# Renewable Biofuels for Residential Heating in New Jersey

In response to the NJ Board of Public Utilities Public Comment Request

## NORA

**Renewable Liquid Fuels for Heating**

**September 2019**

# Contents

# Table of Figures



# List of Tables

# Renewable Biofuels for Residential Heating in New Jersey

## Executive Summary

### New Jersey Master Plan

June 10, 2019, the State of New Jersey released the Draft 2019 Energy Master Plan (EMP), which provides an initial blueprint for the total conversion of New Jersey's energy profile to 100 percent clean energy by 2050, as directed by Governor Murphy's Executive Order 28. The plan defines clean energy as carbon-neutral electricity generation and maximum electrification of the transportation and building sectors to meet or exceed the Global Warming Response Act greenhouse emissions reductions of 80 percent relative to 2006 levels by 2050.

Strategy 4: Reducing Energy Use and Emissions from the Building Sector through decarbonization and electrification, the expansion of statewide net zero carbon homes incentive programs, and the development of EV Ready and Demand Response Ready building codes. In particular, goal 4.2.1 seeks taxpayer or ratepayer funds to incentivize the transition to electrified heat pumps, hot water heaters, and other appliances and goal 4.2.2 requires the development of a transition plan to a fully electrified building sector.

This strategy is based on a series of independent binary analysis which leads the reader to the ultimate conclusion that oil heat homes should be transitioned to electric heat homes and that electric ratepayers and/or taxpayer should pay for this transition.

However, a more scientific approach would likely lead to a different conclusion. This report will examine each of the stated and/or implied binary comparisons to provide the citizens of New Jersey with better economic choices to reach a clean energy future for their homes.

- Liquid biofuels offer a future where zero GHG combustion can be achieved.
- Liquid biofueled thermal heat pumps can provide efficient & comfortable heat.
- Electric Heat Pump conversion from hydronic heated homes is far more expensive that the EMP indicates.
- Conversion to advanced biofuels can be easily managed through normal equipment replacement.
- Conversion economics to biofuels and thermal heat pumps is more cost-effective than electric heat pumps.
- Economies of scale and carbon credits would equally apply to this lower cost solution.
- The reason we heat our homes is simple, to make them comfortable and electric heat pumps fall short.

# Binary Comparisons

A binary comparison looks at two sets of data and compares them. The energy industry in general and home heating in particular re\quires a wholistic approach The EMP, selected a series of discrete binary comparisons of key variables to conclude that advanced cold climate electric heat pumps and a future 100% renewable electric grid is the only pathway to the future and should be regulated and or incentivized now to assure the outcome. Six of these binary comparisons presented in the EMP are discussed below and one additional comparison, not in the EMP, is also discussed.

## Binary Comparison Number 1: Electric Heat Pumps versus Heating Oil

The liquid fuel energy industry has long recognized the need to decarbonize its fuel and is working diligently to make this happen. In fact, the industry is working toward delivering B50[1] to homes by 2030. There are multiple economic and realistic pathways to decarbonize heating oil by blending it with biodiesel and/or advanced cellulosic biofuels like ethyl levulinate.

**Liquid biofuels offer a future where zero GHG combustion can be achieved which should fundamentally change the residential heating goals for New Jersey. In fact, conversion to low/no carbon liquid fuels would not require large transmission and distribution infrastructure costs nor would require, in most cases, the homeowner to spend more than upgrading their burner.**

## Binary Comparison Number 2: Operating Economic Comparison

The EMP states[2]: "*As the state weighs the many competing demands and opportunities to phase out fossil fuel use, transition to a clean energy system, and reduce climate emissions and other air pollutants, reducing reliance on natural gas for building heat will be one of the state's most vexing challenges. According to the U.S. Energy Information Administration, the average consumer price of natural gas heating costs in the Northeast during the 2017-2018 winter season was nearly half the cost of electric heating costs (Table 1). However, the cost differential between electricity and heating oil was considerably less significant; the average cost of using home heating oil was only 2% cheaper than using electricity. Propane had the highest cost, at 32% more expensive than electricity.*"

The EMP presents Table 1[3] as a true energy operating cost comparison of the various fuels. (Note, no biofuels were listed) The basis for Table 1 is aggregated use patterns for the entire Northeast which does not differentiate for age and size of homes, age of installed heating systems, usage patterns and the fact that many electric heat pumps in the Northeast have boilers and/or furnaces that operate when the ambient temperatures fall below where electric heat pumps operate effectively. A second gross assumption is the efficiency of the heating systems. Current cold climate

---

[1] B50 refers to a 50% blend of biodiesel and heating oil.
[2] Draft 2019 New Jersey Energy Master Plan Policy Vision to 2050, Page 68
[3] Ibid

electric heat pump field studies show actual annual performance, including electric resistance backup heating, at a COP[4] of 1.24 even projecting to the future would yield actual seasonal performance of around a 2.5 COP for moderately cold climate heat pumps. Furthermore, Table 1 omits any combustion system improvements like thermal heat pumps which are currently being developed by the U.S. Department of energy with private sector partners.

***Table 1 Average Consumer Expenditures for Heating Fuels in the 2017-2018 Winter in the Northeast U.S.***

| | |
|---|---|
| Natural Gas | $742 |
| Heating Oil | $1,376 |
| Electricity | $1,406 |
| Propane | $1,856 |

**Energy cost is one measure of economics and should include all options including taking into account future technologies like thermal heat pumps.**

## Binary Comparison Number 3: GHG Emissions

The EMP states "*… the choice of building heat carries different pollution profiles. Heating oil emits 161.3 pounds of $CO_2$ per million Btu of energy, compared to 139 pounds of $CO_2$ for propane and 117 pounds of $CO_2$ for natural gas. This is an admittedly imperfect comparison, as the different fuels also carry different pollution profiles in their respective extraction, processing, and distribution systems and we recognize that significant reduction in the use of all fossil fuels will be necessary to meet climate goals.*"

Focusing on the carbon content of existing hydrocarbon fuels is not just imperfect, it can lead to some very bad conclusions. Sustainable low and zero carbon liquid fuels are available today. Renewable gaseous fuels are also available in limited quantities. Table 2 presents three low carbon and no carbon combustion pathways the industry is using (biodiesel blends boilers and furnaces) and is working on for the near future (ethyl levulinate and thermal heat pumps).

***Table 2 Greenhous Gas Emissions Pathways***

| Comparing Future Renewable Liquid Fueled Boiler and Thermal Heat Pump Emissions with Electric Heat Pump Emissions Based on System Average Locational Marginal Unit Emissions for Residential Heating and DHW | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2017 GHG Emissions | | Electric Grid GHG Emissions 25% reduction | | Electric Grid GHG Emissions 50% reduction | | Electric Grid GHG Emissions 75% reduction | | Electric Grid GHG Emissions 100% reduction | |
| Description | Thermal/Electric Eff. % | Boston, MA MMBtu or kWh | Annual CO2 Emissions lbs | Blend Level | Annual CO2 Emissions lbs | Blend Level | Annual CO2 Emissions lbs | Blend Level | Annual CO2 Emissions lbs | Blend Level | Annual CO2 Emissions lbs | Blend Level |
| Electric Heat Pump + Electric Resistance Stage 2 Heating | 250% | 11,266 | 11,660 | | 8,745 | | 5,830 | | 2,915 | | 0 | |
| Biodiesel and ULSD Blend Boiler | 90% | 106.8 | 11,660 | 35.2% | 8,745 | 51.4% | 5,830 | 67.6% | 3,644 | 79.7% | 0 | 100% |
| Biodiesel and ULSD Blend Thermal Heat Pump | 120% | 80.1 | 11,660 | 13.5% | 8,745 | 35.1% | 5,830 | 56.8% | 3,644 | 73.0% | 0 | 100% |
| EL and ULSD Blend Boiler | 90% | 106.8 | 11,660 | 28.6% | 8,745 | 41.9% | 5,830 | 55.1% | 2,915 | 68.3% | -4,085 | 100% |
| EL and ULSD Blend Thermal Heat Pump | 120% | 80.1 | 11,660 | 11% | 8,745 | 28.6% | 5,830 | 46.3% | 2,915 | 63.9% | -3,064 | 100% |
| EL and Biodiesel Blend boiler | 90% | 106.8 | 0 | 0% | -1,021 | 25.0% | -2,043 | 50.0% | -3,064 | 75.0% | -4,085 | 100% |
| EL and Biodiesel Blend Thermal Heat Pump | 120% | 80.1 | 0 | 0% | -766 | 25.0% | -1,532 | 50.0% | -2,298 | 75.0% | -3,064 | 100% |

**Table 2 Clearly demonstrates multiple fuel and equipment pathways to zero and even negative carbon combustion.**

[4] The coefficient of performance or COP of a heat pump is a ratio of heating provided to work required. The COP may exceed 1, because, instead of just converting work to heat (which, if 100% efficient, would be a COP of 1), it pumps additional heat from a heat source (ambient air, ground water, etc.) to where the heat is required.

## Binary Comparison Number 4: Transition Economics

The EMP states: "*Goal 4.2.1: Incentivize transition to electrified heat pumps, hot water heaters, and other appliances. New Jersey should prioritize buildings with oil and propane heating systems for electrification given the cost benefits and pollution reduction potential. Because electrified heat is less expensive than propane and similarly priced to heating oil, the most significant expenditures will be the one-time capital cost of installing the electric heating system, which costs an average of $4,000-$7,000 for a typical residence.*"

The DRAFT EMP uses as its key economic metric to economically justify transitioning NJ homes to electric heating is the low The DRAFT EMP uses as its key economic metric to economically justify transitioning NJ homes to electric heating is the low cost for the homeowner to make this transition. The DRAFT EMP states: "*…the most significant expenditures will be the one-time capital cost of installing the electric heating system, which costs an average of $4,000-$7,000 for a typical residence.*" (p.71)

The basis for these installed costs is an ACEEE Study which states: "*These cost estimates assume that a house has adequate electric service to install a heat pump. For houses that have central air-conditioning, this will generally be the case. But for some old houses without central air-conditioning, upgrading the electric service will be needed. For cold-climate ducted heat pumps, we estimated installed costs at 30% more than a SEER 16 ducted heat pump, based on a suggestion from a major manufacturer that plans to soon introduce a ducted cold-climate heat pump to the US market. For ductless heat pumps, costs come from an ACEEE analysis of a Massachusetts database of installed costs for this equipment. We looked at homes installing two or more multi-head heat pumps, finding an average cost of $7,065 per heat pump. The sample size was 496 homes, nearly all of which purchased two multi-head heat pumps (just six homes installed three)*."

The $7,000 ceiling number came from a study of addon heat pumps with two heads. Two heads can supply heat to largely two rooms and, in some cases, with additional air distribution an additional adjacent room. This is hardly adequate for NJ homes.

According to the American Housing Survey[5] boilers make up 9% of heating systems nationwide. In Northern New Jersey boilers make up 43% of all heating systems and in the Philadelphia MSA (including all of South Jersey) boilers make up 23% of all heating systems.

[5] https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html#?s_areas=a00000&s_year=n2017&s_tableName=Table1&s_byGroup1=a1&s_byGroup2=a1&s_filterGroup1=t1&s_filterGroup2=g1&s_show=S

INSTALLATION COST OF ELECTRIC HEAT - Furnace to air-to-air heat pump

Looking at actual installations for multi split heat pumps applied to oil heated homes with a furnace we find heating cost between $13,500 (small single-story house) and $19,000 for a 1,400 $ft^2$ home. Since the DRAFT EMP' s stated intention is to eliminate fossil fuels including backup heat and domestic hot water heat as well. So, for small homes this means:

| Installed Costs | Small Home and Low-Income Row House | Large Home |
|---|---|---|
| Heating System | $13,500 – $19,000 | $20,000 - $26000 |
| Potential Electric Upgrade | $2,000 – 3,000 | $3,000 – $5,000 |
| HP Water Heater | $3,000 - $4,000 | $3,000 - $4,000 |
| Total | $18,500 - $26,000 | $26,000 - $35,000 |

This brings the true "the one-time capital cost of installing the electric heating system" to approximately $18,500 to $35,000 per existing home that has a furnace.

INSTALLATION COST OF ELECTRIC HEAT - Boiler to air-to-water heat pump

The installation of a heat pump in a home with a boiler is significantly more complex and expensive than the installation of a heat pump in a home with a furnace. And if the home has a steam boiler, as opposed to a hydronic (base board hot water) boiler, the installation of a heat pump is even more complex and expensive.

The most obvious difference between a home with a furnace and one with a boiler is that a furnace by definition has duct work, a home with a boiler might not. In New Jersey 93% of homes use air conditioning, but of that total, only 63%, use central air conditioning.[6]

If the house has existing air conditioning duct work you could install an air to air heat pump for the $18,500 to $35,000 estimated above. But to that you would need to add the cost of draining and removing the existing boiler and the existing baseboard radiators which will cost another $4,000.

However, if you have a boiler you may likely prefer the comfort of the radiant heating a boiler provides.

Existing hydronic boilers heat water to 180 °F, regardless of ambient conditions, and circulate it through baseboards which radiate the heat into the room providing comfort. An air to water heat pump can heat water to 140 °F at 47 °F ambient air temperature and circulate it through baseboards which radiate the heat into the room providing comfort by running a lot longer that the hydronic boiler with 180 F hot water. The problem is 140 °F water may be acceptable to maintain your thermostat's desired setting on early November day, but will not keep you warm at night in the middle of

[6] https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/nj.pdf

January when the ambient temperature has dropped to near 0 °F. The only way this can be solved is by providing more heat transfer service in the home with by adding additions radiant heating devices to each room, by adding new hydronic fan coil units to blow heat into the rooms or be adding a fan coil unit in an attic and or basement to duct addition heated air into the rooms. This all adds money to the equation.

| Installed Costs | Small Home and Low-Income Row House | Large Home |
|---|---|---|
| Heating System | $13,500 - $19,000 | $20,000 - $26000 |
| Potential Electric Upgrade | $2,000 - 3,000 | $3,000 - $5,000 |
| HP Water Heater | $3,000 - $4,000 | $3,000 - $4,000 |
| Additional Radiant Heating Surface Area for 140 °F Hot Water | $3,000 - $5,000 | $4,000 - $6,000 |
| Total | $21,500 - $31,000 | $30,000 - $41,000 |

This brings the true “the one-time capital cost of installing the electric heating system” to approximately $21,500 to $41,000 per existing home that has a hydronic boiler plus the cost of adding necessary additional hydronic piping. The cost of back up heat will be discussed later.

<u>INSTALLATION COST OF ELECTRIC HEAT - Steam Boilers</u>

New Jersey has far more boilers than the national average, we have a large number of steam boilers, especially in the five large Northeastern counties of Bergen, Passaic, Essex, Union, and Hudson.

The laws of thermodynamics prevent residential electric heat pumps from creating steam 212 °F which rises to a cast iron radiator to provide heat for each room. Once the steam cools and condenses back to liquid it returns to the boiler as water. Since the steam supply pipe and the condensate return pipe are different sizes an air to water heat pump cannot work. This means if you want to keep the comfort of a boiler you will first need to convert your steam boiler to a hydronic boiler which will entail ripping open your walls to address the piping and then closing your walls and painting them.

If a home is poorly insulated and a steam boiler is removed, there will need to be an expense to insulate the home to account for the dramatically lessened heat output from the heat pump as compared to the steam boiler. Keep in mind that the home’s walls may have lead paint under many coats of paint that will needlessly need to be disturbed. Additionally, if the home is an older home and does not have central air conditioning, it may only have a 100-amp service which will need to be upgraded to a 200-amp service, at a cost of approximately $3,500. Additionally, if the house is a row house, which are common in many of the urban areas in these five northeastern counties, there are additional costs and limitations for the installation of a heat pump.

This all adds money to the equation.

| Installed Costs | Small Home and Low-Income Row House | Large Home |
|---|---|---|
| Heating System | $13,500 – $19,000 | $20,000 - $26000 |
| Potential Electric Upgrade | $2,000 – 3,000 | $3,000 – $5,000 |
| HP Water Heater | $3,000 - $4,000 | $3,000 - $4,000 |
| Conversion to hydronic system | $4,000 - $6,000 | $5,000 - $7,000 |
| Total | $22,500 - $32,000 | $31,000 - $42,000 |

This brings the true "the one-time capital cost of installing the electric heating system" to approximately $22,500 to $42,000 per existing home that has a hydronic boiler plus the cost of adding necessary additional hydronic piping. The cost of back up heat will be discussed later.

Now let's discuss backup heat. The ACEEE Study's 496 homes, that became the source for the DRAFT EMP flawed cost estimate, was clearly dependent on the existing home's heating systems (which were most likely fossil fuel-based). Most electric heat pumps that would be installed in NJ over the next five years or more will require some form of back-up heat. The DRAFT EMP, does not deal with this issue at all, but implies that this would be electric resistance heating. If this is the case, the heating utility bills will be higher than projected and on very cold years, like the Polar Vortex years, would cause economic hardship for those who can least afford it.

Furthermore, this in no way deals with the installation of a ducted heat pumps to provide whole house heating in a hadronically heated existing home. Nor does it deal with purchasing a moderately cold climate heat pump, removal of the oil storage tank, adding ductwork to the home, and/or upgrading the electrical service to accommodate the new electrical load.

It should also be noted that complete electrification of all energy supplies will have a dramatic impact on the cost of electricity production, transmission and delivery. A quick calculation (Table 3) converting all segments from fossil fuels into electricity would, on the average, increase New Jersey's hourly electricity demand from 8,377 MW per hour to 26,723 MW per hour. Nowhere, are these large infrastructure costs accounted, nor can energy efficiency improvement mitigate this dramatic increase in electric load.

***Table 3 Grid Impact of Converting All Energy Uses to Electricity in New Jersey***

| https://www.eia.gov/electricity/state/newjersey/ | Increase in Electricity Consumption MWh | Average Hourly Impact MW* | Potential Capacity Impact MW** |
|---|---|---|---|
| **Conversion Impact Motor Gasoline to Electric Vehicles** | 20,510,010 | 3,512 | 10,536 |
| **Conversion Impact Motor Distillate Fuel to Electric Vehicles** | 1,928,908 | 991 | 991 |
| **Conversion Impact NG Heating to Cold Climate Heat Pumps** | 39,786,055 | 12,828 | 19,242 |
| **Conversion Impact Oil Heating to Cold Climate Heat Pumps** | 3,052,150 | 1,015 | 1,522 |
| **Potential Total Conversion Impact to Electricity Impact** | **65,277,124** | **18,346** | **32,291** |
| **State Electricity Profiles and avg per hour** | **73,382,940** | **8,377** | **17,823**** |
| **Total State Electic Project w/o EE Improvement** | **138,660,064** | **26,723** | **50,114** |

* Vehicle Hourly Impact based on 16 hour cycle 7 days a week, heating base on expected heating hours - see tables below
** peak assumes vehicle charging and heating peaks at night, so an estimate of 3 times average hourly is used for vehicles and 1.5 for buildings
*** Net summer in state generation capacity (megawatts)

**Conversion from oil heated hydronic and steam heated homes is far more expensive that the EMP indicates. Conversion to thermal heat pumps and biofuels, can be easily managed over the course of normal equipment replacement or can be accelerated using incentives at a much lower cost that electric conversions.**

## Binary Comparison Number 5: Conversion Payback Period

The EMP states: *"The American Council for an Energy-Efficient Economy (ACEEE) found the paybacks to be in the two-year timeframe for oil or propane furnaces, and six to nine years for oil and propane boilers compared to high-efficiency heat pumps. In addition, since the heat pump can also provide high-efficiency air conditioning, there is also an electricity savings. NJBPU should develop a program to ease the financial burden of making this one-time upgrade."*

The ACEEE study[4] states: *"In our analysis, we assessed cold-climate heat pumps only for cold or moderately cold states (Colorado, Missouri, New Jersey, Pennsylvania, and states farther north), finding that these cold-climate heat pumps generally have lower life-cycle costs in these states than high-efficiency heat pumps that are not optimized for cold climates. However, we caution that this result is based on limited performance and cost data on ducted cold-climate heat pumps. We did not examine gas-fired heat pumps in our economic analysis as mainstream products are not yet commercialized, and we therefore did not have a good foundation for estimating costs. <u>Additional analysis is needed on both electric cold-climate heat pumps and gas-fired heat pumps as soon as additional performance and cost data become available.</u>*

*While there are presently many ductless cold-climate heat pumps, ducted cold-climate products are very limited, and many of the systems available do not have enough heating capacity to provide adequate heat in an existing home on a cold day (for instance, only a few of the ducted systems listed in Northeast Energy Efficiency Partnership's database of cold-climate heat pumps can provide 40,000 Btus per hour at an outdoor temperature of 5°F, and none can provide 45,000 Btus or more per hour). <u>More ducted cold-climate products are needed, particularly units with enough heating capacity to fully heat homes in cold climates on cold days."</u>*

The ACEEE study used: *"86% AFUE Oil Boiler (the current federal minimum standard) and 91% AFUE (a common level for condensing oil boilers) versus a preliminary analysis based on one field test that found a seasonal 2.8 coefficient of performance (COP) in Connecticut."*

The economic data in the ACEEE study, in addition to the stated deficiencies uses minimum oil heating efficiency compared to a relatively high cold climate electric heat pump efficiency of 2.8 COP based on a single unit unidentified field test data that does not detail the second stage heating system. ACEEE, did not assess the natural gas thermal heat pump and apparently does not know about the liquid fuel thermal heat pump which is also under development. The ACEEE study assumes that ductless heat pumps will provide whole house heating systems. Yet the theoretical study does not address how heat will be added to all rooms. To properly heat all spaces requires a fan/coil unit is every room including bathrooms. The ACEEE study is silent on this point and the installed costs do not appear to take this in to account. In fact, the ACEEE study discussed the need for more ducted electric heat pump data to serve whole house heating requirements.

Finally, the ACEEE Study states. "

**Conversion economics to biofuels and thermal heat pumps is more cost-effective than the conversion to electric heat pumps especially with electric grid upgrades factored into the equation.**

## Binary Comparison Number 6: [Electric] Heat Pumps Will Become More Economically Attractive in Colder Regions

The EMP states[7]: *"… It is expected that heat pumps will become more economically attractive in colder regions as technology continues to improve and becomes more efficient."*

The above-mentioned electric heat pump reference focuses on a binary comparison of published electric heat pump end-use performance versus a natural gas furnace and projected economies of scale and/or future carbon pricing to levelized economics. (See EPRI report pages 31-32) which states:

> *"Reference scenario, additional locations realize economic benefits from deployment, and their adoption increases. In the Transformation scenario, carbon pricing lowers the price of electricity relative to natural gas, leading to even greater economic advantage."*

**This binary comparison should be rejected in favor of examining renewable fuels, across multiple energy platforms as economies of scale and carbon credits would equally apply to this lower cost solution.**

## Binary Comparison Number 7: Not Addressed by the EMP is Comfort

The reason we heat our homes is simple, to make them comfortable. A heat pump puts out much cooler air than a liquid fueled furnace does which is about 130F to 140F degree air or a liquid fuel boiler delivering 180F hot water to the

[7] Draft 2019 New Jersey Energy Master Plan Policy Vision to 2050, Page 71

registers. In contrast, a heat pump running by itself (with no supplemental backup heat) on a 35F degree day, depending on indoor house temperature might only put out 92F degree air. On a 20F degree day, air supply temperature might drop to 85F degrees.

Since 92F and 85F are below your body temperature (~98.6F), it feels like cold air is blowing when you put your hand in front of the register. But it is still warmer than the indoor house temperature, so it is still putting heat into the house. Unlike a furnace that puts out a lot of heat for short periods of time, a heat pump will put out less heat for longer periods of time.

Now, what if the heat pump really is blowing cold air? In other words, it's not putting out any heat at all. Well this could be caused by several things. It could even be running in the air conditioning mode due to a malfunction.

- Outdoor unit is in defrost mode to remove ice buildup which is a normal operating mode
- Outdoor unit iced-up - weather related
- Snow drift against outdoor unit
- Outdoor unit not running
- Outdoor unit iced-up because of a malfunction
- Low refrigerant charge
- Refrigerant flow-related problem - restriction/bad metering device

Note that heat pumps can be designed and/or applied in ways (e.g. ground sourced heat pumps) to increase air supply temperature, but this always comes at a high cost and more complexity.

## Binary Comparison Number 8: Heat Pump Refrigerant with High Global Warming Potential

Global Warming Potential, or GWP, is a measure of how destructive a climate pollutant is. Refrigerants today are often thousands of times more polluting than carbon dioxide ($CO_2$). The GWP of a gas refers to the total contribution to global warming resulting from the emission of one unit of that gas relative to one unit of the reference gas, $CO_2$, which is assigned a value of 1. GWPs can also be used to define the impact greenhouse gases will have on global warming over different time periods or time horizons. In the summer of 2015, the Environmental Protection Agency added a new rule to their Significant New Alternatives Policy. (SNAP) This new rule, labeled Rule 20, was designed and targeted towards phasing out Hydroflurocarbon refrigerants. HFC refrigerants include some of the most popular refrigerants used today such as R-404A, R-410A, and R-134a.

R410A is the refrigerant used in residential electric heat pumps today. R-410A is a hydrofluorocarbon (HFC), and under the Kigali Amendment to the Montreal Protocol, developed countries — including the U.S. — have agreed to begin to reduce their usage of HFCs by 2019. Developing countries will begin reducing their usage in 2024 or 2028.

R410A has a GWP of 2,088. This should be of concern with respect to the ultimate desire to reduce climate change.

# Examining Electric Heat Pumps as a Pathway

There are several field studies of cold climate field test data. Many of these tests isolate the heat pump from the backup heating systems and examine only the heat pump performance. The Minnesota Department of Commerce 2017[8] study provides cold climate hear pump data, as well as, whole house load data. Based on this study, showing a fleet test average COP of 1.33 excluding electric resistance backup heat[9], one can estimate improvement for cold climate heat pumps in the future potentially yielding seasonable performance on the range of 2.0 COP for cold climates and 2.5 for moderately cold climates like New Jersey.

***Table 4 Impact of location and house load on system COP, energy use, and operating cost[10]***

| House Type | Location | Space Heating Load, therms/yr | ccASHP Site Energy Use, therms/yr | Annual System Heat Pump End-Use COP |
|---|---|---|---|---|
| Passive | Duluth | 108.0 | 95.4 | 1.13 |
| Median | Duluth | 662.0 | 584.9 | 1.13 |
| Leaky/Large | Duluth | 1005.1 | 888.1 | 1.13 |
| Passive | MSP | 95.0 | 76.6 | 1.24 |
| Median | MSP | 582.2 | 469.5 | 1.24 |
| Leaky/Large | MSP | 884.0 | 712.8 | 1.24 |
| Passive | St Cloud | 101.9 | 93.8 | 1.09 |
| Median | St Cloud | 624.9 | 574.7 | 1.09 |
| Leaky/Large | St Cloud | 948.8 | 872.6 | 1.09 |
| Passive | Albert Lea | 85.1 | 63.8 | 1.33 |
| Median | Albert Lea | 521.4 | 391.0 | 1.33 |
| Leaky/Large | Albert Lea | 791.7 | 593.6 | 1.33 |

The best available data for NJ electricity generation emissions is to use PJM data. PJM does not publish GHG emissions[11], however PJM does publish marginal $CO_2$ emissions. In a given five-minute interval, there is one marginal unit on the system plus an additional marginal unit for each transmission constraint that is being experienced. The mathematical average of the emissions rates for all marginal units in each five-minute interval forms a marginal

[8] Conservation Applied Research and Development (CARD) FINAL Report, Prepared for: Minnesota Department of Commerce, Division of Energy Resources, 11/1/2017

[9] It is likely that if states incentivize transition to electric heat pumps, there will be no business model that a liquid fuels industry in the future just to support peak heating demand.

[10] Conservation Applied Research and Development (CARD) FINAL Report, Prepared for: Minnesota Department of Commerce, Division of Energy Resources, 11/1/2017, Table 8, page 44

[11] Table 5 provides the relative GHG impact of methine and nitrous dioxide versus $CO_2$ versus atmospheric lifetime

emissions rate for that interval. These five-minute rates are averaged to form the marginal emissions rates provided. This provides a good impact indicator for displaced electricity. The three main GHG emissions from the oil and natural gas fuel cycle are methane ($CH_4$), carbon dioxide ($CO_2$), and nitrous oxide ($N_2O$) (see Table 5). While $CO_2$ is considered the primary contributor to global warming, methane and nitrous oxide also have significant global warming potential. So, it should be pointed out that $CO_2$ alone under counts PJM's GHG emissions. Furthermore, should the more near-term 20-year atmospheric lifetime data be used, this further undercounts GHG emission because of the much higher methane impact.

***Table 5 Global Warming Potential Values from the IPCC AR5[12] for Power Generation GHGs***

| | Lifetime | GWP time horizon | |
|---|---|---|---|
| | (years) | 20 years | 100 years |
| Carbon dioxide ($CO_2$) | Complex | 1 | 1 |
| Methane ($CH_4$) | 12.4 | 84 | 28 |
| Nitrous oxide ($N_2O$) | 121 | 264 | 265 |

***Table 6 PJM Marginal $CO_2$ Emissions Rates in lbs/MW-hr[13]***

| | $CO_2$ (lbs/MWh) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | Marginal On-Peak | 1,619 | 1,648 | 1,696 | 1,455 | 1,520 | 1,666 | 1,708 | 1,817 | 1,686 | 1,716 | 1,539 | 1,798 | 1,656 |
| | Marginal Off-Peak | 1,752 | 1,722 | 1,704 | 1,606 | 1,658 | 1,655 | 1,652 | 1,670 | 1,766 | 1,723 | 1,703 | 1,777 | 1,699 |
| | PJM System Average | 1,083 | 1,100 | 1,092 | 1,085 | 1,089 | 1,139 | 1,177 | 1,123 | 1,145 | 1,101 | 1,073 | 1,117 | 1,112 |
| 2014 | Marginal On-Peak | 1,548 | 1,439 | 1,453 | 1,522 | 1,636 | 1,729 | 1,740 | 1,690 | 1,750 | 1,692 | 1,721 | 1,810 | 1,646 |
| | Marginal Off-Peak | 1,664 | 1,602 | 1,627 | 1,650 | 1,671 | 1,691 | 1,608 | 1,630 | 1,682 | 1,861 | 1,848 | 1,944 | 1,707 |
| | PJM System Average | 1,194 | 1,212 | 1,187 | 1,088 | 1,049 | 1,116 | 1,121 | 1,092 | 1,059 | 1,017 | 1,077 | 1,036 | 1,108 |
| 2015 | Marginal On-Peak | 1,728 | 1,564 | 1,578 | 1,673 | 1,775 | 1,729 | 1,654 | 1,745 | 1,643 | 1,575 | 1,547 | 1,549 | 1,647 |
| | Marginal Off-Peak | 1,826 | 1,606 | 1,587 | 1,540 | 1,670 | 1,463 | 1,505 | 1,522 | 1,524 | 1,414 | 1,441 | 1,366 | 1,541 |
| | PJM System Average | 1,096 | 1,184 | 1,044 | 942 | 997 | 1,023 | 1,073 | 1,057 | 1,034 | 898 | 899 | 831 | 1,014 |
| 2016 | Marginal On-Peak | 1,617 | 1,632 | 1,696 | 1,692 | 1,669 | 1,604 | 1,711 | 1,799 | 1,814 | 1,373 | 1,660 | 1,616 | 1,617 |
| | Marginal Off-Peak | 1,520 | 1,505 | 1,600 | 1,537 | 1,563 | 1,381 | 1,572 | 1,679 | 1,618 | 1,495 | 1,364 | 1,643 | 1,471 |
| | PJM System Average | 962 | 947 | 842 | 937 | 873 | 1,047 | 1,123 | 1,109 | 1,047 | 973 | 895 | 1,031 | 992 |
| 2017 | Marginal On-Peak | 1,292 | 1,396 | 1,187 | 1,426 | 1,318 | 1,308 | 1,480 | 1,467 | 1,514 | 1,412 | 1,308 | 1,381 | 1,372 |
| | Marginal Off-Peak | 1,588 | 1,428 | 1,255 | 1,363 | 1,340 | 1,192 | 1,340 | 1,347 | 1,277 | 1,480 | 1,439 | 1,444 | 1,376 |
| | PJM System Average | 973 | 920 | 952 | 873 | 926 | 961 | 1,032 | 990 | 945 | 919 | 880 | 963 | 948 |

Using the 2017 marginal PJM $CO_2$ emissions rate from Table 6, of 948 lbs/MW-hr, Table 7 was constructed showing annual CO2 emission for three electric heat pumps. The first is base on cold climate field test in Minnesota.[6] It should be noted that the average system performance (COP of 1.33 – 133% electric to thermal efficiency) did not include second stage hating required when the ambient temperature was too low for the electric heat pump to meet the home's heating load. Therefore, the following comparisons with renewable liquid fuels over estimates the electric heat pump performance. Nevertheless, Table 6 was used to in comparison with a 90% efficiency boiler and a 120% efficient thermal heat pump. Table 6 used the PJM 2017 marginal $CO_2$ emissions as a baseline and reduces grid emission to zero in 25% increment blocks for comparison with renewable liquid fuels.

---

[12] https://www.ipcc.ch/report/ar5/syr/
[13] https://www.pjm.com/-/media/library/reports-notices/special-reports/20180315-2017-emissions-report.ashx?la=en.

***Table 7 Electric Heat Pump $CO_2$ Emissions Based on System Average Locational Marginal Unit Emissions for Residential Heating and DHW of a 2,500 Square Foot Home***

| | | | **2017 GHG Emissions** | **Electric Grid Reduction $CO_2$ Emissions** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **25% reduction** | **50% reduction** | **75% reduction** | **100% reduction** |
| **HP Description** | **Electric Eff. %** | **New Jersey Annual kWh** | **Annual Emissions lbs** | **Annual Emissions lbs** | **Annual Emissions lbs** | **Annual Emissions lbs** | **Annual Emissions lbs** |
| **Electric Heat Pump Excluding Stage 2 Heating** | 133% | 21,177 | 21,917 | 16,437 | 10,958 | 5,479 | 0 |
| | 200% | 14,083 | 14,575 | 10,931 | 7,287 | 3,644 | 0 |
| | 250% | 11,266 | 11,660 | 8,745 | 5,830 | 2,915 | 0 |

New Jersey is considered a moderately cold climate. Given the dearth of complete field test data, including expected performance degradation with age, on cold climate heat pump system performance, even in moderately cold climates like New Jersey, an annual average performance 2.5 COP (250% electric to thermal efficiency including second stage electric resistance for heating[14], cannot be projected.

# Examining Soy-based Biodiesel as a Pathway

The definitive report assessing soy-based biodiesel GHG emissions report[15] from conventional sources in North America was developed by Entropy Research, LLC. The report also presents GHG emissions results for both conventional 100-Year Atmospheric Lifetime assessment and short-term carbon forcing assessment at 20-Year Atmospheric Lifetime. The individual GHG sources along the fuel cycle were classified into three categories: vented, fugitive, and combustion emissions.

## ***Heating Oil Total Fuel Cycle Energy Use and GHG Emissions***

Table 8 and Table 9 summarize the energy use and GHG emissions by the heating oil fuel cycle for 2015. Values are presented for each of the four major fuel cycle segments, and represent the energy used and GHG emissions produced in delivering heating oil to the point of consumption (i.e., to the residential burner tip).

Fuel cycle energy use in Table 8 is separated into two categories:

---

[14] Electric resistance second stage heating must be used in this case because it is unlikely that there would be any successful economic business model that would support combustion technologies to only support residential second stage heating operation in New Jersey.

[15] *Analysis of Fuel Cycle Energy Use and Greenhouse Gas Emissions from Residential Heating Boilers, Hedman, B, Entropy Research LLC, June* 2018

- Fuel Use – the amount of fuel consumed in each fuel cycle stage in terms of Btu per MMBtu of end-use heating oil consumption
- Electricity Use – the amount of electricity used in the fuel cycle in terms of Btu of resource energy (energy used to generate the electricity) per MMBtu of end-use heating oil consumption. The resource energy is based on the average U.S. grid heat rate for 2015 from the AEO 2017 (9,610 Btu/kWh)

As shown in the table, energy use through the fuel cycle to produce, refine and deliver heating oil to the end-user represents about 14 percent of the energy content of the delivered heating oil.

***Table 8 - Energy Use in the Heating Oil Fuel Cycle (2015)***

| | **Fuel Use** | **Electricity Use** | **Total Energy Use** |
|---|---|---|---|
| | **(Btu/MMBtu)** | | |
| Production | 17,739 | 8,661 | 26,399 |
| Transportation and Storage | 18,110 | 0 | 18,110 |
| Refining | 84,463 | 10,852 | 95,315 |
| Bulk Shipments and Delivery | 4,635 | 0 | 4,635 |
| **Total** | **124,946** | **19,513** | **144,459** |

The GHG emissions for each of the four-heating oil fuel cycle segments are shown in Table 9 and are categorized into four categories:

- Non-combustion $CO_2$ – represents $CO_2$ emissions from processes other than combustion, specifically fugitive and vented $CO_2$ from oil well production and from gas processing.
- Combustion $CO_2$ – represents all combustion related $CO_2$ emissions from energy and non-energy use (i.e., flaring) at each stage except for indirect emissions from grid electricity consumption
- $CH_4$ Emissions –emissions of methane converted to $CO_2$ equivalence using the AR5 100-year Global Warming Potential (GWP) with carbon feedback factor of 36
- Indirect $CO_2$ Emissions – off-site emissions related to electricity from the grid. Indirect emissions are based on the average U.S. grid $CO_2$ emissions rate for 2015 from the AEO 2017 (1.55 lbs $CO_2$/kWh)

***Table 9 - GHG Emissions in the Heating Oil Fuel Cycle (2015) – Based on 100-year GWP with Feedback***

| | **Non-Combustion $CO_2$** | **Combustion $CO_2$** | **$CH_4$** | **Indirect $CO_2$** | **Total** |
|---|---|---|---|---|---|
| | **(lbs $CO_2$e/MMBtu)** | | | | |
| Production | 0.072 | 4.712 | 6.298 | 0.969 | 12.051 |
| Transportation and Storage | 0.0 | 3.263 | 0.019 | 0.0 | 3.282 |
| Refining | 0.011 | 13.746 | 0.058 | 1.214 | 15.029 |
| Bulk Shipments and Delivery | 0.0 | 0.811 | 0.027 | 0.0 | 0.838 |
| **Total** | **0.082** | **22.53** | **6.40** | **2.18** | **31.20** |

Table 10 provides a comparison of total heating oil fuel cycle GHG emissions for three AR5 Global Warming Potential (GWP) categories: 20-year GWP, 100-year GWP without carbon-climate feedback, and 100-year GWP with carbon-climate feedback.

***Table 10 - GHG Emissions in the Heating Oil Fuel Cycle including Final Combustion (2015)***

| | **20-Year GWP** | **100-Year GWP without Carbon-Climate Feedback** | **100-Year GWP with Carbon-Climate Feedback** |
|---|---|---|---|
| | **(lbs $CO_2$e/MMBtu)** | | |
| Production | 20.63 | 11.00 | 12.05 |
| Transportation and Storage | 3.31 | 3.28 | 3.28 |
| Refining | 15.11 | 15.02 | 15.03 |
| Bulk Shipments and Delivery | 0.87 | 0.83 | 0.84 |
| **Total for Segments** | **39.91** | **30.13** | **31.30** |
| Final Combustion | 162.40 | 162.04 | 162.12 |
| **Total Fuel Cycle Emissions** | **202.31** | **192.17** | **193.32** |

## ***Biodiesel Total Fuel Cycle Energy Use and GHG Emissions***

Table 11 and Table 12 summarize the energy use and GHG emissions for the soybean-based biodiesel fuel cycle. Values are presented for each of the four major fuel cycle segments, and represent the energy used and GHG emissions generated in producing and delivering biodiesel to the blending facility.

Fuel cycle energy use in Table 11 is shown for two categories:

- Fuel Use – the amount of fossil fuel use in each fuel cycle stage in terms of Btu per MMBtu of end-use biodiesel consumption
- Electricity Use – the amount of electricity used in the fuel cycle in terms of Btu of resource energy (energy used to generate the electricity) per MMBtu of end-use biodiesel consumption

***Table 11 - Energy Use in the Biodiesel Fuel Cycle***

| | Fuel | Electricity | Total |
|---|---|---|---|
| | **(Btu/MMBtu)** | | |
| **Agriculture** | | | |
| Farm Use | 18,507 | 2,633 | 21,140 |
| Fertilizer | 13,618 | 0 | 13,618 |
| **Total** | **32,155** | **2,633** | **34,758** |
| **Soybean Extraction** | | | |
| Extraction | 41,033 | 11,548 | 52,581 |
| Hexane | 765 | 0 | 765 |
| **Total** | **41,798** | **11,548** | **53,346** |
| **Biodiesel Refining** | | | |
| Refining | 25,745 | 10,866 | 36,611 |
| Methanol/Chemicals | 75,196 | 0 | 75,196 |
| **Total** | **100,941** | **10,866** | **111,807** |
| **Transport and Storage** | | | |
| Transport to crusher | 5,698 | 849 | 6,547 |
| Intermediate Transport | 7,814 | 942 | 8,756 |
| Retail Transport | 4,463 | 1,957 | 6,420 |
| **Total** | **17,975** | **3,748** | **21,723** |
| **Total Fuel Cycle to Burner Tip** | **192,839** | **28,795** | **221,634** |

The emissions for the biodiesel fuel cycle segments are shown in Table 12 for the three GWP categories: 100-year without feedback, 100-year with feedback, and 20-year.

***Table 12 - GHG Emissions from the Biodiesel Fuel Cycle***

| | 100-year w/o feedback | 100-year with feedback | 20-year |
|---|---|---|---|
| | **(lbs $CO_2e$/MMBtu)** | | |
| **Agriculture** | | | |
| Farm Use | 4.48 | 4.54 | 5.01 |
| Fertilizer | 14.18 | 15.68 | 14.48 |
| **Total** | **18.66** | **20.22** | **19.49** |
| **Soybean Extraction** | | | |
| Extraction | 8.39 | 8.53 | 9.61 |
| Hexane | 0.03 | 0.03 | 0.05 |
| **Total** | **8.42** | **8.56** | **9.66** |
| **Biodiesel Refining** | | | |
| Refining | 4.99 | 5.10 | 5.93 |
| Methanol/Chemicals | 11.57 | 11.77 | 13.37 |
| **Total** | **16.56** | **16.87** | **19.30** |

| | | | |
|---|---|---|---|
| **Transport and Storage** | | | |
| Transport to crusher | 1.09 | 1.10 | 1.21 |
| Intermediate Transport | 1.53 | 1.55 | 1.68 |
| Retail Transport | 1.08 | 1.09 | 1.19 |
| **Total** | **3.70** | **3.74** | **4.07** |
| **Total Fuel Cycle to Burner Tip** | **47.34** | **49.39** | **52.52** |

## Comparison of Biodiesel Blend Combustion with Electric Heat Pumps

Table 13 shows that blending soy-based biodiesel processed in advance biorefineries using biodiesel fuels and renewable electricity has a viable pathway, blending with today's ULSD, to achieve zero carbon combustion by 2040. This calculation does not account for any improvement on GHG emission from the production of ULSD which would be a highly likely scenario.   Note that the biodiesel pathway does not require redesign or disruption of New Jersey homes and minor changes in current production and delivery systems.

***Table 13 Comparing Future Biodiesel and ULSD Blended Fueled Boiler and Thermal Heat Pump Emissions with Electric Heat Pump Emissions Based on System Average Locational Marginal Unit Emissions for Residential Heating and DHW***

| | | | 2017 GHG Emissions | | Electric Grid GHG Emissions 25% reduction | | Electric Grid GHG Emissions 50% reduction | | Electric Grid GHG Emissions 75% reduction | | Electric Grid GHG Emissions 100% reduction | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Description** | **Thermal/Electric Eff. %** | **Boston, MA MMBtu or kWh** | **Annual CO2 Emissions lbs** | **Biodiesel Blend** | **Annual CO2 Emissions lbs** | **Biodiesel Blend** | **Annual CO2 Emissions lbs** | **Biodiesel Blend** | **Annual CO2 Emissions lbs** | **Biodiesel Blend** | **Annual CO2 Emissions lbs** | **Biodiesel Blend** |
| **Oil boiler** | 90% | 106.8 | 17,979 | | | | | | | | | |
| **Thermal Heat Pump includes Elec parasitic estimate)** | 120% | 80.1 | 13,484 | | | | | | | | | |
| **Biodiesel and ULSD Blend Boiler** | 90% | 106.8 | 11,660 | 35.2% | 8,745 | 51.4% | 5,830 | 67.6% | 3,644 | 79.7% | 0 | 100% |
| **Biodiesel and ULSD Blend Thermal Heat Pump** | 120% | 80.1 | 11,660 | 13.5% | 8,745 | 35.1% | 5,830 | 56.8% | 3,644 | 73.0% | 0 | 100% |
| **Electric Heat Pump + Electric Resistance Stage 2 Heating** | 250% | 11,266 | 11,660 | | 8,745 | | 5,830 | | 2,915 | | 0 | |

# Examining Ethel Levulinate as a Pathway

Ethyl levulinate (EL) fuel is an advanced biobased hydrocarbon produced via acid catalyzed hydrolysis of lignocellulosic biomass and subsequent esterification with ethanol.  The process can use a variety of lignocellulosic materials and produces a high yield of EL, electricity and chemical coproducts (Figure 1). The mix and ratio of co-products depends on the facility scale and the feedstock composition. This section considers production of EL from softwood forest residues and post-consumer waste paper, primarily cardboard, in a pilot scale (100 tonnes (dry mass) feedstock daily) and commercial scale (1,000 tonnes (dry mass) feedstock daily) facilities.

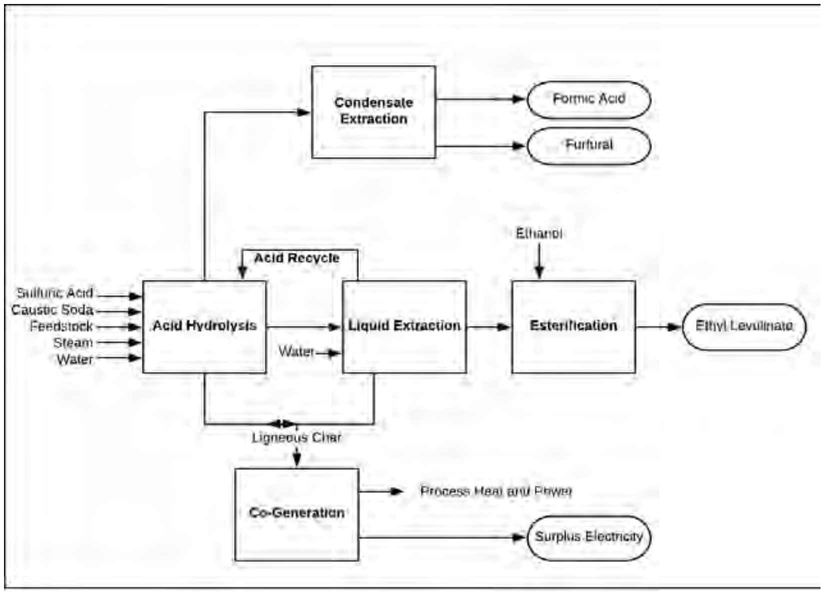


*Figure 1 Process flow for EL production from lignocellulosic biomass at scale (100 tpd).*

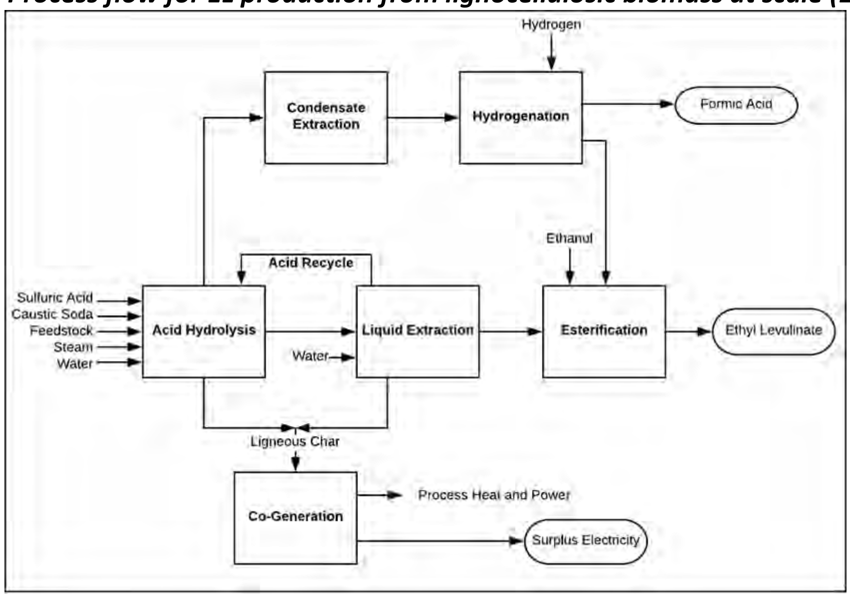


*Figure 2 Process flow for EL from lignocellulosic biomass at commercial scale (1,000 tpd).*

***System Boundaries***

Figure 3 illustrates the general system boundary for production of ethyl levulinate from lignocellulosic material – either forest residues or post-consumer waste paper used for heat. Detailed process flows for the technology are presented in the next section. System boundaries for the soy-based biodiesel and ultra-low sulfur diesel are summarized in **Error! Reference source not found.**.

The system boundary for this study does not include the GHG emissions related to infrastructure processes, such as construction of manufacturing facility and capital equipment.

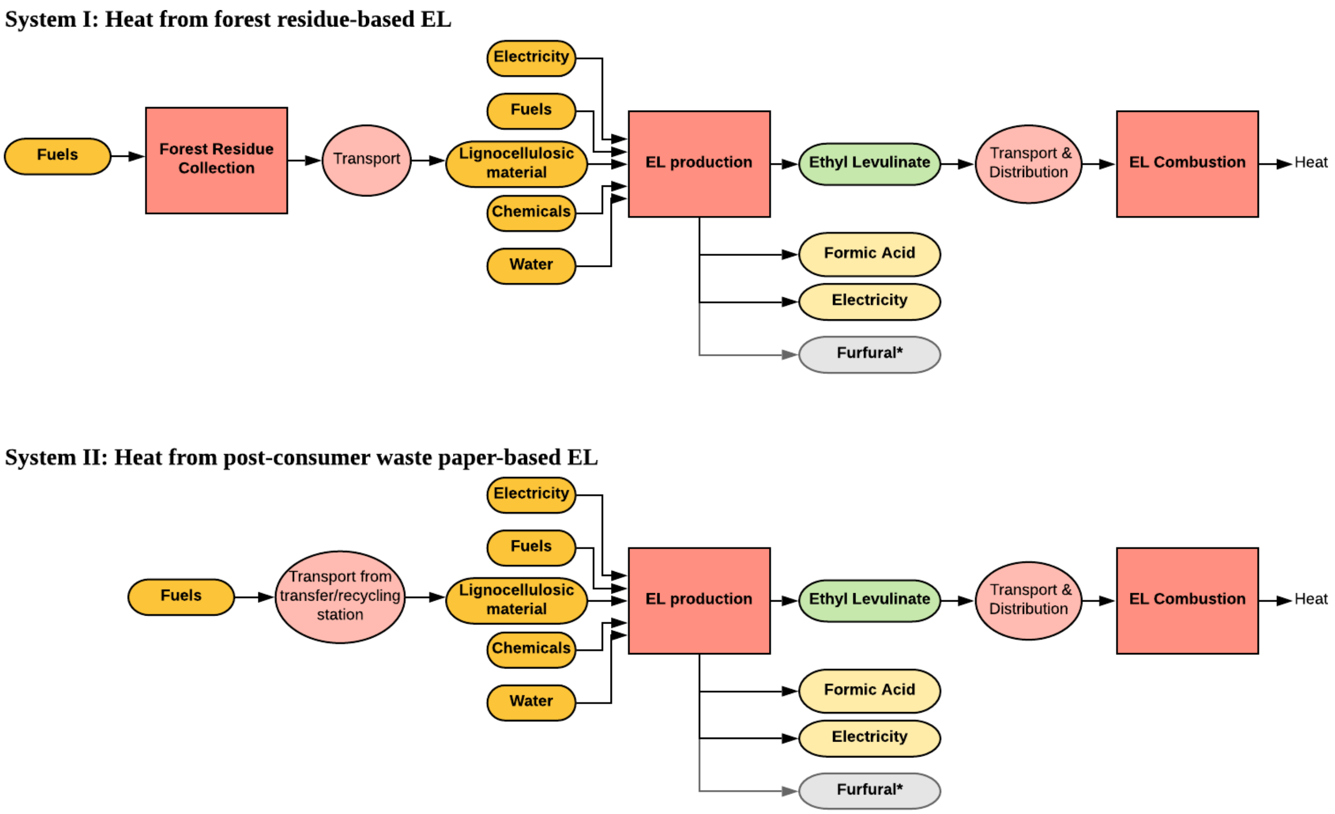


***Figure 3 System boundaries of the Well-to-Burner tip production and use of EL from softwood forest residues (System I, top) and post-consumer waste paper (System II, bottom) for heat. Both the pilot and commercial scale facilities produce formic acid and surplus electricity co-products. The co-product furfural is only produced in the pilot scale (100 tons per day "tpd") facility.***

***<u>Heat produced from EL made from lignocellulosic biomass</u>***

The system boundaries for the Well-to-Burner tip analysis of EL (Figure 3) included the following stages:

- Production of chemicals
- Production (collection) of feedstock, if relevant. The forest residue process includes collection of the residue; the post-consumer waste paper is already collected as part of the municipal services and is not included.
- Transportation of feedstock to the manufacturing facility
- Production of EL
- Transportation and distribution of EL
- Combustion of EL in a residential heater

***Co-Product Allocation***

As shown in Figure 1 and Figure 2, in addition to ethyl levulinate, the EL manufacturing process yields additional co-products: surplus electricity, formic acid, and – for the smaller scale system – furfural. In a multifunctional (multiproduct) system, the environmental burdens must be attributed appropriately across the functions (products).

Co-product allocation is the calculation step in which the environmental burdens of the overall production system are attributed to the primary product and each of the co-products according to some form of relationship. According to ISO 14044, allocation of the process inputs should be avoided by using the system boundary expansion approach where possible. If allocation cannot be avoided, an allocation method – based on physical causality (mass or energy content for example) or a relationship such as economic value – should be used (ISO 14044, 2006b).

System expansion, the ISO-preferred approach, is a method of avoiding allocation whereby an alternative process (route) for manufacturing the coproducts is subtracted from the system. In this study, the system expansion approach was used wherever possible, and physical allocation was used where system expansion could not be applied and to provide a secondary check on the modelling.

***Electricity***

The energy-dense ligneous char produced during hydrolysis and liquid extraction is used internally as a fuel source (heat and power co-generation) for the EL manufacturing process. The char created from the process produces sufficient electricity and steam to power the entire EL manufacturing process, with some excess electricity available to feed back to the grid. System expansion was used to credit the electricity being sent to the grid as per other GREET models, with the EL-related surplus electricity offsetting the equivalent amount from the selected grid.

***Chemical co-products***

The EL production technology also produces formic acid at either scale. Data for alternative formic acid manufacturing processes was obtained from the ecoinvent 3.4 library (Wernet et al 2016) for several routes. The methyl formate route, non-European production[16], is used for the base case. A sensitivity analysis was carried out to evaluate the effect of these assumptions.

The smaller scale system produces furfural as an additional coproduct. However, there remains no alternative manufacturing process in the commercially available LCI databases, nor are robust estimates for the production impacts available in the literature[17]. This study used two approaches: system expansion to account for formic acid coproduction, followed by allocation based on energy content for the remaining EL and furfural products; and a coarse estimate

[16] Ecoinvent 3.4: Formic acid {RoW}| production, methyl formate route | Cut-off, U

[17] A few published LCA studies involve production of furfural as a coproduct in novel biorefinery systems, generally from less common feedstocks. Given the lack of a robust value, we have elected to calculate the value by multiple means to provide a range.

avoided emissions credit calculated with both energy-based and mass-based physical allocation procedures. The latter is used for guiding the sensitivity analysis carried out to evaluate the effect of these assumptions.

For soy-based biodiesel, the co-product impacts are allocated on a mass basis at the process level for the baseline comparison, and the impact of other allocation approaches for co-products for soy-based biodiesel are assessed with a sensitivity analysis (§5.3.2).

### ***Other allocation***

Impacts were also allocated on the basis of both mass and energy as a check on the results and as a means to bound the furfural range. Lower heating values of EL, formic acid and furfural were used to calculate energy-based allocation values (Table 13). The lower heating values were obtained from a report prepared by Shell Global Solutions (Louis 2005) and from PubChem, the NIH Open Chemistry Database[18]. The energy and mass allocation factors for each scenario are shown in Table 1. The 1,000 dry tonne/day capacity plant converts all the furfural into EL, therefore the only allocation approach used was system expansion, with mass and energy-based allocation used as a check.

***Table 14 - Energy and mass-based allocation for each EL plant type***

| Scale (tpd) | *Commercial (1,000 tpd)* | | | | *Pilot (100 tpd)* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Feedstock* | *Forest Residue* | | *Post-Consumer Waste Paper* | | *Forest Residue* | | | *Post-Consumer Waste Paper* | | |
| *Allocation Scheme* | Energy | Mass | Energy | Mass | Energy | Mass | Energy on single co-product | Energy | Mass | Energy on single co-product |
| EL | 92% | 83% | 88% | 78% | 64% | 58% | 71% | 81% | 71% | 92% |
| Formic Acid | 8% | 17% | 12% | 22% | 9% | 9% | | 12% | 23% | |
| Furfural | | | | | 26% | 25% | 29% | 7% | 6% | 8% |

### ***Data Quality, Sources and Assumptions***

The primary data associated with the production of EL was provided by Biofine Developments Northeast (the emissions were determined based on stoichiometric calculations). Heating system, combustion, and final distribution data were provided by NORA, Exergy Partners or modeled directly; sources are identified below. For all other unit processes, the data provided within the GREET model were used, supplemented where necessary with library data from ecoinvent 3.4 and US EI for caustic soda (50%), sulfuric acid, hydrogen, and transportation[5] of these to the Maine manufacturing facility. The ecoinvent process was also used for formic acid.

---

[18] https://pubchem.ncbi.nlm.nih.gov

### Production of chemicals (e.g., fertilizers)

The EL conversion process involves three or four input chemicals depending on scale: sulfuric acid, caustic soda, ethanol, and hydrogen gas for the commercial scale process.

GHG emissions for corn-based ethanol production were calculated in GREET with the SERC (Midwest and Southeast) electricity grid and then reused in the EL model[6]. Soybean production and corn production both have significant agrochemical inputs, which are already well-represented in GREET. GHG emissions for sulfuric acid were calculated in GREET with the US Average electricity grid to reflect the uncertainty in production location. Emissions for steam production (CHP) as part of a biomass conversion process are embedded in the GREET calculation and were used unchanged.

50% caustic soda was added using the ecoinvent library process.[7] The ecoinvent processes used here included the "cradle to gate" life cycle emissions associated with manufacturing of caustic soda. While the available ecoinvent data includes emissions from infrastructure related processes, these processes were excluded in order to be consistent with GREET, which does not include infrastructure processes.

### Production of Feedstock

Both feedstocks considered in the current study are essentially waste products. Neither the forest residue nor post-consumer waste paper feedstock production processes use any chemicals (as is already the case in GREET for the forest residue system), the production of chemicals is therefore excluded for both forest residue and post-consumer waste paper. The default system boundaries for production of forest residue provided in GREET were used for this study. Post-consumer waste paper is assumed to go to landfill if not used here, so no burdens were assigned to it.

### ***Transportation of Feedstock and inputs to the manufacturing facility***

#### Forest Residue:

Transportation of forest residue from the forest field to the facility used a default feedstock catchment radius of 50-75 miles (base case 50 mi), based on woody biomass availability analyses for Maine.

#### Post-consumer waste paper (PCW):

For PCW, the material is already gathered at the local transfer/recycling center before delivery to the conversion facility. A baseline delivery distance of 5 miles was used based on distances to the transfer center in Augusta, ME and Buckston, ME. Impacts for 10-mile collection distances were also assessed.

### Input Chemicals

For ethanol, the default transportation process and distance (520 miles by barge, 600 miles by pipeline, 800 miles by rail and 80 miles by truck) for the transportation of corn-based feedstock to manufacturing facility, given in GREET was used. It is assumed that a comparable transportation distance would be involved for transportation of ethanol to Biofine's facility. The ecoinvent transportation process was used for other inputs. Transportation distances from the chemical manufacturing plant in Illinois to the EL manufacturing facility in Maine 1400 miles, in a 16-32 tonne truck, as previously indicated by Biofine and in keeping with GREET, were used. Transportation parameters for hydrogen were based on available regional suppliers; an average distance of 100 miles was used in place of the GREET default of 30 miles.

### Production of EL (100 and 1,000 dry t/day plant size)

The EL production process involves steam injection acid catalyzed hydrolysis of lignocellulosic material at high temperature. The process inputs for the manufacturing of EL include sulfuric acid to hydrolyze the forest residue, caustic soda (50%), ethanol, hydrogen (in the commercial scale system), steam, and electricity which is produced from lignin-rich process residues. They are covered in Sections 3.1 3.2.1, and 3.2.3. The process flows are shown in Figure 1, and detailed process parameters supplied by Biofine are provided in Section Process Details, Table 3.

The emissions from combustion of biomass to generate steam and electricity in biomass co-generation facilities is already incorporated in the GREET biomass processes. Surplus electricity from combustion of the lignin/char stream is sent to the grid; the grid emissions are calculated in GREET based on the technology type and year. The 2018 and 2030 GREET values were used.

### Distribution EL

Transportation and distribution for EL as heating fuel are very likely to be comparable to other heating oils. Correspondingly, industry-elicited values for average delivery sizes and distances were used to determine effective transport distances per gallon. The transport emissions associated with those fuel deliveries were calculated using GREET's embedded transportation processes. The default transportation and distribution values in GREET for diesel are used to represent the movement of biodiesel and diesel to the terminal. From that point, distribution to the customer is handled as for EL.

| | *# Deliveries* | *Total Distance* | *Average distance* | |
|---|---|---|---|---|
| | | miles | miles per delivery | miles per gallon delivered |
| Average delivery size, industry, arithmetic, gallons | | 185 | | |
| **Distribution Statistics** | | | | |
| Urban | | | 2 | |
| Boston | 40,000 | | | 0.011 |
| Urban New York | 179,690 | 581,424 | | 0.017 |
| Rural | 196,224 | 961,334 | | 0.026 |
| Effective transport & distribution mi/gal (weighted average) | | | | 0.021 |

### EL Production Scenarios

Table 14 shows the GHG emissions for Delivered EL broken down by life cycle stage 1 MMBtu of fuel for all four EL systems using base case values. All base case scenarios result in Carbon negative heat, due offsetting higher GHG intensity electricity and the co-production of formic acid and, in the pilot scale, furfural.

Emissions from combustion during use and processing to fuel dominate the GHG emissions for production and use of EL for heat. Combustion of the EL produces significant GHG emissions, however, these are considered to be offset in total due to the uptake of the carbon during tree growth. The conversion process is fueled by bio-based materials as well, which are also offset by the plant growth. In addition, the conversion process creates electricity and chemicals which can replace those produced elsewhere and so generate a further credit to the system. Thus, the overall change to the market from the production of EL is expected to be a reduction in GHG emissions. Because both feedstocks are essentially waste, the contribute relatively little to the Well-to-Burner tip GHG emissions. Combining all GHG emissions data with the impact of using taste stream recovery means that the net GHG emissions impact of EL is, in fact negative. This means that for every MMBtu of EL fuel that is combusted there actually is a reduction in GHG emissions. For example, for every MMBtu of EL fuel combusted from a commercial scale waste paper plant, 38,3 pounds of GHGs are remove for the global warming cycle.

***Table 15 GHG emissions for Delivered EL broken down by life cycle stage, $CO_{2e}$ lb/MMBtu***

| | Pilot Scale | | Commercial Scale | |
|---|---|---|---|---|
| | **Forest Residue** | **Waste Paper** | **Forest Residue** | **Waste Paper** |
| Feedstock production & transport Processing to fuel (net) Distribution | 7.48 | 0.176 | 6.6 | 0.176 |
| Use | -50.732 | -46.266 | -25.08 | -38.588 |
| Biomass Carbon credit, final combustion | 0.132 | 0.132 | 0.132 | 0.132 |
| Use (net) | 187.88 | 187.88 | 187.88 | 187.88 |
| | -187.88 | -187.88 | -187.88 | -187.88 |
| Total (net) | -43.12 | -45.936 | -18.348 | -38.258 |

## GHG Emission Comparison of Ethyl Levulinate and Biodiesel Blend Combustion with Electric Heat Pump

Using EL produced from a commercial waste paper plant to blend with biodiesel, Table 16 shows that EL/ULSD blended fuels Table 17 shows that have a pathway to zero GHG combustion and even having the ability to technically remove GHGs from the emission cycle during operation. EL will require more development to deliver commercial scale fuel and some changes if fuel pump design. Nevertheless, EL will offer improved fuel cold weather performance characteristics.

***Table 16 Comparing Future EL/ULSD Fueled Boiler and Thermal Heat Pump GHG Emissions with Electric Heat Pump $CO_2$ Emissions Based on System Average Locational Marginal Unit Emissions for Residential Heating and DHW***

| | | | 2017 GHG Emissions | | Electric Grid GHG Emissions 25% reduction | | Electric Grid GHG Emissions 50% reduction | | Electric Grid GHG Emissions 75% reduction | | Electric Grid GHG Emissions 100% reduction | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Description** | **Thermal/Electric Eff. %** | **Boston, MA MMBtu or kWh** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** |
| **Oil boiler** | 90% | 106.8 | 17,979 | | | | | | | | | |
| **Thermal Heat Pump includes Elec parasitic estimate)** | 120% | 80.1 | 13,484 | | | | | | | | | |
| **EL and ULSD Blend Boiler** | 90% | 106.8 | 11,660 | 28.6% | 8,745 | 41.9% | 5,830 | 55.1% | 2,915 | 68.3% | -4,085 | 100% |
| **EL and ULSD Blend Thermal Heat Pump** | 120% | 80.1 | 11,660 | 11.0% | 8,745 | 28.6% | 5,830 | 46.3% | 2,915 | 63.9% | -3,064 | 100% |
| **Electric Heat Pump + Electric Resistance Stage 2 Heating** | 250% | 11,266 | 11,660 | | 8,745 | | 5,830 | | 2,915 | | 0 | |

Table 17 show that any blend of advanced biodiesel with EL provides the ability to technically remove GHGs from the emission cycle during operation.

***Table 17 Comparing Future EL/Biodiesel Fueled Boiler and Thermal Heat Pump GHG Emissions with Electric Heat Pump $CO_2$ Emissions Based on System Average Locational Marginal Unit Emissions for Residential Heating and DHW***

| | | | 2017 GHG Emissions | | Electric Grid GHG Emissions 25% reduction | | Electric Grid GHG Emissions 50% reduction | | Electric Grid GHG Emissions 75% reduction | | Electric Grid GHG Emissions 100% reduction | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Description** | **Thermal/Electric Eff. %** | **Boston, MA MMBtu or kWh** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** | **Annual CO2 Emissions lbs** | **EL Blend** |
| **Biodisel boiler** | 90% | 106.8 | 0 | | | | | | | | | |
| **Thermal Heat Pump includes Elec parasitic estimate)** | 120% | 80.1 | 0 | | | | | | | | | |
| **EL and Biodiesel Blend boiler** | 90% | 106.8 | 0 | 0.0% | -1,021 | 25.0% | -2,043 | 50.0% | -3,064 | 75.0% | -4,085 | 100% |
| **EL and Biodiesel Blend Thermal Heat Pump** | 120% | 80.1 | 0 | 0.0% | -766 | 25.0% | -1,532 | 50.0% | -2,298 | 75.0% | -3,064 | 100% |
| **Electric Heat Pump + Electric Resistance Stage 2 Heating** | 250% | 11,266 | 11,660 | | 8,745 | | 5,830 | | 2,915 | | 0 | |