, given that the increasing cost of pipeline replacement projects typically exceeds the cost of electrifying connected buildings on affected street segments.[23] Finally, given an increasingly electrified and efficient building stock, coordinated zonal transition strategies – such as those being implemented in parts of Europe[24] – will be needed to leverage local energy thermal resources, construction of energy networks, and optimized upgrading of the electrification system.

Achieving decarbonization of buildings is a systems problem that requires planning for the transition of multiple connected energy assets. The assumption that buildings can be decarbonized by simply dropping in a substitute fuel (whether it be delivered by pipe or by truck) ignores the opportunity and planning needs of non-combustion strategies, along with the scalability challenges associated with alternative fuels discussed in this report.

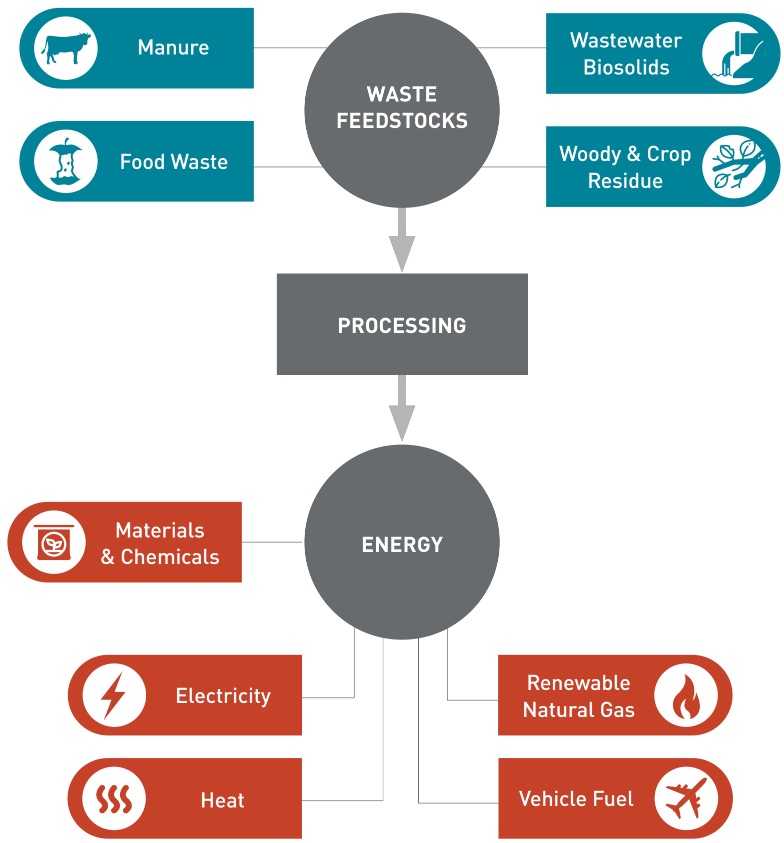
Managing Residual Combustion Uses in Pursuit of Net Zero

The balance of this report focuses on the question of what fuels New England's policymakers should be planning to combust in those residual use cases that cannot be electrified with current technology as the region moves toward 2050, recognizing the overarching directionality and primacy of solar, wind, and ambient heat in driving decarbonization.

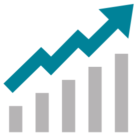
Generally, locally available bioenergy should be prioritized for hard-to-electrify end-uses like aviation fuel (Figure 1). Limited strategic use of fossil fuels will be a preferable transition strategy in other cases where combustion is still necessary. Pipeline-quality RNG, for example, has a very high production and purification cost that, relative to the cost of fossil gas, exceeds the social cost of carbon and the emissions abatement costs of other fuels. Its production and use require infrastructure that will be increasingly underutilized over time as the buildings sector, writ large, electrifies. A policy assumption that gas can be decarbonized will delay necessary decisions to rightsize the gas system to manage its costs better. RNG production assets and gas distribution infrastructure are significantly at risk of being underused in a deeply electrified future, at the expense and responsibility of ratepayers.

The feedstocks for RNG can instead be used to produce higher-value fuels and products, and such feedstocks are of limited supply.

Figure 1.
BIOENERGY PRODUCTION



Summary for Policymakers



Compared with efforts to reduce fuel consumption, overreliance on biofuels will increase consumer energy costs and make it difficult to impossible to achieve the region's climate goals.

There is consensus among state climate plans,[1,2,4,5,25] utilities,[26–28] and ISO New England[29,30] on the large-scale deployment of renewables and the electrification of most transportation and heat end-uses. There remain outstanding questions surrounding the scale of certain strategies relative to others, the pace of implementation, and the role of future technologies. For example, the gas utilities have argued for a continued role of the gas system at its current size but with lower throughput to serve as a "backup" to the widespread deployment of heat pumps.[26–28] Other studies have argued that rightsizing the gas system may be a more cost-effective strategy.[1,20]

Despite such outstanding questions, fuel-saving strategies have clear economic, social, and environmental benefits. States, the federal government, and other decision-makers should embrace a fuel-saving industrial policy that advances these strategies as aggressively as possible:

1. New all-electric building standards for most building classes (buildings that may require fuels for resiliency or high-temperature uses should carefully evaluate whether or not such fuels are best met with pipeline gas or an alternative like propane to avoid stranded asset risks associated with expanding the gas system).
2. Firm yet adaptable zero emissions vehicle, appliance, and heating equipment targets (e.g., policies implemented by California and New York[17,31,32]).
3. Sufficient incentives to bridge funding gaps between conventional combustion-based equipment and electric and efficient buildings.
4. Modernization and decarbonization of the electrical grid to support and respond to increasing consumer demand for electrification (increase distribution capacity, add renewables, and enhance reliability and resiliency).
5. Aggressive energy efficiency (e.g., building shells, thermal networks) and flexible electric system measures to moderate the costs of grid modernization and electrification while improving building habitability.
6. Workforce and supply chain development to support the above strategies.
7. Gas system rightsizing to reduce costs associated with maintaining aging and, because of electrification, increasingly redundant utility infrastructure.

Careful and strategic consideration of biofuels is necessary to ensure that New England reduces its greenhouse gas emissions, secures affordable energy for its residents, and prevents harmful air and water pollution.

2. FROM FIELDS AND FORESTS TO USABLE FUELS: BIOENERGY PRODUCTION

Like fossil fuels, any kind of bioenergy needs to be processed from an initial resource into a usable form and then transported to the location where it is combusted. Table 2 on page 11 segments the components of the bioenergy production chain.

Bioenergy production begins with collecting energy-rich raw organic material known as *feedstock*. The feedstock is then converted into a usable energy carrier or fuel at a production facility, such as a biorefinery for liquid fuels. The fuel may then be transported, stored, and finally delivered to a particular energy application. Each of these steps incurs both a cost and an energy penalty that can significantly influence the relative efficacy and cost-effectiveness of bioenergy as a tool in decarbonization.

This section reviews these components.

BIOENERGY TERMINOLOGY

The language surrounding bioenergy can be confusing, even for experts in the field. Many terms are often used interchangeably and inconsistently. For example, "biofuel" and "biomass" are often used interchangeably with "bioenergy" to describe all energy produced from bioresources. Sometimes "biofuel" is used to refer to liquid fuels, while "biomass" refers to solid fuels used in electricity generation. Likewise, the term "bioproduct" is often used interchangeably with "bioresource" to be inclusive of energy but is used in this report explicitly to refer to biologically derived materials and chemicals derived from biological feedstocks. Similarly, the term "organic" is sometimes used interchangeably with the prefix "bio-." Use of the term "organic" in this report does not connote organic farming cultivation practices but is used to describe waste of biogenic origin.

Bioenergy Feedstocks

In general, feedstocks fall into one of two categories:

- **Purpose-grown feedstocks** are derived from intentionally cultivated crops. Examples include corn or soy crops and harvested trees.
- **Waste feedstocks** result from some other activity. Examples include forestry and agricultural residues, animal manure, food processing residues, food scraps, and wastewater treatment plant sludge.

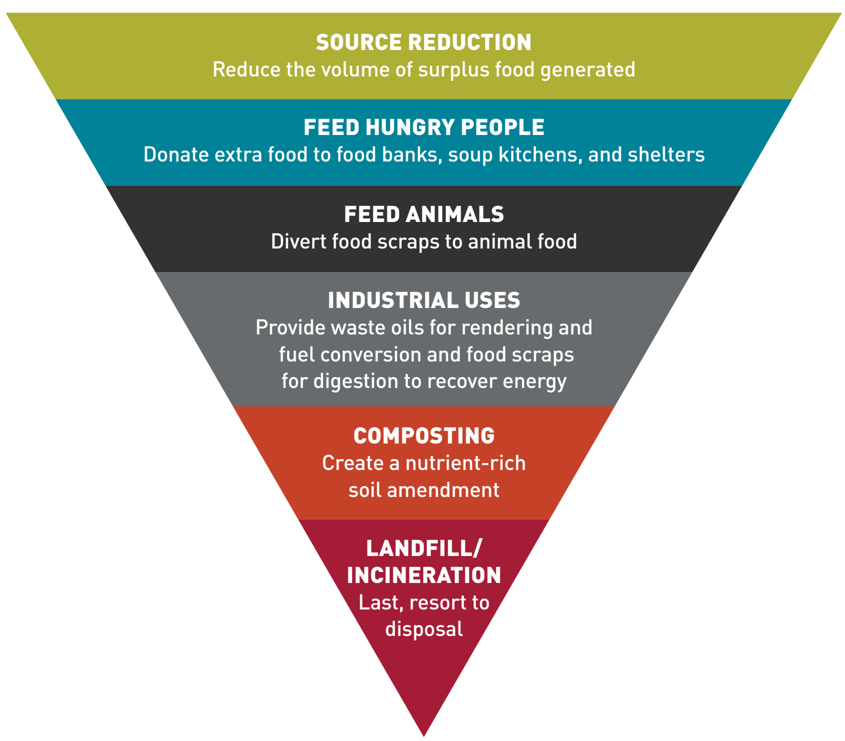
Using purpose-grown feedstocks to produce bioenergy requires the dedication of various inputs. These include land, water, nutrients, energy for cultivation, capital, and labor. Using purpose-grown bioresources also results in ecological impacts that vary greatly depending on the resource and how it is cultivated.[33] The use of these resources thus has the potential to incur climate and other ecological, economic, and social impacts.

Using waste feedstocks for specific, targeted energy uses may be preferable to incinerating them or dumping them in methane-producing waste-handling places like landfills or manure lagoons, but it is critical to first prioritize waste reduction.

WASTE MANAGEMENT HIERARCHY

While energy recovery from organic waste generates an energy resource alternative to fossil fuels, other waste management strategies can deliver greater environmental benefits and tend to be preferable depending on the circumstance. This concept is commonly referred to as a "waste management hierarchy" (Figure 2) and has been used in various forms to guide waste management.

Figure 2.
WASTE MANAGEMENT HIERARCHY



Reducing waste generation by consuming fewer goods is universally regarded as the first step in sustainable waste management. Such source reduction avoids waste generation by avoiding unnecessary consumption or diverting products to places where they can be reused (e.g., food donations).

Where practical, recycling is often preferable over energy recovery. With paper recycling, there is less need to extract and process wood for producing paper, resulting in both resource and energy savings. Alternative business models are emerging seeking to recover food waste that is unsuitable for human consumption and repurpose it as animal feed.[34] These may obviate the need for food waste energy recovery but are energy-intensive due to the heat demand needed for drying food wastes.

Burning solid waste in incinerators and landfilling organic waste are the least preferable options. If reduction and recycling are not options, finding a way to extract energy from the waste before incineration should be considered.

Where practical, recycling is often preferable over energy recovery.

Conversion of Feedstocks into Usable Energy

Biomass is barely usable in energy applications in its raw form. Even combustion of raw biomass requires some aggregation, cutting, and/or drying before actual use. To render them usable as fuel, raw feedstocks undergo a conversion process, or a series of conversion processes, that usually entails:

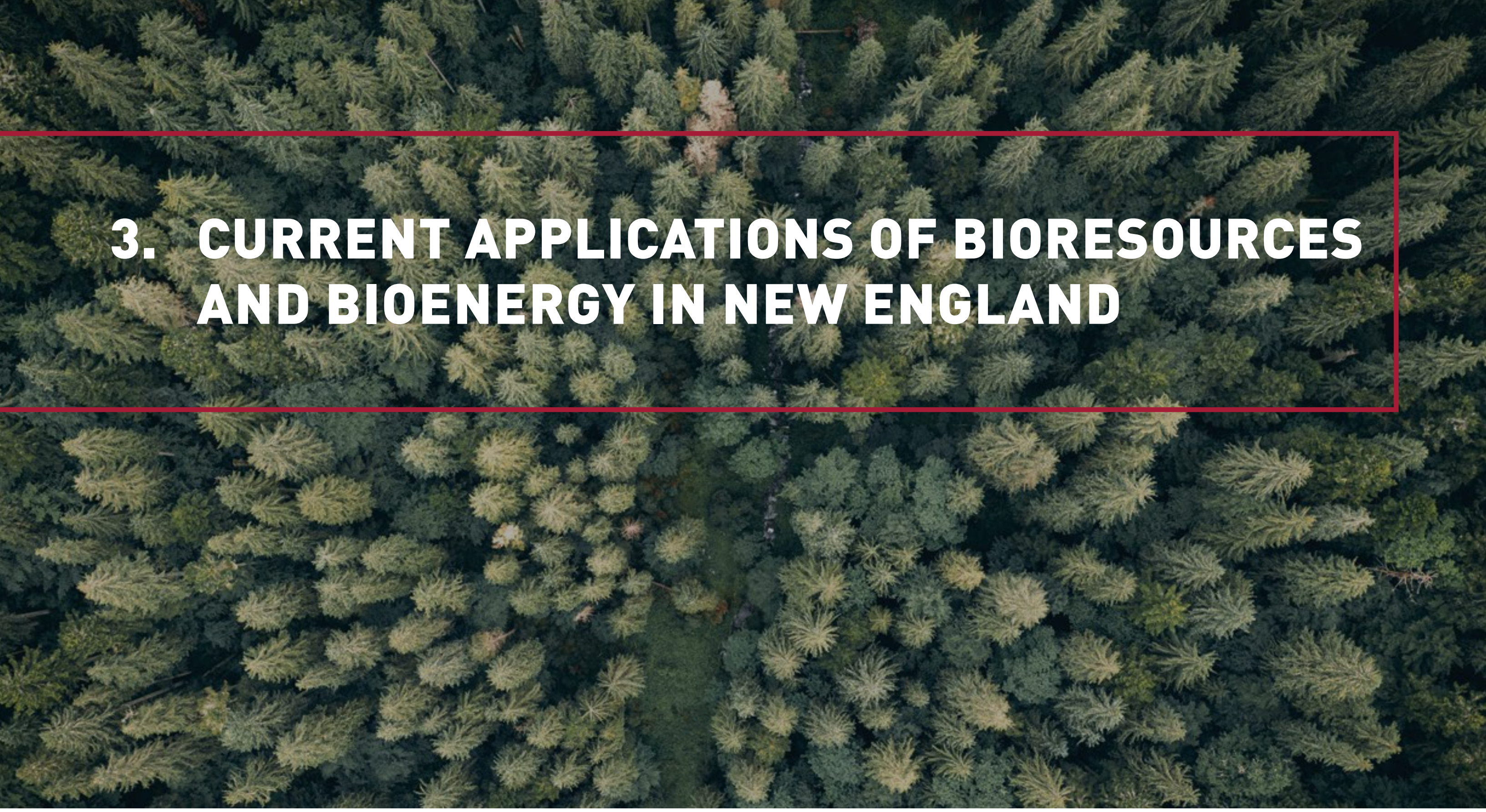
- Collecting the feedstocks and transporting them to a conversion facility.
- Transforming the biomass at the facility into a usable energy carrier or fuel.
- Distributing that energy carrier to specific uses.

Usable energy carriers include biomass ready for combustion, pipeline-quality RNG, hydrogen, liquid fuels, and electricity. Generally, almost any feedstock can be converted into a solid, liquid, or gaseous fuel – although some pathways are more advantageous than others in terms of yield, input energy demands, and distribution. These, in turn, influence the economic viability and the greenhouse gas impact of the final fuel product.

Table 2.

BIOENERGY CONVERSION PROCESSES, THEIR FEEDSTOCKS, PRODUCTS, AND RELEVANCE TO NEW ENGLAND'S ENERGY CONTEXT

PROCESS TYPE	PROCESS NAME	BIOENERGY FEEDSTOCKS	PRIMARY PRODUCTS	PROCESS DESCRIPTION	NEW ENGLAND CONTEXT
SOLID FUEL CONVERSION PROCESSES	Mechanical	Roundwood, wood waste	Cordwood, woodchips	Wood scraps are cut or chipped down to scales suitable for combustion based on the needs of the combustion system.	Northern New England's wood industry generates sufficient biomass to support a small portion of the region's heat and electricity demand (~3%).[35]
	Pelletization	Scrap, sawdust	Biomass pellets	Wood scraps are pulverized and pressed into pellets.	
LIQUID FUEL CONVERSION PROCESSES	Fermentation	Sugar crops (corn, sugar-cane, kelp)	Ethanol	Simple sugars are biologically converted to ethanol that is then distilled to fuel-grade concentrations.	New England currently consumes Mid-West corn-derived ethanol in its gasoline.
	Transesterification / hydrogenation	Oil crops Waste fats, oils, and greases Bio-oils from HTL (see below)	Liquid hydrocarbon fuels	Various plant and animal-derived fats and oils are processed to usable liquid fuels.	Several small biodiesel producers collect oil waste and upgrade it for blending into heating fuel and transportation diesel.
THERMAL CONVERSION PROCESSES	Gasification	Any dry biological material	Methane, hydrogen, liquid hydrocarbon fuels	Biomass is burned at high temperatures with varying degrees of oxygen and steam to produce the desired fuels.	A Fischer-Tropsch gasification facility is proposed in northern Maine to produce sustainable aviation fuels.[36,37] Production of RNG by gasification has been proposed by the gas industry.[38,39]
	Pyrolysis	Any dry biological material	Methane, hydrogen, liquid hydrocarbon fuels	Biomass is burned at medium temperatures in a low-oxygen environment to produce the desired fuels.	Biomass pyrolysis for energy has not yet emerged in the region.
	Hydrothermal liquefaction (HTL)	Any wet biological material	Liquid hydrocarbon fuels	Biological material is treated with high pressure and temperature to create a biocrude oil that can be refined to higher-value fuels.	HTL for energy has not yet emerged in the region.
ORGANIC WASTE MANAGEMENT	Landfilling	Municipal and commercial organic waste	Methane	Anaerobic decomposition of organic waste buried in land-fills leads to the production of methane-containing biogas, some of which is captured via collection systems, with the remainder leaking into the atmosphere.	About 20 New England landfills currently capture and burn their landfill gas for electricity.[40] Several utilities have explored upgrading the methane to pipeline quality at local landfills.[41]
	Anaerobic digestion	Food waste Biosolids Manure Some dry biomass	Methane	Controlled decomposition of organic waste without oxygen produces methane-containing biogas.	Several digesters across the region burn manure, biosolids, and food waste. At most sites, biogas is combusted to generate electricity and heat.
WASTE INCINERATION	Waste incineration	Municipal and commercial organic waste	Heat, electricity	The combustion of organic wastes produces heat and electricity.	Approximately 15 incinerators in the region burn municipal and commercial solid wastes.



3. CURRENT APPLICATIONS OF BIORESOURCES AND BIOENERGY IN NEW ENGLAND

Bioenergy resources, both local and imported, are currently used across the electricity generation, building heat, and transportation sectors in New England. While local feedstocks are harvested for those uses, it is important to consider first the value provided by these resources when kept in place.

Forest Carbon Sequestration

New England's forests cover 75% of its land and store carbon equivalent to 12 billion metric tons of CO_2 in its trees, other above-ground biomass, and soils.[42] If released into the atmosphere, it would equal two years of the entire United States' greenhouse gas emissions. Each year, the region's forests sequester carbon equivalent to 24 million metric tons of CO_2 to this stock, removing it from the atmosphere. This is equivalent to 21% of the region's fossil greenhouse gas emissions.

New England's forests are a sink for CO_2 because they have meaningfully regrown after the deforestation of the 1800s.[43] This capability to sequester emissions will likely continue for some time and is likely to be enhanced by factors like warmer temperatures and longer growing seasons.[44]

Such sequestration is at risk of climate-driven extreme storm events, drought, fire, and pestilence like the emerald ash borer.[45,46] Given such increasing threats to the region's forests, efforts to enhance the natural carbon stock should also integrate best practices in forest resilience.

Further, poor historical management practices have hampered the forests' pace of carbon storage.[47] Unsustainable logging and land conversion limit New England's natural forests' storage of carbon.[48] According to a report from Highstead, titled *New England's Climate Imperative: Our Forests as a Natural Climate Solution*,[42] New England could sequester an additional 11 million metric tons of CO_2e annually through better forest management and preservation practices.

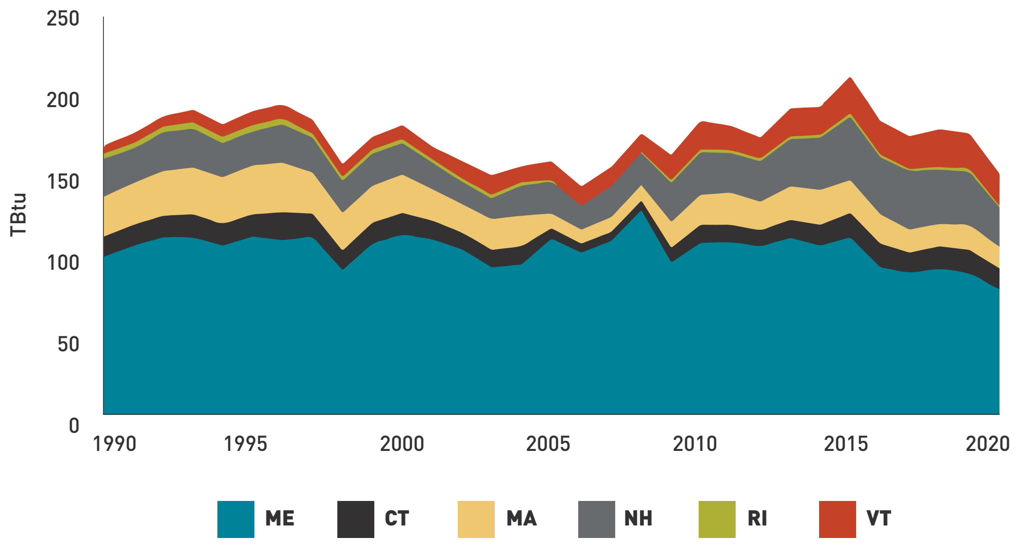
Wood Bioenergy

New England has a long relationship with wood as an energy resource. Today, the existing paper and lumber industries drive the harvest and collection of wood for lumber and paper products. While tree harvesting seeks to maximize high-value lumber production, it also generates a stream of collected residues, sawdust, and other wood-processing byproducts that are diverted to energy uses. Land development for commercial or residential use also creates a source of woody biomass feedstock.

This waste feedstock produces pellets, wood chips, and firewood that provide heat and electricity across the region. Figure 3 shows the distribution of New England's biomass demand, noting that the bulk of this use has been in Maine – the region's largest stock of wood and home to most of its wood products industry. Maine's industrial paper and wood products industry is a big driver of such consumption, using a significant portion of its wood waste to power its facilities. A modest amount of dedicated roundwood harvest also exists in New England and is used for heat.

What is notable about this figure is the flat and recently declining levels of consumption across most feedstocks and end-uses despite a push by some states in the early 2000s to promote the use of this resource for energy.

Figure 3.
NEW ENGLAND (1990–2020) WOOD CONSUMPTION BY STATE
Source: EIA.[35]



Wood consumption for electricity has dropped significantly since 2015 in both relative and absolute terms on New England's grid. This reflects a recent policy move away from woody biomass for electricity generation.

The conversion of solid woody biomass into electricity faces future challenges. Conventional biomass-combustion facilities function best when operating continuously, providing a consistent power output. While such facilities can be used seasonally, they will be challenged operationally and economically in a future grid dominated by variable renewable electricity such as wind and solar. Unlike modern gas-fired electric generation facilities (combined cycle turbines) that are effective *peaking* or *load-following* plants, New England's conventional woody biomass plants[10] face operational challenges in supporting the variable output inherent in wind and solar energy. Advanced biomass load-following facilities could conceivably be built but at a higher cost, limiting their competitiveness in the region's energy markets.

The other major use of wood is in home heating. Approximately 3% of homes in New England use wood as their primary heating fuel, with an additional 13% of households using it to provide supplemental heat. Most of these homes are in northern and rural New England, where they are closer to forestry and lumber industries, largely beyond the extent of pipeline gas distribution systems, and otherwise reliant on expensive oil, kerosene, or propane delivery. Pellet and cord wood stoves have efficiencies that top out at 80%.[49] The direct combustion of biomass at home and at the generator level incurs significant harmful air quality impacts[13] (discussed in Chapter 5). There may, however, be limited use cases where wood heat may provide some value, as, for instance, with highly efficient stoves supporting heat pumps in rural areas.

On the whole, burning wood may be customary in some parts of the region, but it negatively impacts air quality and does not pair well with the growing energy system of the future.

Crop Biofuels

Bioenergy used in the transportation sector is predominantly corn ethanol blended into gasoline – with a much smaller amount of biodiesel blends and other fuels such as RNG used for transportation as compressed natural gas. A 2022 analysis of the Environmental Protection Agency's (EPA) standard corn ethanol requirement has estimated that the emissions intensity of corn ethanol is either similar to or up to as much as 24% higher than gasoline when accounting for energy inputs and land-use changes.[50] The future of the EPA's standard for bioenergy blending in gasoline is in flux, being challenged by reduced demand for gasoline as light-duty vehicles electrify. Declining demand for corn ethanol could allow the rewilding of the land or the repurposing of the land it uses toward higher-productivity energy crops for advanced fuels and other beneficial uses.[17]

Bioenergy from Waste Treatment

Various waste treatment pathways serve as bioenergy conversion processes. The crudest pathways are incineration and landfilling.

CONVENTIONAL WASTE TO ENERGY PATHWAYS

Incineration combusts solid waste to generate heat and electricity. Food waste, paper products, and wood are typically burned alongside plastic. Plastic combustion releases fossil emissions, while combusting organic material releases biogenic carbon. This process is a relatively inefficient way of generating electricity, especially for high-moisture-content food waste. The siting of several incineration facilities at or adjacent to environmental justice communities also raises concerns because such facilities generate adverse air quality impacts even with pollution control technology, to say nothing of the high concentration of heavy, diesel-burning garbage trucks serving the facilities.

There are 15 solid waste combustors in New England – approximately 20% of all such facilities in the country. These generate about 3% of the region's electricity annually.[51] Many of these facilities are reaching the end of their design lifetime. As low-cost wind and solar electric capacity continues to expand in the region, these electric generation resources will face economic challenges due to their inability to provide value to the grid.[8,52]

More than 20 landfills in New England are also considered a bioenergy resource. At these, the anaerobic decomposition of buried organic waste, largely food scraps, generates landfill gas, a mixture of CO_2, CH_4, and some minor impurities. Landfills of a particular size are required to install methane capture and destruction systems to mitigate the climate impact of produced methane.[53]

Some landfills opt to generate electricity from the captured gas to sell to the grid. Various state renewable portfolio standards provide additional revenue for these projects via renewable electricity credits. Landfill electricity generation contributes to approximately 0.4% of the region's electricity generation capacity.[51] While such generation is inflexible, fuel is provided at zero cost, and revenue generated can cover or exceed methane capture regulation compliance costs.

The methane generated from landfills will decline over the next several decades as the digestible waste in landfills is exhausted. While new landfill proposals emerge[54] and several continue to accept waste, the closure of most landfills in New England and the emergence of alternative food waste treatment pathways and regulations will mean that this resource will steadily fade away.

Landfill gas can be directly burned to generate electricity.

UTILITY EFFORTS TO PROMOTE RNG

In the meantime, several New England gas distribution companies have sought to develop projects to convert landfill gas to RNG and inject it into the gas distribution system. The purification or upgrading process requires significant energy inputs, which can reduce potential greenhouse gas emissions benefits. Alternatively, and more commonly, landfill gas can be directly burned to generate electricity. Given this common practice, it makes little sense to spend energy and capital refining that limited supply of gas for injection into the pipeline system rather than using it to directly generate electricity that would offset burning fossil gas for electricity generation.

In 2022, Liberty Utilities petitioned the Massachusetts Department of Public Utilities (DPU) to develop an RNG production facility at a landfill in Fall River, MA.[41] In December 2022, the DPU denied that request, noting that Liberty Utilities could not demonstrate clear greenhouse gas emissions reductions or benefits to its customers.

Such bioenergy projects exemplify how siloed decarbonization policy can lead to suboptimal outcomes. Utility commissions and gas distribution companies are tasked with pursuing emissions reductions solely on a greenhouse gas accounting basis and without considering more optimal uses of such bioenergy resources. A narrow focus not only places climate targets at risk but also has the potential to put the financial risk associated with such projects onto customers.

MANAGING FOOD AND AGRICULTURAL WASTE

New England has begun to get more active in its food waste treatment. Massachusetts (effective 2014), Vermont (effective 2014), Connecticut (effective 2014), and Rhode Island (effective 2016) have organic waste disposal bans of varying stringency[55] that typically cover commercial institutions such as grocery stores, food processors, restaurants, universities, and other large food waste producers. These institutions must divert their food away from conventional waste treatment (landfilling, incineration) to alternative strategies such as composting, food donation, or anaerobic digestion. In 2020, Vermont expanded its policy to cover residential food waste. Similarly, cities such as Cambridge, MA, and Boston, MA, have begun to collect residential food waste. While some of this waste is sent to composting facilities or fed to animals, siting challenges, costs, and limited compost off-takers challenge the ability of compost to scale in the region.

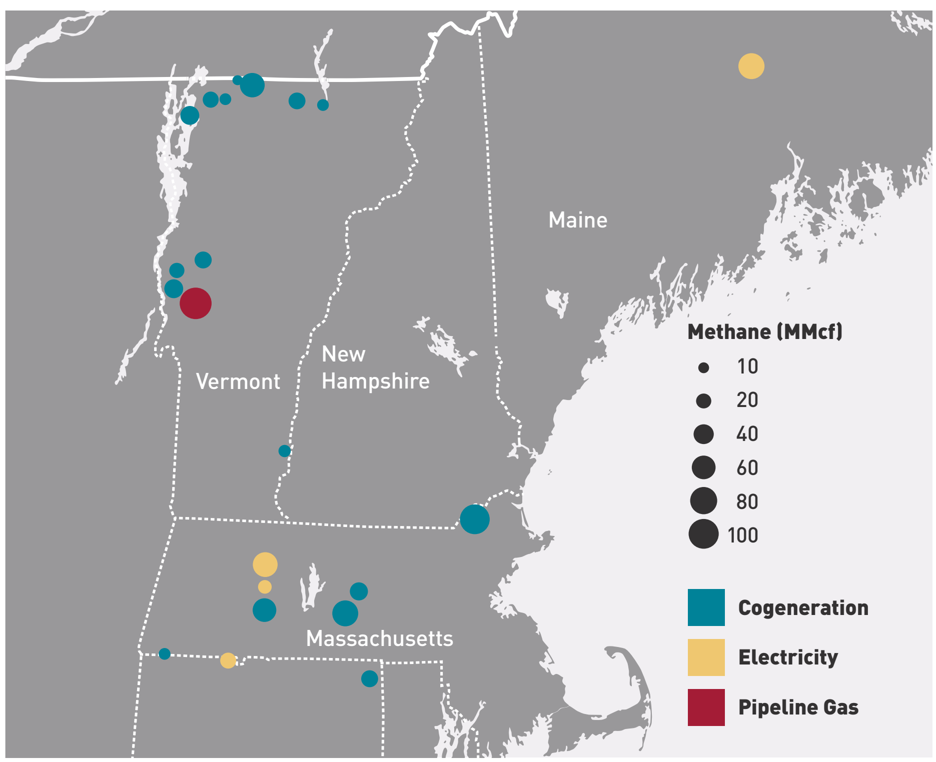
Managed anaerobic digestion has been growing as a waste management strategy, having been used for decades to treat municipal wastewater biosolids and generate energy for wastewater treatment plants. Over the past decade, anaerobic digestion has been adopted at several regional farms to manage manure from cattle (Figure 4). Several of these facilities have begun accepting food waste that can be co-digested with manure or biosolids.

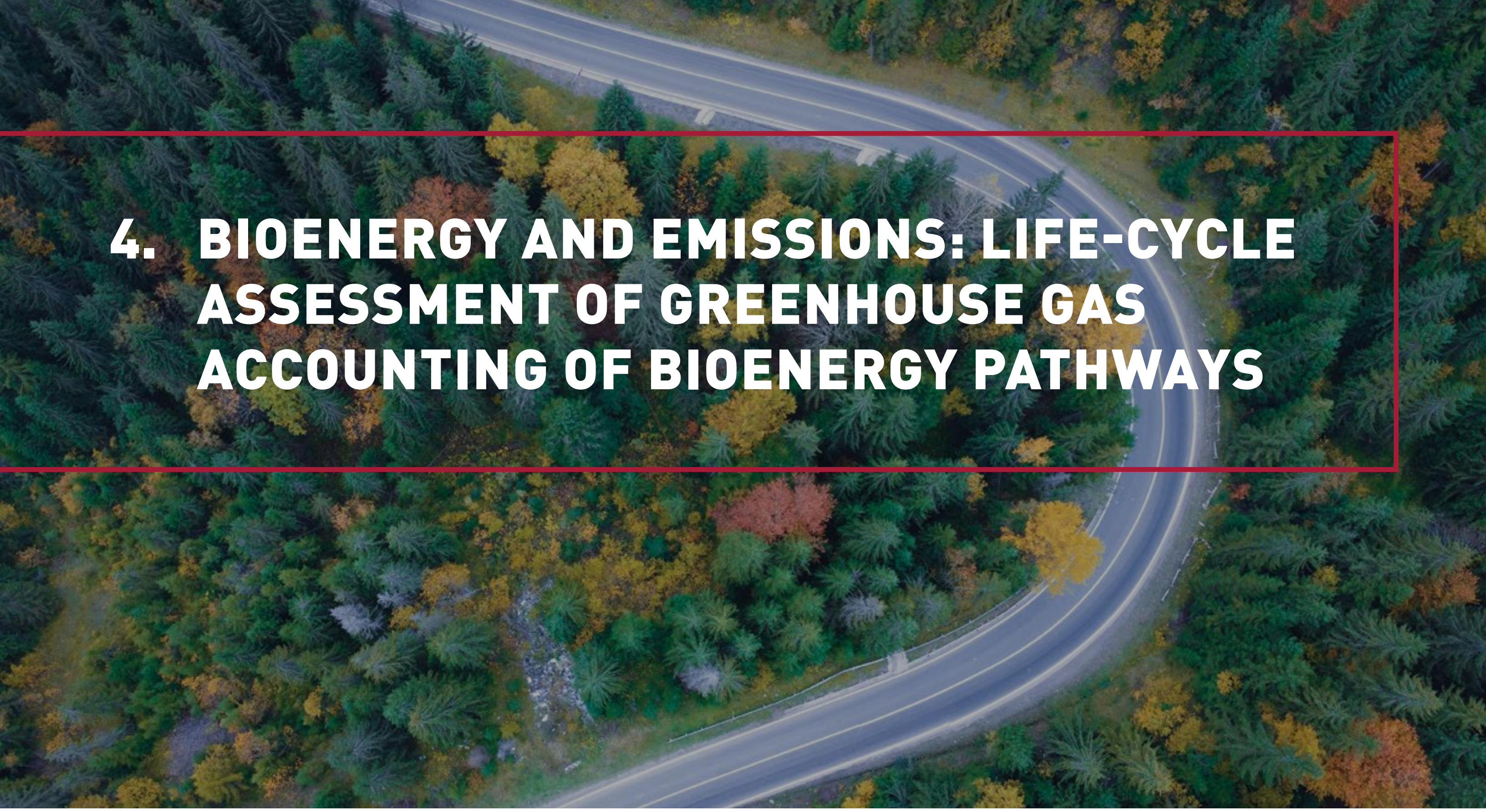
Controlled digestion in tanks converts organic material to biogas and a residue digestate. The biogas is combusted directly at most facilities to generate heat and electricity, although one farm in Vermont is now refining biogas into RNG and other farms may follow suit. Excess electricity is sold to the grid – contributing a negligible amount of regional electricity in 2021.[51] The digestate is often used as a nutrient-rich soil amendment. There is increasing concern regarding various contaminants (per- and polyfluoroalkyl substances, perfluorooctanoic acid, pharmaceuticals) in digestate from municipal wastewater treatment, which can have devastating financial and environmental impacts for farmers who use them.[56] The State of Maine has subsequently banned the application of such material to land,[57] and Vermont has taken steps to reduce PFAS concentrations in food waste.[58]

Figure 4.

MAP OF ANAEROBIC DIGESTERS IN NEW ENGLAND PLOTTED BY ENERGY OUTPUT (COLORS) AND TOTAL EQUIVALENT METHANE PRODUCTION

Source: EPA Livestock Anaerobic Digestor Database.[59]





4. BIOENERGY AND EMISSIONS: LIFE-CYCLE ASSESSMENT OF GREENHOUSE GAS ACCOUNTING OF BIOENERGY PATHWAYS

The Greenhouse Gas Impacts of Bioenergy Are Often Underestimated and Misunderstood

It is often erroneously assumed that bioenergy use has no climate impact. In reality, the climate impact can be considerable – as the EPA states, "depending on the feedstock and production process, biofuels can emit even more greenhouse gases than some fossil fuels on an energy-equivalent basis."[60] This is for two key reasons.

First, like and often more so than fossil fuels, production of bioenergy resources requires significant energy inputs. These inputs come from the cultivation, collection, transport, and processing necessary to make the bioenergy usable, akin to the energy-intensive refining of crude oil into gasoline. Because bioenergy resources are more spatially diffuse and less energy dense than primary fossil resources, these energy inputs tend to be higher than those needed for refining fossil resources.[61] These energy demands generate "life-cycle" greenhouse gas emissions, given the greenhouse gas intensity of today's energy inputs. While such energy inputs could be decarbonized with renewable energy, such application of limited renewable energy would be misguided given the high energy demands and other environmental and social impacts of bioenergy production and the more beneficial uses of renewable energy, such as heating buildings and powering electric vehicles.

Second, the use of bioenergy resources and the intentional production of methane gas from some bioenergy resources can increase net accumulations of carbon dioxide and methane in the atmosphere by disrupting the natural cycling of these gases.

Like the carbon stored in fossil fuels, the carbon stored in natural resources is a stock that, if depleted and released into the atmosphere, causes an increase in atmospheric CO_2 levels, leading to increased warming. Some biomass (grasses, leaves, debris, food) rapidly decomposes and is regenerated on short, often annual, timescales.

Use of these resources for energy has little impact on the carbon cycle when viewed within a silo, but can have large impacts on the carbon cycle when bioresource cultivation drives land use changes, like the conversion of forests and grasslands to create new bioresource croplands. Harvesting a whole tree for energy, by contrast, will require decades to regenerate the stock of carbon. Changing a whole swath of land from a carbon-rich forest to a sprawled development leads to long-term to permanent releases of carbon from the biosphere. Both of these activities create a net impact to warming that can be greater than the use of coal.

Conventional methods of accounting for emissions across sectors and jurisdictions do not provide a sufficient understanding of these impacts for decision-making and robust policy design. Exacerbating this problem is the fact that these emissions from the production and use of bioenergy often cross jurisdictional boundaries. Further, nations and states may have different ways of accounting for such activities (see page 20).

The practical implications of this can lead to unfortunate outcomes. Taken to the extreme, whole forests can be felled in one jurisdiction and shipped to another that claims to be using a carbon-neutral fuel because its accounting system only tracks changes in its jurisdictional carbon stock. This approach has been common in Europe for years.[12] The lack of clarity and consistency in greenhouse gas accounting approaches can still result in undesirable outcomes.

This section details major emissions drivers in the bioenergy life cycle, including cultivation, production, transportation, and combustion. Such an understanding of *life-cycle processes* is needed to inform robust policy design in economy-wide strategies (e.g., carbon tax or cap and trade), sector-specific strategies (e.g., clean heat or renewable transportation fuels standards), institutional climate planning, and the pursuit of individual projects.

It will take years to regenerate the stock of carbon released when a tree is harvested.

BIOENERGY AND NEW ENGLAND STATE GREENHOUSE GAS INVENTORIES

Across the board, New England states do not count direct bioenergy emissions in their reporting of total state-wide greenhouse gas emissions inventories. States generally use the EPA's State Inventory Tool,[62] following the greenhouse gas accounting methodology used in the *U.S. Greenhouse Gas Inventory*, in which "net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry."[63] These approaches are informed by and seek to align with practices established by the Intergovernmental Panel on Climate Change, although some practices differ.

Even though this approach is an analytically sound way of tracking changes in emissions at aggregate levels, it severs the relationship between the consumption of bioenergy, upstream emissions, and perturbations to the biological carbon cycle. The EPA addresses this gap by reporting emissions from wood biomass and biofuels separately from fossil fuels, yet it does not provide guidance in the tool for doing the same at the state level.

In New England, three states (Maine, Massachusetts, and Vermont) maintain accounts for bioenergy emissions. These states, along with Rhode Island, calculate land-use emissions, although, at the state level, there is no expectation that this approach will accurately account for the net emissions from bioenergy use since there is considerable interstate trade in energy. There is no expectation that the state that burns the biofuel will be the same state to grow replacement biomass. Since these greenhouse gas inventories are defined geographically, this ambiguity can lead to a mismatch between bioenergy emissions and the bioenergy-related fraction of land-use emissions reported by any given state, to say nothing of the vast uncertainty in land-use emissions accounting generally.[64]

States present bioenergy emissions in various ways to try to mitigate the confusion, including offering total emissions inventories with and without bioenergy (Maine) and displaying bioenergy and land-use emissions together (Vermont and Massachusetts). Rhode Island acknowledges the emissions from bioenergy but does not present any data; Connecticut excludes both bioenergy and land-use sectors; and New Hampshire appears to rely solely on EPA data rather than maintaining its own state-level accounts.

The constraints of the state-level greenhouse gas inventory model are largely to blame for the shortcomings related to bioenergy emissions. One of the fundamental principles of greenhouse gas accounting is to avoid double-counting. The Massachusetts inventory warns, "to the extent that biomass harvested in MA is combusted in MA, associated CO_2 emissions are double-reported in combustion and [land-use] emissions." The biomass harvested outside of the state is (presumably) reported in those states' inventories, so if MA were to report direct bioenergy emissions, it would lead to the undesirable situation that the sum of all state- and territory-level inventories would be greater than the EPA-calculated U.S. inventory. The same concerns are raised for reporting fuel cycle and other indirect emissions associated with bioenergy. Since these emissions should be accounted for in other sector or state inventories, reporting them as bioenergy emissions too would lead to a notable overcount.

No approach is perfect and different methodologies involve tradeoffs. States must recognize the limitations of these approaches and not rely on the inventories to assess the effects of bioenergy. Rather, states should consider adopting targeted and well-informed models of bioenergy emissions based on life-cycle assessment to inform bioenergy policy.

COMBUSTION: DIRECT EMISSIONS

Direct emissions are those that occur when fuel is burned, such as occurs in vehicles, heating equipment, and electricity generation facilities. They are thus the "tailpipe," "burner tip," and "smokestack" emissions that result from burning carbon-based fuels.

Direct emissions from fossil fuels are the main driver of atmospheric CO_2 accumulation as they release carbon stored deep underground that would not otherwise enter the atmosphere ("fossil carbon"). Direct emissions from bioenergy release carbon that was relatively recently removed from the atmosphere through photosynthesis ("biogenic carbon"). Table 3 shows the direct emissions of fossil and biogenic CO_2 from the combustion of various fuels. Direct CO_2 emissions depend on both the energy and the carbon content of the fuel.

Table 3.

GRAMS OF CO_2 RELEASED PER KWH OF ENERGY IN SELECT FOSSIL AND COMPARABLE BIOENERGY FUELS

	FOSSIL	BIOENERGY
GASEOUS FUEL	Natural gas – 183	RNG – 183
LIQUIFIED GASES	Propane – 215	Renewable propane (DME) – 217
LIQUID FUEL	Diesel – 250	Biodiesel – 253
SOLID FUEL	Coal for electricity – 322	Wood – 333

CARBON STORAGE LOSS AND LAND-USE CHANGE

For most bioenergy derived from agricultural crops, the CO_2 released when the bioenergy is combusted may be temporarily restored in the next growing season, assuming a similar amount of the same feedstock is cultivated. This results in a roughly months-to-year-long fluctuation in the amount of carbon stored in these ecosystems. In the case of trees and soils that may be cut down or permanently disturbed, respectively – not only for direct biomass energy but also to clear land for food or energy crops – the carbon stored therein was removed from the atmosphere decades or even centuries ago. The release of that carbon depletes the carbon stored in ecosystems and transfers it to the atmosphere, leading to the net accumulation of CO_2 and affecting the global climate.

Accounting for such depletion of ecosystem carbon and its release into the atmosphere is an essential but often overlooked element of accounting for the impacts of bioenergy.[11,65] Biogenic emissions contribute to the accumulation of CO_2 in the atmosphere if biogenic CO_2 removal (e.g., photosynthesis) is not happening at a sufficiently rapid pace to regenerate the stored carbon.

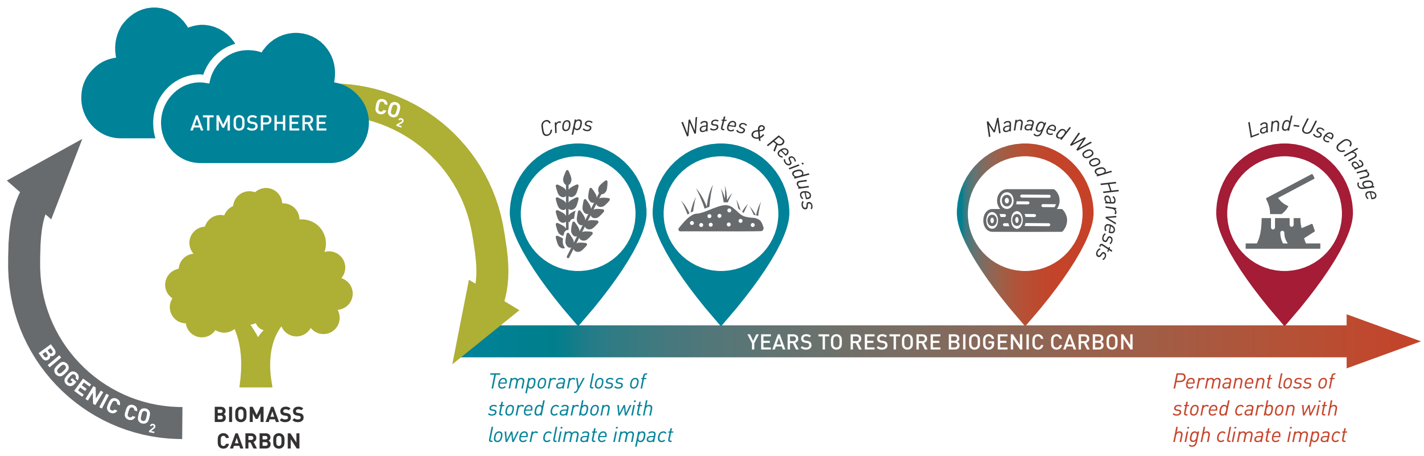


Figure 5.
Illustration of how biogenic carbon can contribute to atmospheric CO_2 accumulation if not restored in short timescales.

Figure 5 illustrates *carbon storage loss* and the approximate storage *payback period* of different strategies. Wastes and residues that rapidly decompose and come from rapidly regenerating sources (e.g., food waste, wastewater sludge, etc.) are not long-term stores of carbon and thus have shorter payback periods. Capture and treatment – including conversion to bioenergy – of some wastes may also avoid generating methane emissions from the decomposition of organic matter if less impactful, alternative disposal methods are not available.

At the other extreme, harvested wood can take decades to pay back and regenerate, leading to a significant loss of carbon storage. Generally, fuels with decade-plus paybacks and that lead to continual depletion of ecosystem carbon contribute to the accumulation of greenhouse gases in the atmosphere.

Activities that result in permanent land-use change, such as deforestation for energy crops or food, never restore ecosystem carbon. Land-use change not only depletes ecosystem carbon but also makes it impossible for these ecosystems to grow their carbon stock. This *loss of sequestration potential* counters global goals to enhance natural carbon stocks as part of ambitious climate pathways.[66]

Young forests such as New England's are still paying back their carbon debt from the region's prior agricultural and industrial period.

A stand of trees will continue to sequester more and more carbon as the trees grow. Trees in cultivated forests are removed when doing so maximizes economic returns. Had the trees been left standing, they would have continued removing CO_2 from the atmosphere for decades more. The carbon storage opportunity cost of *not harvesting* thus defines the carbon debt that results from their harvest and combustion.[67] Not only does it take decades for the harvested carbon to be restored but, due to changes in soil carbon resulting from dead trees being removed from the forest instead of decomposing into the ground, the forest carbon storage can never catch up to the no-harvest counterfactual. This is especially relevant with young forests such as New England's that are still paying back their carbon debt from the region's prior agricultural and industrial period.

Land that is not being directly harvested for bioenergy resources can also contribute to net greenhouse gas emissions through *induced* or *indirect land-use change*.[68] Bioenergy resources compete for land with food crops, leading to food price increases. These price increases are often sufficient motivation to bring more land into agricultural cultivation. The net greenhouse gas emissions from permanent land-use change from forest or grassland to farm are allocated to the bioenergy demand that stimulated it. The specific values of this indirect land-use change can be difficult to ascertain, however, especially because the effects can happen internationally.

METHANE LEAKS

Methane leaks are a pernicious problem in fossil natural gas, biogas, and RNG systems due to the high global warming potential of methane. Leaks occur at every step of gas production, transmission, storage, delivery, and use.

Using organic wastes for energy can generate varying levels of fugitive methane emissions depending on facility design, feedstocks, and conversation processes. Measurements of fugitive emissions indicate that loss rates in agricultural bioenergy facilities may range between 0.5% and 8%, and may be as high as 15% in wastewater treatment plants with biogas production.[69] A small number of super-emitter facilities may also be responsible for a significant portion of the overall methane leaks.[70] A 2% leakage rate increases the climate impact of methane consumption by 25% to 64% relative to emitted CO_2 based on 100-year and 20-year time horizons, respectively. An 8% leakage rate increases the climate impact of methane consumption by 108% to 273% on those same time horizons. As such, policy pathways contemplating RNG must ensure that fugitive methane loss is accurately measured. In addition to these production leaks, leaks in older gas distribution systems can be as high as 2.5%, half of which may come from stoves, furnaces, and other equipment behind the meter.[71] There is no strategy for mitigating these leaks. Despite six years of accelerated replacement of old distribution lines, the gas system in the Metro-Boston region has not exhibited any noticeable leak reduction. Thus, while RNG has been proposed as a drop-in substitute for fossil gas, continued reliance on the pipeline distribution of methane – of fossil or biological origin – creates significant challenges for the elimination of greenhouse gases.

Methane leaks are a pernicious problem due to the gas's high global warming potential.

INDIRECT AND HIGHER-ORDER EMISSIONS

Indirect emissions are those that stem from energy and material inputs to producing, refining, processing, storing, and transporting bioenergy. (Leaks are sometimes also classified as indirect emissions.) These emissions are highly variable and depend on local factors such as the emissions intensity of the local electricity supply, the energy requirements of a particular conversion process, agricultural practices, transportation distances, etc. Indirect emissions accumulate in the atmosphere and are not typically reabsorbed by new bioresource growth. They thus can cause much of bioenergies' impact on climate change. As efforts to reduce emissions across all parts of the economy proceed in the coming years and decades, these indirect emissions are expected to decline.

Life-Cycle Assessment Is One Way to Calculate Accurate Greenhouse Gas Emissions from Bioenergy

Accounting for all the different sources of greenhouse gas emissions from bioenergy, ranging from the cultivation of bioenergy resources through fuel production to final combustion, is the approach taken in life-cycle assessment: a technique for comparing the environmental impacts of technology choices. The term "life cycle" refers to the chain of activities that contribute to the production and use of a given product, including acquiring or cultivating raw materials and feedstocks, manufacturing, refining, transporting, using, and disposing of resources (Figure 6). By examining and quantifying all of the energy and resource inputs and greenhouse gas emissions and waste outputs in each of the life-cycle stages, environmental burdens can be calculated and compared. The currently accepted approach to life-cycle assessment has been standardized by the International Organization for Standardization as ISO 14040 and ISO 14044.

Figure 6.
Diagram of a product life cycle. The dotted line connecting the "end-of-life" box with production indicates recycling.

A life-cycle assessment can be a useful tool for calculating greenhouse gas emissions from bioenergy and other energy sources if the focus is on accurate and transparent emissions accounting with the goal of facilitating genuine decarbonization. Importantly, however, life-cycle assessments can also be misleading when constructed poorly, applied in vague situations, or used by those with the intent of promoting a particular energy strategy. They can be manipulated in ways that could cause policymakers to support or invest in polluting technologies rather than truly low-greenhouse gas technologies. If policymakers are considering adopting energy life-cycle assessments to guide technology selection, they must use caution and provide ample time, staffing, and financial resources. Policymakers must ensure that trusted experts are retained by the regulator to construct fair and accurate models and that polluting industry interests are not permitted to influence the models in ways that could make polluting technologies appear cleaner than they are. Doing so is essential if states are to adopt policies that allow them to meet their greenhouse gas reduction requirements and targets.

The following sections provide a high-level overview of life-cycle emissions from various bioenergy fuels.

The most carbon-intensive sources of electricity involve fuels that use whole tree biomass or require substantial processing.

OVERVIEW OF BIOENERGY LIFE-CYCLE GREENHOUSE GAS EMISSIONS

Electricity

The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy has for many years studied the life-cycle greenhouse gas emissions of different electricity sources by synthesizing and harmonizing thousands of life-cycle assessment results from the academic literature.[72] The results largely validate the common understanding of the environmental preferability of different electricity sources: fossil fuels are significantly more greenhouse gas emissions-intensive than renewables. In general, coal electricity has the highest life-cycle greenhouse gas emissions, followed by oil and natural gas. Renewable electricity is much less emissions-intensive, ranging from ocean power at the low end to biopower at the high end.

Complicating this story is the variability in emissions intensities within each energy technology. The NREL team found enormous ranges in emissions intensities, the most striking of which is for bioenergy-powered electricity. At the high end, one study calculated the life-cycle greenhouse gas emissions intensity of bioelectricity to be higher than that found in any other study except for some life-cycle assessments of coal electricity. On the other end, studies also found that bioelectricity is able to *avoid* large quantities of greenhouse gas emissions even without the use of carbon capture and storage.

The drivers of this wide range of life-cycle assessment results include differences in system boundary decisions and data sources as well as variations among different types of bioresource feedstocks that can be used to generate electricity. The most carbon-intensive sources of electricity involve fuels that use whole tree biomass or substantial processing. Alternatively, the review included carbon capture and storage pathways that generate a "negative emission" with the production of electricity. The review's quantitative approach also assigned negative carbon intensity values to pathways that avoided methane emissions in the generation of electricity, such as those from landfill gas or anaerobic digestion of manure, with the assumption that such bioenergy pathways are exclusively responsible for methane reductions – an assumption that cannot be categorically applied given a range of options for manure management.[73] Policymakers should pay particular attention to assumptions about the alternative disposition of wastes and whether the baseline is accurate before accepting a negative life-cycle assessment figure for bioenergy-powered electricity.[74]

How Bioenergy Compares with Wind, Hydro, and Solar Photovoltaics

Traditionally, bioenergy has been grouped with wind, hydropower, and solar photovoltaics as a renewable energy technology. As the costs of wind, water, and solar technologies have plummeted, a gap has formed between them and bioenergy in terms of the role they might play in the future energy system. In an NREL study, the median life-cycle emissions factors for solar photovoltaics, hydropower, and wind power were found to be 43, 21, and 13 g CO_2e/kWh, respectively, with relatively narrow ranges around those values. Bioenergy, although having a median emissions factor not much above, at 52 g CO_2e/kWh, has a range spanning from 1,300 to –1,000 g CO_2e/kWh.

These results suggest that wind, water, and solar energy represent not only a more effective pathway toward decarbonization but a more scalable one too. As production capacity for photovoltaics and wind turbines continues to expand worldwide, economies of scale and technological learning curves are driving efficiency gains, decreasing life-cycle emissions further.

Illustrative Life-Cycle Assessment of Selected Bioenergy Pathways

The NREL data are useful in visualizing the ranges in emissions intensities of the various electricity sources. However, the fact that the biopower values span nearly the entire range of emissions intensity values and beyond makes that analysis unhelpful for informing bioenergy decisions and even less so in a specific geographic region like New England. In this section, we present representative life-cycle greenhouse gas emissions results for a number of specific bioenergy pathways with the goal of comparing bioenergy pathways, identifying key emissions drivers, and highlighting sources of uncertainty.

We present the results in four main life-cycle phases (depending on the bioenergy pathway reported, there may be some variation to the scheme):

- **Feedstock preparation**, including agricultural and forestry management, chemical and fuel inputs, energy for harvesting and collection, and transportation.
- **Conversion emissions**, including the energy used to power a fuel production process and related transportation.
- **Combustion emissions**, including all CO_2 produced when burning the fuel, including biogenic CO_2.
- **Carbon uptake**, which accounts for the biogenic removal of CO_2 from the atmosphere due to replacement of crops and trees. Differences between biogenic combustion emissions and carbon uptake values can be explained by carbon storage loss. The greater the carbon uptake figure in a life-cycle emissions calculation, the more room there is for uncertainty in real-world applications.

Our presentation of these four phases is intended to better illustrate the generation of emissions for a broad audience. Is it an accurate accounting for emissions incurred at different steps in the life cycle, based on current assumptions for some products. Our presentation of these steps is novel as it seeks to emphasize the emissions debt that is incurred by the first three categories as well as the importance of ensuring near-complete carbon uptake. For a bioenergy strategy to effectively reduce emissions, the emissions from the first two categories must be minimized, while those from the last two categories must be balanced. It is important to remember that a bioenergy pathway that effectively reduces emissions on a life-cycle basis may not necessarily be the highest and best use of a bioenergy resource, effectively use input energy, or be the most cost-effective strategy.

Honest life-cycle analyses rely on transparency. Often, greenhouse gas emissions and other environmental impacts are reported as single-point values. These are easy to communicate but can obscure vital details, variabilities, and assumptions. For example, we have noted that assumptions around carbon storage loss can drastically change the environmental preferability of different biofuels. Further, we have highlighted how fuel processing and methane leaks can contribute to emissions. Carbon uptake (if present) is a negative emissions process that reduces overall carbon intensity, leading to an estimate of net emissions – the sum of the four emissions categories.

This, or similar disaggregation, can be a powerful tool for regulators and policymakers in the evaluation and application of bioenergy pathways. Understanding the magnitude and composition of conversion emissions can give insight into the efficiency of a process. Likewise, disaggregating carbon uptake places an emphasis on ensuring that the bioenergy resource is produced sustainably. This prompts regulators with the need to intentionally consider each step and provide robust data quantifying the impact in each category. It places the onus on the pathway proposer to demonstrate that the approach is consistent with broad climate goals. While such quantified disaggregation could be applied to the direct regulation of a bioenergy pathway, at minimum regulators should evaluate pathways using such multidimensional frameworks.

The following sections are used to illustrate these processes using several broadly applicable pathways. It must be reiterated that the models and values presented here are not definitive but merely representative of each pathway and the contributions of its life-cycle phases. Accordingly, the specific emissions values presented here *must not* be used to dictate a specific policy's design. Instead, along with the supporting discussions, they should be used as a guide to identifying the highest and best uses of bioenergy resources in mitigating climate warming in specific geographic and economic contexts.

SOLID FUELS

We analyzed representative life-cycle greenhouse gas emissions for four types of wood fuels – roundwood timber, forest residue, mill residue, and pellets. The results show that gross greenhouse gas emissions from wood bioenergy, without considering carbon uptake, are larger than those from fossil fuels. The degree of carbon storage loss associated with each of these fuels, which influences the carbon uptake, is therefore a key driver of the net greenhouse gas emissions from these fuels. The amount of carbon storage loss that is associated with wood energy production in New England forests is not clear; we use 20% here as a conservative figure, although it may be much higher. From these results, wood pellets appear to be 15%–25% more emissions-intensive than the other three wood fuels. The main driver of this difference is the pellet production process.

The other three fuels have lower greenhouse gas emissions intensities than pellets. Timber has the largest feedstock emissions because of the fuel and chemicals used in forest management and harvest. Forest residues and mill wastes have lower feedstock emissions because they are waste materials.

LIQUID FUELS

A bioenergy alternative for liquefied petroleum gas (LPG) is biopropane, a fuel that is functionally equivalent to fossil propane but can be produced from biological sources. Figure 7 presents representative life-cycle greenhouse gas emissions data for biopropane produced from gasification of forest residue and from gasification of black liquor, a waste product from the pulp and paper industry. This life-cycle model is based on the production of dimethyl ether (DME), a close relative of propane, for which there is much more data on the environmental impacts of production. DME is sometimes called "biopropane" or mixed into fossil LPG tanks. We assume the same conservative carbon storage loss factor of 20% that we used above. Life-cycle emissions for biopropane are presented alongside two fossil fuel-based comparisons: fossil propane and synthetic propane produced from fossil natural gas.

The results show that, like for wood energy, the gross greenhouse gas emissions for biopropane are much larger than for fossil propane or LPG. One major reason for this is the large consumption of bioenergy for heating the gasification processes. We assume that all the energy inputs for the forest residue case come from wood energy, while energy requirements for the gasification of black liquor are satisfied with both bioenergy and electricity. Carbon uptake offsets some of the biogenic emissions from combustion and conversion; when it is considered, the net greenhouse gas emissions range from 120 g CO_2e/kWh to 210 g CO_2e/kWh, lower than the 300–350 g CO_2e/kWh associated with fossil and synthetic propane.

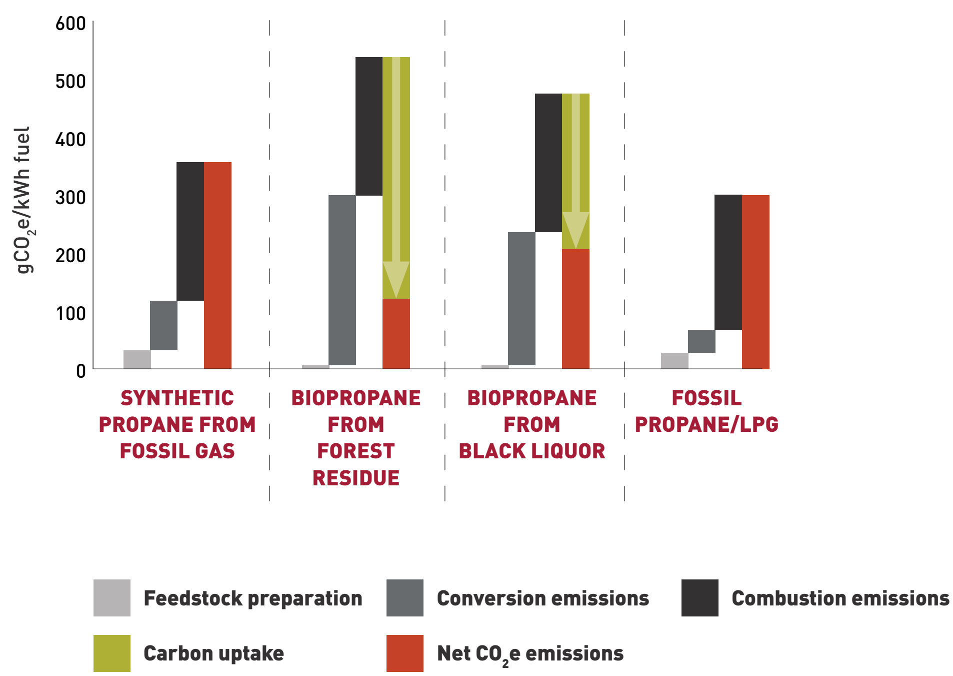
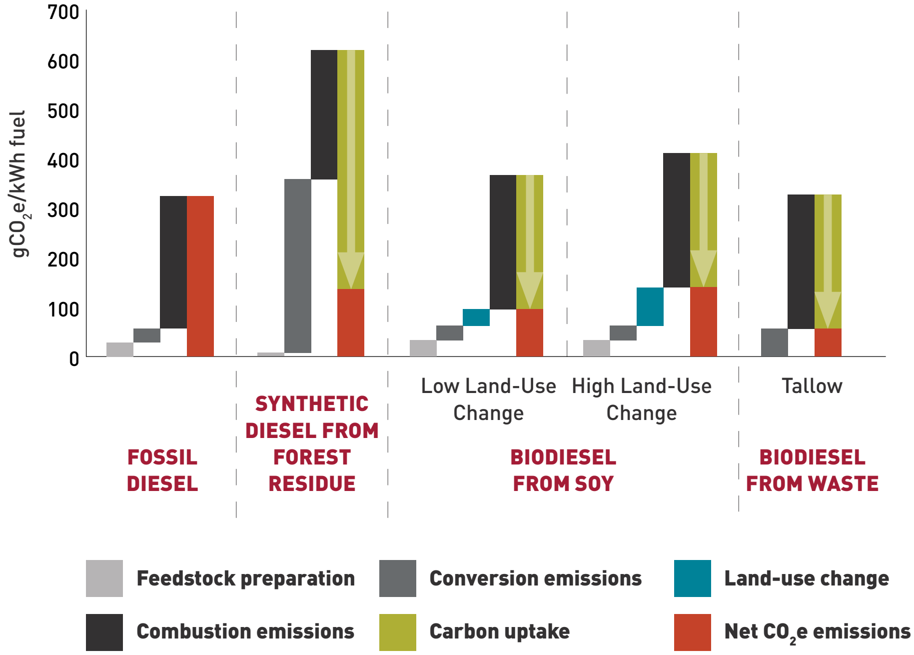


Figure 7.
Representative life-cycle greenhouse gas emissions of propane/LPG based on different conversion pathways, including synthetic propane produced from fossil gas, forest residues, black liquor (a waste product from the paper industry), and fossil propane. Synthetic propane from bioresource feedstocks is called "biopropane" and assumes a conservative carbon storage loss of 20%.

There are also many bioenergy pathways for liquid fuels like gasoline, fuel oil, and jet fuel. Figure 8 presents representative life-cycle greenhouse gas emissions of diesel and biodiesel fuels. In addition to the life-cycle emissions of fossil diesel, we show data for synthetic diesel fuel produced from forest residues and biodiesel, a near-drop-in replacement for diesel fuel produced via the transesterification of soybeans and waste animal fat.

Figure 8.
Representative life-cycle greenhouse gas emissions of diesel and biodiesel fuels from a variety of production pathways. Fossil diesel refers to diesel fuel produced from crude oil. Synthetic diesel is a completely drop-in replacement for fossil diesel produced with the Fischer-Tropsch process; results are shown for production from forest residues with 20% carbon storage loss, as a conservative figure. Biodiesel, a near-drop-in replacement for fossil diesel as well as other liquid fuels like fuel oil, is produced via the transesterification of oily feedstocks, including crops and wastes. We show results for biodiesel produced from soy that includes the effect of different land-use change scenarios. The results for tallow biodiesel are also broadly applicable to other oily wastes like used cooking oil.



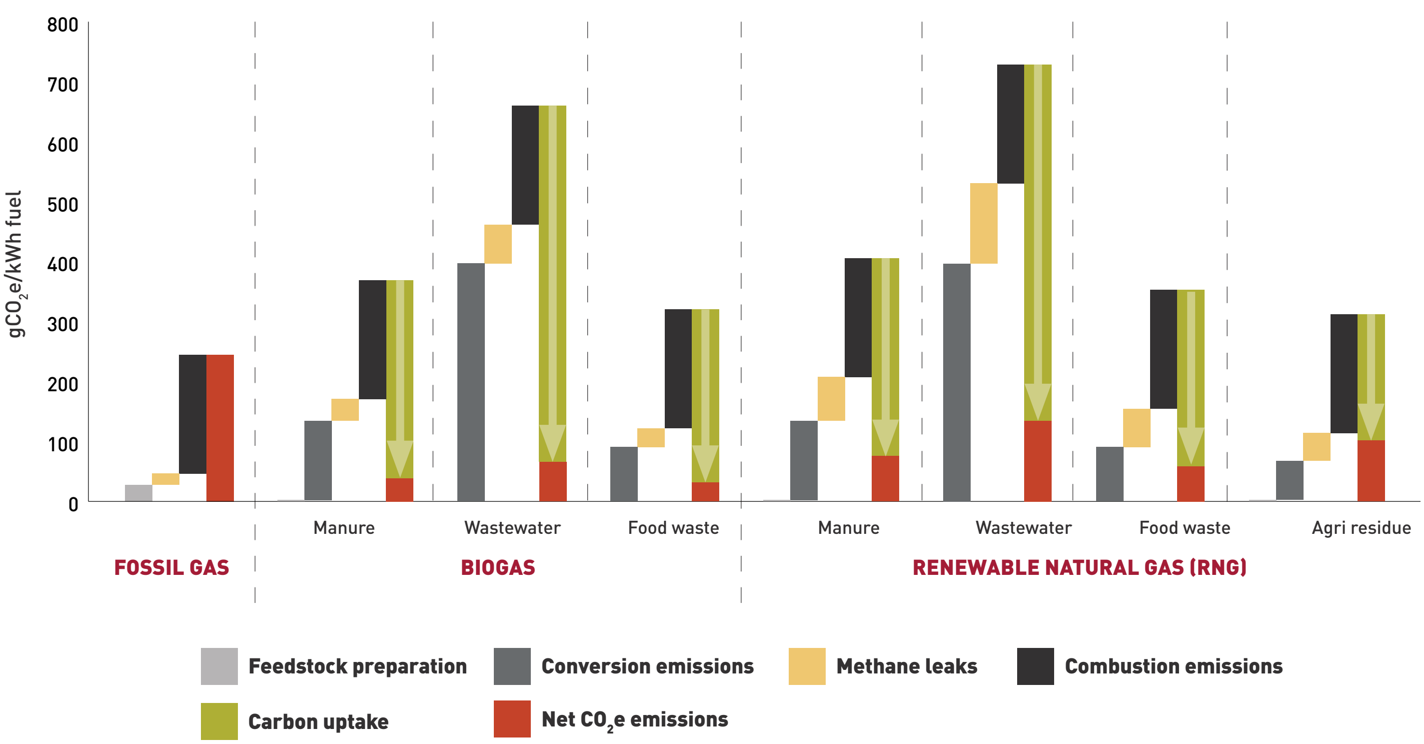
Gross greenhouse gas emissions for biopropane are much larger than for fossil propane or LPG.

GASEOUS FUELS

The bioenergy replacements for fossil natural gas are also methane-based fuels. Figure 9 presents representative life-cycle greenhouse gas emissions for two types of methane-based fuels produced from bioresources – biogas and RNG – as well as fossil natural gas as a comparison. Biogas is produced from the anaerobic digestion of organic wastes like manure, wastewater sludge, and food scraps. RNG is produced by either upgrading biogas (increasing the concentration of CH_4 to pipeline gas standards) or gasifying agricultural residue.

Feedstock emissions are largely negligible for waste resources like these. There are some transportation impacts, but they are small compared to the other emissions sources. Fuel conversion emissions can be quite large due to the energy required to operate the anaerobic digestion and upgrading facilities. All the conversion pathways examined here are at least partially self-powered, with some being completely self-powered. This means that some fraction of the fuel being produced is burned onsite to produce heat and electricity to power the process. Because these emissions are biogenic and New England is expected to see little land-use change or carbon storage loss associated with the use of these waste resources, the self-powered conversion emissions are ultimately zeroed out in the summation, along with combustion emissions. The largest net contributor to the life-cycle greenhouse gas emissions of these fuels, therefore, is methane leakage. Biogas production is conservatively assumed to have a 1% leakage rate, while RNG production is conservatively estimated to have a 2% leakage rate. As noted on page 23, fugitive methane losses can range significantly above 2%.[69] This model does not account for leakage from transmission, distribution, and end-use equipment, which can be considerable in older pipeline systems.[71]

Figure 9.
Representative life-cycle greenhouse gas emissions of methane-based fuels, including fossil natural gas; biogas produced from anaerobic digestion of manure, wastewater, and food waste; and RNG produced from upgrading biogas or gasifying agricultural residues.



The results show that biogas has an emissions intensity between 30 g CO_2e/kWh and 70 g CO_2e/kWh, while RNG has an emissions intensity between 60 g CO_2e/kWh and 135 g CO_2e/kWh, depending on the production pathway. This compares with the 245 g CO_2e/kWh life-cycle emissions intensity of fossil gas (which likely undercounts the contribution of methane leaks from natural gas production infrastructure).

There are at least two life-cycle activities that we are excluding from this analysis. First, we are not comparing these results with a waste management counterfactual scenario, as is commonly done to make RNG appear to have negative emissions. We believe this is a misleading technique, and it is more responsible to clearly identify the emissions associated with RNG production. Waste impacts can be presented in parallel if they can be reliably ascertained. For example, in New England, the management of 1 kWh-eq of manure has a life-cycle greenhouse gas emissions impact of approximately 16 g CO_2. So, we could claim that the net greenhouse gas impact of manure-based RNG in New England is 60 g CO_2e/kWh, rather than the 75 g CO_2e/kWh shown in Figure 9.

Second, we do not consider the emissions impacts of land application of digestate sludge. Depending on environmental conditions, the sludge, which contains quantities of carbon and nitrogen, can be oxidized to CO_2 and N_2O, decomposed to CH_4, and/or sequestered in the soil. The impact of this process is highly uncertain and variable across time and geography, and, as such, we exclude it from this analysis.

COMPARING ELECTRICITY AND BUILDING SECTOR LIFE-CYCLE EMISSIONS FROM BIOGAS AND RNG USAGE

Assuming 100% carbon uptake from waste-based biogas and RNG production, the life-cycle analysis conducted in this report shows that biogas has embodied emissions between 32 g CO_2e/kWh_{fuel} and 66 g CO_2e/kWh_{fuel}, and RNG has embodied emissions between 58 g CO_2e/kWh_{fuel} and 135 g CO_2e/kWh_{fuel}, depending on the production pathway. These upstream emissions figures tell only part of the story, however. Use of these fuels in different applications and different technological contexts also drives emissions.

We consider five reasonable use cases:

1. RNG used in home heating in an older, more leak-prone system (2.5% system leakage rate, 70% efficiency home furnace). Actual leakage rates in an older gas system may be significantly higher.[69]
2. RNG used in home heating in a newer, low-leak system (1% system leakage rate, 95% efficiency home furnace).
3. RNG burned in a gas turbine power plant (0% system leakage rate, 33% efficiency electricity production).
4. Biogas burned in a gas turbine power plant (0% system leakage rate, 33% efficiency electricity production).
5. Biogas burned in a reciprocating engine power plant (2% system leakage rate, 30% efficiency electricity production).

The first scenario represents a typical, older gas-burning system in Boston, where leaky gas distribution infrastructure, including home meters and appliances, has been estimated to be 2.5% or greater and older-generation furnaces have low conversion efficiency.[71] The second scenario assumes a recently constructed gas distribution system and new, high-efficiency heating appliances.

The third and fourth scenarios examine the gaseous fuels burned in a 33% efficient gas turbine power plant. These plants are often connected directly to high-pressure transmission lines with little to no fugitive emissions. The reciprocating engines contemplated in the fifth scenario, which are often used to burn biogas at landfills and other facilities that produce biogas directly, are estimated to have lower conversion efficiency and an average 2% leakage rate, but actual leakage rates may be significantly higher. Using averages of the upstream emissions factor ranges shown above (45 g CO_2e/kWh_{biogas} and 93 g CO_2e/kWh_{RNG}), we calculated the overall cradle-to-grave life-cycle emissions for the five scenarios (Tables 4a and 4b).

Tables 4a & 4b.

SCENARIO		EMISSIONS (G CO_2E/KWH HEATING)		
		FUEL PRODUCTION	LEAKAGE	TOTAL
1.	RNG used in home heating (combustion) in a higher-leak gas distribution system	134	82.5	217
2.	RNG used in home heating (combustion) in a lower-leak gas distribution system	98.4	24.2	123

SCENARIO		EMISSIONS (G CO_2E/KWH ELECTRICITY)		
		FUEL PRODUCTION	LEAKAGE	TOTAL
3.	RNG used to produce electricity in a gas turbine	280	0	280
4.	Biogas used to produce electricity in a gas turbine	138	0	138
5.	Biogas used to produce electricity in a reciprocating engine	151	151	302

It is clear that system leaks and conversion efficiency play a large role in driving emissions in the use of gaseous biofuels like biogas and RNG. For large metropolitan areas with old distribution and use infrastructure, any perceived benefits of using RNG are undercut by the significant methane leakage emissions.

In electricity production, upgrading biogas to pipeline-quality RNG has a large emissions penalty. If there is the option to directly use biogas in a low-leak application such as an on-site gas turbine, that is preferable. However, if there is a high risk of leaks, directly flaring the fuel may be acceptable.

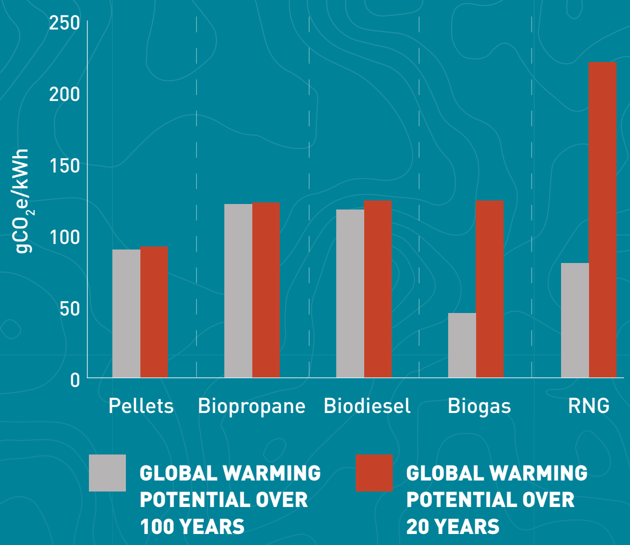
To compare the uses of these fuels across two energy services (electricity and home heating), consider a third alternative to the two provided here: heating using an air-source heat pump. If a heat pump with an average performance coefficient of 2.5 were to be powered by electricity produced by RNG, life-cycle emissions would total 112 g CO_2e/kWh heat. If it were powered by biogas burned in a gas turbine, the greenhouse gas emissions would be just 55 g CO_2e/kWh. A geothermal network system with a COP of 5 that runs on biogas electricity from a gas turbine plant would have a life-cycle emissions factor of roughly 27.5 g CO_2e/kWh heating. All of these are less than the low-leak heating scenario. With a limited supply of organic waste from which to produce bioenergy, it is usually preferable to put that resource to work producing electricity rather than burning it in homes.

WHAT IS THE "CORRECT" TIMESCALE FOR GLOBAL WARMING POTENTIAL?

The historical method to account for the climate change impact of different greenhouse gases is GWP-100, or global warming potential over 100 years. This approach has emerged as the default when converting greenhouse gases like methane, nitrous oxide, and hydrofluorocarbons into a common base unit of carbon dioxide-equivalents (CO_2e). The selection of this equivalence factor is a policy choice. GWP-100 looks at the amount of heat absorbed by a given greenhouse gas in the atmosphere over 100 years, normalized to the effects of carbon dioxide. A similar method uses a 20-year time period instead (GWP-20). Gases that have atmospheric lifetimes of less than 100 years will see their GWP-100 values differ, sometimes significantly, from their GWP-20 values. The difference between the two is most prominent for methane, which has a GWP-100 value of 29.8 and a GWP-20 value of 82.5. This difference is due to methane's high radiative forcing but relatively short atmospheric lifetime.

To illustrate the effects of different timescales on life-cycle assessment results, we examined a selection of the results presented earlier using both GWP-100 and GWP-20 (both using the three main greenhouse gases). We also examined the results using the full list of greenhouse gases, but there was little difference from the results of just using the three main greenhouse gases. This is because those other gases are largely combustion products, and we did not include data on the combustion of our fuels in real engines, turbines, furnaces, etc. Figure 10 presents the results of the comparison. For wood pellets, biopropane, and biodiesel, the difference between the two methods is negligible. Using GWP-100, biogas and RNG appear to be much more climate-friendly than the other three fuels. Using GWP-20, on the other hand, the preference switches, and biogas and RNG become the least climate-friendly. This change is due to the outsized role that methane plays in biogas and RNG life-cycle emissions compared to the other fuels. Given the pressing need to reduce greenhouse gas emissions over the next 20 years to forestall the worst effects of climate change, this difference is significant. Shifting to the use of GWP-20 would more accurately reflect the warming effects methane is having now and over the next three decades while discounting future warming and broader impacts of CO_2 emissions such as ocean acidification.

Figure 10.
Life-cycle greenhouse gas emissions for sample bioenergy fuels using GWP-100 and GWP-20 equivalence factors for the three major greenhouse gases (CO_2, CH_4, and N_2O).



*Please note the differences between GWP, described here, and carbon storage loss and land-use changes, discussed on pages 21 and 22. That distinction is especially important for wood-based bioenergies.

Life-Cycle Accounting Can Be Manipulated to Greenwash Bioenergy

Biogas that is produced from animal manure is often credited as having very low or even negative life-cycle emissions. This claim comes from assumptions about what would have happened to the manure had it not been used to create biogas. The most greenhouse gas-intensive manure disposal method, "lagooning," stores manure in pits where the moisture level results in significant methane emissions. Biogas or RNG produced from manure is often assumed to avoid lagooning emissions, which shows up as a large negative emission of greenhouse gas in a life-cycle analysis model.

Many life-cycle analyses, including those using GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), a widely utilized and freely available tool from the Argonne National Laboratory, assume by default that lagooning is the alternative fate of any manure that is manufactured into biogas or RNG. This is a particularly false assumption in New England, where less than 10% of cow and pig farms use lagooning.[75] Instead, New England farms most often use low-emission manure management methods like field spreading, composting, solid storage, and manure drying. But even nationally, where lagooning is more common, that baseline is changing via the EPA's AgStar program to encourage environmentally responsible practices.[75]

The fact that default assumptions overstate these avoided emissions has led to some unintended and undesirable consequences. The California Low Carbon Fuel Standard, which uses GREET data to assign carbon intensity values to different fuel types, assigns values "as low as –630 g CO_2e/MJ for dairy biomethane-based electricity, –530 g CO_2e/MJ for dairy manure biomethane-based compressed natural gas, and –360 g CO_2e/MJ for swine manure-based biomethane LNG."[76] Under the California Low Carbon Fuel Standard (LCFS), for example, these avoided emissions become extremely valuable, which results in several perverse outcomes:

1. It heavily subsidizes manure-generating facilities, their activity, and biomethane production.
2. It incentivizes manure-generating facilities away from other methane mitigation strategies that may have greater climate, ecological, and economic impacts.
3. It currently incentivizes production of the lowest-value renewable fuel.
4. The large subsidy creates a significant risk for these facilities if the subsidy is removed.

An initial analysis of this feature of the LCFS conducted by an economist at UC Davis suggested that the subsidy to a participating dairy farmer could be as much as 50% of the total revenue of selling milk.[77] With these numbers, it becomes entirely possible that large farms will choose to expand their dairy or swine herds – and associated emissions - *because* of the subsidy. Environmental groups have petitioned the California Air Resources Board (which oversees the LCFS) to make changes to address these perverse incentives, but with little success so far.[76]

One lesson from the experience of the California LCFS is to be careful with the use of life-cycle factors and life-cycle assessment tools. Models are developed for specific purposes in specific contexts. When they are used outside of those contexts and for other purposes, some modeling decisions that may not have been originally significant could turn out to be destabilizing, as in the manure case. It is not a reason to discard the model but instead is a call to take care and potentially adjust the underlying modeling assumptions, ensuring that the data are representative of your new context. In New England, for instance, any attempts to claim large, avoided emissions from manure-based biogas run up against the reality of manure management in the region.

Conclusions

Examining representative life-cycle emissions intensities for different bioenergy pathways can be illuminating. It can reveal hidden sources of greenhouse gas emissions and clarify the erroneous claim that biogenic CO_2 emissions have no impact on the climate. It can also show how, in general, different bioenergy fuels stack up against each other and against fossil and renewable alternatives. However, there are real limitations in the use of quantitative life-cycle assessment results alone to guide policy at a high level. There is so much variability in the factors that go into a bioenergy life-cycle model that it is simply impossible to claim a definitive life-cycle emissions factor for each type of bioenergy. An attempt to do this in California's LCFS has led to unintended consequences. We have also learned that the land-based effects of bioenergy – land-use change and forest carbon storage loss – are some of the most powerful factors defining the life-cycle emissions of bioenergy, and yet we have huge gaps in knowledge about them.

This is not to say that life-cycle assessment has no role in guiding bioenergy and decarbonization decision-making. In situations that call for specific project analysis and technology alternatives assessment, it is a useful tool. Good analysts can look at the details of projects and locations, carefully and transparently craft life-cycle models, and work closely with project stakeholders to understand their positions. Results from the models can show tradeoffs, hidden impacts, and unintended consequences. This is the scale at which life-cycle assessment thrives because it is possible to input enough real data about projects to minimize uncertainty.

Life-cycle assessment should play an important role in guiding bioenergy and decarbonization policy, but such policy should not be decided through use of quantitative results alone. Instead, the logic that goes into constructing a life-cycle assessment model, sometimes known as "life-cycle thinking," can be sufficient to ensure that policymakers and the policies themselves take into account all of the various sources of both emissions and uncertainty. Policy competence in life-cycle thinking can also make it more difficult for representatives of polluting industries to use life-cycle assessment to manipulate perceptions of their technologies.

Land-use change and forest carbon storage loss are some of the most powerful factors defining the life-cycle emissions of bioenergy.

5. COST AND ECONOMIC CONSIDERATIONS

Production and Use Costs

Evaluating the cost of a bioenergy strategy faces similar challenges to assessing its impact on emissions. Costs are incurred throughout the fuel's life cycle.

The cost of energy production and market prices are useful indicators of whether a particular decarbonization strategy is economical. However, those indicators fail to account for the financial cost of the harms caused by use of fuels, such as human health impacts from worsened air quality and the financial costs of future generations because of greenhouse gases emitted today.

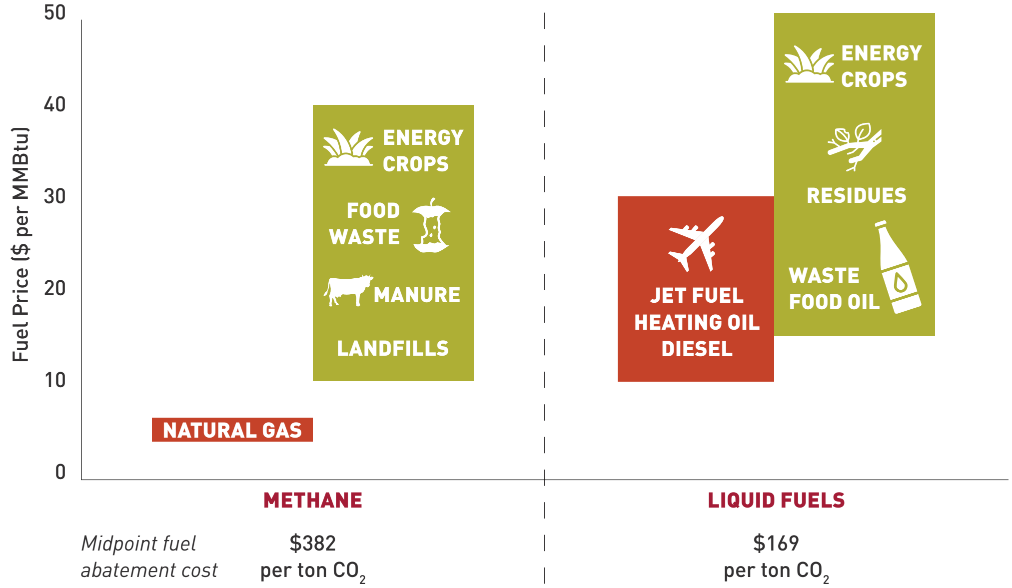
The cost of emissions is considerable. The EPA has recently estimated that the cost of emitting a ton of carbon dioxide creates a society-wide impact of nearly $200 (the social cost of carbon) and an impact of approximately $1,700 per ton of methane (2023 interpolation of EPA proposed social cost of carbon guidance[78]). Such costs will increase over time as the impacts of climate change are more acutely felt.

This section explores the drivers of bioenergy costs as well as some consequential costs and economic impacts.

Figure 11.

ABATEMENT COST OF BIOENERGY

Comparisons of production costs for fossil fuels (orange) and illustrative estimates for the production costs of each fuel's renewable counterpart (green). Abatement cost ranges are shown below each fuel. Fossil prices are obtained from Energy Information Administration wholesale or city gate prices for New England between 2019 and 2021.[35] Low prices for RNG are based on recent RNG cost[79] or cost proposals[41] in the region. The low price of liquid fuels is based on estimates of production from food waste.[80] High values are based on estimates of a study of Low Carbon Fuels in Net-Zero Energy Systems[81] and are in line with the range of estimates from other studies of RNG and renewable fuel prices.[8,18,39,82]



The differences between methane gas and liquid fuels shown in Figure 11 are notable. Bioenergy costs more than fossil energy because it requires substantial refinement of raw biomass, fossil fuels have greater economies of scale, and externalities created by agriculture are better reflected in crop prices whereas the externalities of fossil fuels are more broadly incurred by society. This cost differential is especially high in the case of methane. Fossil gas has to undergo relatively modest processing to separate methane, some valuable hydrocarbons (e.g., ethane, propane), and contaminants. RNG requires substantial refinement of biomass into a purified gas. The difference between liquid biofuels and fossil fuels is smaller as the resource demands of producing liquid biofuels are similar to refining crude oil into fossil liquids.[61]

As a result, the abatement cost – the cost to mitigate carbon dioxide combustion emissions – of methane (pipeline gas) is typically much higher than that of liquid fuels. This differential lies at the core of the imperative to prioritize the limited amount of bioenergy resources for the "highest and best uses." It is cheaper to defossilize a liquid fuel than pipeline gas. Ensuring that bioenergy resources are prioritized for hard-to-electrify sectors ensures more efficient, low-cost, and low-risk decarbonization. The low cost of fossil methane challenges the cost-effectiveness of electrifying buildings that use gas, but RNG poses *a greater* cost-effectiveness challenge, leaving its application dubious. The Massachusetts 2025/2030 Clean Energy and Climate Plan[83] showed that even if pipeline gas (methane) is still used in high demand, it should be the last fuel to be decarbonized. That is, it would be better to continue burning fossil methane for decades to come if burning gas is still necessary than to pay for alternative gases.

WHAT ABOUT HYDROGEN?

Adopting 100% green hydrogen as a heat source would incur considerable costs and disruption. Pure hydrogen is not compatible with the current pipeline gas distribution system. Hydrogen causes embrittlement of cast-iron pipes and also can affect the molecular structure of some plastic pipes.[84] A new pipeline distribution system, including new building distribution systems, would be needed. All appliances would at least need a change of burner tips, if not a full replacement, to be hydrogen compatible. Hydrogen has a global warming potential 11 times larger than CO_2 and, as a smaller molecule, is more susceptible to leakage.[85] Renewable energy resources deployed to create green hydrogen could be put to more efficient use in directly displacing fossil fuels in electricity generation or supporting electric heating. Given the limited potential benefits, efforts to incorporate hydrogen into the gas system would be a misallocation of resources.

The gradual blending of RNG and hydrogen into the pipeline system obscures an important price signal that should prompt customers to adopt more cost-effective carbon mitigation strategies. It obscures the fact that, long-term, such fuels will substantially increase consumer costs. Reliance on such fuels requires reliance on an expensive-to- maintain alternate energy distribution system, which further increases costs if such a system becomes redundant. Wealthier people will have more ability to leave the natural gas system by investing in cold climate heat pumps and weatherization projects, while lower-income people will likely become burdened with the resulting higher rates.

Broader Environmental and Socioeconomic Impacts

AIR QUALITY AND HEALTH

The combustion of fuels for energy releases various pollutants such as particulate matter, volatile organic compounds, and nitrogen oxides. The last two facilitate the production of ozone. High concentrations of these pollutants lead to adverse health outcomes: asthma, cardiac illness, cancer, and premature death.

The transition from coal to gas has resulted in a remarkable reduction in air pollution nationally and a concomitant reduction in mortality from air pollution arising from stationary sources.[13] During this time, renewable energy policies around the country reinforced wood biomass consumption across several sectors. Displacement of coal for wood biomass in industrial boilers and maintaining wood and pellet home heating position woody biomass as the most significant contributor to mortality – despite incidences of mortality being down nationally.[13] In all New England states, wood is the largest generator of such point source air pollution, largely from home heating.

The coming years may see an additional reduction in point source air pollution as the economy decarbonizes.[6,86] These improvements will be driven by a number of factors:

- Growth in wind, solar, and storage reduces reliance on combustion-based generation.
- Proliferation of electric heating technology dramatically reduces combustion for heat – possibly eliminating such combustion in some locations.
- Building retrofits are associated with improved indoor air quality stemming from electrification of cooking and improved ventilation.[87]

For sectors still reliant on combustion, replacing fossil fuels with bioenergy maintains the production of harmful pollutants.[88,89] Using RNG for cooking will likely result in the accumulation of indoor air pollution similar to that observed with fossil gas, but may involve different contaminants.[90] Burning bioenergy fuels in vehicles, kitchens, and building heating equipment means limited potential to apply pollution controls because these are decentralized facilities. For example, combustion of methane for cooking and methane leaks in the home have been associated with higher levels of indoor air pollution.[90,91]

Bioenergy production, from cultivation to management to delivery, will likely also involve the generation of adverse air pollution. The scope and the scale depend greatly on the process and any mitigation steps: for example, electrification of trucks transporting feedstock and fuels. Conversion facilities may be a source of potential pollutants if not properly regulated. Siting of facilities should consider such impacts.

ECONOMIC AND OTHER IMPACTS

Decarbonization shifts spending from out-of-region energy purchases to in-region capital energy infrastructure assets (Figure 12).[8,83] Increasing energy production from wind, solar, ambient heat, and modest local bioenergy resources not only leads to a reduction in the reliance on imported fuels but also results in periods where the region is a net exporter of energy – likely via an increased electric transmission with neighboring states and Canadian provinces.[91]

This brings incredible economic opportunities. Investment in local low-carbon assets can bring significant co-benefits ranging from the increased comfort associated with building electrification and efficiency retrofits to more sustainable waste management to a net increase in jobs.[4,83,92,93]

Overreliance on fossil or bioenergy imports can hinder such opportunities from being realized. As noted earlier, regional bioenergy resources can only amount to a small fraction of the region's energy demand. As a result, job creation from the development of regional bioenergy resources is limited compared to the job creation associated with renewable electricity, building retrofits, and the upgrade of transmission and distribution infrastructure.

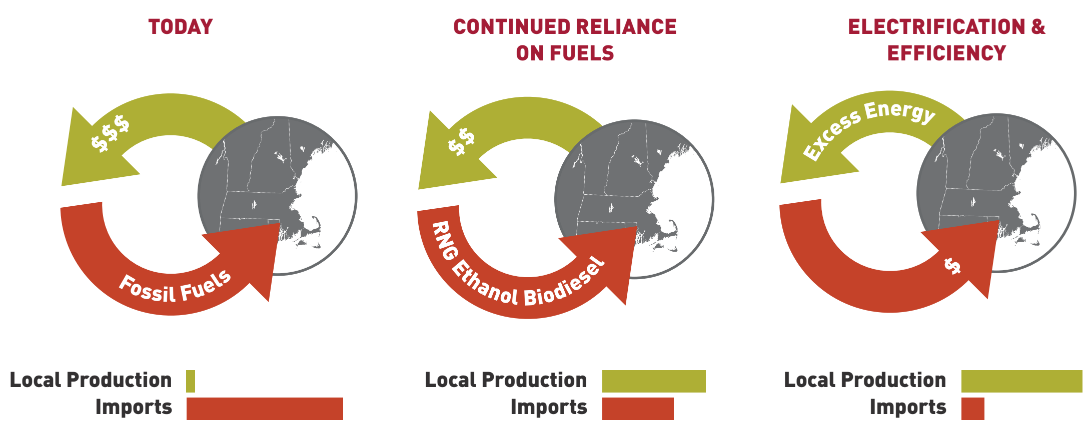
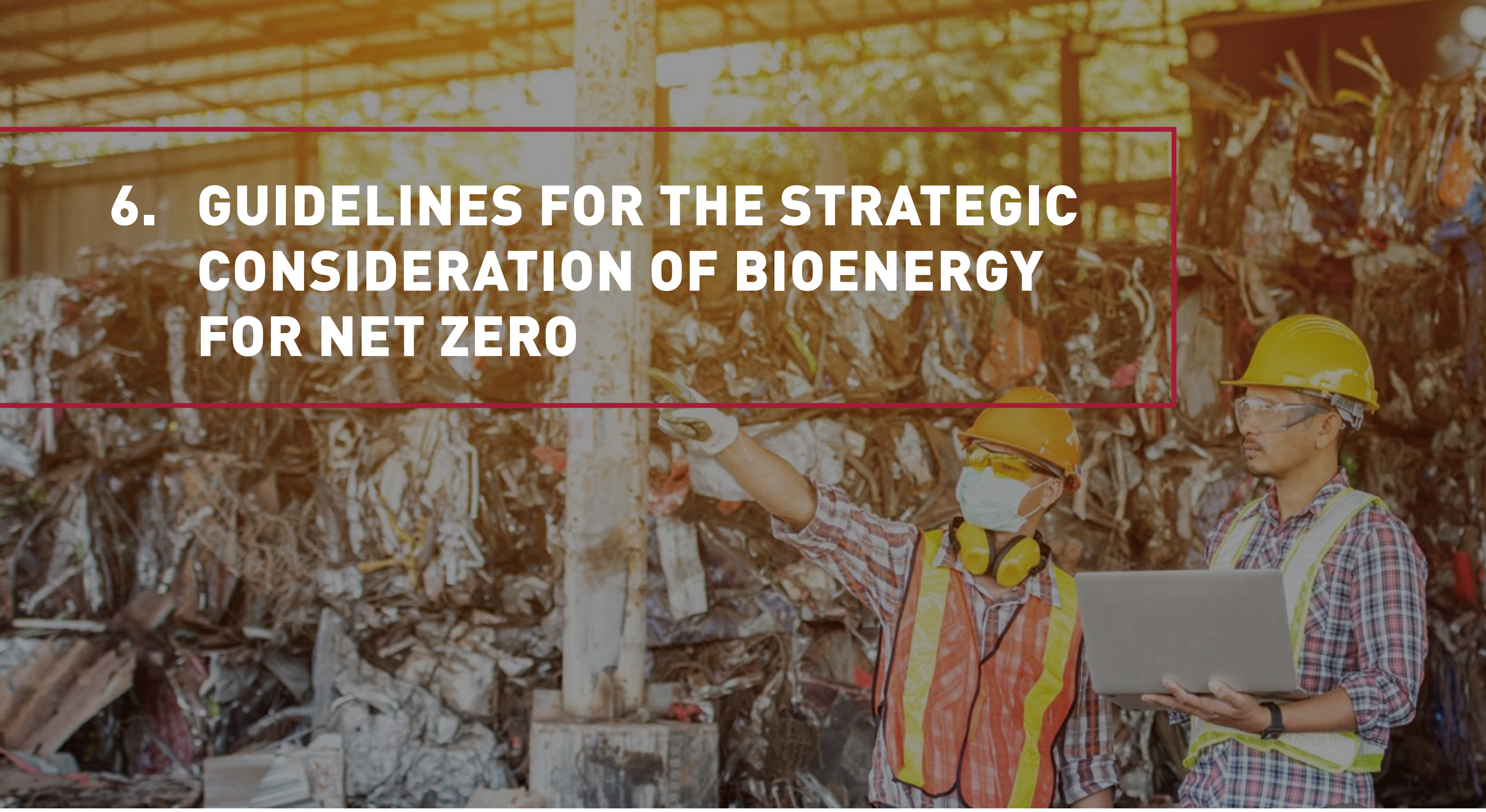


Figure 12.
Energy spending today, a future that continues to rely on fuels, and an electrified and efficient future. The findings of the Massachusetts Decarbonization Roadmap[8,83,94] inspire the diagram.



6. GUIDELINES FOR THE STRATEGIC CONSIDERATION OF BIOENERGY FOR NET ZERO

Aligning the energy system and society's bioresources with climate goals involves complex tradeoffs and dynamics. In addition to the goal of eliminating emissions, many New England states have sought to integrate other criteria into evaluating climate strategies: costs, health, equity, employment, reliability, resiliency, and safety, among others.

Even if climate impact is the sole evaluation criterion for a given strategy, life-cycle greenhouse gas accounting, especially for bioenergy, is limited because **(1)** use of bioenergy can create sprawling, higher-order impacts that are difficult to measure and attribute with certainty; **(2)** bioenergy use creates impacts that evolve due to the growth cycles of potential bioresources; and **(3)** bioenergy strategies can involve biomethane or displaced fossil methane, which are potent greenhouse gases that undergo time-dependent atmospheric evolution.

A *systems perspective* is essential to evaluating the efficacy of a bioenergy strategy – a policy or a project – in supporting the region's climate goals. Many regional,[3,8,95] national,[6] and global[96,97,98] studies of ambitious climate transitions have identified common actions (often referred to as properties, pillars, features, or characteristics) needed to drive forward these goals. Table 5 adapts these actions within a bioenergy context to evaluation criteria for bioenergy strategies.

Generally, good strategies use waste and residual biomass feedstocks in hard-to-decarbonize sectors. Poor bioenergy strategies rely on dedicated crops, unsustainable harvesting of woody biomass, and easy-to-electrify applications that are poorly suited for carbon capture (e.g., building heating and transportation).

For example, Princeton University's Net Zero America Study demonstrated scenarios where the country could achieve zero emissions without increasing land use for bioenergy production.[6] In these scenarios, bioenergy was exclusively dedicated for use in hard-to-electrify sectors or to support carbon capture and storage. An increase in overall bioenergy use was simulated, with limited expansion of energy crops, through increased collection of wastes and residues and the shifting of corn ethanol to more productive perennial crops, which have the added benefit of increasing soil carbon and improving other ecosystems.

Given the urgency of climate change, the Table 5 criteria are essential for guiding the climate-optimal use of bioenergy. However, consideration of bioenergy strategies should also incorporate criteria that reflect social, economic, and other environmental values.

Table 5.

STRATEGIC EVALUATION CRITERIA FOR THE USE OF BIOENERGY RESOURCES

NET-ZERO ACTION	EVALUATION QUESTIONS	EXAMPLE BEST ALIGNED WITH NET-ZERO TARGETS	EXAMPLE INCONSISTENT WITH NET-ZERO TARGETS
CLEAN ELECTRICITY	• Does the bioenergy use support or hinder the scaling of low-cost wind and solar resources? • Is bioenergy being used in a way that generates low-to-negative emission electricity when factoring in reasonable life-cycle assumptions?	• Electricity generation from unavoidable biogas or landfill gas. • Potentially, electricity generation from waste and residues using carbon capture and sequestration.	• Unsustainable management of forest cutting for biomass combustion. • Legacy or existing inflexible biomass power plants.
EFFICIENCY IN ENERGY AND MATERIAL USE	• Are energy inputs for feedstock production, conversion, and distribution low relative to the usable energy produced? • Does the process result in fugitive greenhouse gas emissions?	• Utilization of wastes with low energy demands for collection and production. • Energy-efficient and high-energy-yielding conversion processes. • Use of bioenergy in certain combined heat and power situations.	• Energy-intensive crops or conversion processes (e.g., corn ethanol). • Conventional biomass combustion for electricity with high unrecovered waste heat. • Electricity-demanding purification of biogas to RNG when direct electricity generation from biogas is viable, and RNG has a high potential for leakage.
ELECTRIFICATION AND SMART USE OF FUELS	• Is the fuel being used in a difficult-to-electrify sector or end-use? • Would a fossil fuel (coupled with CO_2 removal) be better than a renewable fuel, based on cost and life-cycle impacts, and allow for better use of a bioenergy resource? • Is bioenergy being positioned as a complement or an alternative to electrification?	• Renewable fuels used for aviation, shipping, and industry. • Some situations may benefit from a hybrid strategy depending on the availability of a waste resource (e.g., a modest number of oil- or gas-heated homes may benefit from a heat pump supplemented by a pellet stove heating system).	• RNG used for building heating. • Credit systems that treat electrification and renewable fuels as fungible decarbonization strategies risk deferring necessary electrification.
APPROPRIATE USE OF WASTE RESOURCES	• Does the bioenergy strategy help reduce the waste's climate and other environmental impacts? • Does the production of bioenergy overincentivize the generation of waste?	• Waste bioenergy strategies are implemented with waste source reduction, reuse, and recycling policies to reduce upstream emissions, enhance food security, and minimize other unsustainable practices.	• Valorized waste can disincentivize efforts to reduce production of waste and unnecessary production and consumption. This is a lost opportunity to avoid reducing upstream greenhouse gas emissions.
SUPPORTS CARBON DIOXIDE REMOVAL	• Does the use of bioenergy feedstocks result in long-term distribution to natural carbon stocks and the ability of such stocks to remove carbon from the atmosphere? • Is the carbon released from the use of bioenergy captured and permanently sequestrated?	• Waste and residues that would otherwise quickly decompose are used as feedstock in various bioenergy with carbon capture and storage technologies. • Production of feedstock that enhances the ability of natural lands to sequester and store carbon.	• Indiscriminate use of bioenergy in applications without carbon capture and storage. • Use of bioenergy at scales that reduce the ability of natural systems to sequester carbon.

Example Application of Guidelines to Pending Bioenergy Strategies in New England

The following sections apply the guidelines above to pending policy frameworks and projects relevant to New England.

RNG AND HYDROGEN BLENDING ARE UNSUITED FOR BUILDING HEAT

New England's natural gas utilities have proposed blending RNG and hydrogen into their distributed gas.[26,27,41] The utilities' prime motivation is maintaining the gas system's size, as they earn returns on the size and ability to reinvest in the system. But alternative approaches would provide significant cost benefits while maintaining flexibility.

Electrification of most heat demand and other end-uses is much more cost-effective than RNG and will likely become cost-competitive with fossil gas given long-term forecasts in the costs of pipeline gas delivery in the Northeast.[20] Building upgrades will provide customers with increased value (e.g., improved health and more comfortable homes). Partial electrification, if chosen by a customer, can be achieved with non-pipeline fuels. Those who prefer cooking over a flame can utilize propane if pipeline gas service becomes unavailable or uneconomical, though propane combustion will continue to emit harmful indoor air pollution and greenhouse gas emissions. Studies[8,83] and assessments of gas system investment needs[23] indicate that downsizing the gas system can generate substantial cost savings relative to electrification costs.

The question then becomes: as gas demand declines, should RNG substitute fossil methane? With the urgent need to reduce emissions, the answer may seem obvious. A direct life-cycle comparison of RNG to fossil gas shows that it may provide modest reduction of greenhouse gases relative to fossil methane – with a lot depending on leaks and avoided feedstock emissions. However, comprehensively evaluating this strategy (Table 6) shows significant deficiencies in its utility as a decarbonization strategy. The qualitative assessment aligns with the analysis conducted by the Massachusetts Executive Office of Energy and Environmental Affairs, which demonstrated that decarbonization of pipeline gas is the most expensive emissions abatement action.[8,83] This aligns with other research[81] exploring the optimal use of fuels. Using RNG for building heat would be an expensive misallocation of bioenergy resources that are better suited for decarbonizing other sectors.

Another way of understanding this dynamic is that if some emissions are still allowed from the energy system in 2050, those residual emissions should emanate from the most expensive-to-abate sectors. The decarbonization of pipeline gas is the most expensive-to-abate fuel (Figure 11). Even if the policy required the elimination of energy sector emissions – but some high-quality offset mechanism was allowed – the high abatement cost of RNG and green hydrogen would compete with the use of fossil methane offset by a removal. The need to mitigate leaks would further disadvantage any use of gas in such a scenario.

In summary, policy should avoid frameworks that consider renewable gas as a viable building's decarbonization strategy. Achieving building sector emissions reduction requires robust and direct policies that maximize the promulgation of electrification and efficiency while winding down the gas system to align with the region's climate targets.

Table 6.

RNG FROM VARIOUS SOURCES FOR USE IN BUILDING HEAT

NET-ZERO ACTION	EVALUATION QUESTIONS	ASSESSMENT
CLEAN ELECTRICITY	• Does the bioenergy use support or hinder the scaling of low-cost wind and solar resources? • Is bioenergy being used in a way that generates low-to-negative emission electricity when factoring in reasonable life-cycle assumptions?	**Not consistent with net-zero action:** Landfill gas or biogas (from digestors) used to produce RNG could otherwise be directly burned to generate low-carbon electricity. Biogas can be stored in short timescales and be used as a firm electricity resource that can complement wind and solar generation.
EFFICIENCY IN ENERGY AND MATERIAL USE	• Are energy inputs for feedstock production, conversion, and distribution low relative to the usable energy produced? • Does the process result in fugitive greenhouse gas emissions?	**Not consistent with net-zero action:** RNG requires significant energy inputs for purification, upgrading, and compression for pipeline injection. These result in significant losses, and while fossil gas remains the marginal fuel on the grid, it limits life-cycle emissions reductions of RNG. These energy losses are particularly remarkable compared to electrification using heat pumps and renewable electricity. Like fossil methane, RNG has a high global warming potential. Even a modest amount of RNG leakage can obviate any emissions savings relative to fossil methane.
ELECTRIFICATION AND SMART USE OF FUELS	• Is the fuel being used in a difficult-to-electrify sector or end-use? • Would a fossil fuel (coupled with removal) be better than a renewable fuel, based on cost and life-cycle impacts, and allow for better use of a bioenergy resource? • Is bioenergy being positioned as a complement or an alternative to electrification?	**Not consistent with net-zero action:** Injection of RNG into the pipeline is intended to decarbonize aggregate pipeline gas consumption for heat. Electrification is a more suitable, efficient, and cost-effective strategy for decarbonizing building heat. Application of RNG seeks to prevent rather than complement building electrification. Allocation of bioenergy feedstocks for RNG is better suited to liquid fuels and harder-to-electrify sectors.
APPROPRIATE USE OF WASTE RESOURCES	• Does the bioenergy strategy help reduce the waste's climate and other environmental impacts? • Does the production of bioenergy overincentivize the generation of waste?	**Consistent with net-zero action, but not unique to RNG. Policy design can potentially overincentivize waste:** RNG can help to manage waste; however, so can other waste energy recovery and non-energy waste management strategies that may be more aligned with other climate goals. Appropriate design of incentives is needed to ensure that waste production does not get overincentivized and that resources aren't shifted away from sectors that would better use them.
SUPPORTS CARBON DIOXIDE REMOVAL	• Does the use of bioenergy feedstocks result in long-term distribution to natural carbon stocks and the ability of such stocks to remove carbon from the atmosphere? • Is the carbon released from the use of bioenergy captured and permanently sequestrated?	**Not consistent with net-zero goals:** The demand for RNG to displace fossil gas consumption at current scales will cause land-use change due to the need to use dedicated crops and competition with other sectors that require renewable fuels. Feedstocks allocation to RNG eschews opportunities for carbon capture and storage.

INDICATOR CATEGORY/ NAME	EVALUATION CRITERIA	ASSESSMENT
ENVIRONMENTAL		
AIR QUALITY	What are the types and quantities of non-greenhouse gas emissions (particulates, NOx, SO_2, VOCs [volatile organic compounds], dioxins, and other toxic emissions) that result from producing and consuming a bioenergy resource?	**Adverse impact:** Continued reliance on fuel combustion for building heat maintains indoor and outdoor air quality impacts.
WATER QUANTITY AND QUALITY	What are the effects of the use of this bioenergy resource on water quality?	**Indirect potential beneficial impact from modest use, but not exclusive to RNG:** Collection of animal wastes for energy recovery may reduce nutrient loading from untreated waste. **Excessive use leads to adverse indirect land-use change driven by expanding energy crops:** Growing dedicated bioenergy crops can lead to land-use change, impacting watersheds.
SOIL QUALITY	What are the effects of this bioenergy resource on soil quality?	**Indirect potential beneficial impact from modest use, but not exclusive to RNG:** Anaerobic digestion yields a nutrient-rich soil amendment that can enhance soil quality but that may contain contaminants, such as PFAS, if contained in the feedstock. **Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change, impacting soil quality.
BIODIVERSITY	What are the effects of the use of this bioenergy resource on biodiversity?	**Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change, reducing biodiversity.
SOCIAL		
FOOD AVAILABILITY	Does this bioenergy resource reduce food availability or increase food costs?	**Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change, leading to competition with food production. **Adverse impact from improper waste management:** The availability of a food waste energy recovery pathway could reduce incentives to rescue usable food.
LAND USE	What are the effects of this bioenergy resource on land use?	**Adverse impact from excessive use:** Growing dedicated bioenergy crops for RNG can lead to land-use change.
JOBS	Does the use of this bioenergy resource shift jobs out of the region?	**Adverse impact from excessive use:** Strategies that are overreliant on fuels require importing fuels from outside the region. This shifts out-of-state spending relative to electrification and efficiency strategies that create local jobs through local investment.
ENVIRON-MENTAL JUSTICE	Does the use of this bioenergy resource reproduce historical patterns of environmental injustice?	**Adverse impact:** Strategies that maintain the gas distribution system do not rectify the ongoing impact of methane leaks and air pollution on burdened communities. Decarbonizing heat using RNG is generally a higher-cost strategy relative to electrification that will exacerbate energy cost burdens.
PUBLIC HEALTH	What are the effects of this bioenergy resource on public health?	**Adverse impact:** Strategies that maintain the gas distribution system at current scales do not rectify the ongoing health impact of methane leaks and air pollution.
ECONOMIC		
COST	How does incorporating a bioenergy strategy affect systems costs and how would consumers realize these costs?	**Adverse impact:** RNG is more expensive than electrification for most heating needs. Decarbonizing peak heating demands through renewable non-pipeline fuels or offsets will likely be cheaper than using RNG.
LONG-TERM RISK	Does the application of bioenergy reduce or increase or mitigate risks associated with energy systems?	**Adverse impact:** RNG production will need to scale as gas consumption declines. RNG strategies require developing and maintaining expensive production and distribution infrastructure. Ratepayers are typically responsible for the risks of such infrastructure.
LOCAL SPENDING VS. ENERGY IMPORTS	Is the use of bioenergy creating local economic benefits or is it continuing the practice of spending money on fuel imports that accrue wealth outside the region?	**Adverse impact from excessive use:** Strategies that are overreliant on fuels require importing fuels from outside the region. This shifts out-of-state spending relative to electrification and efficiency strategies that create local jobs through local investment.

REFERENCES

1. *Massachusetts Clean Energy and Climate Plan for 2025 and 2030*. https://www.mass.gov/info-details/massachusetts-clean-energy-and-climate-plan-for-2025-and-2030 (2022).

2. *Massachusetts Clean Energy and Climate Plan for 2050.* https://www.mass.gov/info-details/massachusetts-clean-energy-and-climate-plan-for-2050.

3. Executive Office of Energy and Environmental Affairs. *Massachusetts 2050 Decarbonization Roadmap: Summary Report*. https://www.mass.gov/doc/ma-2050-decarbonization-roadmap/download (2020).

4. Cadmus Group and Energy Futures Group. *Vermont Pathways Analysis Report*. 102. https://climatechange.vermont.gov/sites/climatecouncilsandbox/files/2022-03/Pathways%20Analysis%20Report_Version%202.0.pdf (2022).

5. *What's the Plan?* | Maine Climate Plan. https://www.maine.gov/climateplan/the-plan.

6. Net-Zero America. https://netzeroamerica.princeton.edu/.

7. Brooks, A. *Renewable Energy Resource Assessment Information for the United States*. EXEC-2020-003533, 1855910, 8837. https://www.osti.gov/servlets/purl/1855910/ (2022) doi:10.2172/1855910.

8. Kan, C., McLeod, A., Walsh, M. & Jones, R. *Economic and Health Impacts Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study* (2020).

9. EFI (Energy Futures Initiative) & E3 (Energy and Environmental Economics Inc.). *Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future* (2020).

10. U.S. EIA. Form EIA-923 detailed data with previous form data (EIA-906/920). https://www.eia.gov/electricity/data/eia923/.

11. Fehrenbach, H., Bischoff, M., Böttcher, H., Reise, J. & Hennenberg, K. J. The missing limb: Including impacts of biomass extraction on forest carbon stocks in greenhouse gas balances of wood use. *Forests* 13, 365 (2022).

12. Robinson, E., Böttcher, H., Hennenberg, K. J. & Soimakallio, S. Why burning primary woody biomass is worse than fossil fuels for climate. *Euractiv.* https://www.euractiv.com/section/biomass/opinion/why-burning-primary-woody-biomass-is-worse-than-fossil-fuels-for-climate/ (2022).

13. Buonocore, J. J., Salimifard, P., Michanowicz, D. R. & Allen, J. G. A decade of the U.S. energy mix transitioning away from coal: Historical reconstruction of the reductions in the public health burden of energy. *Environmental Research Letters* 16, 054030 (2021).

14. Inflation Reduction Act of 2022. https://www.democrats.senate.gov/inflation-reduction-act-of-2022.

15. Mui, S. U.S. races ahead in EV manufacturing investments.*NRDC*. https://www.nrdc.org/experts/simon-mui/us-races-ahead-ev-manufacturing-investments (2023).

16. California's Zero Emissions Vehicle Rule and its nationwide impacts. *AAF*. https://www.americanactionforum.org/insight/california-zero-emissions-vehicle-rule-and-its-nationwide-impacts/.

17. Zero-Emission Vehicle Program | California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program.

18. Energy Environmental Economics (E3). *The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals Independent Consultant Report* (2022).

19. Massachusetts Office of the Attorney General. *Regulating Uncertainty, The Office of the Attorney General's Recommendations to Guide the Commonwealth's Gas Transition to a Net-Zero Future*. https://www.mass.gov/doc/ago-future-of-natural-gas-regulatory-framework-utility-and-technical-comments/download (2022).

20. Walsh, M. & Bloomberg, M. The future of gas in New York State. *Building Decarbonization Coalition.* https://buildingdecarb.org/resource/the-future-of-gas-in-nys (2023).

21. MA DPU 20-80. https://eeaonline.eea.state.ma.us/DPU/Fileroom/dockets/bynumber/20-80.

22. Massachusetts Department of Energy Resources. *Summary of Stretch Code Study Energy Efficiency Analysis*. https://www.mass.gov/doc/summary-of-stretch-code-study-energy-efficiency-analysis-feb-2022/download (2022).

23. Seavey, D. *GSEP at the Six-Year Mark: A Review of the Massachusetts Gas System Enhancement Program* (2021).

24. NPR. To fight climate change, and now Russia, too, Zurich turns off natural gas. https://www.npr.org/transcripts/1092429073 (2022).

25. *Commission on Clean Heat Issues Final Report.* https://www.mass.gov/info-details/commission-on-clean-heat-issues-final-report.

26. Eversource. *Eversource Net Zero Enablement Plan*. https://fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/14633282.

27. National Grid. *National Grid Net Zero Enablement Plan*. https://fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/14633280.

28. MA DPU. *Common Regulatory Framework and Overview of Net Zero Enablement Plans*. https://fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/14633273 (2022).

29. ISO New England. *Final 2022 Heating Electrification Forecast*. (2022).

30 Analysis Group. *Pathways Study: Evaluation of Pathways to a Future Grid*. https://www.iso-ne.com/static-assets/documents/2022/04/schatzki-et-al-pathways-final.pdf.

31 *2022 Scoping Plan Documents* | California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan/2022-scoping-plan-documents.

32 New York State Climate Action Council. *New York State Climate Action Council Scoping Plan*. climate.ny.gov/ScopingPlan (2022).

33 Calvin, K. *et al.* Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy* 13, 1346–1371 (2021).

34 Fitpatrick, A. A new startup wants to turn your food waste into chicken feed. *AXIOS.* https://www.axios.com/2023/01/18/food-waste-mill.

35 U.S. EIA. *Open Data*. https://www.eia.gov/opendata/index.php.

36 Brown, D. DG Fuels signs key Maine Land Agreement | DGFuels. https://dgfuels.com/2022/11/14/dg-fuels-signs-key-maine-land-agreement/.

37 DG Fuels announces plans to develop SAF facility in Maine | Biomassmagazine.com. https://biomassmagazine.com/articles/19544/dg-fuels-announces-plans-to-develop-saf-facility-in-maine.

38 American Gas Association. *Net-Zero Emissions Opportunities for Gas Utilities*. https://www.aga.org/wp-content/uploads/2022/02/aga-net-zero-emissions-opportunities-for-gas-utilities.pdf.

39 American Gas Foundation. *Renewable Sources of Natural Gas*. https://gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/ (2019).

40 U.S. EPA. *LMOP Landfill and Project Database*. https://www.epa.gov/lmop/lmop-landfill-and-project-database (2016).

41 Liberty Utilities. *Petition of Liberty Utilities (New England Natural Gas Company) Corp. d/b/a Liberty for Approval of an Agreement to Purchase Renewable Natural Gas from Fall River RNG LLC and of the Liberty RNG Program* (2022).

42 Meyer, S. *New England's Climate Imperative: Our Forests as a Natural Climate Solution*. https://harvardforest1.fas.harvard.edu/sites/harvardforest.fas.harvard.edu/files/publications/pdfs/Meyer_NEClimateImperative_2022.pdf (2022).

43 *Changes to the Land: Four Scenarios for the Future of the Massachusetts Landscape* | Harvard Forest. https://harvardforest.fas.harvard.edu/changes-to-the-land.

44 Thompson, J., Laflower, D., Plisinski, J. & MacLean, M. *Massachusetts 2050 Decarbonization Roadmap: Land Sector Report*. https://www.mass.gov/doc/land-sector-technical-report/download (2020).

45 Holt, J. R. *et al.* Emerald ash borer intensifies harvest regimes on private land. *Ecological Applications* 32, e2508 (2022).

46 WBUR. New England has been suffering from frequent droughts all summer. *NPR*. https://www.npr.org/2022/08/30/1120023677/new-england-has-been-suffering-from-frequent-droughts-all-summer (2022).

47 Gunn, J. S., Ducey, M. J. & Belair, E. Evaluating degradation in a North American temperate forest. *Forest Ecology and Management* 432, 415–426 (2019).

48 MacLean, M. G. *et al.* Forest carbon trajectories: Consequences of alternative land-use scenarios in New England. *Global Environmental Change* 69, 102310 (2021).

49 *Woodstove Database* | Burnwise | US EPA. https://bit.ly/3LzTihX.

50 Lark, T. J. *et al.* Environmental outcomes of the US Renewable Fuel Standard. *Proceedings of the National Academy of Sciences* 119, e2101084119 (2022).

51 ISO New England. *Resource Mix*. https://www.iso-ne.com/about/key-stats/resource-mix (2018).

52 Krones, J. *Massachusetts 2050 Decarbonization Roadmap: Non-Energy Sector Report*. https://www.mass.gov/doc/non-energy-sector-technical-report/download (2020).

53 Federal Plan Requirements for Municipal Solid Waste Landfills That Commenced Construction On or Before July 17, 2014, and Have Not Been Modified or Reconstructed Since July 17, 2014. *Federal Register.* https://www.federalregister.gov/documents/2021/05/21/2021-10109/federal-plan-requirements-for-municipal-solid-waste-landfills-that-commenced-construction-on-or (2021).

54 As landfill space dwindles in Massachusetts, New Hampshire has become the state's dumping ground. *Boston Globe*. https://www.bostonglobe.com/2021/07/19/metro/landfill-space-dwindles-massachusetts-new-hampshire-has-become-states-dumping-ground/.

55 Sandson, K. & Leib, E. B. *Bans and Beyond: Designing and Implementing Organic Waste Bans and Mandatory Organics Recycling Laws*. https://chlpi.org/wp-content/uploads/2013/12/Organic-Waste-Bans_FINAL-compressed.pdf (2019).

56 Thompson, K. A. *et al.* Poly- and perfluoroalkyl substances in municipal wastewater treatment plants in the United States: Seasonal patterns and meta-analysis of long-term trends and average concentrations. *ACS EST Water* 2, 690–700 (2022).

57 World's first ban on products with PFAS adopted in Maine. *Chemical & Engineering News*. https://cen.acs.org/environment/persistent-pollutants/Worlds-first-ban-products-PFAS/99/web/2021/07 (2021).

58 Bill Status H.446 (Act 170). https://legislature.vermont.gov/bill/status/2022/H.446.

59 U.S. EPA. *Livestock Anaerobic Digester Database*. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.

60 U.S. EPA. *Biofuels and the Environment*. https://www.epa.gov/risk/biofuels-and-environment (2021).

61 Argonne National Laboratory. *GREET Models*. https://greet.es.anl.gov/greet.models.

62 U.S. EPA. S*tate Inventory and Projection Tool.* https://www.epa.gov/statelocalenergy/state-inventory-and-projection-tool (2017).

63 U.S. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020*. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020 (2022).

64 McGlynn, E., Li, S., Berger, M., Amend, M. & Harper, K. Addressing uncertainty and bias in land use, land use change, and forestry greenhouse gas inventories. *Climatic Change* 170, 5 (2022).

65 Soimakallio, S. *et al.* Closing an open balance: The impact of increased tree harvest on forest carbon. *GCB Bioenergy* 14, 989–1000 (2022).

66 IPCC. *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. https://www.ipcc.ch/sr15/ (2018).

67 Sterman, J., Moomaw, W., Rooney-Varga, J. N. & Siegel, L. Does wood bioenergy help or harm the climate? *Bulletin of the Atomic Scientists* 78, 128–138 (2022).

68 Fritsche, U. R., Sims, R. E. H. & Monti, A. Direct and indirect land-use competition issues for energy crops and their sustainable production – An overview. *Biofuels, Bioproducts and Biorefining* 4, 692–704 (2010).

69 Grubert, E. At scale, renewable natural gas systems could be climate intensive: The influence of methane feedstock and leakage rates. *Environmental Research Letters* 15, 084041 (2020).

70 Bakkaloglu, S., Cooper, J. & Hawkes, A. Methane emissions along biomethane and biogas supply chains are underestimated. *One Earth* 5, 724–736 (2022).

71 Sargent, M. R. *et al.* Majority of US urban natural gas emissions unaccounted for in inventories. *Proceedings of the National Academy of Sciences of the United States of America* 118 (2021).

72 NREL. *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update*. https://www.nrel.gov/docs/fy21osti/80580.pdf (2021).

73 EPRI. *Literature Review and Sensitivity Analysis of Biopower Life Cycle Assessments and Greenhouse Gas Emission*. https://www.epri.com/research/products/1026852 (2013).

74 Martin, J. *Comment to CARB on LCFS: Manure Biomethane Analysis*. (2022).

75 U.S. EPA. *Practices to Reduce Methane Emissions from Livestock Manure Management*. https://www.epa.gov/agstar/practices-reduce-methane-emissions-livestock-manure-management (2022).

76 Committee on Current Methods for Life Cycle Analyses of Low-Carbon Transportation Fuels in the United States, Board on Environmental Studies and Toxicology, Division on Earth and Life Studies, & National Academies of Sciences, Engineering, and Medicine. *Current Methods for Life Cycle Analyses of Low-Carbon Transportation Fuels in the United States*. 26402 (National Academies Press, 2022). doi:10.17226/26402.

77 Smith, A. What's worth more: A cow's milk or its poop? *Aaron Smith*. https://asmith.ucdavis.edu/news/cow-power-rising (2021).

78 Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review": EPA External Review Draft of Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances.

79 Rates & Billing. *VGS*. https://vgsvt.com/service/rates/.

80 Huq, N. A. *et al.* Toward net-zero sustainable aviation fuel with wet waste–derived volatile fatty acids. *Proceedings of the National Academy of Sciences* 118, e2023008118 (2021).

81 Low Carbon Fuels in Net-Zero Energy Systems. *Evolved Energy Research*. https://www.evolved.energy/post/low-carbon-fuels-in-net-zero-energy-systems (2022).

82 ICF. *Michigan Renewable Natural Gas Study*. https://www.michigan.gov/mpsc/-/media/Project/Websites/mpsc/workgroups/RenewableNaturalGas/MI-RNG-Study-Final-Report-9-23-22.pdf?rev=213e31ab46c24ce1b799eeb8a42f0824&hash=5B8C2CEB98C8F8F20C7D65F4C4153CE1 (2022).

83 Cooper, N. (EEA). *Appendices to the Massachusetts Clean Energy and Climate Plan for 2025 and 2030*.

84 Topolski, K. *et al. Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology*. NREL/TP-5400-81704, 1893355, MainId:82477. https://www.osti.gov/servlets/purl/1893355/ (2022) doi:10.2172/1893355.

85 UK Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy. Atmospheric implications of increased hydrogen use. *GOV.UK*. https://www.gov.uk/government/publications/atmospheric-implications-of-increased-hydrogen-use (2022).

86 Bistline, J. E. T. *et al.* Economy-wide evaluation of CO_2 and air quality impacts of electrification in the United States. *Nature Communications* 13, 6693 (2022).

87 Gruenwald, T., Seals, B. A., Knibbs, L. D. & Hosgood, H. D. Population attributable fraction of gas stoves and childhood asthma in the United States. *International Journal of Environmental Research and Public Health* 20, 75 (2023).

88 Alternative Fuels Data Center: Biodiesel Vehicle Emissions. https://afdc.energy.gov/vehicles/diesels_emissions.html.

89 Kashtan, Y. S. *et al.* Gas and propane combustion from stoves emits benzene and increases indoor air pollution. *Environmental Science & Technology* 57, 9653–9663 (2023). https://pubs.acs.org/doi/epdf/10.1021/acs.est.2c09289

90 O'Malley, J. & Searle, S. *Air Quality Impacts of Biodiesel in the United States*. ICCT White Paper. International Council on Clean Transportation (March 2021). https://theicct.org/publication/air-quality-impacts-of-biodiesel-in-the-united-states/.

91 Lebel, E. D., Finnegan, C. J., Ouyang, Z. & Jackson, R. B. Methane and NOx emissions from natural gas stoves, cooktops, and ovens in residential homes. *Environmental Science and Technology* 56, 2529–2539 (2022).

92 Lebel, E. D. *et al.* Composition, emissions, and air quality impacts of hazardous air pollutants in unburned natural gas from residential stoves in California. *Environmental Science and Technology* 56, 15828–15838 (2022).

93 Haley, B. Decarbonizing the Northeast. *Evolved Energy Research*. https://www.evolved.energy/post/2018/04/09/decarbonizing-the-northeast-and-coordination-with-hydro-québec (2018).

94 *Strengthening Maine's Clean Energy Economy*. http://climatecouncil.maine.gov/future/sites/maine.gov.future/files/inline-files/StrengtheningMainesCleanEnergyEconomy_Nov92020.pdf (2020).

95 Kan, C., McLeod, A., Walsh, M. & Jones, R. *Economic and Health Impacts Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study* (2020).

96 *Carbon Free Boston*. http://sites.bu.edu/cfb/technical-reports. (2019).

97 *AR6 Climate Change 2022: Mitigation of Climate Change — IPCC*. https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

98 Clarke, L. *et al.* Assessing transformation pathways. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Edenhofer, O. *et al.*) (Cambridge University Press, 2014).

www.clf.org