Annual CO_2e Emissions from Residential Heating Systems

in New Jersey

Technical Notes by Raymond J. Albrecht PE

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Biography for Raymond J. Albrecht PE

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Consulting environmental engineer in the subject area of renewable heating technologies and power generation. Technical specialties have included electric and thermally-driven heat pumps, solid biomass and liquid renewable fuel-fired thermal systems, and liquid renewable fuels for power generation. Have performed work for manufacturing companies, trade organizations and environmental agencies relating to equipment design, fuel utilization, regulatory permitting, emissions testing, and life-cycle analysis. Member of the ISO New England Planning Advisory Committee and active with the ISO New England Load Forecasting Committee. Spent 30 years as lead technical staff person for heating technology and fuels R&D at the New York State Energy Research and Development Authority (NYSERDA). NYSERDA work also included field testing of first ground-source heat pump installation in northeastern United States in the early 1980s. Principal of Raymond J. Albrecht LLC for the past 16 years.

Graduate of Cornell University with a Bachelor of Science degree in engineering and a Master of Science degree in Theoretical and Applied Mechanics. Life Member of the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) and past chairman of ASHRAE Technical Committee 6.10 for Fuels and Combustion. Received the ASHRAE Distinguished Service Award in 2015. Licensed professional engineer (No. 056935) in New York. Served as a 1st Lt (Infantry) in the United States Army during 1970-80 including active plus reserve duty. Graduate of the US Army Infantry Officer School at Fort Benning, Georgia. Fulfilled my active reserve obligation in northeastern Kenya near the Somali border.

SUMMARY

According to the most recent Argonne National Laboratory GREET model, biodiesel has an approximately 64 to 84 percent lower carbon intensity than traditional heating oil depending on feedstock used for production. Continuous reductions in biodiesel carbon intensity are being achieved through improvements in agriculture plus the use of renewable energy in production facilities.

Each 1% biodiesel blend increase in heating oil cuts carbon intensity by the equivalent of the installation of $392 million of next generation, more efficient heat pumps. This means that scaling up blend levels will have a more immediate and higher impact than waiting for significantly more renewable grid power to come on line or for waiting for cold climate heat pumps to be installed at scale and at future higher levels of efficiency. This increases to $ 2 billion per 1% biodiesel blend increase when accounting for costs necessary to provide renewable power from some solar, offshore wind, 48 hours of battery backup power, and transmission and distribution upgrades.

Burners and boilers with B100 (100% biodiesel) firing capability have recently been introduced to the residential and commercial building market by major equipment manufacturers.

The efficiency of cold-climate air-to-air heat pumps in the field has been documented as 20% to 30% below current manufacturer ratings.

Cold-climate heat pump technologies currently achieve only about 10 percent greenhouse gas savings, compared to traditional heating oil, when upstream emissions of CO_2 and methane are included in life-cycle accounting for electricity in the PJM control area. The high carbon intensity of electricity generation within the PJM control area, due to the extensive use of coal as well as lower-efficiency, simple-cycle gas-fired power plants, has limited the net greenhouse gas savings accomplished by existing heat pumps. Future generation heat pumps are under development with support from the US Department of Energy Heat Pump Challenge program and are expected to increase heat pump savings to approximately 25 percent in the PJM territory.

Multiple field test studies indicate very low heat pump utilization by homeowners below 30°F. Since heat pump power demand increases dramatically as the outdoor temperature drops below freezing, due to increasing Btu/hr heat load plus decreasing heat pump efficiency, homeowners have shown an increased drop-out rate under decreasing temperatures. The studies consistently indicate that approximately 60 to 80% of homeowners shut down their heat pumps for the winter starting in October or November.

Hybrid heating systems, comprised of biodiesel-fired boilers and future generation, cold-climate heat pumps, would also be able to achieve higher CO_2e savings than possible with just heat pumps by avoiding the use of electricity during periods of high carbon intensity and cost for the grid. For this reason, new heat pump customers should be encouraged to retain their fuel-fired boilers, to be operated with renewable fuels.

A boiler or furnace can be thought of as a high efficiency peaker plant for a home. Although peaker plants can provide reliable and affordable electric generation at times of wind drought and low solar production, they are extremely low efficiency and typically produce higher NOx emissions than baseload generation units.

During extreme cold weather, the COP of a cold-climate heat pump can drop to 1.50 while the corresponding generation efficiency can be 30% or even less. The net fuel-electric-heat conversion process can thus be only 45% compared to an 87% or higher efficiency boiler. This results in a near doubling of the natural gas pipeline supply required for power generation for heat pumps compared to operation of gas-fired boilers. Such dramatic increase in natural gas demand would be problematic in exceeding the capacity of natural gas infrastructure.

At approximately B40 (40%) and higher biodiesel blend levels the carbon intensity of heat pump operation in the PJM region is higher than for boiler operation during nearly all hours of the heating season. At B40 biodiesel blend levels and higher, until the construction of approximately 10,000 MW of offshore wind capacity dedicated solely to operation of heat pumps, there is no environmental justification in New Jersey for the use of a heat pump. 20,000 MW of dedicated, offshore wind nameplate capacity, beyond what is necessary for the existing grid, would be necessary to cover the entire winter thermal load of residential and commercial buildings in New Jersey.

10,000 MW of offshore wind nameplate capacity, dedicated to the use of heat pumps, would enable heat pumps to be nearly equal in performance to soy-based, B100-fired boilers in residential and commercial buildings, though still almost double in carbon intensity compared to waste-based, B100-fired boilers. 20,000 MW of dedicated, offshore wind nameplate capacity would be necessary to cover the entire winter thermal load of residential and commercial buildings in New Jersey. Marginal New Jersey generation will remain nearly 100% fossil-based until at least 5,000 to 10,000 MW of offshore wind capacity has become fully operational, at which point there will begin to occur some very occasional hours, mostly during April, when renewable electricity reaches the margin of New Jersey grid load.

Offshore wind generation-transmission-distribution infrastructure would drive the levelized capital cost of electricity to just over $1 per kWh according to analysis of long-term costs involved. This price could drive energy poverty and have severe negative economic impact at nearly six times the current New Jersey residential electricity rates of $0.17/kWh. This price is the equivalent of over $42 per gallon of fuel oil on a per unit of energy basis.

$915 billion for 20,000 MW of heating loads is estimated for capital cost for renewable electricity and heat pumps over a 30 year timeline, with about 2/3 allocated for residential and 1/3 allocated for commercial installations. For the residential component, this amounts to $200,000 per home which consists of $40,000 for heat pump installation and overhauls at 10 and 20 years after original installation and about $160,000 for wind and solar generation/battery storage/distribution infrastructure. This does not account for costs of capital, operation, maintenance, insurance, taxes, etc.

Battery storage has an extremely high cost per unit of stored energy. At the residential scale, an $8,500 to $11,500 Tesla Powerwall can store about 11.5kWh or $1.95 worth of electricity at $0.17/kWh. Substantial battery storage capacity would be necessary to enable heat pump operation during prolonged periods of heavy thermal loads and low renewable electricity output. For a typical peak demand of 6 kW for a full-capacity heat pump system, with 48 hour duration, this translates into a utility-scale battery storage cost of about $115,000 per residential unit; although this is extremely expensive, it is less than half the cost of a residential battery equivalent.

Existing air-to-water heat pumps show higher carbon intensity characteristics than traditional heating oil due to the high carbon intensity of the PJM grid. Air-to-water, hydronic heat pumps operate at approximately 20 percent lower efficiencies than their air-to-air counterparts due to their required higher supply temperatures. . Future generation air-to-water heat pumps, even with significant performance improvements, are expected to offer only modest environmental benefits to New Jersey.

New Jersey policy makers should evaluate the capital expenses that would be necessary for expansion of generation, transmission, battery storage and distribution capacity of renewable electricity for residential and commercial heat pumps. While a moderate, initial increase in electricity consumption by heat pumps can be met by existing generation, transmission and distribution infrastructure in New Jersey, the cost of a multi-fold expansion in grid loads will present an enormous economic and logistical challenge.

REFERENCES USED IN PREPARATION OF TECHNICAL NOTES

As the first step in preparation of these technical notes, I compiled and reviewed several key testing reports that have been published over the past ten years relating to actual field performance of cold-climate heat pumps. The reports are listed below and represent the most frequently cited literature that has been published on field performance of cold-climate heat pumps.

1) Commonwealth Edison Company (2020). Cold Climate Ductless Heat Pump Pilot Executive Summary. Chicago, IL. https://www.comedemergingtech.com/images/documents/ComEd-Emerging-Technologies-Cold-Climate-Ductless-Heat-Pump.pdf

2) ISO New England (2020), Final 2020 Heating Electrification Forecast. Holyoke, MA. https://www.iso-ne.com/static-assets/documents/2020/04/final_2020_heat_elec_forecast.pdf

3) The Levy Partnership/NYSERDA (2019). Downstate (NY) Air Source Heat Pump Demonstration. Albany, NY. https://static1.squarespace.com/static/5a5518914c0dbf4226cd5a8e/t/5d963d39f515f87c7bafe3ff/1570127329734/TLP+ASHP+Demo+Presentation+9.26.19.pdf

4) slipstream/Michigan Electric Cooperative Association (2019). Dual Fuel Air-Source Heat Pump Monitoring Report. Grand Rapids, MI. https://slipstreaminc.org/sites/default/files/documents/research/dual-fuel-air-source-heat-pump-pilot.pdf

5) Center for Energy and Environment (2018). Case Study 1 – Field Test of Cold Climate Air Source Heat Pumps. St. Paul, MN. https://www.mncee.org/MNCEE/media/PDFs/ccashp-Study-1-Duplex.pdf

6) Center for Energy and Environment (2018). Case Study 2 – Field Test of Cold Climate Air Source Heat Pumps. Minneapolis, MN. https://www.mncee.org/MNCEE/media/PDFs/ccashp-Study-2-MPLS.pdf

7) Center for Energy and Environment/Minnesota Department of Commerce, Division of Energy Resources (2017). Cold Climate Air Source Heat Pump. Minneapolis, MN. https://www.mncee.org/MNCEE/media/PDFs/86417-Cold-Climate-Air-Source-Heat-Pump-(CARD-Final-Report-2018).pdf

8) The Cadmus Group/Vermont Public Service Department (2017). Evaluation of Cold Climate Heat Pumps in Vermont. Montpelier, VT. https://publicservice.vermont.gov/sites/dps/files/documents/Energy_Efficiency/Reports/Evaluation%20of%20Cold%20Climate%20Heat%20Pumps%20in%20Vermont.pdf

9) The Cadmus Group/Massachusetts and Rhode Island Electric and Gas Program Administrators (2016). Ductless Mini-Split Heat Pump Impact Evaluation. MA and RI. http://www.ripuc.ri.gov/eventsactions/docket/4755-TRM-DMSHP%20Evaluation%20Report%2012-30-2016.pdf

10) Center for Energy and Environment/American Council for an Energy-Efficient Economy/Minnesota Department of Commerce, Division of Energy Resources (2016). *Field Assessment of Cold Climate Air Source Heat Pumps*. 2016 ACEEE Summer Study on Energy Efficiency in Buildings. https://www.aceee.org/files/proceedings/2016/data/papers/1_700.pdf

11) Steven Winter Associates, Inc./National Renewable Energy Laboratory (2015). Field Performance of inverter-Driven Heat Pumps in Cold Climates. VT and MA. https://www.nrel.gov/docs/fy15osti/63913.pdf

12) The Levy Partnership and CDH Energy Corp./NYSERDA (2014). Measured Performance of Four Passive Houses on Three Sites in New York State. Albany, NY. https://static1.squarespace.com/static/5a5518914c0dbf4226cd5a8e/t/5ab273db562fa758761512bd/1521644514205/Measured-Performance-of-three-Passive-Houses+%283%29.pdf

13) Tesla Powerwall 3 Specifications: https://service.tesla.com/docs/Public/Energy/Powerwall/Powerwall-3-with-Gateway-3-Installation-Manual-NA-EN/GUID-EC527BC7-4750-4425-BBC4-DB8C000339B3.html

14) Distillate Fuel Oil Consumption Estimates in 2022 (residential, commercial, industrial): https://www.eia.gov/state/SEDS/data.php?incfile=/state/seds/sep_fuel/html/fuel_use_df.html&sid=NJ

Additional field studies of cold-climate heat pump performance are known to be currently underway in Massachusetts and New York, but no information has been published relating to their scope or results.

Briefly, the published field-testing reports show a significant drop in actual, cold-climate heat pump performance compared to manufacturer efficiency ratings. Many of the reports showed efficiencies that were 20 to 30 percent lower than manufacturer ratings. Identified causes included excessive compressor cycling under part-load conditions, sub-optimal defrost operation, and airflow restrictions in indoor units. Some of the efficiency differences can also be attributed to manufacturer ratings that are based on weather data for USDOE Climate Zone 4, which covers much of the warmer, mid-Atlantic region.

The analyses provided in this document include, however, the expectation that cold-climate heat pumps will achieve 25% improvements in COP performance by the year 2030, in response to the USDOE Heat Pump Challenge, stricter State mandates, and general product improvements by manufacturers.

These technical notes are also based on resources from Argonne National Laboratory (GREET model), the National Renewable Energy Laboratory (NREL), and the United Nations Intergovernmental Panel on Climate Change (UN IPCC) 2019 guidance update on life-cycle analysis of fuels and power generation.

This paper refers to biodiesel as the alternate fuel to traditional petroleum based heating oil since that has been the baseline alternative for the past decade. In the past few years the production of renewable diesel has eclipsed that of biodiesel, in part because it is easier to scale renewable diesel production and its operational characteristics mirror diesel almost exactly. Both biodiesel and renewable diesel are made from the same feedstocks - vegetable oil, used cooking oil, tallow, etc., although they have a different manufacturing process. Renewable diesel has a slightly higher carbon intensity than biodiesel.

EVALUATION OF RESULTS FROM FIELD TESTING OF COLD-CLIMATE AIR-TO-AIR HEAT PUMPS

The efficiency of cold-climate air-to-air heat pumps in the field has been documented as 20% to 30% below current manufacturer ratings. Based on the data included in the reports listed above, I have put together a series of graphs that illustrate heat pump performance and homeowner characteristics noted regarding utilization of their heat pumps.

Figure 1 below shows heat pump Coefficients of Performance (COPs) vs. outdoor temperature, as derived from the field-testing studies. The graph includes average manufacturer ratings of heat pumps (red data curve) used in the various field studies listed above. The graph also shows actual field-testing results published in the listed reports. The graph shows how heat pump COPs vary with outdoor temperature. It is also possible to see the trend of actual performance falling below manufacturer ratings for most studies.

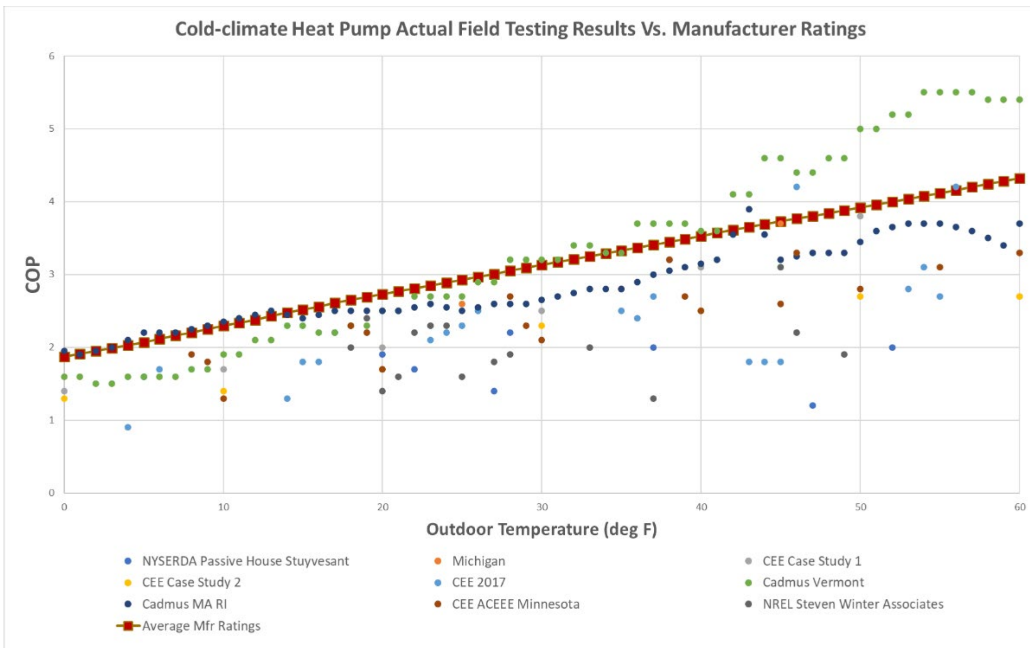


Figure 1. Cold-climate Heat Pump Actual Field-Testing Results vs. Manufacturer Ratings

The next graph shows annual, cold-climate heat pump COP field data as published by the references used for these technical notes. Annual cold-climate heat pump COPs indicate much lower field efficiency than manufacturer ratings. Higher reported field efficiency by VT and MA/RI field testing was due to low utilization in colder weather, thus skewing the statistics in favor of mild weather operation. Power demand graphs in the cited references indicate that the drop-out rate by heat pump owners increased as the outdoor temperature went down. As noted again, such homeowner behavior resulted in artificially high, measured annual COP values since the performance data was skewed toward warmer temperatures. The remaining studies generally entailed, by design or mandate, a high utilization factor through the winter, but then lower COP values.

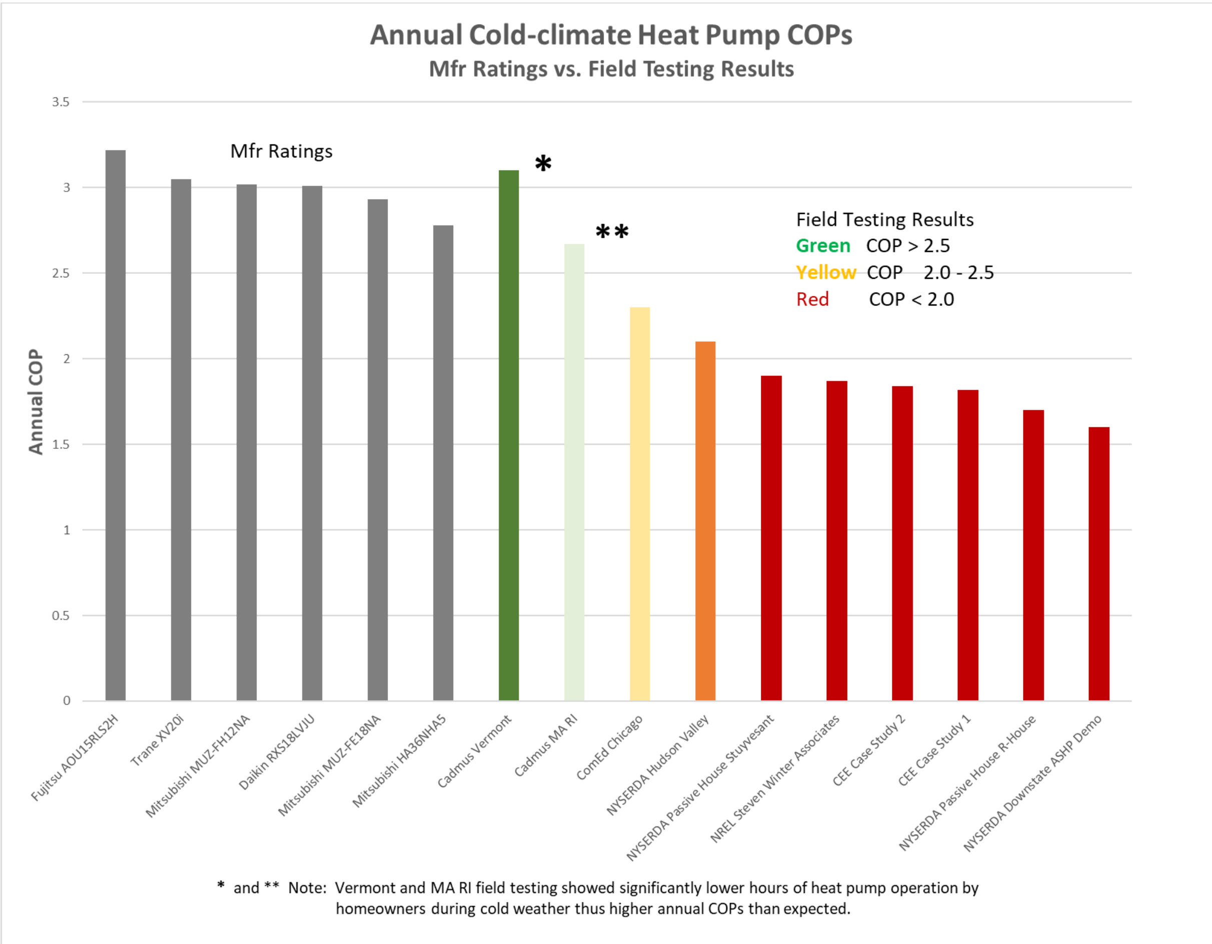


Figure 2. Annual Cold-climate Heat Pump COPs – Manufacturer Ratings vs. Field Testing Results

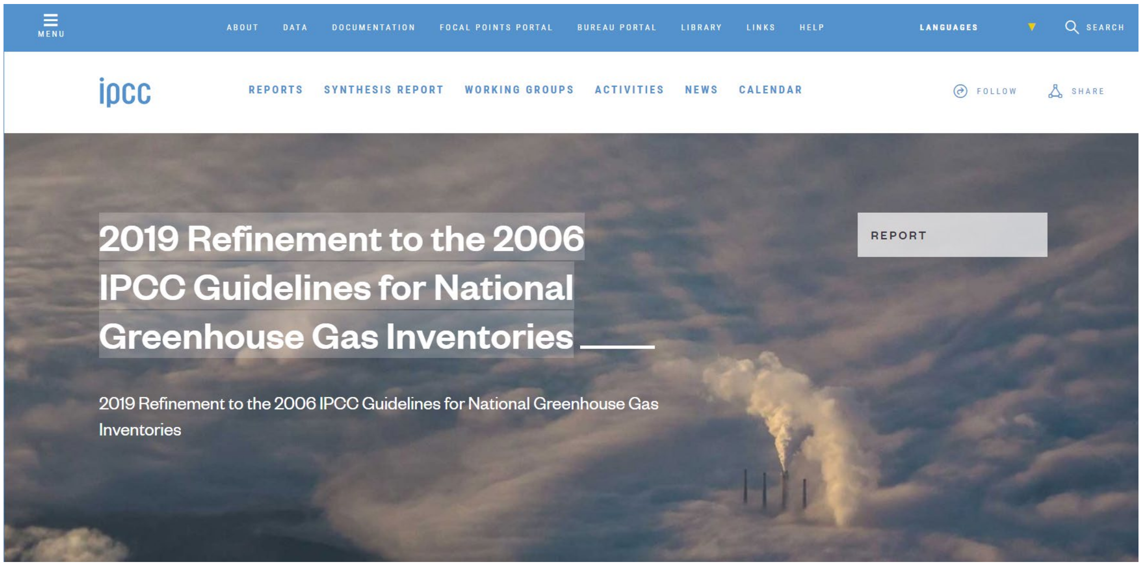
The manufacturer-rated seasonal COPs are generally around 3 or so, but the actual field-testing results show values in the range of about 1.6 to 2.3 (see color coding of graph bars), which translates into a loss of about 20 to 30% from manufacturer-rated values.

USE OF LIFE-CYCLE ANALYSIS OF ENERGY RESOURCES

It is of critical importance to use life-cycle analysis for energy policymaking. Onsite-based emissions evaluations generally fail to realistically address the real-world performance of the power grid. Argonne National Laboratory has been the host administrator of the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model for many years. The GREET model is a highly respected tool for evaluating the life-cycle characteristics of energy resources. Also, the United Nations Intergovernmental Panel on Climate Change (UN IPCC) has issued a series of updates to its comprehensive documentation relating to evaluation of energy resources.

The two major reference sources for life-cycle analysis used in the preparation of these notes include the Argonne National Laboratory GREET model, as well as the recent United Nations Intergovernmental Panel on Climate Change (IPCC) 2019 update report on guidance for life-cycle assessment protocols.

Both sources have recently addressed the problem of methane leakage in compounding the environmental impact of natural gas, including that used for power generation.



The UN IPCC is comprised of several thousand dedicated, respected scientists and engineers and is the premier organization for understanding and addressing climate change. It is understood that the UN IPCC 2019 guidelines are inconvenient to electrification advocates who might wish to assign a carbon intensity of zero to electricity used for heat pumps. But it is nevertheless incumbent on New Jersey policymakers to give due heed to the UN IPCC.

Both the GREET and IPCC references incorporate a methane leakage rate of approximately 0.7% of the volume of natural gas used for power generation. This accounts for methane loss during natural gas production and high-pressure transmission directly to power plants, but not through any local distribution piping.

If a 100-year timeframe is used for analysis (GHG factor for NG = 25 compared to CO2), the 0.7% methane leakage rate results in about a 9 percent increase in the carbon intensity of natural gas that reaches the power plant. If a 20-year timeframe is used, however, for analysis (GHG factor for NG = 84 compared to CO2), the 0.7% methane leakage rate results in a 20+ percent increase in the carbon intensity of natural gas used for power generation. There is growing support, and mandate in neighboring New York, for the use of 20-year greenhouse gas analysis since that reflects the timeframe that is now perceived as necessary for addressing climate change.

Combined with the impact of an approximate 10% increase in carbon intensity resulting from direct CO2 emissions during natural gas production and high-pressure transmission, the CO2e emissions characteristic of natural gas used for power generation is approximately 38% higher than the 117 lb/MMBTU onsite emissions figure frequently used, thus approximately 160 lb/MMBTU of fuel input.

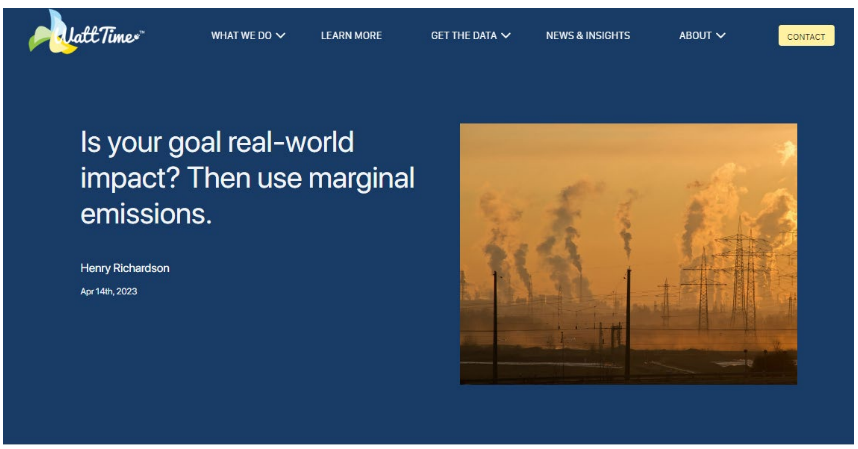
National Renewable Energy Laboratory (NREL) figures are used for evaluating wind power. NREL carbon intensity figures for offshore wind are sparse but indicate significant carbon content for fabrication and construction steps.

ACCOUNTING FOR TRANSMISSION AND DISTRIBUTION LINE LOSSES IN ANALYSIS OF GRID IMPACTS OF ELECTRIFICATION

When the electrical load increases in a building, the corresponding increase in necessary power generation will be greater due to line losses that occur between the powerplant and end-use sites. The average line loss in transmission and distribution networks will usually be somewhere in the range of 8 percent in the northeastern United States. This factor must be included in analyses of electrification and renewable power generation to maintain accuracy and integrity of results. The practical consideration is that the MW quantity of renewable power generation necessary to serve an increased grid load will be measurably greater than the load itself. It is noted here, additionally, that since line losses are an I^2R issue, with losses proportional to the square of the current flow rate, thus more than just a linear relationship, the incremental loss for increased grid loads during peak periods will typically be in the mid-teen percentage point range, with the exact figure defined as the calculus derivative of the governing, line-loss mathematical equation. The significant policy impact of increased line losses during peak grid load conditions, due to electrification, needs to be recognized and addressed by energy policymakers.

NEED FOR USE OF MARGINAL EMISSION RATES FOR ELECTRICITY

Energy policy makers need to recognize the need for using marginal emission rates for electricity, rather than average grid mix figures. The *WattTime* organization, a subsidiary of the Rocky Mountain Institute (RMI), has established a nationwide program to support efforts by commercial, industrial, and institutional customers to undertake energy measures which are based on how the grid actually works.



Everyone knows you can't manage what you don't measure. Less often pointed out? You can't manage what you measure *incorrectly.*

Corporate net-zero targets are at an all-time high, per reporting from *The Economist*. In fact, fully 75% of the world's largest corporate greenhouse gas emitters have set net-zero by 2050 (or sooner) targets, as of an October 2022 benchmarking analysis by Climate Action 100. This is good news.

Or... it should be. Of course, these targets will only genuinely decarbonize the atmosphere if they measure the real thing. And, unfortunately, that's not always what happens.

See https://www.watttime.org/news/is-your-goal-real-world-impact-then-use-marginal-emissions/ for more information on the need for using marginal emission rates for electricity.

A more detailed primer on the value of using Marginal Emission Rates is included in the appendix to this document.

Electrification advocates routinely use average, annual grid mix values for electricity, rather than marginal emission rates, in the calculation of environmental benefits from heat pumps and EVs. The use of average grid mix hides the fact that intentional grid load increases in New Jersey are met almost entirely by fossil-fired generation, with only limited, net CO_2 savings compared to the direct use of fossil fuels.

It is recommended that New Jersey policy makers perform hourly, marginal grid analyses, incorporating the principle of cause-and-effect logic, to better evaluate the impact of intentional grid loads.

Some policymakers claim that fossil-based electricity will soon disappear, even with increased grid loads, and therefore heat pumps/EVs will be fully renewable and thus the sole pathway toward decarbonization. To the contrary, USEPA AVoided Emissions and geneRation Tool (AVERT) software and WattTime data show that even if grid loads were to remain constant (i.e., no heat pump/EV market penetration), marginal New Jersey generation will remain nearly 100% fossil-based until at least 5,000 to 10,000 MW of offshore wind capacity has become fully operational, at which point there will begin to occur some very occasional hours, mostly during April, when renewable electricity reaches the margin of New Jersey grid load.

See also https://www.watttime.org/app/uploads/2019/03/Automated-Emissions-Reduction-Primer_RMI-Validation_June2017.pdf and https://www.watttime.org/marginal-emissions-methodology/ for multiple additional references on the use of marginal emission rates for energy analysis. WattTime collects and disseminates hourly, real-world data on grid performance to enable environmentally responsible electricity choices by large customers.

An additional article on the need for using marginal emission rates, entitled, "*US Policy Action Necessary to Ensure Accurate Assessment of the Air Emission Reduction Benefits of Increased Use of Energy Efficiency and Renewable Energy Technologies*", published in the Journal of Energy & Environmental Law, can be found at https://gwjeel.com/wp-content/uploads/2013/07/1-1-jh.pdf . The article is based on research funded by the US Department of Energy's Office of Energy Efficiency and Renewable Energy through its Clean Energy/Air Quality Integration Initiative.

POWER GRID ANALYSIS SOFTWARE

I used WattTime (subsidiary of the Rocky Mountain Institute) hourly Marginal Emissions Rate (MER) data to do an hourly analysis of grid impacts from residential and commercial heat pumps and to calculate required capacities of renewable power that would be necessary to meet expected New Jersey heating loads using heat pumps.

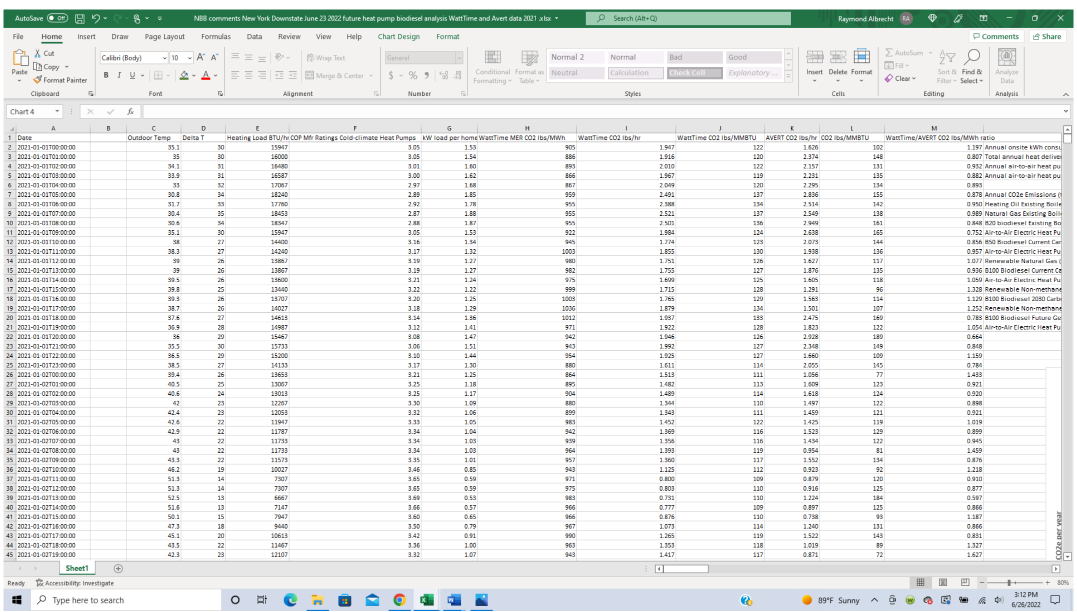
Average grid mix values are incorrectly used by many energy policymakers in the northeastern United States (see article by the Rocky Mountain Institute in the Appendix). Hourly MER data enables the analysis of how power plants would increase/decrease their output in response to grid load changes, and what corresponding changes in fuel use and emissions would occur.

METHODOLOGY FOR HOURLY EVALUATION OF COMBINED HEAT PUMP PERFORMANCE AND PJM – NEW JERSEY GRID CARBON INTENSITY FOR RESIDENTIAL AND COMMERCIAL HEATING

These technical notes are based on an hourly, coincidental temporal analysis of heating loads and power grid performance. Digital weather data from Visual Crossing.com for Princeton, NJ was used to model hourly heating loads in a representative single-family residential unit that would have a peak heating load of 32,000 Btu/hr at an outdoor temperature of 5 deg F. The described heating load formula is intended to be broadly representative for residential buildings located in the northeastern United States.

Temperature delta T values are determined using a base of 65 deg F as is customary for heating degree day analysis. Carbon intensities for common fuels including heating oil, natural gas, propane and biodiesel are derived from the GREET model, as described earlier in this document. Heat pump COPs vs. outdoor temperature are determined through a formula based on the field test results included in the references described earlier.

Figure 3 below shows a screenshot of an Excel spreadsheet that was created to perform the described hourly analysis of heating loads, grid performance, fuel/electricity input options, carbon intensities and resulting CO2 emission rates. The table includes input and output figures for the approximately 5000 hours that occur during the October through April heating season.



	Date		Outdoor Temp	Delta T	Heating Load BTU/hr	COP Mfr Ratings Cold-climate Heat Pumps	kW load per home	WattTime MER CO2 lbs/MWh	WattTime CO2 lbs/hr	WattTime CO2 lbs/MMBTU	AVERT CO2 lbs/hr	CO2 lbs/MMBTU	WattTime/AVERT CO2 lbs/MWh ratio	
2	2021-01-01T00:00:00		35.1	30	15947	3.05	1.53	905	1.947	122	1.626	102	1.197	Annual onsite kWh consu
3	2021-01-01T01:00:00		35	30	16000	3.05	1.54	886	1.916	120	2.374	148	0.807	Total annual heat delive
4	2021-01-01T02:00:00		34.1	31	16480	3.01	1.60	893	2.010	122	2.157	131	0.932	Annual air-to-air heat pu
5	2021-01-01T03:00:00		33.9	31	16587	3.00	1.62	866	1.967	119	2.231	135	0.882	Annual air-to-air heat pu
6	2021-01-01T04:00:00		33	32	17067	2.97	1.68	867	2.049	120	2.295	134	0.893	
7	2021-01-01T05:00:00		30.8	34	18240	2.89	1.85	959	2.491	137	2.836	155	0.878	Annual CO2e Emissions (
8	2021-01-01T06:00:00		31.7	33	17760	2.92	1.78	955	2.388	134	2.514	142	0.950	Heating Oil Existing Boile
9	2021-01-01T07:00:00		30.4	35	18453	2.87	1.88	955	2.521	137	2.549	138	0.989	Natural Gas Existing Boil
10	2021-01-01T08:00:00		30.6	34	18347	2.88	1.87	955	2.501	136	2.949	161	0.848	B20 biodiesel Existing Bo
11	2021-01-01T09:00:00		35.1	30	15947	3.05	1.53	922	1.984	124	2.638	165	0.752	Air-to-Air Electric Heat Pu
12	2021-01-01T10:00:00		38	27	14400	3.16	1.34	945	1.774	123	2.073	144	0.856	B50 Biodiesel Current Car
13	2021-01-01T11:00:00		38.3	27	14240	3.17	1.32	1003	1.855	130	1.938	136	0.957	Air-to-Air Electric Heat Pu
14	2021-01-01T12:00:00		39	26	13867	3.19	1.27	980	1.751	126	1.627	117	1.077	Renewable Natural Gas (
15	2021-01-01T13:00:00		39	26	13867	3.19	1.27	982	1.755	127	1.876	135	0.936	B100 Biodiesel Current Ca
16	2021-01-01T14:00:00		39.5	26	13600	3.21	1.24	975	1.699	125	1.605	118	1.059	Air-to-Air Electric Heat Pu
17	2021-01-01T15:00:00		39.8	25	13440	3.22	1.22	999	1.715	128	1.291	96	1.328	Renewable Non-methane
18	2021-01-01T16:00:00		39.3	26	13707	3.20	1.25	1003	1.765	129	1.563	114	1.129	B100 Biodiesel 2030 Carb
19	2021-01-01T17:00:00		38.7	26	14027	3.18	1.29	1036	1.879	134	1.501	107	1.252	Renewable Non-methane
20	2021-01-01T18:00:00		37.6	27	14613	3.14	1.36	1012	1.937	133	2.475	169	0.783	B100 Biodiesel Future Ge
21	2021-01-01T19:00:00		36.9	28	14987	3.12	1.41	971	1.922	128	1.823	122	1.054	Air-to-Air Electric Heat Pu
22	2021-01-01T20:00:00		36	29	15467	3.08	1.47	942	1.946	126	2.928	189	0.664	
23	2021-01-01T21:00:00		35.5	30	15733	3.06	1.51	943	1.992	127	2.348	149	0.848	
24	2021-01-01T22:00:00		36.5	29	15200	3.10	1.44	954	1.925	127	1.660	109	1.159	
25	2021-01-01T23:00:00		38.5	27	14133	3.17	1.30	880	1.611	114	2.055	145	0.784	
26	2021-01-02T00:00:00		39.4	26	13653	3.21	1.25	864	1.513	111	1.056	77	1.433	
27	2021-01-02T01:00:00		40.5	25	13067	3.25	1.18	895	1.482	113	1.609	123	0.921	
28	2021-01-02T02:00:00		40.6	24	13013	3.25	1.17	904	1.489	114	1.618	124	0.920	
29	2021-01-02T03:00:00		42	23	12267	3.30	1.09	880	1.344	110	1.497	122	0.898	
30	2021-01-02T04:00:00		42.4	23	12053	3.32	1.06	899	1.343	111	1.459	121	0.921	
31	2021-01-02T05:00:00		42.6	22	11947	3.33	1.05	983	1.452	122	1.425	119	1.019	
32	2021-01-02T06:00:00		42.9	22	11787	3.34	1.04	942	1.369	116	1.523	129	0.899	
33	2021-01-02T07:00:00		43	22	11733	3.34	1.03	939	1.356	116	1.434	122	0.945	
34	2021-01-02T08:00:00		43	22	11733	3.34	1.03	964	1.393	119	0.954	81	1.459	
35	2021-01-02T09:00:00		43.3	22	11573	3.35	1.01	957	1.360	117	1.552	134	0.876	
36	2021-01-02T10:00:00		46.2	19	10027	3.46	0.85	943	1.125	112	0.923	92	1.218	
37	2021-01-02T11:00:00		51.3	14	7307	3.65	0.59	971	0.800	109	0.879	120	0.910	
38	2021-01-02T12:00:00		51.3	14	7307	3.65	0.59	975	0.803	110	0.916	125	0.877	
39	2021-01-02T13:00:00		52.5	13	6667	3.69	0.53	983	0.731	110	1.224	184	0.597	
40	2021-01-02T14:00:00		51.6	13	7147	3.66	0.57	966	0.777	109	0.897	125	0.866	
41	2021-01-02T15:00:00		50.1	15	7947	3.60	0.65	966	0.876	110	0.738	93	1.187	
42	2021-01-02T16:00:00		47.3	18	9440	3.50	0.79	967	1.073	114	1.240	131	0.866	
43	2021-01-02T17:00:00		45.1	20	10613	3.42	0.91	990	1.265	119	1.522	143	0.831	
44	2021-01-02T18:00:00		43.5	22	11467	3.36	1.00	963	1.353	118	1.019	89	1.327	
45	2021-01-02T19:00:00		42.3	23	12107	3.32	1.07	943	1.417	117	0.871	72	1.627	

Figure 3. Screenshot of hourly heating system and power grid performance Excel spreadsheet.

After hourly heating loads and corresponding grid load increases have been determined, the Excel table then calculates generation and CO2 emissions changes.

ANALYTICAL RESULTS AND TECHNICAL COMMENTS

<u>Carbon Intensities Vs. Outdoor Temperature for Single Family Homes in New Jersey</u>

The following graph shows carbon intensities (lbs CO2e per MMBTU of delivered heat) for future generation, air-to-air heat pumps and liquid fuel options ranging from traditional heating oil to biodiesel blends up to B100. The carbon intensity of future generation, cold-climate heat pumps, using electricity from the PJM grid, increases at lower outdoor temperatures. It is important to note that the data points in the graph are time-weighted (i.e., one hour per dot) rather than load-weighted. Each data point corresponds to energy consumption based on the difference between indoor and outdoor temperature. This means that most energy consumption for heating occurs in the left half of the graph.

The carbon intensity of heat pumps will be lower than for B20 biodiesel blends during mild and moderate weather. The graph illustrates that there remain substantial heating loads below 30 deg F when the carbon intensity of heat pumps will be higher than for B20 blends. There is a logical argument for encouraging the use of hybrid heating systems that would employ lower carbon fuels, rather than heat pumps, during cold weather and other periods of grid stress.

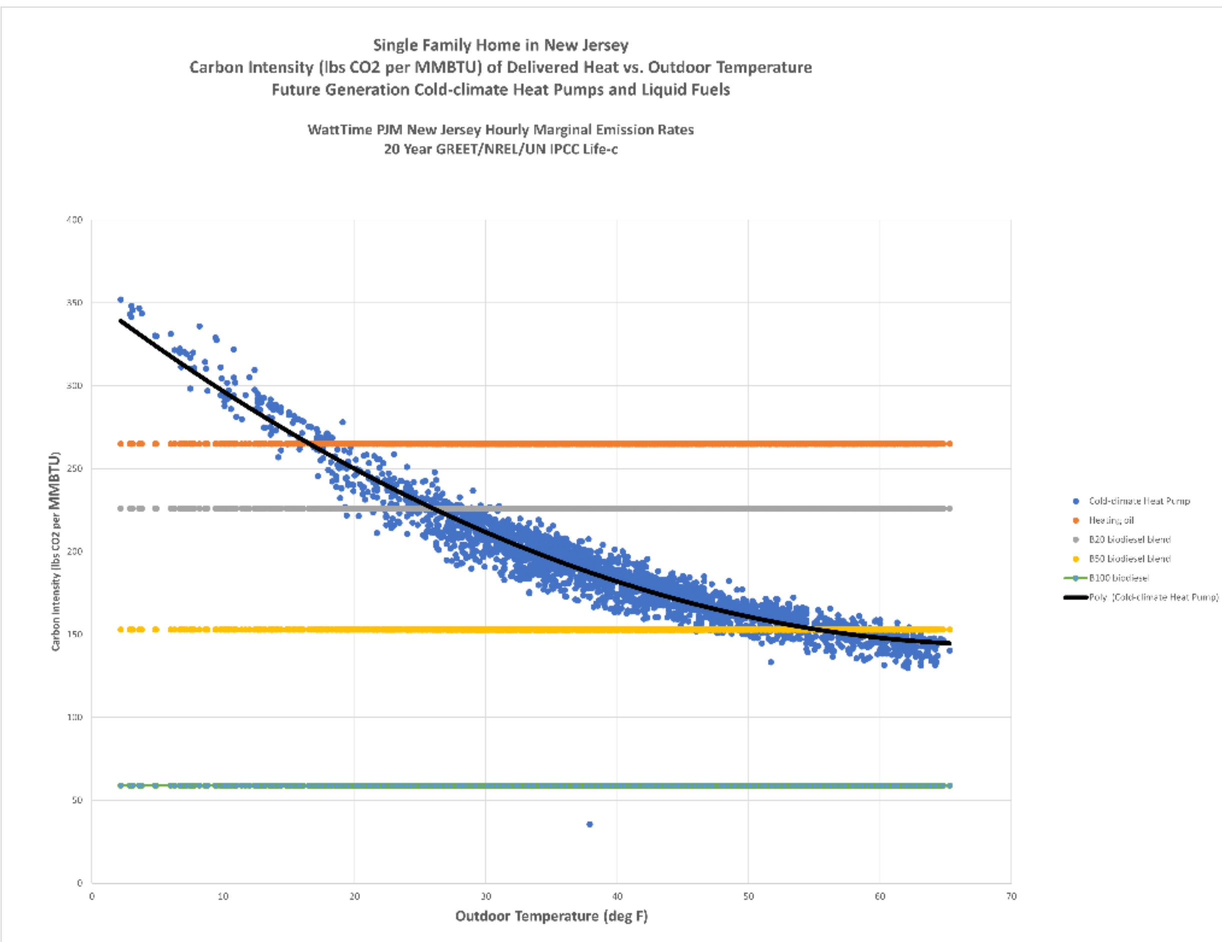


Figure 4. Carbon Intensity of Year 2030 Heating System Technologies vs. Outdoor Temperature

The graph also shows that the B50 biodiesel blend option has lower carbon intensity than cold-climate heat pumps during all but about 100 hours of the heating season, with such exceptions occurring almost exclusively during mild weather. Hourly analysis shows that a hybrid heating system consisting of a B50 UCO biodiesel-fired boiler and a future generation, air-to-air heat pump, would use the boiler for delivery of 99 percent of total delivered heat.

Smart controls for hybrid systems incorporating lower percentage biodiesel blends, such as B20, could selectively operate individual components based on relative carbon intensity to achieve optimized environmental performance and to reduce grid load impacts. Smart controls could favor heat pump operation during mild weather and lower grid load periods (e.g., late evening, very early morning and mid-day hours) and high renewable wind/solar output when heat pump and power generation efficiencies are higher. Likewise, smart controls could favor renewable fuel-fired boiler operation during prolonged cold weather or renewable generation drought, also high grid load hours, and rapid, upward grid-load ramping periods (e.g., morning and late afternoon) when grid stability is under greatest stress.

To note, the vertical data scatter shown for each temperature point in the above graph is primarily the result of grid performance variations relating to hourly on/off-peak periods (morning and evening peaks vs. mid-day and nighttime), generation output ramp-up rate (simple cycle systems can ramp up faster than combined cycle), plus weekday/weekend differences in typical grid load profiles.

<u>Annual CO2e Emissions from Single-family Homes in New Jersey</u>

Figure 5 below shows results for annual CO2e emissions by a representative single-family home in New Jersey under different fuel and technology options that are feasible by the years 2030 and 2050. New Jersey has approximately 3.78 million residential housing units plus a broad array of commercial, industrial and institutional buildings. Traditional fuel options include heating oil, propane and natural gas. Renewable fuel options include biodiesel blends as well as B100 biodiesel. Heat pump options include current air-to-air technology plus improved, future generation technology as well as air-to-water technology. The graph also includes scenarios for the existing grid plus options for partial and full-capacity renewable power generation for operation of heat pumps.

Note: This study is only focused on the alternative fuels of biodiesel and renewable diesel. There are lower carbon alternatives to other incumbent fossil fuels such as renewable propane, renewable natural gas, and green hydrogen, the analysis of which are outside the scope of this analysis.

It needs to be noted that the option for full-capacity renewable power generation, which would be challenging to achieve by the year 2050, and which is shown as a long-term goal, also includes the requirement for 1.15 million MWh of battery storage to be sufficient for 48 hours of operation during prolonged periods of cold temperature with low offshore wind output. Recent cost figures for utility-scale battery storage have been in the range of approximately $400,000 per MWh of capacity. For a typical peak demand of 6 kW for a full-capacity heat pump system, this translates into a battery storage capital cost of about $115,000 per residential unit.

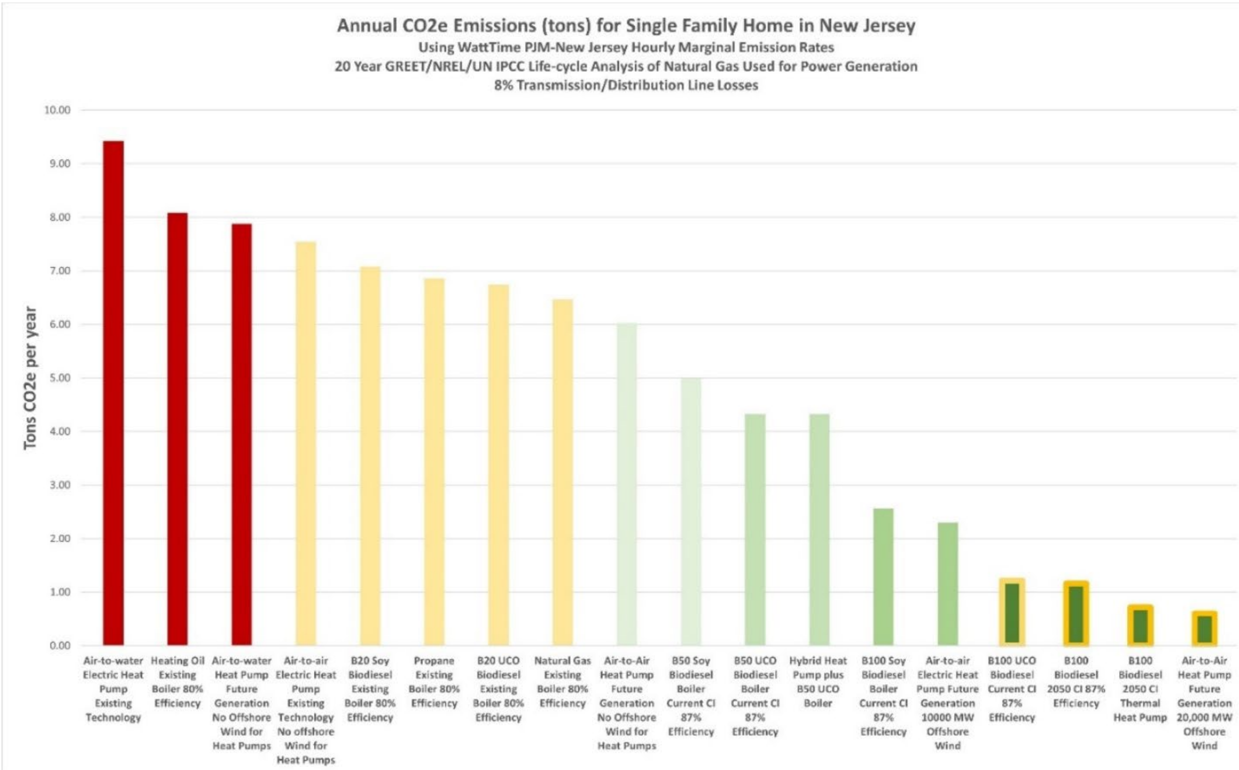


Figure 5. Annual CO2e Emissions for Single Family Homes in New Jersey.

The three red-colored bars to the left in Figure 5 show traditional heating oil, current air-to-water heat pump technology, as well as future generation air-to-water heat pump technology, as the highest emission options. The representative home would use approximately 530 gallons of oil for space heating plus an additional 200 gallons approximately for domestic hot water purposes. This analysis focuses, however, only on space heating. CO2e emissions for traditional heating oil would be about 9.50 tons per year.

Air-to-water heat pumps need to operate at higher supply temperatures than air-to-air heat pumps due to the requirements of hydronic distribution systems. They therefore experience approximately 25% lower efficiency than air-to-air heat pumps. This helps to explain why air-to-water heat pumps, even with expected future improvements, would achieve only limited CO2e savings in the PJM control area.

As illustrated by the five yellow-colored bars in the graph, CO2e savings in the range of 15 to 20 percent, compared to traditional heating oil, are achieved by propane and natural gas-fired boilers, current air-to-air heat pump technology and B20 biodiesel-fired boilers.

The options of future generation air-to-water heat pump technology and B50 soy biodiesel blends (see the two light green bars) are then shown as achieving more significant CO2e savings in the range of 30 and almost 40 percent respectively compared to traditional heating oil.

The options of B50 UCO (waste-based) biodiesel blends plus a hybrid B50/heat pump system (see medium green bars) both achieve a solid 40 percent savings compared to traditional heating oil. The hybrid system is included to illustrate the point that for B50 and higher biodiesel blend levels, there are essentially no benefits achieved by adding an air-to-air heat pump to the heating system.

There is then a more substantial trend (see the darker green bars) toward declining CO2e emissions as biodiesel concentrations increase to the 100 percent level, and as dedicated, offshore wind capacity growth to a total of 10,000 MW nameplate capacity is accomplished, in this analytical case, by New Jersey, above and beyond the capacity that is needed to decarbonize the existing New Jersey grid. Dedicated offshore wind 10,000 MW, for New Jersey, which represents half of the 20,000 MW nameplate capacity ultimately needed by that state for fully renewable heat pump operation, would achieve about 70 percent CO2e savings compared to heat pumps that use the existing grid.

The final four bars (dark green with gold borders) show a continuing downward trend in CO2e emissions. Biodiesel achieves further improvements in feedstock production and processing (e.g., GPS-controlled planting and fertilizer application in agriculture, use of solar PV electricity in crushing operations, use of renewable methanol as an esterification reactant, etc.) as well as higher, end-use equipment efficiency (e.g., fuel-fired absorption heat pumps) for space heating in residential and commercial buildings. Absorption heat pumps can achieve efficiency levels of up to 140 percent, depending on manufacturing design and operating conditions.

The final bar in the group shows estimated carbon intensity, based on data provided by the National Renewable Energy Laboratory (NREL), for heat pump operation when supplied with full capacity, solar and wind power. NREL carbon intensity data for solar and wind relates to energy usage during construction as well as embedded energy in materials such as steel and concrete.

Dedicated wind power nameplate capacity of about 20,000 MW for New Jersey would provide for renewable heat pump utilization during the peak heating months of the winter but as previously described, would also require approximately 1,150,000 MWh of battery storage to maintain continued grid operation for up to 48 hours of full-load equivalent operation during cold weather combined with prolonged, low wind (or solar) output conditions.

NEED FOR HIGHER LEVELS OF RENEWABLE POWER GENERATION BEFORE ELECTRIFICATION CAN ACHIEVE ENVIRONMENTAL BENEFITS IN NEW JERSEY

The next graph shows the offshore wind capacity that would be required to meet the winter heating loads of cold-climate heat pumps for residential and commercial buildings in New Jersey. The blue bars represent monthly MWh consumption by residential and commercial heat pumps. The orange bars represent monthly MWh production by 20,000 MW of nameplate capacity offshore wind power. The gray bars represent MWh production by 10,000 MW of nameplate capacity offshore wind power. Monthly MWh production figures are provided by the USEPA AVERT model based on historical weather data for the New Jersey offshore region.

The graph indicates that an installed nameplate capacity of 20,000 MW of offshore wind would approximately meet the needs of residential and commercial heat pumps in New Jersey, assuming the ample availability of battery storage. If it were possible to install such quantity of offshore wind capacity at a cost of $5 million per MW, the total capital expense would be approximately $100 billion, or about $22,000 per heat pump for the referenced population of almost 3 million residential heat pumps and 1.5 million small commercial heat pumps.

An installed nameplate capacity of 10,000 MW of offshore wind would meet approximately 68 percent of the annual residential and commercial heat pump load. Other provisions for renewable generation would be necessary, however.

Just to note, if floating-type offshore wind platforms are required due to water depths of greater than 180 feet, an upward revision to the wind machine capital expense figure may become necessary.

As noted earlier, fully renewable operation of heat pumps would require the availability of 1.15 million MWh battery storage.

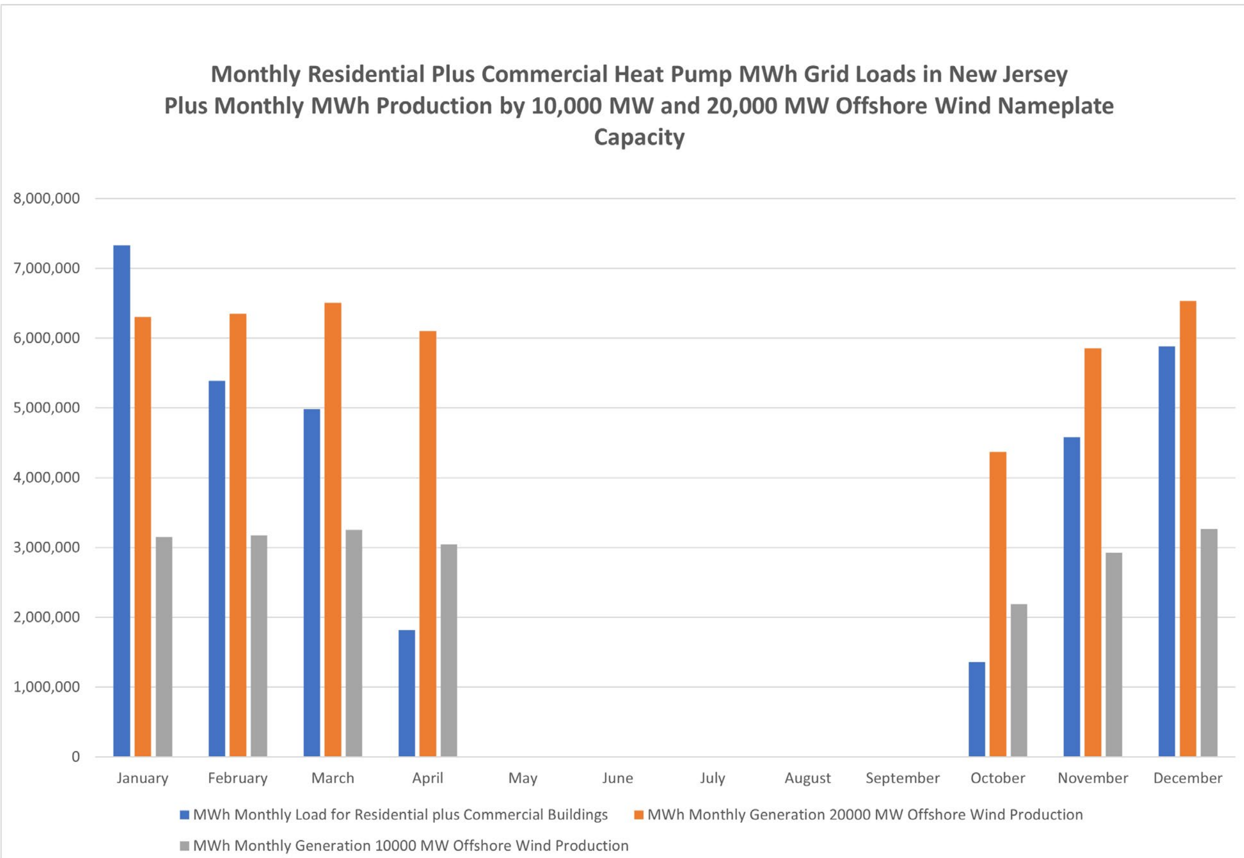


Figure 6. New Jersey Monthly Grid Loads for Residential and Commercial Heat Pumps Plus Offshore Wind Production for 10,000 MW and 20,000 MW Nameplate Capacity Options

PERFORMANCE OF COLD-CLIMATE AIR-TO-WATER HEAT PUMPS

Air-to-water heat pumps are gaining popularity in the hydronic heating sector. Air-to-water heat pumps are intended to replace fuel-fired hydronic boilers in residential and commercial buildings. Air-to-water heat pumps use refrigeration cycles that are similar to air-to-air heat pumps but face the challenge of having to produce higher temperature output due to the limitations of hydronic distribution systems.

The following graph shows an example COP rating chart from a leading manufacturer of air-to-water heat pumps. The graph shows, for an outdoor temperature of 30 deg F and supply water temperature of

130 deg F, a COP manufacturer rating of about 2.5, which is about 20 percent lower than shown previously for air-to-air heat pumps at the same outdoor temperature.

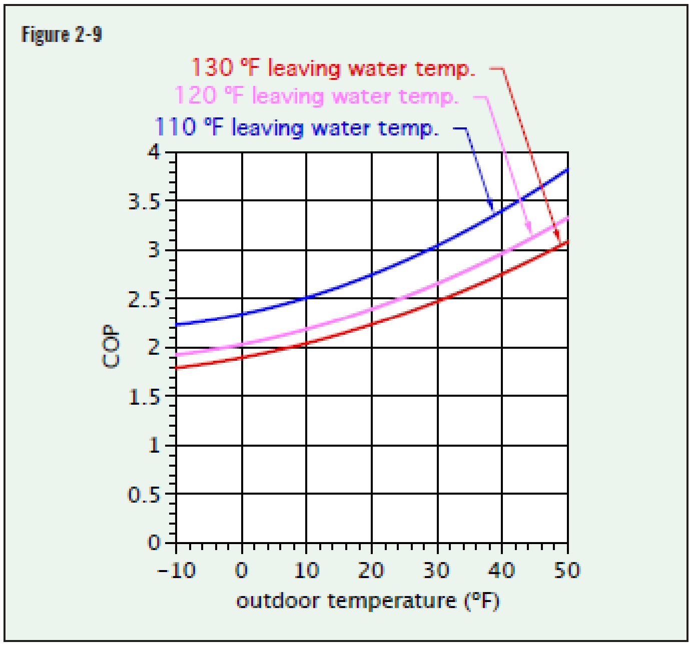


Figure 7. Example Manufacturer COP Rating Chart for Air-to-water Heat Pump vs. Supply Water and Outdoor Temperatures

The following graph shows average COP manufacturer ratings for air-to-air and air-to-water heat pumps vs. outdoor temperature. The blue trend line shows typical values for air-to-air heat pumps operating at a supply air temperature of 95 deg F. The orange line shows corresponding values for air-to-water heat pumps operating at a supply water temperature of 140 deg F. It can be readily seen that air-to-water heat pumps can experience 20 to 30 percent lower COPs than their air-to-air counterparts.

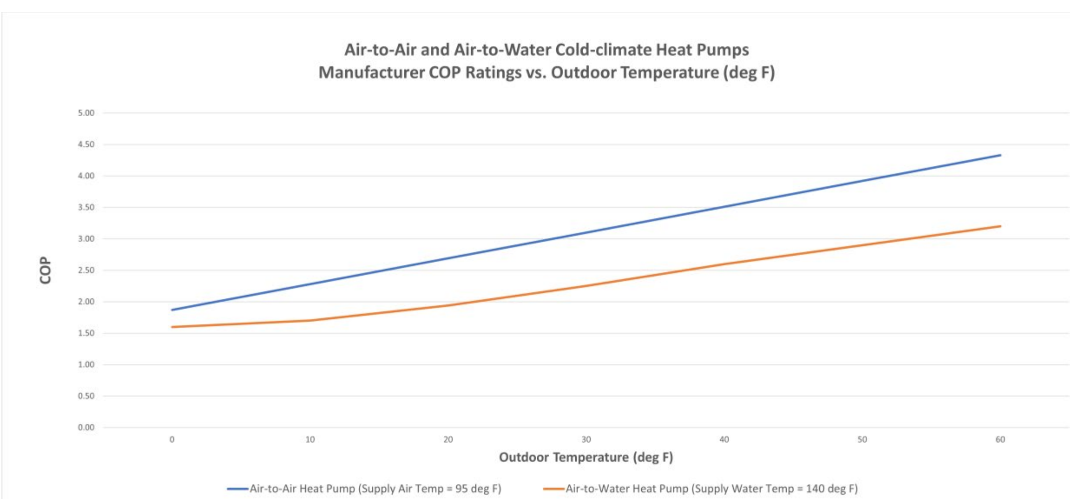


Figure 8. Comparison of Typical Manufacturer COP Ratings for Air-to-Air vs. Air-to-Water Heat Pumps vs. Outdoor Temperature

The combination of differences between manufacturer ratings and actual field performance, and losses in performance due to operating temperature, will negatively impact the ability of air-to-water heat pumps to contribute toward decarbonization of buildings until the PJM grid has been substantially transformed to reduce its carbon intensity.

ELECTRICAL DEMAND OF HEAT PUMPS

The graph below shows average electrical demand vs. outdoor temperature within the heat pump populations of the three largest field studies noted earlier. The graph shows a representative electric demand for a full-sized heat pump with capacity of 40,000 Btu/hr at 0 deg F, also for a partial-sized heat pump with a capacity of 15,000 Btu/hr at 0 deg F. The data curves for the three field studies show that actual electricity consumption was only a small fraction of what would be expected with full heat pump utilization. Note that the actual electrical demand curves are relatively flat below 30 deg F. This indicates very low heat pump utilization below 30°F. Since heat pump power demand increases dramatically as the outdoor temperature drops further, due to increasing heat load plus decreasing heat pump COP, this means further that the homeowner percentage drop-out rate is increasing as the temperature drops.

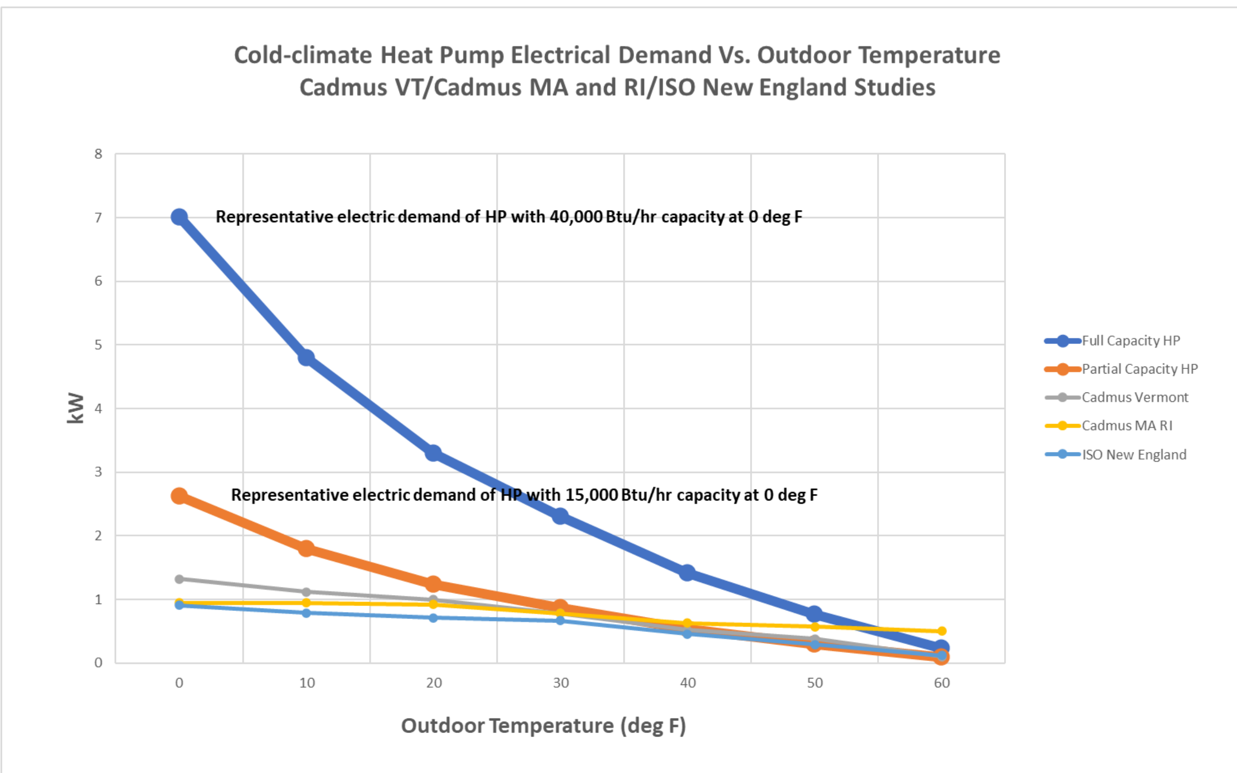


Figure 9. Cold-climate Heat Pump Electrical Demand vs. Outdoor Temperature

Homeowners have on average, been using their heat pumps for less than half of the potential winter hours of operation. The bar graph below illustrates, in a different format, the same message re: low homeowner utilization of heat pumps during the winter. Some homeowners indeed used their heat pumps dutifully even during the coldest days of winter, but most dropped out at some point as the weather got colder, or never even turned on the systems at all for heating purposes.

This raises the thorny issue of homeowners taking advantage of heat pump incentive programs to purchase systems that are used substantially for cooling and only partially for heating, and whether upfront incentives vs. pay-for-performance should be provided to homeowners, also whether ratepayer vs. utility shareholder funds should be used for heat pump incentive programs. There is direct relevance of the heat pump utilization question to policymaking for incentive programs in New Jersey.

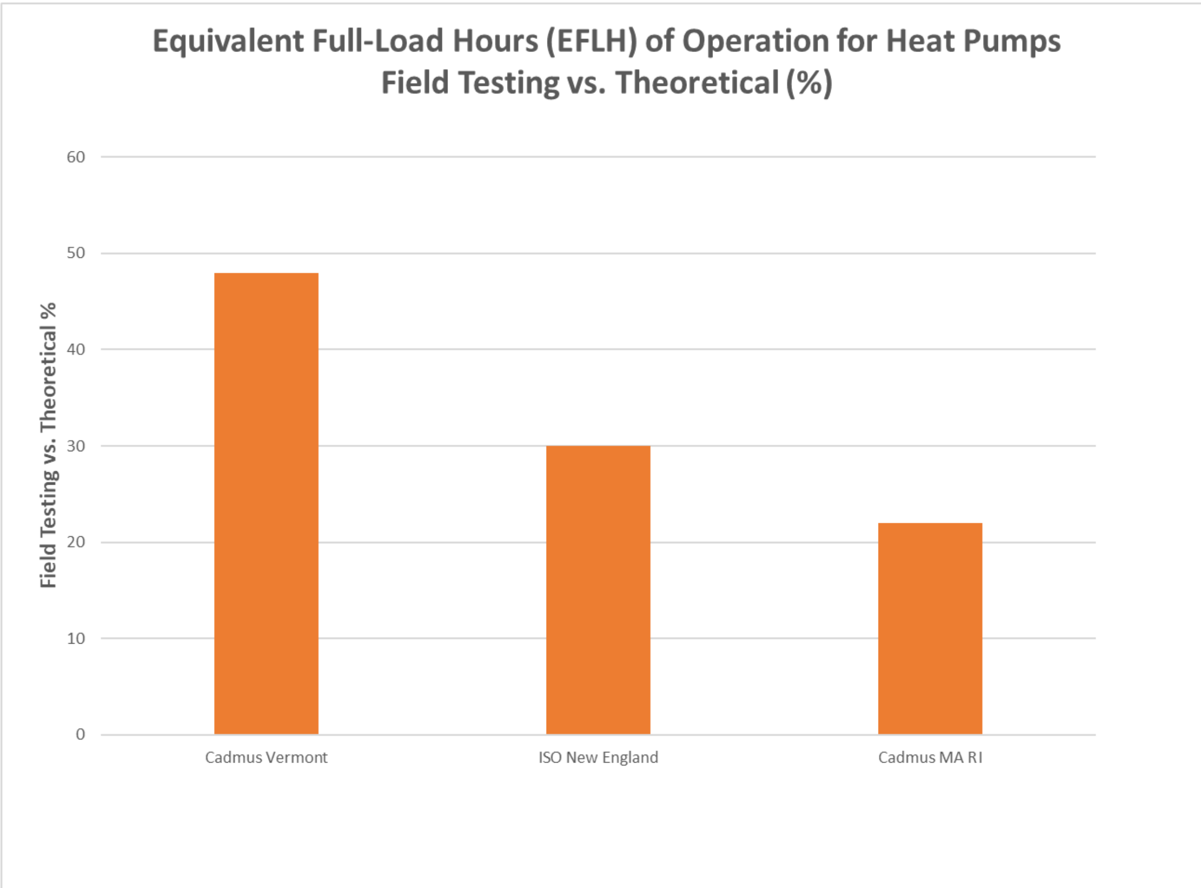


Figure 10. Equivalent Full-Load Hours of Operation for Heat Pumps

IMPACT ON GRID LOADS IN NEW JERSEY

The next graph shows the expected grid load growth that would occur in New Jersey if heat pumps were to be installed in 3 million homes plus the commercial building sector. Installing heat pumps throughout the residential and commercial sector would incur an additional grid load of approximately 25000 MW, which does not include the additional grid load incurred for electric vehicles. The corresponding load growth would take us into completely uncharted territory and would double or triple the existing grid load. The wind projects planned for the next 10 to 20 years off the New Jersey shore, even if fully developed, will be just barely sufficient to start eliminating fossil generation for present grid loads, without accounting for heat pumps or EV growth.

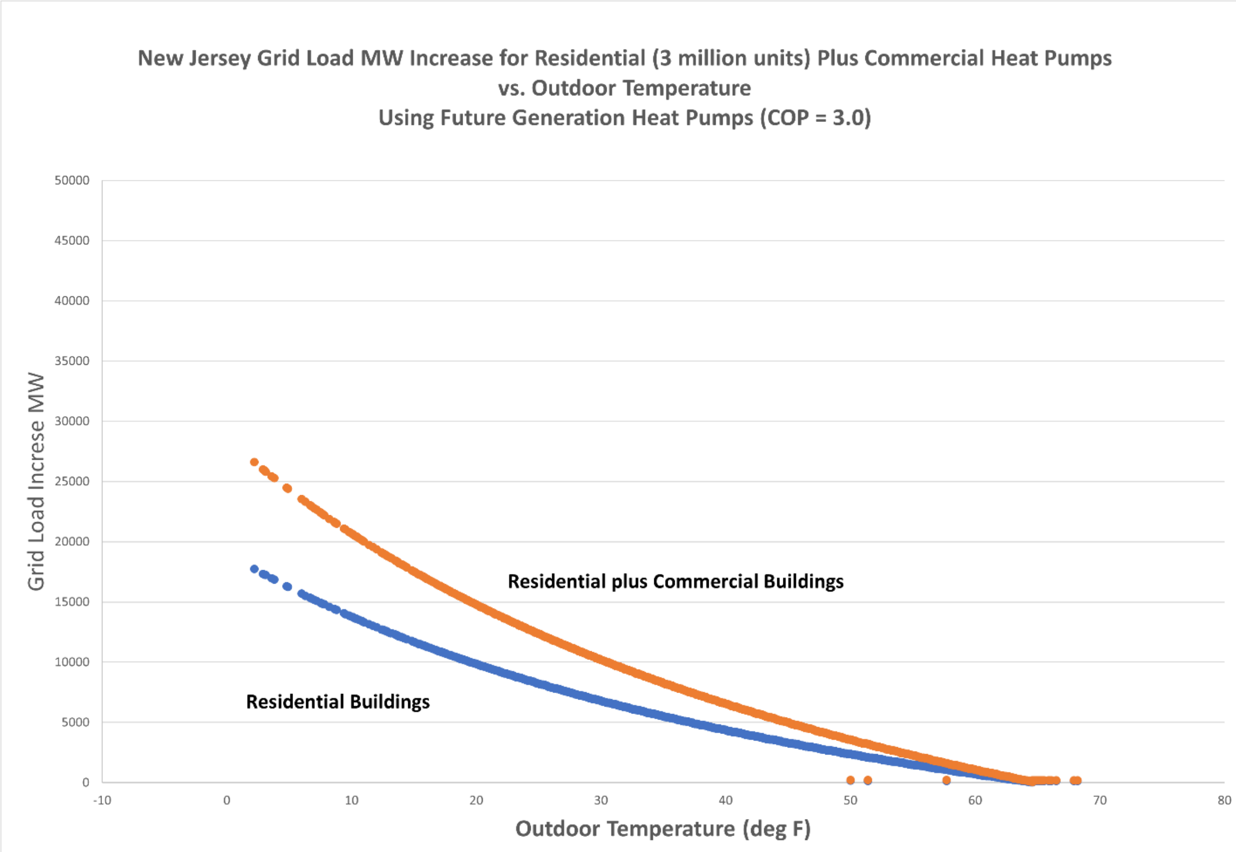


Figure 10. New Jersey Grid Load Increase vs. Outdoor Temperature for Heat Pumps in 3,000,000 Residential Units Plus Commercial Buildings

LONG-TERM CAPITAL COSTS OF ELECTRICITY GRID UPGRADES IN NEW JERSET FOR IMPLEMENTATION OF RESIDENTIAL AND COMMERCIAL HEAT PUMPS

Wind and solar projects planned for the next 10 to 20 years in New Jersey, even if fully developed, will make a good start toward eliminating fossil generation for existing grid loads, but will not provide the substantial growth in capacity necessary for full implementation of heat pumps in the residential and commercial building sectors. Substantial capital investments will be required beyond current plans for renewable power generation and battery storage to replace fossil-based generation that would be necessary to meet increased grid loads. Major investments will also be required for transmission and distribution networks to allow renewable electricity to reach end-use customers.

Approximately 22,500 MW of grid load growth in New Jersey will result from operation of residential and commercial heat pumps during peak winter conditions. The data are based on the presumption that whole-house heat pumps would be used with no fuel-fired back-up. As stated earlier, such grid load growth would double or triple the existing winter peak load in the New Jersey zone of PJM.

An installed nameplate capacity of 20,000 MW of offshore wind power would approximately meet the needs of residential and commercial heat pumps in New Jersey during the coldest months of the heating season, assuming sufficient availability of battery storage. If it were possible to install the described 20,000 MW of offshore wind capacity at a cost of $5 million per MW, the total capital expense for generation would be approximately $100 billion. If floating-type offshore wind platforms are required, which is likely to be the case, due to water depths of greater than 60 meters, an upward revision to the wind turbine capital expense figure would become necessary.

For a New Jersey peak grid load of about 22,500 MW for residential and commercial heat pumps, the required nominal, 48 hour, battery storage capacity, to enable continued operation during extended cold temperature and low windspeed conditions, with output of 20% of rated capacity, would be approximately 865,000 MWh.

If utility-scale battery storage were to cost $200,000 per MWh capacity, based on NREL mid-range cost projections for the year 2030, the initial capital expense for battery storage would be approximately $175 billion, to cover the 48 hour storage discharge needed during a wind drought. This figure may be subject to adjustment, however, based on battery material price increases/decreases which might occur as the wind and solar industries grow. Increased production volumes may contribute to economies of scale, which might provide downward pressure on costs. Increased volumes of mining/extraction of materials for batteries, on the other hand, could trigger higher prices due to supply shortages. Lithium and cobalt commodity prices have recently increased multifold with corresponding upward pressure on battery storage prices, although new, cheaper materials and battery designs are also under development. An expected service life of 10 years is used for analysis of battery costs.

Increased grid transmission capacity in New Jersey would also be necessary to enable full implementation of residential and commercial heat pumps. While transmission upgrade costs will vary widely on a local basis depending on existing capacity and load characteristics, this analysis uses the same average annual cost figure of $94 per kw-yr as developed in the 2021 Avoided Energy Supply Component Update report by Synapse Energy Economics for electric utilities and state regulatory agencies located in the ISO New England grid. The $94 figure represents a combination of construction and operating cost, e.g., labor, administration, insurance, and taxes. The corresponding, total combined capital and operating cost figure could have an order of magnitude value of $2000 per kw of increased transmission capacity, although actual cost figures are highly dependent on specific circumstances. Using the figure of $2000 per kW of increased transmission capacity, the corresponding cost for 22,500 MW of transmission upgrades in New Jersey could be approximately $45 billion.

Increased local electricity distribution capacity would also be necessary for implementation of residential and commercial heat pumps in New Jersey. Synapse Energy Economics has identified a wide range of accounting practices used by electric utilities in New England, with corresponding cost figures that range from *de minimis* to over $200 per kW-yr. More consistent accounting practices used in other states, such as New York, have indicated distribution upgrade costs ranging from $50 to $250 per kW-yr, representing variations in cost and difficulty of distribution network construction which occur in rural through dense urban environments. A corresponding equivalent capital cost figure of $3000 per kW, to be amortized over 30 years, is used for this analysis. The corresponding cost for 22,500 MW of distribution upgrades would be approximately $65 billion.

The estimates do not account for the probable necessity for use of floating platforms due to water depths of over 60 meters, which occur throughout most of the Northeast coast. The estimates do not account for options such as underground burial of transmission and distribution cable or alternate routing options, whose necessity could be triggered by Not-In-My-Backyard (NIMBY) opposition from local residents subject to dislocation via eminent domain. The estimates also do not account for regional and national security concerns that may arise relating to protection of distant offshore infrastructure.

Recent capital cost analyses for residential heat pumps have centered on an approximate figure of $20,000 per onsite installation. The corresponding capital cost for installation of about 3 million residential heat pumps in New Jersey would be approximately $60 billion. The commercial building sector uses about 50% as much heating equipment capacity and energy consumption as the residential sector. The total capital cost for installation of residential and commercial heat pumps in New Jersey would thus be approximately $90 billion.

The following table presents the long-term capital cost figures estimated above for offshore wind generation capacity, battery storage, transmission and distribution upgrades, as well as for onsite installation of residential heat pumps, for full implementation of residential and commercial heat pumps in New Jersey.

Time Horizon	10 yrs	20 yrs	30 yrs
Wind	$ 100 billion	$ 100 billion	$ 100 billion
Battery Storage	$ 175 billion	$ 350 billion	$ 525 billion
Transmission	$ 45 billion	$ 45 billion	$ 45 billion
Distribution	$ 65 billion	$ 65 billion	$ 65 billion
Onsite Heat Pump Installation	$ 90 billion	$ 135 billion	$ 180 billion
Total	$ 475 billion	$ 695 billion	$ 915 billion

Table 1. Summary of capital costs for full implementation of residential and commercial heat pumps in New Jersey

The above table shows capital cost figures for three different time horizons. A service life of 30 years is used for the analysis of wind generation, transmission and distribution systems. A service life of 10 years is used for battery storage systems, to reflect the limited lifetime of batteries used for daily charge/discharge cycles with depth of discharge (DOD) values in the range of 80 percent. Full battery replacement plus major maintenance/upgrades of charging controls and physical facilities have been presumed at the 10 and 20 year marks. Similarly, an initial service life of 10 years has been used for cold-climate heat pumps that are used for full heating season operation, with major (e.g., compressor/controls) component replacement required at the 10 and 20 year marks. The significant impact on long-term, total capital costs by short-lived equipment components can be seen in the table.

Approximately 35 million MWh of electricity would be generated per heating season by the described combination offshore wind system. A high fraction of the potential output of the dedicated wind generation capacity necessary for winter heating would be foregone during the summer due to the high ratio of winter-to-summer peak load that would occur with electrification of heating. A total of approximately 1 billion MWh would be produced over the course of 30 years.

The total capital cost of the generation/transmission/battery storage/distribution cost components would be $915 billion over the described 30 year time horizon. The corresponding energy supply cost for the described wind/solar generation system can be calculated as the $915 billion total capital cost divided by the 1 billion MWh of generation over the same 30 year time horizon. The resulting marginal cost of infrastructure for electricity generation/transmission/distribution would thus be approximately $915 per MWh or $0.95 per kWh if an interest rate of zero percent is used for capital cost levelization. Generation, battery storage and some of the transmission costs would be embedded in the supply charge portion of an electric bill. Additional transmission costs, plus costs for distribution infrastructure, administration, operations, taxes, etc., would be additional and embedded into the energy delivery portion of an electric bill.

There are two principles of significance to note in this analysis. First, battery storage is conspicuous as an expensive component of the total capital cost for a renewable power-heat pump concept for the residential and commercial building sectors. Battery storage systems are expensive, plus they do not have the same 30 year lifetimes as for generation/transmission/distribution equipment and thus need periodic replacement in approximately 10 year cycles. Second, the capital cost of the renewable power-heat pump concept suffers from an overall low capacity factor due to the relatively high magnitude of peak loads compared to total annual energy consumption. Renewable fuels can therefore play a key role in maintaining acceptable cost effectiveness while achieving our environmental goals.

APPENDIX

On the Importance of Marginal Emissions Factors for Policy Analysis

Environmental nonprofits WattTime and Rocky Mountain Institute recommend marginal rather than average emissions factors be used for analysis of policies whose goal is to reduce carbon emissions. This primer explains why.

The purpose of average emissions factors is to apportion environmental responsibility.

A common technique in environmental analysis is to divide responsibility for cleaning up pollution equally between the different actors in a power grid on the basis of their relative power consumption. For example, if a given city consumes 5% of all the electricity produced in a given power grid, it is simple and intuitive to call it responsible for 5% of all the emissions in that grid.

The virtue of this technique is its simplicity. Each city or company on a power grid can simply calculate the average emissions per each kilowatt-hour on its local power grid; measure its own kilowatt-hours consumed; and multiply to determine its "share" of a given grid's pollution.[1]

Average emissions factors should *not* be used to measure environmental impact.

Historically, average emissions rates have been a convenient way to apportion "ownership" of different organizations' responsibility for emissions. Unfortunately, as momentum builds for institutions to more actively manage emissions, a worrisome trend is the growing number of organizations mis-applying average emissions factors to estimate the impact of environmental decisions. Yet this approach does not accurately measure environmental consequences. Returning to the previous example, it's entirely possible that the exact 5% of the grid's electricity that city is consuming comes predominantly from aging natural gas power plants, which would mean comparatively high emissions.

The correct way to measure environmental impact is using marginal emissions factors.

To protect against this mistake, the correct way to measure the impact of environmental decisions is to use *marginal* emissions factors.[2] Marginal emissions factors measure the actual environmental consequences of taking different potential actions on the power grid.

If the example city is evaluating an energy efficiency measure to conserve one megawatt-hour of electricity consumption, this program will reduce local emissions by reducing output at one or more power plants. But *which* power plants? Many sources of power, for example most solar panels, are designed to send all the energy they can to the power grid no matter the level of energy demand. Thus, they will be completely unaffected.

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[1] See, e.g. the GHG Protocol Corporate Standard.

[2] See, e.g. the GHG Protocol for Grid-Connected Electricity Projects.

Conserving energy only affects some power plants: those which can scale up or down in response, known as the "marginal" power plants. Marginal emissions measure the emissions per kilowatt-hour only from these power plants, thus accurately measuring real-world results.

Why using average emissions can lead to incorrect policy conclusions.

When a power grid experiences a change in energy demand—for example, adding electric vehicles, or installing new clean power—that changes the emissions from local power plants. But some power plants are completely unaffected, for example, most solar panels and nuclear plants.

Using average emissions factors to measure the effect of environmental decisions implicitly assumes that energy policy-making affects all power plants equally. This overestimates the effects on these unaffected plants, and underestimates the effects on the marginal plants which actually do change in response to policy. If these plants have different emissions rates, this can lead to incorrect measurement of policies.

This is a growing problem because the more "always-on" clean energy a region installs, the more inaccurate any analyses using average emissions factors become. For example, on Friday May 3rd, 2019 at 1:30 PM, the CAISO website reported the following data regarding real-time energy supply and emissions. CAISO was delivering 23, 690 MW of power at an emissions rate of 3,042 $mTCO_2$/hour. Nearly 50% of the total supply (12,086 MW), was from renewable sources. Using an approach of average emissions, one would say that the current emissions rate was 283lbs CO_2/MWh.[3]

However, the marginal emissions rate for the same time was much higher, at 927 lbs CO_2/MWh. Despite the high penetration of midday solar, if 1 MWh of load was added to the grid at this time, the solar plants would likely not be the type of fuel responding to the increased load. It is more likely that an inefficient gas generator would ramp to meet the increased load, thus creating an emissions impact of 927 lbs of CO_2.[4]

As seen here, true emissions rates can be up to four times higher than average emissions-based estimates would imply, with major consequences for policy evaluation.

If policymakers were to only allow technologies that were below the average emissions levels, they might inadvertently allow existing, inefficient generators to operate more than they intend. The result would be restricting projects are that good for the environment, instead of encouraging them.

[3] California ISO real-time energy data.
[4] WattTime marginal emissions data.

Common situations in which marginal emissions is most important.

Marginal emission factors should nearly always be used in environmental impact analysis. Leading researchers apply them when measuring everything from renewable energy, to electric vehicles, to energy storage.[5] But they have particular importance for public policy whenever a policy measure is comparing different options, for example:

- *Comparing what times are best to use or store energy*. Marginal emissions should be used to select which times are cleanest, such as for energy storage.[6]
- *Comparing where is best to site a new energy asset*. Marginal emission rates should be used to measure the impact of new renewable energy, particularly in selecting locations.[7]
- *Evaluating electrification*. Marginal emissions rates should be used when evaluating the environmental impact of electrifying fossil fuel technologies such as vehicles, water heaters, and appliances. For example, in some coal-heavy regions, switching from a gasoline-powered car to an electric vehicle can actually increase, not decrease emissions.
- *Evaluating low-emissions energy sources*. Marginal emissions rates should be used to evaluate the environmental impact of low-pollution electricity generation technologies such as fuel cells and biomass. These technologies are sometimes mistakenly thought to increase emissions if they emit more than the local average emissions rate. But in reality they reduce emissions anywhere they less than the local marginal emissions rate.

For more information about average vs. marginal emissions, see this joint WattTime-RMI post.

How to properly design policy based on data-driven marginal emissions rates

Several large, influential public agencies (the CPUC), and private customers are committed to accurately reducing carbon emissions by using marginal emissions analysis. In December of 2018, the CPUC staff released a draft regulation directing the commission to require entities utilizing public incentives in the Self Generation Incentive Program (SGIP) to use marginal emissions rates to determine the net GHG impact of their project.[8]

Creating effective regulations and policy, as the CPUC has done, requires thorough data analysis and stakeholder engagement. As an independent, third-party non-profit, WattTime was founded to guide policy makers and regulators through this process to ensure that their efforts accurately reduce greenhouse gas emissions.

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[5] See, e.g. Hittinger and Azevedo (2015), Callaway et al (2017) or Fares and Weber (2017).
[6] E.g. the California Public Utilities Commission's decision to use marginal emissions in real time for energy storage.
[7] See, e.g. Boston University's recent decision to buy renewable energy outside Boston using marginal emissions.