# *future*fuel

*understanding the viability of advanced biofuels and combustion technologies to deliver zero net carbon combustion in the future*

*and*

*examining advanced biofuels as an alternative to electric heat pumps and other fossil fuel combustion in tomorrow's homes*

***national oilheat research alliance***

***september 2018***

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# *executive summary*

Electricity, natural gas, heating oil and biodiesel blended with heating oil provide space heating and hot water services in the residential sector. Choosing a specific energy source for these services has significant implications in terms of energy efficiency, economics and environmental impact. While the ultimate fuel choice is made by builders and consumers, and most often based on economics, this choice is also influenced by perceptions of how efficiently, or inefficiently, our energy resources are being used and how the choice might impact the environment, including the release of greenhouse gases (GHG) into the atmosphere.

Jurisdictions that are generally interested in facilitating future residential energy supply and usage trajectories should focus on four specific impact attributes: 1) energy efficiency, 2) economic impact, 3) environmental impact and 4) efficacy. Narrowing this question to consider how we will heat our homes in the future, each approach should be measured by these four benchmarks.

Table 1 provides a ranking of these four specific impact attributes looking at five energy sources. Green circles mean best possible outcome versus the other alternatives presented. Blue means a good outcome versus the other alternatives presented. Finally, black is the lease favorable outcome versus the other alternatives presented. What should be clear from Table 1 is that liquid biofuels (B100 and Tri-Mix) provide the best possible outcome for all impact attributes.

> *"The capability of the oil heating industry to innovate and meet state's decarbonization agenda has not been adequately recognized. It is not furnaces or boilers that produce carbon emissions, it's the fuel they run on. Therefore, it is premature for policy makers to consider regulating against oil heating when all liquid fuel furnaces and boilers could be run on a low carbon alternative fuel* ***before*** *2035."*
>
> *John Huber*
>
> *National OilHeat Research Alliance*

| | efficiency[1] | economic impact[2] | environmental impact | Heating Comfort |
|---|---|---|---|---|
| Natural Gas | green | blue | blue | green |
| Electricity | blue | black | blue | blue |
| ULSD[3] | green | green | black | green |
| B100 | green | green | green | green |
| Tri-Mix[4] | green | green | green | green |

***Table 1 - Impact Assessment of Achieving Low Carbon Goals in 2050***

[1] Electric heat-pump source-based COP of 1.09, thermal heat pump source-based COP of 1.3
[2] Economic impact refers to the cost of transitioning from a home with one energy source to another e.g. from liquid-fueled furnace to electric heat pump including any infrastructure costs to support the transition e.g. transmission and distribution capacity upgrades or battery storage for internment renewable power sources.
[3] ULSD - < 15 ppm sulfur diesel
[4] 1/3 ULSD, 1/3 B100 and 1/3 Ethyl Levulinate

# *introduction*

Recent studies and position papers advocating development of public policies and public incentives for fuel switching from fossil fuel-based residential heating systems to electric heat pumps must be corrected. This is particularly true with the case of the oil heating industry. The oil heating industry has been investing in its transformation into an energy efficient renewably-fueled supply industry for the future. Table 2 shows the common errors in recent reports and position papers in need of correction.

ACEEE's July 2018 report titled: "*Energy Savings, Consumer Economics, and Greenhouse Gas Emissions Reductions from Replacing Oil and Propane Furnaces, Boilers, and Water Heaters with Air-Source Heat Pumps"*, recommends "*… programs to promote high-efficiency heat pumps to replace less-efficient oil and electric systems ... Such efforts can build on successful programs in the Northeast and Northwest. In addition, programs to promote heat pumps in new construction deserve attention."*

In addition, the ACEEE *"calculated the life-cycle cost for each system type and location, assuming a 21-year equipment life and a 5% real discount rate"* using DOE estimates and utility cost of capital. The fuel-switching capital costs were not explained. The conclusions differ dramatically from the June 18, peer reviewed ASHRAE paper[5] which found[6] that renewable liquid-fueled thermal heat pumps integrated with multi-split air conditioning units are generally more cost effective than cold climate high efficiency electric heat pumps.

Rocky Mountain Institute's "RMI's" – "*The Economics of Electrifying Buildings*" paper concludes: *"Prioritize rapid electrification of buildings currently using propane and heating oil in space and water heating. Although these represent less than 10% of US households, they account for more than 20% of space and water heating emissions. Electrification is very cost-effective for propane customers, and has a comparable cost to heating oil depending on local pricing."* Like ACEEE, RMI misses the mark assessing oil as the industry's *futurefuel*, does not appear to know about research and development work on a renewably liquid-fueled thermal heat pump, and does not fully evaluate fuel switching cost.

National Grid's *80 x50 Pathway* brochure, created by a large electric and natural gas utility, states: "*A transformation of the heat sector, by doubling the rate of efficiency retrofits and converting nearly all of the region's 5 million oil-heated buildings to electric heat pumps or natural gas"* is the only residential pathway to 80 x 50. National Grid further encouraged policymakers to allow public funds for fuel switching saying, *"Additional incentives for heat electrification and green gas production will be important."* Being a gas utility, National Grid knows about thermal heat pumps, but apparently only natural gas-fired ones, as well as, renewable gas, but apparently biodiesel and advanced liquid biofuels are not mentioned. "Beyond 2030, the heat sector will require sustained efficiency investment and conversion to heat pumps, the steady decarbonization of natural gas supply (through renewable natural gas, hydrogen, and synthetic fuels), and conversion of many natural gas homes to hybrid natural gas-heat pump configuration".

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[5] "*Energy, Cost and $CO_{2e}$ Savings Analyses of Reversible, Hybrid and Heating-Only Liquid Fuel Fired Absorption Heat Pumps in the Northeastern United States*", ASHRAE Summer Meeting, Christopher Keinath, PhD, Thomas Butcher, PhD, Michael Garrabrant, PE, June 2018

[6] See "*heat pump economics in the northeast*" section of this report for details. (Hybrid THP/14 SEER AC or Heating only THP and 14 SEER AC boilers more cost effective than 18SEER- 12 HSPF CCEHP with Boiler backup or Hybrid THP/14 SEER AC or Heating only THP and 14 SEER AC furnace is more cost effective than 18SEER- 12 HSPF CCEHP with Furnace backup or 18SEER- 12 HSPF CCEHP with Resistance backup)

| | Does not evaluate biodiesel | Does not evaluate advanced biofuels | Does not evaluate thermal liquid-fueled heat pumps | Does not cost grid upgrades required for 80% renewables | Does not evaluate low ambient comfort |
|---|---|---|---|---|---|
| ACEEE's July 2018 report | ● | ● | ● | ● | ● |
| RMI's - The Economics of Electrifying Buildings | ● | ● | ● | ● | ● |
| National Grid's 80 x50 Pathway brochure | ● | ● | ● | ● | ● |

***Table 2 - Assumption Errors in Recent Residential Heating Policy Studies and Promotions***

This report examines three approaches to fuel a low carbon future in residential heating systems. The data presented in the report is compiled from the following studies:

1. "*Analysis of Fuel Cycle Energy Use and Greenhouse Gas Emissions from Residential Heating Boilers*", Bruce Hedman, Entropy Research LLC, June 2018
2. "*Energy, Cost and $CO_{2e}$ Savings Analyses of Reversible, Hybrid and Heating-Only Liquid Fuel Fired Absorption Heat Pumps in the Northeastern United States*", ASHRAE Summer Meeting, Christopher Keinath, PhD, Thomas Butcher, PhD, Michael Garrabrant, PE, June 2018
3. "*Implications of Policy-Driven Residential Electrification*", American Gas Association Study, prepared by ICF, July 2018
4. "*Comparison of Ethyl Levulinate with Gasoline and Diesel: Well to Wheels Analysis*", Harnoor Dhaliwal and Lise Laurin, EarthShift, June 2009
5. "*U. S. National Electrification Assessment*", Electric Power Research Institute, April 2018
6. *"Northeast 80x50 Pathway*" National Grid, June 2018

Residential heating energy in the U.S. is largely supplied by fossil fuels with 64% of households currently using fossil fuel combustion to heat their homes according to the Department of Energy's 2015 Residential Energy Consumption Survey (RECS). Table 3 provides overall energy use by climate zone and Table 4 focuses on homes where space heating is mainly provided by electricity or fossil fuel combustion. It is easy to see that fossil fuels dominates cold/very cold and mixed-humid climates for home heating. This reflects current market conditions driven by customer economics and comfort.

| | | Climate region[7] | | | | |
|---|---|---|---|---|---|---|
| | Total U.S.[8] | Very cold/ cold | Mixed-humid | Mixed-dry/ Hot-dry | Hot-humid | Marine |
| **All homes** | 118.2 | 42.5 | 33.5 | 12.7 | 22.8 | 6.7 |
| **Fuels used for any use (more than one may apply)** | | | | | | |
| Electricity | 118.2 | 42.5 | 33.5 | 12.7 | 22.8 | 6.7 |
| Natural gas | 68.6 | 29.3 | 17.5 | 10.4 | 7.5 | 3.9 |
| Propane[4] | 11.6 | 5.0 | 3.9 | 0.6 | 1.5 | 0.6 |
| Wood | 12.5 | 5.0 | 3.7 | 0.8 | 1.7 | 1.2 |
| Fuel oil/kerosene | 6.9 | 4.1 | 2.7 | | | |

*Table 3 - Fuels Used for Primary and Secondary Heating in U.S. Homes by Climate Region (Millions)*

| | | Climate region[3] | | | | |
|---|---|---|---|---|---|---|
| | Total U.S.[2] | Very cold/ cold | Mixed-humid | Mixed-dry/ Hot-dry | Hot-humid | Marine |
| Electricity mainly used for heating | 40.9 | 7.5 | 13.1 | 3.7 | 14.0 | 2.7 |
| Natural gas, Propane, Wood, and Fuel oil/kerosene mainly used for heating | 72.0 | 34.8 | 20.3 | 6.9 | 6.1 | 3.3 |
| Fossil fuel Percent of Total | 64% | 82% | 61% | 65% | 30% | 55% |

*Table 4 - Fuels Used as the Primary Heating Source in U.S. Homes by Climate Region (Millions)[9]*

Table 5 shows current market share of residential fossil-fueled heating systems by fuel type. Natural gas dominates this sector because of current fuel cost. Homes with a biodiesel blend of at least 20% biodiesel and 80% ULSD is used in less than 1% of the fossil fueled homes today. Recognizing that carbon reduction is an increasing requirement and that biodiesel and advanced liquid biofuels appear to be one of the most viable pathways toward zero carbon residential heating, one might expect to see significant bioblend market share growth in the next ten years.

| | Total U.S.[2] | Percent |
|---|---|---|
| Natural Gas | 40.9 | 74.1% |
| Propane | 5 | 9.1% |
| Wood | 3.5 | 6.3% |
| Oil | 5.3 | 9.6% |
| ~B20 or more | 0.5 | 0.9% |
| Total | 55.2 | 100.0% |

*Table 5 - Current Residential Heating Market Share by Fuel Type, Exclusive of Electricity (Millions)*

[7] These climate regions were created by the Building America program, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).
[8] Total U.S. includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military houses, and group quarters are excluded.
[9] 118.2 million homes are heated in the US, 112.9 million homes use energy as a primary means of heating. The remaining homes 5.3 million homes have only spot or secondary means of home heating.

# beneficial electrification for home heating

The future of home heating is the focus of the environmental community, some policy makers and, of course, electric utilities (who increase load when fossil fuel customers switch to electric heat pumps). Many of these groups have been promoting Beneficial Electrification which assumes that by 2050 all or most home heating energy will be supplied by an electric grid that is exclusively powered by renewables.

There are a number of fundamental flaws in this policy-driven movement that affects the heating oil industry and all other energy providers:

1. Policy-driven electrification would increase the average residential household cost – largely because intermittent renewables and batteries would substantially increase the electric infrastructure. A vastly oversized grid and a dramatic increase in production will be necessary to ensure that the electric operating system does not collapse during a sustained freeze when demand is high and heat pump efficiency is low or fails to provide heat.

2. Despite the desire to move to renewably-fueled electric power plants, the electric grid in 2050 will not be 100% renewable. It will likely require natural gas combined cycle combustion turbines (CCCTs) operating, at the margin, to fulfill the increased demand of millions of households currently using natural gas or heating oil. In fact, the Electric Power Research Institute's April 2018 National Grid Assessment predicts, in its Transformation Model, that the final delivered energy from the electric grid will account for only 47% of the total delivered energy needed by end-users.

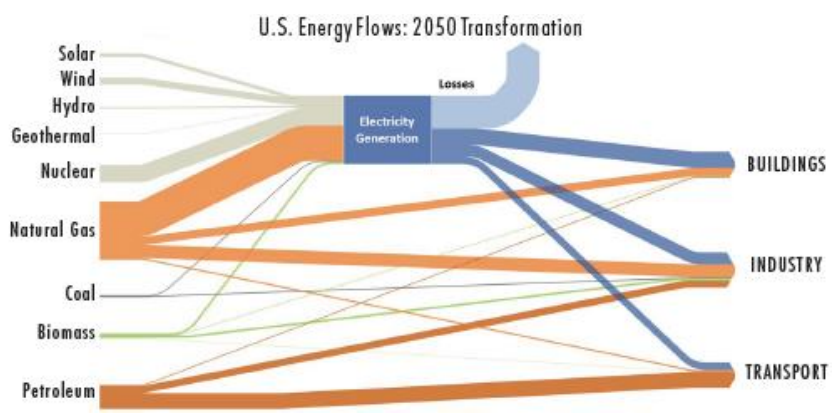


*Figure 1 - Sankey view of 2050 EPRI's Transformation scenario projection[10].*

Figure 1 shows EPRI's model results for its most aggressive carbon reduction scenario (Transformation) in 2050. Most notable is large dependence on nuclear and natural gas power generation and significant requirement for fossil fuel combustion in buildings and industry.

3. According to the AGA Report[11]., fuel switching residential heating (oil, propane and gas) to electric heat pumps would only result in GHG emissions reduction by 1 to 1.5 percent.

4. Decarbonized power systems dominated by variable renewables such as wind and solar energy are physically larger, requiring much greater total installed capacity.

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[10] This EPRI Sankey diagram represents the flow of electric energy from generation source on the left (solar, wind, coal, oil, natural gas, nuclear, etc.) to the load served on the right (buildings, industry and transportation). The width of the arrows is shown proportionally to the energy flow quantity used.

[11] "Implications of Policy-Driven Residential Electrification", American Gas Association Study, prepared by ICF, July 2018. *"See fuel switching residential heating to electric heat pumps would only result in GHG emissions reduction by 1 to 1.5 percent"* for more detail.

a. Due to the variability of wind and solar energy, power systems with high shares of these resources have much greater overall installed capacity than more diversified power systems, and must maintain significant dispatch-able capacity to ensure demand can be met at all times. For example:

b. Pleßmann and Blenchinger[12] present a scenario for decarbonizing the European power system by 2050 (achieving 98.4% below 1990 emissions levels) that relies heavily on an expansion of wind and solar energy. Total installed capacity in this scenario is 4.2-times larger than the peak demand.

c. Similarly, a 100% renewable electricity scenario for Australia outlined by Elliston, MacGill, and Diesendorf[13] features total capacity roughly three times the peak demand in the system.

d. Brick and Thernstrom[14] likewise conclude that total installed capacity is 3.5 to 5.5 times larger for wind and solar-dominated power systems than more balanced systems.

e. Total U.S. generating capacity is roughly double today's installed capacity in a set of 80% renewable electricity scenarios described by Mai, Mulcahy, et al.[15].

f. Greater required installed capacity and the lower energy-density of wind and solar resources also significantly increase the land use consequences of power systems dominated by variable renewable resources.

5. The heating oil industry today is moving away from traditional oil-based fuels to biofuels with the goal of fleet conversion from B5-B20 to a $^1/_3$ Biodiesel - $^1/_3$ Advanced Biofuel[16] and $^1/_3$ ULSD by 2035. The advanced biofuel under consideration yields negative carbon due to avoided carbon emissions. As a result, this fuel would yield carbon free combustion for heating.

6. The U.S. Department of Energy is supporting the development of thermal heat pump technology[17] that will be more efficient, provide much more comfortable heating and be lower cost. Additionally, it would make the electric grid less vulnerable to failure, and make any failure less catastrophic.

Biodiesel and advanced biofuels <u>must not</u> be ignored by policy makers when developing their carbon and methane reduction plans for the future. Renewable biofuels may provide the most cost-effective method to reduce carbon and can make other GHG reduction strategies more easily obtainable.

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[12] Pleßmann, G., and P. Blechinger. 2017. "How to Meet EU GHG Emission Reduction Targets? A Model Based Decarbonization Pathway for Europe's Electricity Supply System until 2050." Energy Strategy Reviews 15: 19–32. doi:10.1016/j.esr.2016.11.003.

[13] Elliston, B., I. MacGill, and M. Diesendorf. 2014. "Comparing Least Cost Scenarios for 100% Renewable Electricity with Low Emission Fossil Fuel Scenarios in the Australian National Electricity Market." Renewable Energy 66: 196–204. doi:10.1016/j. renene.2013.12.010.

[14] Brick, S., and S. Thernstrom. 2016. "Renewables and Decarbonization: Studies of California, Wisconsin and Germany." The Electricity Journal 29 (3): 6–12.
doi:10.1016/j.tej.2016.03.001.

[15] Mai, Trieu, David Mulcahy, M. Maureen Hand, and Samuel F. Baldwin. 2014. "Envisioning a Renewable Electricity Future for the United States." Energy 65. Elsevier Ltd: 374–86. doi:10.1016/j. energy.2013.11.029.

[16] There are several pathways moving toward advanced biofuels, two of which are listed. 1) Biofine Technology, LLC. Has developed a cellulosic biodiesel for use in residential heating, and 2) Synthetic Genomics, Inc. (SGI) and ExxonMobil have developed a strain of algae able to convert carbon into a record amount of energy-rich fat, which can then be processed into biodiesel.

[17] See Pathway to Energy Efficiency for description of thermal heat pump technology

# *beneficial residential electrification*

*policy-driven electrification by fuel switching residential heating to electric heat pumps would increase the average residential household energy-related costs about 38 percent to 46 percent.*

Policy-driven electrification would increase the average residential household energy-related costs (amortized appliance and electric system upgrade costs and utility bill payments) of affected households by between $750 and $910 per year, or about 38 percent to 46 percent. Widespread residential electrification will lead to increases in peak electric demand and could shift the U.S. electric grid from summer peaking to winter peaking in every region of the country, resulting in the need for new investments in the electric grid including generation capacity, transmission capacity, and distribution capacity.

The Energy Innovation Reform Project outlined daunting barriers to developing a low/no carbon renewable electric solution by 2050.[18]

The electric power sector is widely expected to be the linchpin of efforts to reduce greenhouse gas (GHG) emissions. Most studies exploring climate stabilization pathways envision a decline in global anthropogenic GHGs of 50-90% below current levels by 2050[19]. To reach these goals, the power sector would need to cut emissions nearly to zero, while expanding to electrify (and consequently decarbonize) portions of the transportation, heating, and industrial sectors[20].

1. Deep decarbonization of the power sector is significantly more difficult than more modest emissions reductions.
2. Achieving deep decarbonization primarily (or entirely) with renewable energy may be theoretically possible but it would be significantly more challenging and costlier than pathways employing a diverse portfolio of low-carbon resources.
3. Decarbonized power systems dominated by variable renewables such as wind and solar energy are physically larger, requiring much greater total installed capacity.
4. Wind and solar-heavy power systems require substantial dispatchable power capacity to ensure demand can be met at all times. This amounts to a "shadow" system of conventional generation to back up intermittent renewables.
5. Without a fleet of reliable, dispatchable resources able to step in when wind and solar output fade, scenarios with very high renewable energy shares must rely on long-duration seasonal energy storage.
6. Very high shares of wind and solar entail significant curtailment—even with energy storage, transmission, or demand response.
7. High renewable energy scenarios also envision a significant expansion of long-distance transmission grids.

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[18] "*Deep Decarbonization of the Electric Power Sector Insights from Recent Literature*", Jesse D. Jenkins and Samuel Thernstrom, March 2017

[19] "*A critical review of global decarbonization scenarios: what do they tell us about feasibility?*", Peter J. Loftus, Armond M. Cohen, Jane C. S. Long, Jesse D. Jenkins, 06 November 2014

[20] "Transport Electrification: A Key Element for Energy System Transformation and Climate Stabilization." McCollum, David, Volker Krey, Peter Kolp, Yu Nagai, and Keywan Riahi. 2014. Climatic Change 123 (3–4): 651– 64. doi:10.1007/s10584-013-0969-z. and "Getting from Here to There – Energy Technology Transformation Pathways in the EMF27 Scenarios", Krey, Volker, Gunnar Luderer, Leon Clarke, and Elmar Kriegler. 2014.." Climatic Change 123 (3–4): 369–82. doi:10.1007/s10584-013-0947-5.

## *fuel switching residential heating to electric heat pumps would only result in GHG emissions reduction by 1 to 1.5 percent*

The U.S. Energy Information Administration (EIA) projects in their baseline case that by 2035, the sum of natural gas, propane and fuel oil used in the residential sector will account for less than 6 percent of total GHG emissions. Reductions from policy-driven residential electrification would reduce GHG emissions by 1 percent to 1.5 percent of U.S. GHG emissions in 2035 from the EIA AEO 2017 Baseline emissions. This result is based on the efficiency of the average newly installed heat pump is assumed to increase by about 1 percent per year, reaching an HSPF of 12.5 by 2035. This results in an average reported HSPF of 11.5 (COP of 3.4) for the heat pumps used to replace the furnaces converted to electricity due to the residential electrification policy over the time period from 2023 through 2035. New furnace efficiency was assumed to be same as the existing furnace efficiency to ensure that the analysis does not overstate potential furnace efficiency. This compares an all renewable grid solution versus a market-based grid solution.

## *the cost impacts from electrification policies include*

**Consumer Costs:** The direct costs to consumers of policy-driven electrification include:

1. The incremental costs for new or replacement electric heating and hot water equipment relative to the natural gas or other direct fuel alternative.
2. Costs of upgrading or renovating existing home HVAC and electrical systems.
3. Difference in energy costs (utility bills) between the electricity options and the natural gas and other direct fuel options.

Most of the affected households will be existing households retrofitting from natural gas, heating oil, propane, biodiesel blends and advanced biodiesel blends. The costs for these customers typically will be higher than the incremental costs for new households installing the equipment.

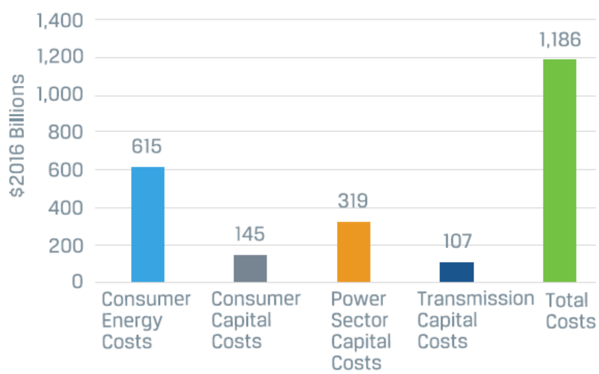
**Power Generation Costs:** The capital cost of new electric generating capacity needed to supply the increased electricity demand.

**Transmission Costs:** The cost of new electric transmission infrastructure required to serve the increased load and generation.

The latter two costs are often neglected by most studies that promote the concept of beneficial electrification. The reason generally stated is that electric heat pump high efficiency and future energy efficiency programs will essentially reduce electric demand. Note, since the cost of these future energy efficiency programs is never calculated and added into consumer energy costs. Therefore, additional electric capacity (generation, transmission and distribution capacity) “fuel-switching” for a fossil fuel to electricity must be added.

“Table 6 summarizes these costs for the Renewables- Only Case showing that the total cumulative cost increase relative to the Reference Case is nearly $1.2 trillion by 2035. Roughly half of this cost is the increase in consumer energy costs. One third is the cost of new generating capacity and consumer equipment, and transmission costs make up the remainder. The Market-Based Generation Case has a total cumulative cost increase of $590 billion by 2035, shown in Table 6. The consumer energy costs are lower in this case because it does not include electrification of the Midwestern, Plains, and Rockies regions, which have higher heating loads, greater saturation of gas heating equipment, and colder temperatures, which result in lower efficiency for electric heat pumps. The other costs are also somewhat lower, especially the capital cost of new generating capacity. The generating cost is lower because the model is selecting the lowest cost option, rather than being limited to only renewable sources, which increases costs, especially for battery storage, in the Renewables-Only Case.

**Total Cost of Renewables-Only Case by Sector**




**Total Cost of Market-Based Generation Case by Sector**

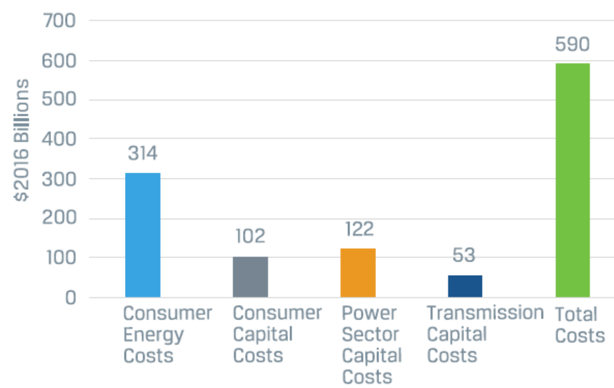



*Table 6 - Renewables- Only Case and Market-Based Generation Case*

The overall magnitude of the costs of policy-driven residential electrification is expected to place a significant burden on consumers. Table 7 shows the cumulative and annualized costs of the conversion to electricity spread out over the total number of converted households. These costs include the direct costs per household, including the direct consumer costs (appliance and energy costs), and an allocation of the capital cost for electric generating plants and electric transmission. The costs are discounted to 2023 and expressed in real 2016 dollars."[21]

| Region | Renewables-Only Case | | Market-Based Generation Case | |
|---|---|---|---|---|
| | Cumulative Change In Costs Per Converted Household | Annualized Change In Costs Per Converted Household | Cumulative Change In Costs Per Converted Household | Annualized Change In Costs Per Converted Household |
| East Coast | 18,440 | 1,240 | 16,550 | 1,110 |
| Midwest | 25,920 | 1,740 | Policy Not Implemented | |
| New York | 58,580 | 3,930 | 57,770 | 3,880 |
| New England | 41,210 | 2,770 | 35,340 | 2,370 |
| Plains | 29,120 | 1,950 | Policy Not Implemented | |
| Rockies | 25,060 | 1,680 | Policy Not Implemented | |
| South | 7,820 | 520 | 650 | 40 |
| Texas | 1,970 | 130 | 740 | 50 |
| West | 5,880 | 390 | 5,140 | 340 |
| **Total U.S.** | **21,140** | **1,420** | **15,830** | **1,060** |

*Table 7 - Annual Per Household Total Costs of Electrification Policies (Real 2016 $)*

Figure 2 provides an understanding of the fuel/energy cost tracked by U.S. DOE's Energy Information Administration. These energy costs combined with appliance efficiency (electric heat pump source energy COP 1.09 and liquid fueled thermal heat pump source energy COP 1.3 provide a reasonable assessment

[21] "*Implications of Policy-Driven Residential Electrification*", An American Gas Association Study prepared by ICF, July 2018

that renewable liquid fueled heat pumps will have low operating costs compared to other electric heat pumps.

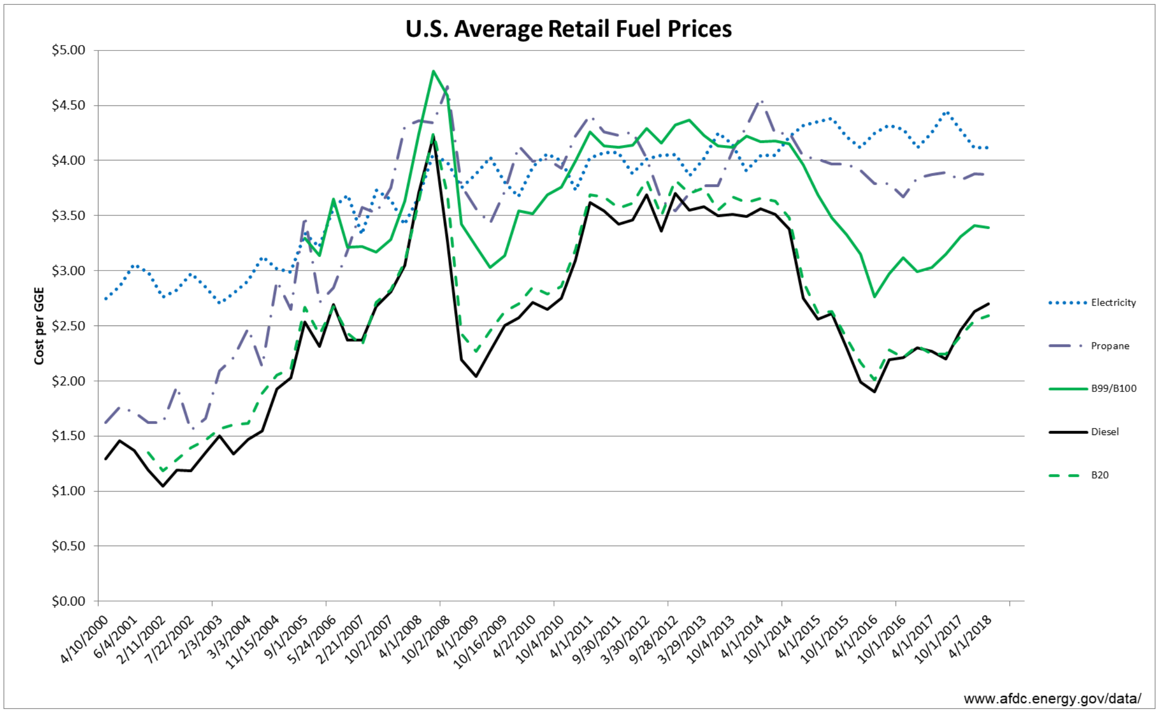



*Figure 2 - EIA U.S. Average Retail Fuel Prices*[22]

## heat pump economics in the northeast[23]

The simple payback and 15-year total cost for two thermal heat pump (THP) installation configurations were investigated. The first configuration assumed a heating only THP would be nested or installed in the same package as an electric air conditioner (EAC). This design is designated as the “Hybrid” system. The design of this system allows for the highest efficiency heating and cooling to be performed by “one” system. The second configuration assumed a heating only THP and EAC are installed as separate entities. The two configurations are identical for the purpose of seasonal modeling and correspond to the heating only THP and 14 SEER electric air conditioning system. The installation cost specific to each configuration will be different and will factor into payback and 15-year life calculations. In addition to the THP configurations, the simple payback and 15-year total cost of the cold climate electric heat pump (CCEHP) with boiler, furnace and resistance backup were investigated.

Installed cost of each system was estimated based on equipment pricing estimates and feedback from contractors in the Northeast. Capital cost for commercially available equipment was estimated based on available pricing. Capital cost estimates for the THP equipment were developed from a supply chain

[22] The Alternative Fuel Price Report is a snapshot in time of retail fuel prices for vehicles presenting data in dollars per gasoline gallon equivalent (GGE) which allows an equivalent comparison. The data is presented as delivered by EIA except electricity is changed to remove the 3.4 factor to adjusted for efficiency because electric vehicles are 3.4 times as efficient as internal combustion engines. In fact, electric heat pumps have a source efficiency of 1.09 COP and liquid-fueled thermal heat pumps have a source energy efficiency of 1.3 COP.

[23] “Energy, Cost and CO2e Savings Analyses of Reversible, Hybrid and Heating-Only Liquid Fuel-Fired Absorption Heat Pumps in the Northeastern United States”, ASHRAE Summer Meeting, Christopher Keinath, PhD, Thomas Butcher, PhD, Michael Garrabrant, PE, June 2018

analysis to include reasonable mark-ups and assuming a minimum production level.[24] Table 8 shows that an integrated THP/EAC system ranks among the best economic alternatives for future residential space conditioning (heating and cooling) even without evaluating the infrastructure costs of expanding and hardening the electric grid to service electric heat pumps.

| Baseline Heating / Cooling System | Radiator Based Boiler, 14 SEER Minisplit AC | | | Forced Air System with Condensing Furnace, 14 SEER Central AC | | | |
|---|---|---|---|---|---|---|---|
| **Replacement Technology** | Hybrid THP/14 SEER AC | Heating only THP and 14 SEER AC | 18SEER- 12 HSPF CCEHP with Boiler backup | Hybrid THP/14 SEER AC | Heating only THP and 14 SEER AC | 18SEER- 12 HSPF CCEHP with Furnace backup | 18SEER- 12 HSPF CCEHP with Resistance backup |
| **Location** | **Payback Period, Years** | | | | | | |
| Portland, ME | 0.8 | 3.6 | 8.6 | 4.7 | 4.8 | 9.5 | 5 |
| Hartford, CT | 0.7 | 3.4 | 9.8 | 4.3 | 4.4 | 12 | 7.6 |
| NYC, NY | 0.9 | 3.9 | Never[25] | 5 | 5.1 | Never[15] | Never[15] |
| Albany, NY | 0.6 | 2.9 | 7.8 | 3.8 | 3.8 | 9.3 | 5.2 |
| Concord, NH | 0.7 | 3.3 | 14 | 4.2 | 4.3 | 20.9 | Never[15] |
| Burlington, VT | 0.6 | 3 | 15.5 | 3.9 | 3.9 | Never[15] | Never[15] |
| Worcester, MA | 0.7 | 3.2 | 10 | 4.1 | 4.1 | 13 | 7.3 |
| **Location** | **15 Year Total Cost, USD** | | | | | | |
| Portland, ME | $33,625 | $35,575 | $36,728 | $31,250 | $31,300 | $31,833 | $28,876 |
| Hartford, CT | $36,889 | $38,839 | $42,729 | $34,435 | $34,485 | $38,063 | $36,433 |
| NYC, NY | $37,240 | $39,190 | $49,964 | $35,061 | $35,111 | $45,703 | $42,441 |
| Albany, NY | $39,081 | $41,031 | $43,119 | $36,444 | $36,494 | $38,444 | $36,231 |
| Concord, NH | $39,365 | $41,315 | $49,640 | $36,710 | $36,760 | $44,585 | $46,941 |
| Burlington, VT | $43,153 | $45,103 | $55,576 | $40,244 | $40,294 | $50,106 | $56,924 |
| Worcester, MA | $37,405 | $39,355 | $44,226 | $34,913 | $34,963 | $39,809 | $37,087 |

*Table 8 - Simple Payback and 15 Year Total Cost*

# comparing liquid biofuels with natural gas

This analysis compares the relative energy resources consumed and GHG impacts associated with pipeline natural gas, ultra-low sulfur heating oil, and soybean-based biodiesel blends (B5, B20 and B100) used for residential space heating boilers and water heating. Consideration was given not only to impacts at the point of ultimate energy consumption -- i.e., the efficiency of use at the residence -- but also to those impacts associated with the production, conversion, transmission and distribution of energy to the household. The analysis presents the total resource energy requirements and fuel cycle GHG emissions for heating services supplied by high efficiency natural gas, heating oil and biodiesel products based on typical residential usage.

## analysis

The three main GHG emissions from the oil and natural gas fuel cycle are methane ($CH_4$), carbon dioxide ($CO_2$), and nitrous oxide ($N_2O$). While $CO_2$ is considered the primary contributor to global warming, methane and nitrous oxide also have significant global warming potential. The analysis estimated the GHG emissions of each fuel at each stage of the fuel cycle, from well to burner-tip, in terms of $CO_2$ equivalent, or

[24] Local heating oil (IEA, NYSERDA, CT.GOV, New England Oil, Maine Oil, 2016) and electricity (Electricity Local, 2016) prices assumed for each location. The table shows that there is a significant range in heating oil ($2.049 to $2.753/gallon) and electricity ($0.0694 to $0.2321/kWh) pricing in the Northeast. This variation in pricing impacted the savings potential for each location. Higher fuel prices will result in increased savings per gallon of heating oil saved. Variation in electricity cost impacted savings because the AHP and EHP systems use more electricity than the boiler and furnace systems.

[25] Never indicates payback over 25 years

$CO_2e$ [26]. This 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[27]. The individual GHG sources along the fuel cycle were classified into three categories: vented, fugitive, and combustion emissions.

- Vented emissions are the designed and intentional equipment vents to the atmosphere. For example, pneumatic devices are engineered to leak small amounts of natural gas when in operation and these emissions are classified as vents.
- Fugitive emissions are the unintentional equipment leaks. For example, leaks from flanges and valves at a wellhead are classified as fugitives, and
- Combustion emissions are the emissions associated with the combustion of fuel. Combustion emissions may be for either energy use or non-energy use. Energy use refers to any combustion of fuel where energy is extracted for beneficial use, such as natural gas used as fuel and combusted in compressor engines and heaters. Non-energy combustion refers to any combustion of fuel in flares where there is no energy extraction.

## *assessing Biodiesel – Land Use Change*

Calculating biodiesel GHG impact requires understanding that the cultivation of energy crops on agricultural land can lead to an indirect or induced land use change (ILUC). The impact of ILUC is that agricultural land now used for the energy crop area is no longer available for food and feed production, and cultivation for these purposes may be moved to other, possibly new, cultivated areas. To prevent the deforestation of tropical rainforests potentially caused by the cultivation of energy crops, there are calls to create induced land use change (ILUC) factors, which are then added to the carbon footprint of biofuels as additional $CO_2$ emissions. This approach is very controversial, especially since indirect land-use changes are extremely difficult to quantify. It is, for example, generally not known whether a replacement foodstuff is grown specifically due to a certain land use change or, if it is grown, in the exact location. To achieve this, all regional and global trade relations would theoretically have to be included in the evaluation. The range of different studies and models are correspondingly broad. Nevertheless, this report includes the best available ILUC factors when presenting this data[28].

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[26] $CO_2e$ ($CO_2$ equivalent) emissions include $CO_2$, $N_2O$ and methane all calculated for their global warming potential (GWP) in terms of a $CO_2$ baseline = 1. This analysis used the recognized 100-year GWP time horizon with carbon feedback in evaluating the relative GWP of methane (36 x $CO_2$) and nitrous oxide $N_2O$ (298 x $CO_2$) and recognized 20-year GWP time horizon in evaluating the relative GWP of methane (85 x $CO_2$) and nitrous oxide $N_2O$ (264 x $CO_2$)

[27] In the mid-90s, policymakers for the Kyoto Protocol chose a 100-year time frame for comparing greenhouse gas impacts using GWPs. The choice of time horizon determines how policymakers weigh the short- and long-term costs and benefits of different strategies for tackling climate change. According to the Intergovernmental Panel on Climate Change, the decision to evaluate global warming impacts over a specific time frame is strictly a policy decision—it is not a matter of science: "the selection of a time horizon of a radiative forcing index is largely a 'user' choice (i.e. a policy decision)" [and] "if the policy emphasis is to help guard against the possible occurrence of potentially abrupt, non-linear climate responses in the relatively near future, then a choice of a 20-year time horizon would yield an index that is relevant to making such decisions regarding appropriate greenhouse gas abatement strategies." Short-lived pollutants that scientists are targeting today, which actually warm the atmosphere, are methane and hydrofluorocarbons (HFCs) which are greenhouse gases like $CO_2$, trapping radiation after it is reflected from the ground. There is a growing scientific movement to calculate GHG emissions potential based on the short-term carbon forcing gases.

[28] Awgustow A, et al, "Production of GHG-reduced liquid fuels", September 21 2017, TU Bergakademie Freiberg for Institut für Warm und Oeltechnik IWO e.V.

## summary of results

- It is critical to compare the energy and emissions performance of fuels in terms of the full fuel-cycle and actual (as opposed to rated) efficiencies at the point of use.
- Combustion of ultra-low sulfur heating oil (< 15 ppm sulfur) is the equivalent of natural gas combustion with respect to $SO_2$, NOx and particulates.
- Heating oil, with modest levels of soybean-based biofuel blending (20 to 25 percent), remains a competitive alternative to natural gas for residential heating in terms of overall energy use and GHG emissions based on conventional 100-year atmospheric lifetime calculations.

  To illustrate, Boston is one of six cities where boiler performance and GHG emissions were calculated for natural gas, heating oil and heating oil/biofuel blends. Figure 3 shows that, for Boston, the GHG emissions of a typical replacement residential oil boiler using a B20[29] blend are equivalent to the emissions from a typical replacement natural gas boiler based on 100-year atmospheric lifetime calculations without considering induced land use change impacts. Blends up to B100[30] have been used in the field today, with B20 blend being quite typical.

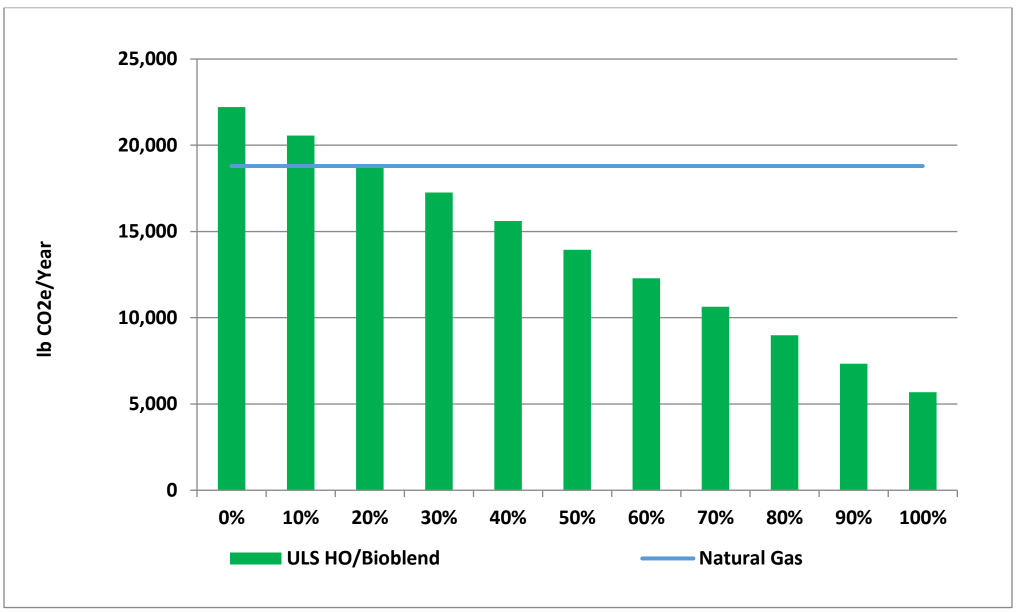


*Figure 3 - 100 Year Atmospheric Lifetime with Feedback and without Indirect Land Use*

- Heating oil with even lower levels of biofuel blending (7 percent) remains a competitive alternative to natural gas for residential heating in terms of overall energy use and GHG emissions based on carbon forcing 20-year atmospheric lifetime calculations.

  Figure 4 shows that, for Boston, the GHG emissions of a typical replacement residential oil boiler using a B7[31] blend of heating oil are equivalent to the emissions from a typical replacement natural gas boiler

[29] B20 is 20% biodiesel and 80% ultra-low sulfur diesel
[30] B100 (100% biodiesel) has been applied in the field, but very special care must be taken with respect to cold flow properties.
[31] B7 is 7% biodiesel and 93% ultra-low sulfur diesel

based on 20-year atmospheric lifetime calculations without considering induced land use change impacts. Again, blends up to B100[32] have been used in the field today, with B20 blend being quite typical.

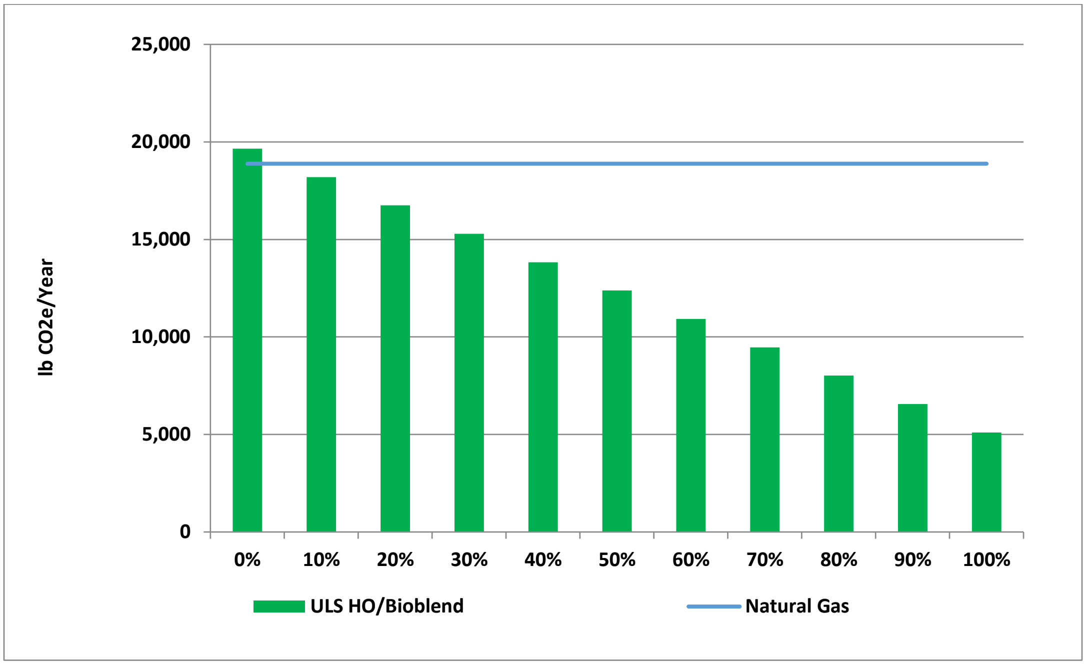


*Figure 4 - 20 Year Atmospheric Lifetime without Indirect Land Use*

- The heating oil industry is actively incorporating existing biofuels into product blends in order to reduce GHG emissions and is working with suppliers to ensure these product blends are compatible with existing and new oil heating equipment.
- Advanced biofuels, such as ethyl levulinate, show even greater promise at reducing the GHG footprint of heating oil blends, well beyond the levels of competing fuels such as natural gas. Figure 5 illustrates the total annual GHG emissions from providing heating and hot water services to a representative 2,500 square foot house in the Boston area for typical replacement boilers being sold today using a blend of ULS heating oil, biodiesel and ethyl levulinate as fuel. A blend of just 10% biodiesel, 10% ethyl levulinate and 80% ULSD has lower annual GHG emissions than natural gas. The graph shows that increasing biodiesel and ethyl levulinate blend content significantly improves GHG emission compared to natural gas. In fact, because of the feedstock used, production techniques and multiple usable products, ethyl levulinate actually enables the potential for reduction of GHG beyond a neutral point – a blend of 79% soybean-based biodiesel and 21% ethyl levulinate contributes zero total fuel cycle GHG emissions, based on using the 100-year atmospheric lifetime global warming potential (GWP) factors with carbon feedback.

[32] B100 (100% biodiesel) has been applied in the field, but very special care must be taken with respect to cold flow properties.

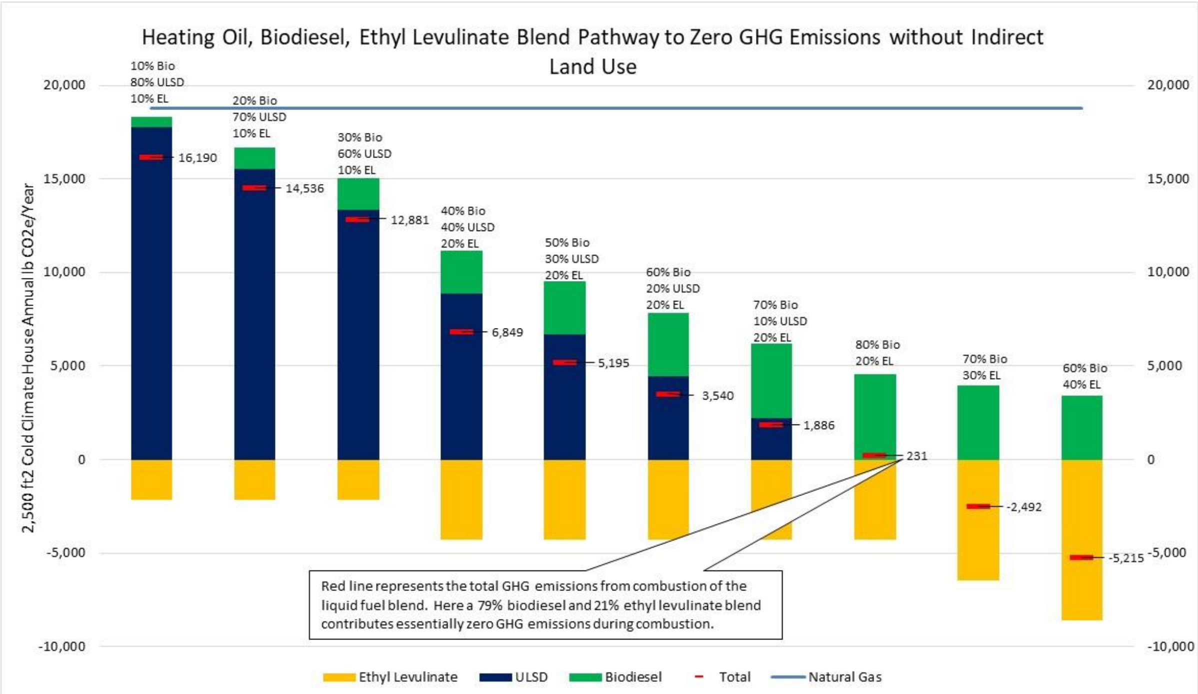


*Figure 5 - Heating System Emissions Comparison with Advanced Biodiesel Blends*

## residential heating policy implications

There are discussions among policy makers about converting the existing, primarily fossil-fueled residential energy infrastructure to electricity in order to meet GHG emissions goals. Such a conversion would require an unparalleled increase in renewable electricity production to meet increased demand without increasing GHG emissions from the power sector. Wind and solar energy are variable resources, and increased reliance on these resources opens the question of how to provide power if the immediate output of these resources cannot continuously meet instantaneous demand. The primary options to address this issue are to (i) curtail load (i.e., modify or fail to satisfy demand) at times when energy is not available, (ii) deploy large amounts of energy storage, or (iii) provide supplemental energy sources that can be dispatched when needed. It is not yet clear if it is possible to curtail loads, especially over long durations, without incurring large economic costs. There are no electric storage systems available today that can affordably and dependably store the vast amounts of energy needed to reliably satisfy demand using expanded wind and solar power generation alone. These facts have led many analysts to recognize the importance of maintaining a broad portfolio of electricity generation technologies, including low-carbon, high efficiency fossil-fueled sources, that can be dispatched when needed.

In addition to technical limits on the sole reliance of renewable resources to meet the increased demand of economy-wide electrification, there are economic limits. The costs of expanding renewable capacity to meet this increased demand would be significant. Added to that would be the equally significant cost of expanding the electric transmission and distribution system. The Electric Power Research Institute (EPRI) evaluated both technical and economic limitations to electrification in its recent U.S. National Electrification Assessment.[33] EPRI concluded that there are significant cost and technology questions about

[33] U.S. National Electrification Assessment, Electric Power Research Institute, April 2018,

the ability to convert more than 47% of end-use energy use to electricity even under the most aggressive scenario. It seems clear that ultimate decarbonization of the economy will require a mix of electrification in areas where technology and costs can support such conversions, and deployment of high efficiency, low carbon fossil-fuel end-use alternatives in many other regions.

Domestic liquid fuels have the potential to play an important role in the future national energy mix, with or without increased electrification. The high energy density of liquid fuels makes transporting and storage simple and cost-efficient, and technical advancements in biofuels and technology can provide low carbon energy services at the point of use, unburdening the electricity supply and transmission system, supporting grid stability and enhancing energy resilience:

- Advanced biofuel blends with ultra-low sulfur diesel heating oil can become a clean and cost-effective net zero GHG emissions residential heat source alternative before 2050.
- Development of new, renewably fueled, thermally driven (heating only) heat pump technologies promise to rival source energy efficiencies of electric heat pumps and provide greater comfort at low ambient temperatures.

# *pathway to energy efficiency*

**Details do matter. New homes are different from existing homes and boilers are different from furnaces and heat pumps.**

Energy efficiency is a significant factor in achieving carbon reduction. The less fuel used in generating electricity or in directly fueling appliances, the lower the carbon emissions. One important aspect with respect to carbon emissions is that site efficiency (energy used in the home like kilowatts and Btus) must be considered in evaluating different heating fuels. More importantly for electricity, the source energy and impact of demand fluctuations on efficiency, grid reliability and total carbon emissions must be considered when comparing heating energy sources.

**Boilers:** typical fossil fueled boilers sold today, to existing homes, are 82-86% efficient. This is largely because the hydronic loops were designed for high temperatures. New hydronically heated homes can use condensing boilers at 96% efficiency.

**Furnaces:** all homes can take advantage of higher cost modern condensing furnaces at 96% efficiency.

**Electric Heat Pumps:** an electric heat pump with a site-based COP of 3.2 heating has a source-based COP of 1.09[34]. Note: delivered electricity is 34 HHV[35] percent efficient when measured from fuel to the power plant to electricity delivered to the electric socket in your home.

**Thermal Heat Pumps:** an exciting new technology, in late stage development, is the air-sourced thermally-driven heat pump. This technology would, in today's world, deliver heating at a source coefficient of performance (COP) of about 1.3. Thermal heat pumps, when fully developed can be integrated with existing and new home furnaces and boilers. And their coefficient of performance and delivered air temperature would not drop precipitously during cold weather like electric heat pumps.

[34] Site efficiency 3.2 COP x 34% efficient electric grid = source efficiency of 1.09
[35] Higher Heating Value

# thermal heat pump

A thermal heat pump (THP) uses the heat energy from combustion to drive a thermodynamic cycle that can produce heating or cooling (or both at the same time). Most often used for air-conditioning for more than 100 years, the cycle is actually much better (more efficient) for heating than cooling. Absorption cycles are a thermally driven cousin to conventional vapor compression cycles driven by electric energy.

In heating mode, thermal energy (at a relatively low temperature) from outside ambient air enters the heat pump through the evaporator coil, and is raised to a higher useful temperature using the thermodynamic leverage of heat from combustion. Energy from both the colder outdoor air and a liquid fuel is combined and delivered to the heating target (building or water). Thus, the total useful energy is greater than the fuel energy alone, resulting in a net fuel-input efficiency greater than 100% - breaking the so-called "100% barrier". In addition, because approximately 35% of the delivered heat energy comes from the outdoor air, the THP is a partially renewable energy technology, and is recognized as such in some regulatory systems.

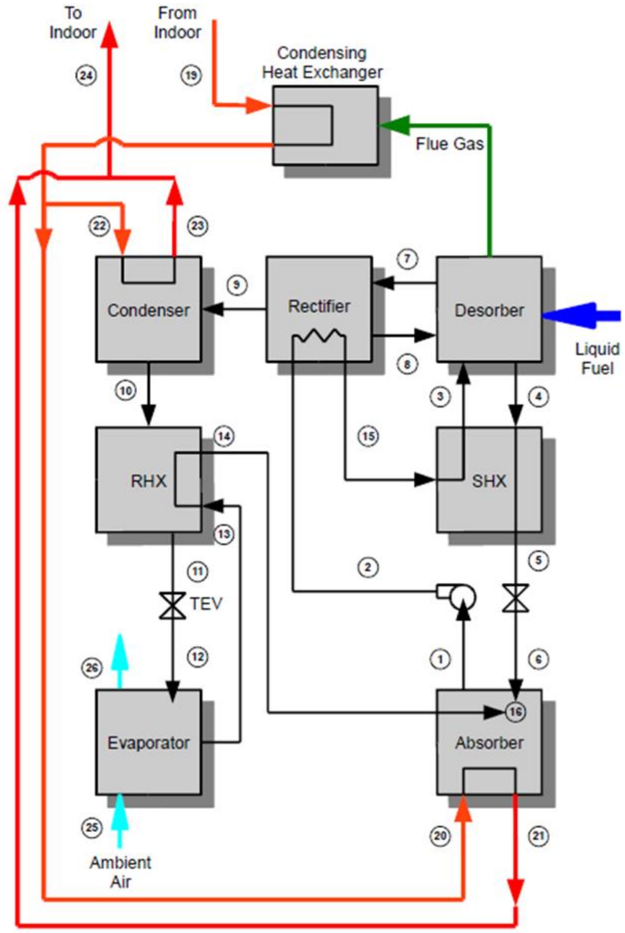


*Figure 6 - The Single Effect Ammonia-Water Cycle*

A THP is comprised of a set of specialized heat exchangers and small custom pump, all of which circulate the refrigerant and absorbent pair. This set of heat exchangers and pump is often called a "sealed system" or Thermal Compressor. To complete the end-user heating product, certain controls, fans, motors, piping and a surrounding cabinet must be added to the Thermal Compressor.

The ammonia-water absorption cycle (Figure 6) heats a heat-delivery fluid (water or glycol-water mixture) through a heat-exchanger. The ammonia-water mix is separate, always remains sealed inside the Thermal Compressor, and is NOT circulated throughout the building or in hot water tanks. Stone Mountain's overall design and the separate use of water as a "working" or heat-delivery fluid enables many positive attributes for building space and water heating:

- The main heating equipment can sit outside next to the building, freeing up space inside tight mechanical rooms.
- Liquid fuel-fired heating COP's range between 110% and 160% depending on the outside and water temperatures.
- Superior performance at very low ambient temperatures compared to electric heat pumps.

- Ammonia is a natural refrigerant with a greenhouse gas impact and ozone depletion level of zero. It is not under threat of being phased out as are the most common vapor compression fluids used in electric heat pumps and air conditioning.
- Combination space and domestic hot water heating systems can be provided from the same unit.
- The cycle can also be used for cooling (either simultaneously or separately) if there is an appropriate cooling load (e.g. hospitality and restaurants).
- A THP can easily be retrofitted to existing forced air heating systems by tying the heat-delivery fluid (water) to the existing central blower or air-handler.
- The THP's heat-delivery fluid can easily be routed and divided between multiple fan-coil units for zoned heating applications, including baseboard registers, 4-pipe systems, and in-floor radiant heating applications.
- The GHAP cycle operates at relatively low pressure (below 400 psi), resulting in small heat exchanger wall thicknesses with low materials and production costs.
- Ammonia has a high enthalpy of vaporization (hfg) and thermal conductivity, making it suitable for low flow rates, compact heat exchangers, and smaller pump sizes.
- Expensive stainless steel or copper is not needed for heat exchanger construction.

**Cycle:** The majority of $NH_3$-$H_2O$ heat pump research and technology development over the past 30 years has focused on high efficiency cooling cycles (such as GAX), using exotic proprietary heat and mass transfer surfaces. Impact on the market has been negligible, as the manufacturing cost to execute these complicated cycles and heat exchangers has out-paced the energy cost savings due to the efficiency improvements. Additionally, advances in electric vapor compression for cooling have outpaced gains made by absorption.

Instead of emphasizing the cooling side, Stone Mountain's focus is on heating applications, which allows use of the much simpler single-effect cycle. The maximum temperature of the single-effect cycle is also below the point where metal corrosion becomes a reliability concern.

**How It Works:** A schematic for a single-effect heating cycle is shown in Figure 1. Ammonia is vaporized from ammonia-water solution at the high side pressure using fuel combustion heat applied to the desorber. $NH_3$ is then purified in the rectifier and condensed in the hydronically cooled condenser. The liquid ammonia is evaporated in the ambient air-coupled evaporator after expanding to the low-side pressure in the thermal expansion valve (TEV). Energy from the outside air enters the cycle through the evaporator coil. The vapor is re-absorbed into the water solution in the hydronically cooled absorber (HCA) before being pumped back to the high pressure desorber by a small positive displacement pump.

The thermal energy delivery loop (i.e. the "working fluid") is coupled to the inside conditioned space via an air handler or radiant system. This loop takes its heat via energy extracted from the condenser and absorber. Generally, energy from the condenser equals the energy harvested from the outdoor air in the evaporator, and energy from the absorber equals the fuel energy input to the desorber. Condensing combustion efficiencies are obtained using the cool hydronic fluid returning from the indoor space.

**Thermal Compressor:** The "sealed system" or Thermal Compressor is a set of specialized heat exchangers and a small pump that circulates the ammonia-water solution. The components that comprise the Thermal Compressor (Figure 7) include the liquid fuel-fired desorber, absorber, rectifier, solution heat exchanger (SHX), refrigerant heat exchanger (RHX), evaporator coil, condenser, and solution pump. All of the heat exchangers are fabricated using low-cost thin-wall tubing. The solution pump is a specialized pump designed specifically for this application.

*Figure 7 - Thermal Compressor*

**Balance of System:** By itself, the Thermal Compressor does not provide a fully functional heat pump and several components and sub-systems need to be added. These added components and features can be tailored to match the market segment or application. However, the Thermal Compressor is identical across all applications.

**Applications Configurations:**

Figures 8 – 10 provide three typical configurations for boiler, furnace and combination boiler/furnace and domestic hot water heating.

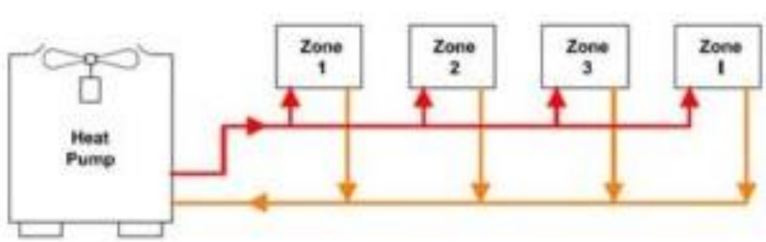


*Figure 8 - Hydronic*

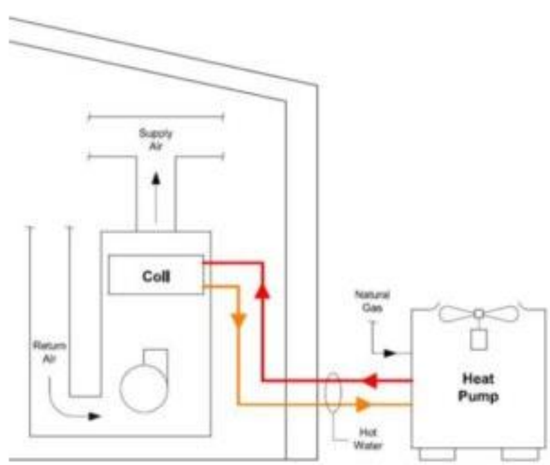

***Figure 9 - Forced Air***

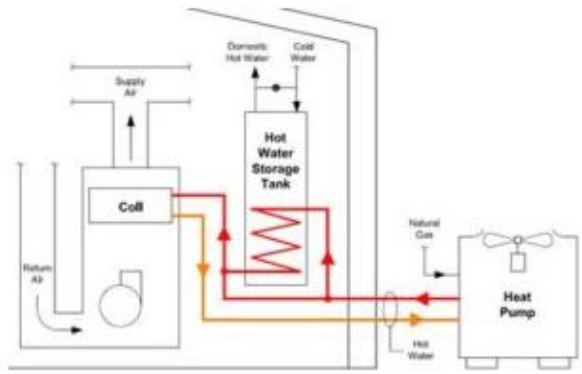


***Figure 10 - Combi***

# *pathway to low carbon fuels*

*"Several reduced carbon liquid fuels in the field and under development would offer an almost drop-in replacement for heating oil, overcoming the significant cost and practical issues of replacing an entire heating system, as well as, upgrading expensive energy delivery networks. There is also a well-developed and competent network of supply, installer and servicing businesses already in place who could continue to support consumers at little or no additional cost."*

*Dr. Thomas Butcher, Brookhaven National Laboratory*

Based on a peer reviewed site energy performance and emissions study[36], Tables 1 and 2 show that moving from non-condensing appliances to condensing appliances and finally to thermal heat pump technologies significantly reduces carbon emissions. Furthermore, shifting to low carbon fuel blends dramatically reduces greenhouse gas emissions. Looking forward to the industry's 2035 implementation goal, Tables 1 and 2 show that in the case of boiler and furnace-based home heating and cooling systems, all three liquid fuels-based heating technologies coupled with three specific fuel approaches [100% biodiesel and ultra-low sulfur diesel (ULSD), biodiesel and one advanced biofuel (ethyl levulinate)] reduce carbon emissions greater than cold climate electric heat pumps using electricity from low emissions advanced CCCTs. The yellow cells indicate liquid fuel pathways to no carbon combustion. Note that the remaining carbon emissions for liquid fuels pathways in the last two columns are from the electric grid (marginal CCCT production) for cooling and ancillary equipment. Zero net carbon is from combustion.

| | 2018 | 2025 | 2030 | 2035 | | |
|---|---|---|---|---|---|---|
| | ULSD | B20 | B40 | B100 | ULSD40, B50 & EL10 | 1/3 ULSD, 1/3 B100 & 1/3 EL |
| Standard Boiler, 14 SEER Minisplit AC | 0% | 14% | 29% | 71% | 95% | 95% |
| Condensing Boiler, 14 SEER Minisplit AC | 14% | 26% | 39% | 74% | 95% | 95% |
| Heating only LF-AHP and 14 SEER Minisplit | 35% | 43% | 54% | 78% | 93% | 93% |
| 14 SEER Minisplit Heat Pump with Boiler Back-up | 25% | 34% | 46% | 70% | 85% | 85% |
| 18 SEER 5 RT Cold Climate Heat pump with Boiler Backup | 57% | 59% | 64% | 66% | 69% | 69% |

***Table 9 - Percent Reduction in $CO_{2e}$ Annual Emissions from Heating and Cooling a Single-Family Home (Hydronic-Cold Air)***

| | **2018** | **2025** | **2030** | **2035** | | |
|---|---|---|---|---|---|---|
| | ULSD | B20 | B40 | B100 | ULSD40, B50 & EL10 | 1/3 ULSD, 1/3 B100 & 1/3 EL |
| Non-Condensing Furnace, 14 SEER Central AC | 0% | 14% | 28% | 72% | 83% | 87% |
| Condensing Furnace, 14 SEER Central AC | 14% | 26% | 38% | 75% | 84% | 88% |
| Heating only LF-AHP and 14 SEER Central AC | 38% | 47% | 55% | 81% | 87% | 89% |
| 14 SEER Electric Heat Pump with Resistance Back-up | 28% | 28% | 28% | 41% | 28% | 28% |
| 18 SEER 5 RT Cold Climate Heat pump with Resistance Backup | 58% | 58% | 58% | 66% | 58% | 58% |

***Table 10 - Percent Reduction in $CO_{2e}$ Annual Emissions from Heating and Cooling a Single-Family Home (Hot-Cold Air)***

Liquid fuels-based heating technologies (boilers, furnaces and thermal heat pumps) coupled with three already identified fuel approaches in the field and under development today reduce carbon emissions greater than cold climate electric heat pumps using a future grid projected electricity from low emissions advanced combined cycle combustion turbines.

[36] "Energy, Cost and CO2e Analyses of Reversible, Hybrid and Heating- Only LF-AHP in the Northeast", Christopher Keinath, PhD, Thomas Butcher, PhD and Michael Garrabrant, PE, ASHRAE, June 2018