A Study of CO2 Emissions from CHP Systems and Comparable Alternatives in Massachusetts

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Frontier Energy, Inc.
12949 Alcosta Blvd., Suite 101,
San Ramon, CA 94583
Primary Contact: Daniel Robb
Phone: 315-962-9029
Email: drobb@frontierenergy.com

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EXECUTIVE SUMMARY

States, energy agencies, and municipalities nationwide are promoting electrification as a primary tool to address climate challenges and meet greenhouse gas (GHG) reduction targets. While effective in delivering CO_2 emissions reductions, electrification comes with many challenges and is not a suitable technology for all applications. This is especially true at facilities with steam thermal loads or where resiliency is required.

While a zero-emission grid is the long-term goal, there are varying levels of emissions currently associated with each MWh consumed from the electric grid. Understanding current grid emissions and the rate at which they are declining is critical for planning future energy projects and capital investments while also working to achieve emission reduction targets.

Presently, CHP delivers emissions reductions compared to a conventional grid and boiler system. This is mainly because CHP systems regularly operate with combined (electrical + thermal) efficiencies exceeding 70% HHV, while simple cycle and combined cycle gas power generation operate at significantly lower efficiencies. In addition, the distributed nature of most CHP systems avoids the additional transmission and distribution losses of 5.4 % associated with power delivered by the northeastern electric grid. Moreover, in the long term, CHP systems can further improve their emission reduction advantages compared to conventional grid and boiler systems by using low carbon fuels (LCF). This study shows that, in many instances, CHP systems can serve a facility's electric and thermal loads in a distributed manner while providing resiliency and reducing emissions compared to feasible alternatives.

A wide variety of technologies need deployment in as short a timeline as possible to meet the demanding emissions reductions targets set in Massachusetts. Those targets are described in the state's recently released Clean Energy and Climate Plan for 2030 and Energy Pathways Decarbonization Roadmap to 2050. While the projections for 2050 in these documents include a significantly cleaner electric grid, in many of the modeled scenarios modest amounts of natural gas combustion for power generation is still assumed to be required in 2050. Even then, and for as long as natural gas combustion is being used, CHP facilities will provide the most efficient use of natural gas in the power generation sector and should therefore be included in the portfolio of technologies that will be relied upon to achieve the state's emission reduction goals.

MAJOR FINDINGS

This comparison of CHP emissions of CO_2 to the CO_2 emissions from comparable technologies has resulted in the following findings.

- In the near term, at least through 2026, high performing CHP systems will provide emissions reductions compared to traditional grid and boiler systems, regardless of the grid emissions model to which they are compared.

- In the long run, through 2050, depending on the emissions reductions actually achieved by the grid in the decades to come, CHP systems may provide emissions reductions throughout that period compared to emissions caused by reliance for replacement heat and power on conventional heating systems and on the electric grid.

- Moreover, for facilities with steam needs and/or pressing reliability requirements, such as hospitals, critical manufacturing, academic or industrial campuses, and district energy, CHP will provide the most efficient and lowest carbon emission option using fossil fuel. (On-site solar electricity production, combined with heat pumps, which would have lower carbon emissions, have siting and operational constraints that make them infeasible for many of these applications.)

- In the not-too-distant future, emissions reductions can be achieved with even greater certainty and in greater quantities by substituting low or zero-carbon fuels for natural gas at CHP facilities. Direct procurement of renewable natural gas or other zero-carbon fuels would enable individual CHP systems to reduce CO_2 emissions to zero.

- Finally, a comparison of marginal grid emissions with CHP emissions on an hourly basis through the year will show that the marginal grid emissions rate is usually higher than the CHP emissions rate throughout the year. Indeed, the example presented at the conclusion of this report shows that, over the 8,760 hours in a year, the CHP emissions rate was lower than the marginal grid emissions rate 95% of the time.

GRID EMISSIONS FACTORS

Quantifying the emissions associated with grid purchased electricity is complex due to the varied mix of generating resources serving the grid and the methods these resources are dispatched to balance generation and grid loads. There are several variations of accepted grid emissions rates, including fossil, marginal, average, time weighted, and load weighted which each are applicable in different use cases. Understanding what each of these emissions rates mean, and the differences between them, is critical in knowing which to use when comparing emissions from CHP and alternative technologies.

ISO Dispatching

The way independent system operators (ISO), such as ISO-NE, procure and deploy generation to satisfy demand and balance power flows on the grid leads to important differences between average and marginal emissions. A uniform clearing price auction is used to set the clearing price for power during each hour of the day. Power generators submit day ahead price bids to supply power to specific regions of the grid (known as locational marginal pricing or LMP) for each hour of the day. ISO NE assembles these price bids, and the associated generation capacity, into a bid stack. (See Figure 1 below.) The bid stack ranks price bids based on submitted cost per MWh to determine the cumulative generation needed to fulfill demand in each hour of the day. The bid stack, along with the projected grid demand is then used to determine which generation units are called upon to run and when they run.

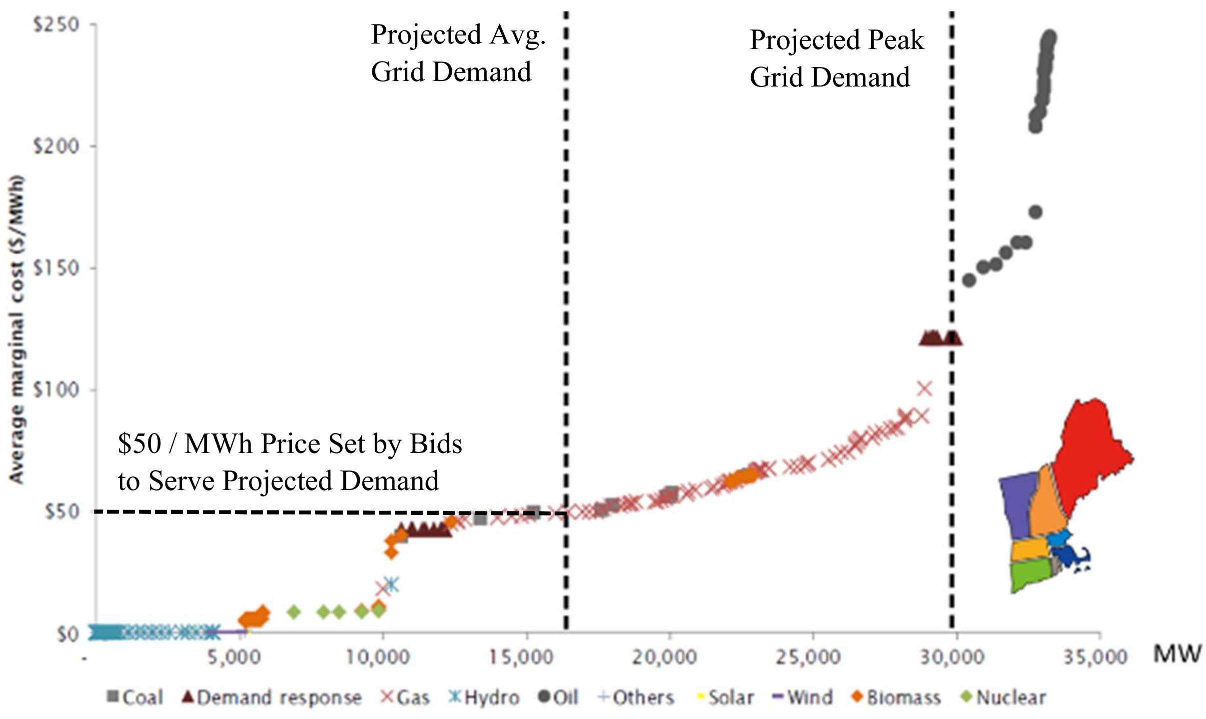


Figure 1. Representative Example of an ISO Bid Stack

All generating resources with an LMP bid that is below the clearing price in a given hour will be scheduled for operation based on this day ahead market. If grid demand exceeds the projection, the next lowest priced resource will be called on to satisfy additional demand. A generating resource that is turned on or increases output to satisfy additional demand is known as the “marginal” resource. When a CHP facility stops operating, the system operator must immediately call upon another generating resource that is already operating to increase its output or call upon a generating unit that is not operating to start to do so. The emissions that are associated with these increases in output are known as “marginal emissions.”

While the bid stack is based on the cost for generating electricity there is a correlation between low cost and low emission resources. Hydro, nuclear, solar, and wind are often both the lowest priced and lowest emitting resources and as a result they operate most often. Power from these types of resources is known as “base load generation.” Whenever a generating unit stops operating, for whatever reason, or grid demand increases the system operator must call upon a marginal resource to start operating, regardless of its emissions. The reasons a unit might stop operating or reduce its output vary widely, including mechanical or safety problems, increasing fuel costs, and even weather. In the case of solar and wind generation, resources whose ability to provide power is “intermittent”, the power output varies across the day according to changes in the weather which cannot be controlled. Whatever the reason, when a CHP unit stops operating, the electrical demand it had been satisfying must be met by increasing or turning on the supply of power from that hour’s marginal resource.

CHP systems have an important place in the grid stack and support grid operations in several ways:

- Behind the meter CHP provides demand reduction, reducing the need to operate additional marginal generation.
- Large CHP (district energy or utility scale) can bid into the day ahead market at lower prices than typical natural gas fired combined cycle plants because of lower net operating costs due to the additional value generated from the utilized thermal resource.
- These systems have higher efficiencies, and therefore produce power at lower cost and with lower emissions, than coal, oil, or natural gas combined cycle power plants where thermal resources are not utilized.

For all these reasons, during many hours of the year, when CHP facilities stop operating the usual result is that system power costs and system carbon emissions increase. Sometimes CHP output can be replaced by low or zero carbon emitting generation such as those using solar, wind, hydro or nuclear fuel. However, because these are baseload facilities, they are usually operating full capacity and their ability to increase output is limited. In those circumstances, it is more likely a carbon-emitting unit that uses natural gas that will be called upon to replace the power lost from the CHP facility.

Emissions Rates

An emissions rate is the measure of pollutant produced per MWh generated. In this study the pollutant of interest is carbon dioxide (CO_2), and the emissions rate is in units of lb CO_2 / MWh. Three are three (3) different grid emissions rates typically used depending on the application and analysis:

- Total - A measure (in lbs / MWh) of average emissions of all generation sources over a given period of time. This includes lower emission, base load, resources such as nuclear and hydro. This emissions rate is most appropriate when assessing power sector emissions of a given region throughout the year.
- Marginal (or Non-Baseload) - A measure (in lbs / MWh) of average emissions from a unit that would typically increase its output if the regional energy demand were higher during a given period of time. Historically, marginal generating units have been natural gas, oil, and coal fired however with increased deployment of wind and solar generation renewable sources are occasionally operating on the margin. This emissions rate is most appropriate for evaluating emissions impacts from the generation being displaced.
- Fossil - A measure (in lbs / MWh) of average emissions from all units that operate on fossil fuels. This represents the highest emissions rate associated with grid electricity. This rate was used historically when fossil fueled generators (coal, oil, natural gas) were more common but are not as frequently used presently since natural gas is the primary fossil fuel used for power generation.

The U.S. Environmental Protection Agency (EPA) Combined Heat and Power Partnership published a Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems in February 2015[1] stating that non-baseload emissions factor should be utilized for CHP systems with low annual capacity factors (< 6,500 hrs) when most generation occurs during periods of high system demand. This same report stated that fossil emissions rates should be used for CHP systems with high capacity factors (> 6,500 hrs). Another EPA published document from 2018, Quantifying the Emissions and Health Benefits of Energy Efficiency and Renewable Energy[2], stated that marginal emissions factors should be used for basic emissions analysis of energy efficiency or renewable energy projects.

Based on these EPA reports, the average marginal emissions rates have been used in this study, independent of annual system runtime.

Within the marginal emissions rate there are two different methods of calculating marginal emission rates; time-weighted and load weighted.

- Time-Weighted - Emissions rate (lb CO_2 / MWh) calculated based on percentage of time that a locational marginal unit (LMU) operates. Assumes when multiple LMU's are marginal that they all contribute equally to meeting loads on the grid.

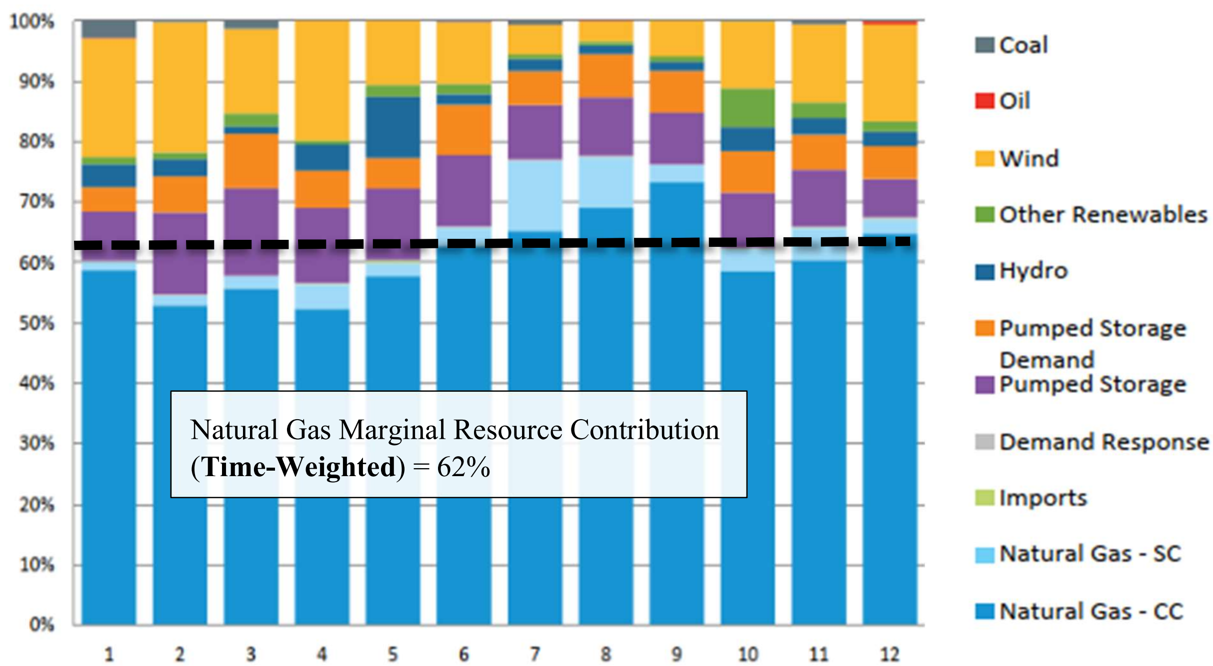
[1] https://www.epa.gov/sites/production/files/2015-07/documents/fuel_and_carbon_dioxide_emissions_savings_calculation_methodology_for_combined_heat_and_power_systems.pdf
[2] https://www.epa.gov/sites/production/files/2018-07/documents/mbg_2-4_emissionshealthbenefits.pdf

- Load-Weighted – A metric ISO-NE began calculating and reporting in 2018[3] that reflects the share of load (MWh generation) served by a marginal unit.

Time-weighted emission rates are based on the amount of time a resource is on the margin while load-weighted emission rates are based on the MWhs of generation from each resource. Load-weighted emission factors are important for two reasons:

- There can be significant differences in the amount of time a resource is on the margin and the amount of energy delivered on the margin.
- Intermittent resources can be on the margin for a large percentage of the time but deliver a much smaller fraction of the marginal energy. For example, during 2019 in ISO-NE wind is on the margin roughly 20% of the time but served < 5% of the marginal load.
- Base load or high-capacity factor generation, such as natural gas, is on the margin for a lower percent of the time (62%) but serves a higher portion of the load (75%).
- The load-weighted emission factor provides an actual lb CO_2 / MWh of grid-purchased electricity while the time-weighted emission factor is an approximation based on the resources' capacity and time it is on the margin.

These differences between time-weighted and load-weighted marginal emissions from 2019 ISO-NE data can be seen below in Figure 2 and Figure 3.



[3] https://www.iso-ne.com/system-planning/system-plans-studies/emissions/

Figure 2. ISO NE 2019 Time Weighted Marginal Generation by Type[4]

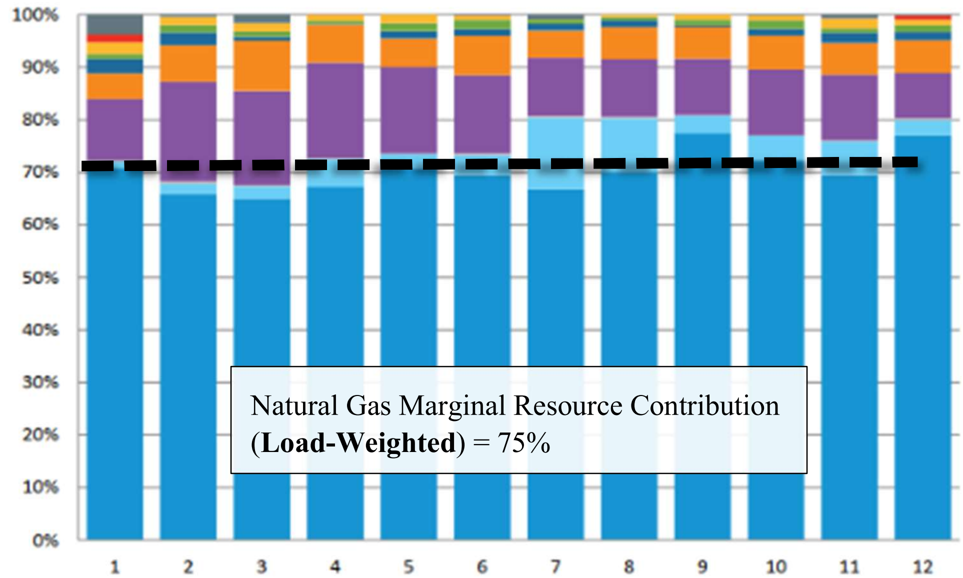


Figure 3 ISO NE 2019 Load Weighted Marginal Generation by Type[3]

Load weighted, marginal / non-baseload emissions rates are most appropriate for comparison with CHP emissions and are used for emissions calculations in the study.

Emission Factor Boundary Conditions

The study utilizes source emissions for the electric grid and natural gas pipeline. Source emissions are a compromise between site-specific emissions and lifecycle emissions. Source emission rates were used so that grid transmission and distribution losses and pipeline losses could be accounted for without requiring a complete life-cycle emission analysis for every electric generator and fuel source. For low carbon fuels (LCF) such as renewable natural gas (RNG) and hydrogen, however, life-cycle emissions are used to account for the emissions involved in the production of these fuels. While inconsistent, using life-cycle emissions for LCFs and source emissions for the grid and pipeline is a conservative assumption because lifecycle emissions analysis of grid electricity and natural gas would result in increased emissions from those sources. Figure 4 below shows the relative variations in emissions and Figure 5 schematically shows the boundary condition used for emissions calculations.

[4] https://www.iso-ne.com/static-assets/documents/2021/03/2019_air_emissions_report.pdf

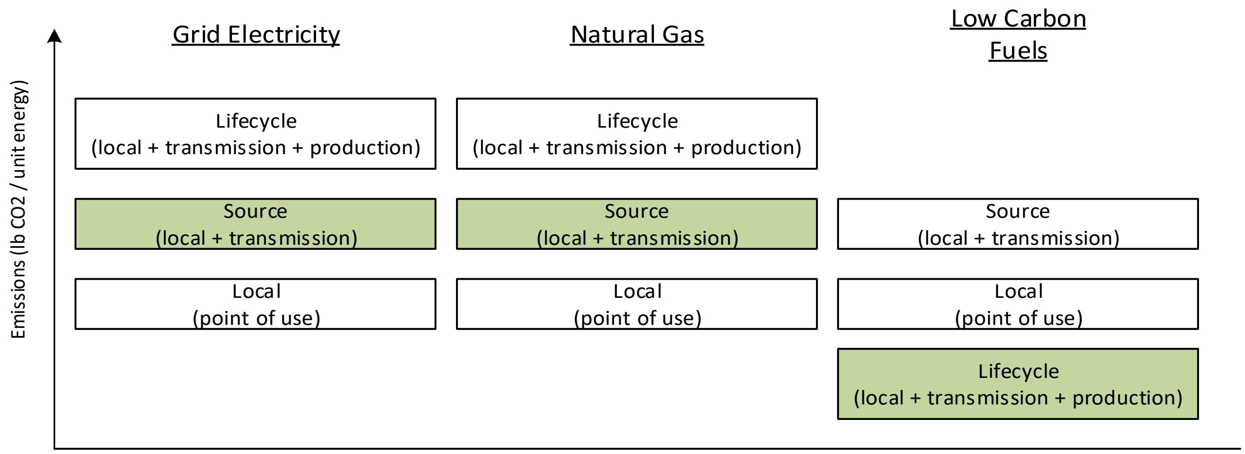


Figure 4. Representation of Relative Locational Impact on Emissions

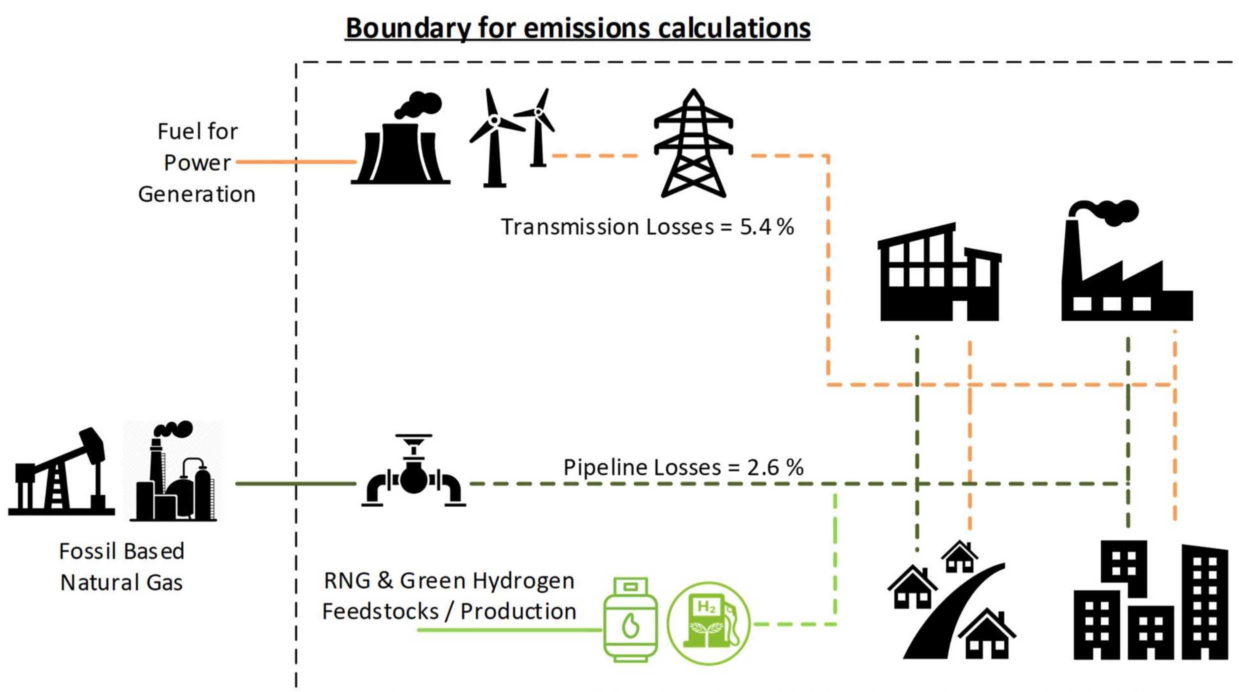


Figure 5. Boundary Conditions for Establishing Emissions Rates

Electric Grid Emissions Data

There are several sources for published grid emissions rates in MA. Values presented by the US Environmental Protection Agency (EPA) eGRID methodology and by ISO-NE are the two that are most widely accepted. The EPA published guidance on appropriate emissions rates to use for assessing impacts of CHP in 2015 [5] and general guidance on quantifying emissions and health benefits of energy efficiency and renewable energy in a 2018 document.[6] Both EPA documents recommend use of marginal eGRID emissions factors to evaluate emissions associated with CHP. The 2015 report provides greater detail in stating that eGRID fossil fuel output emissions should be used for CHP systems operating as baseload capacity (greater than 6,500 hrs / year) while the eGRID non-baseload emissions factor should be used for systems operating in non-baseload capacity (less than 6,500 hrs / year). For this study, the non-baseload emissions factor is being used regardless of the annual system operating hours as it is a more conservative assumption than using fossil fuel emissions rates. This also better reflects the grid mix since marginal generation units are no longer comprised of 100% fossil fuel generators like in the past.

While eGRID emissions data is referenced in the study, the primary data source used is the ISO-NE 2019 Air Emissions Report.[7] The time-weighted marginal emission rates for all LMU's (Appendix Table 14) were used as the starting point for calculating MA load-weighted marginal emissions. Since ISO-NE encompasses six (6) states, and the focus of the study is MA, a locational adjustment factor was calculated using the 2019 emissions from MA (see Figure 6). In addition to adjusting ISO-NE emissions for location, a second adjustment factor was developed to adjust time-weighted to load-weighted emissions factors, using 2019 data (see Figure 7).

2019 ISO New England System
Annual Average Generator Emission Rates (lbs/MWh)

State	NO_x	SO_2	CO_2
Connecticut	0.18	0.02	560
Maine	0.31	0.09	495
Massachusetts	0.50	0.09	877
New Hampshire	0.18	0.06	443
Rhode Island	0.14	0.01	898
Vermont	0.27	0.02	533
New England	0.26	0.05	633

Figure 6. 2019 ISO-NE Annual Average Generator Emissions - By State

[5] https://www.epa.gov/sites/production/files/2015-07/documents/fuel_and_carbon_dioxide_emissions_savings_calculation_methodology_for_combined_heat_and_power_systems.pdf
[6] https://www.epa.gov/sites/production/files/2018-07/documents/mbg_2-4_emissionshealthbenefits.pdf
[7] https://www.iso-ne.com/static-assets/documents/2021/03/2019_air_emissions_report.pdf

2019 Time-Weighted and Load-Weighted LMU Marginal Emission Rates (lbs/MWh)

LMU Marginal Emissions			
	2019 Time-Weighted Annual Rate (lbs/MWh)	2019 Load-Weighted Annual Rate (lbs/MWh)	2019 Load-Weighted vs. 2019 Time-Weighted (%)
All LMUs			
NO_X	0.101	0.108	6.9
SO_2	0.021	0.028	33.3
CO_2	648	719	11.0
Emitting LMUs			
NO_X	0.155	0.145	-6.5
SO_2	0.039	0.039	0.0
CO_2	970	943	-2.8

Figure 7. 2019 ISO-NE Time-Weighted and Load Weighted LMU Marginal Emissions Rates

The equation used to calculate location and load-weighted adjustment factors, as well as adjusted marginal emission rates, can be found below in Equation 1.

Equation 1. Location and Load-Weighted Marginal Emissions Adjustment

ISO-NE MA & Load Weighted Adj. Marginal Emissions =

ISO-NE Time-Weighted Marginal Emissions Rates * Location Adj. Factor * Load-Weighted Adj. Factor

Where:

Location Adj. Factor = 2019 MA Emissions / 2019 ISO-NE Emissions = (877 / 633) = 138.5%

Load-Weighted Adj. Factor = 2019 Load-Weighted / 2019 Time -Weighted = (719 / 648) = 111%

The data sources and adjustments mentioned above were used to develop the plot, and trend lines, seen in Figure 8. Details regarding each data set, and the developed trend lines, can be found below.

Data Sets

- ISO NE – Average Generator Emission Rates (light purple) – Average grid emissions from ISO-NE 2019 Air Emissions Report.
- ISO NE – Time Weighted LMU Marginal Emission Rates (dark purple) – Time-weighted marginal emissions rates from ISO-NE 2019 air emissions report.
- ISO-NE – MA and Load Weighted Adj. Marginal (dark blue) – ISO-NE time-weighted marginal emission rates, adjusted using Locational and Load-Weighted Adj. Factors developed above.
- ISO-NE – 2017 to 2019 (red) – Three (3) most recent years of ISO-NE MA and Load Weighted Adj. Marginal data. These three years exclude the emissions impact of closing Brayton Point; the last coal power plant in MA rated for 1,500 MW.

Trendlines

- eGRID MA – Non-Baseload Output Emissions Rate – Calculated from 2018 and 2019 eGRID non-baseload emissions data for MA.
- ISO-NE – MA and Load Weighted Adj. Marginal – Trendline reflecting the rate of adjusted emissions reductions between 2015 and 2019. Includes large reduction from 2016 to 2017 due to closure of last MA coal plant.
- ISO NE – 2017 to 2019 – Best fit line through the adjusted ISO-NE data from 2017 to 2019. This trend excludes the step change in emissions caused by the closure of the last coal fired power plant in MA and represents the gradual decline in emissions observed over these years.

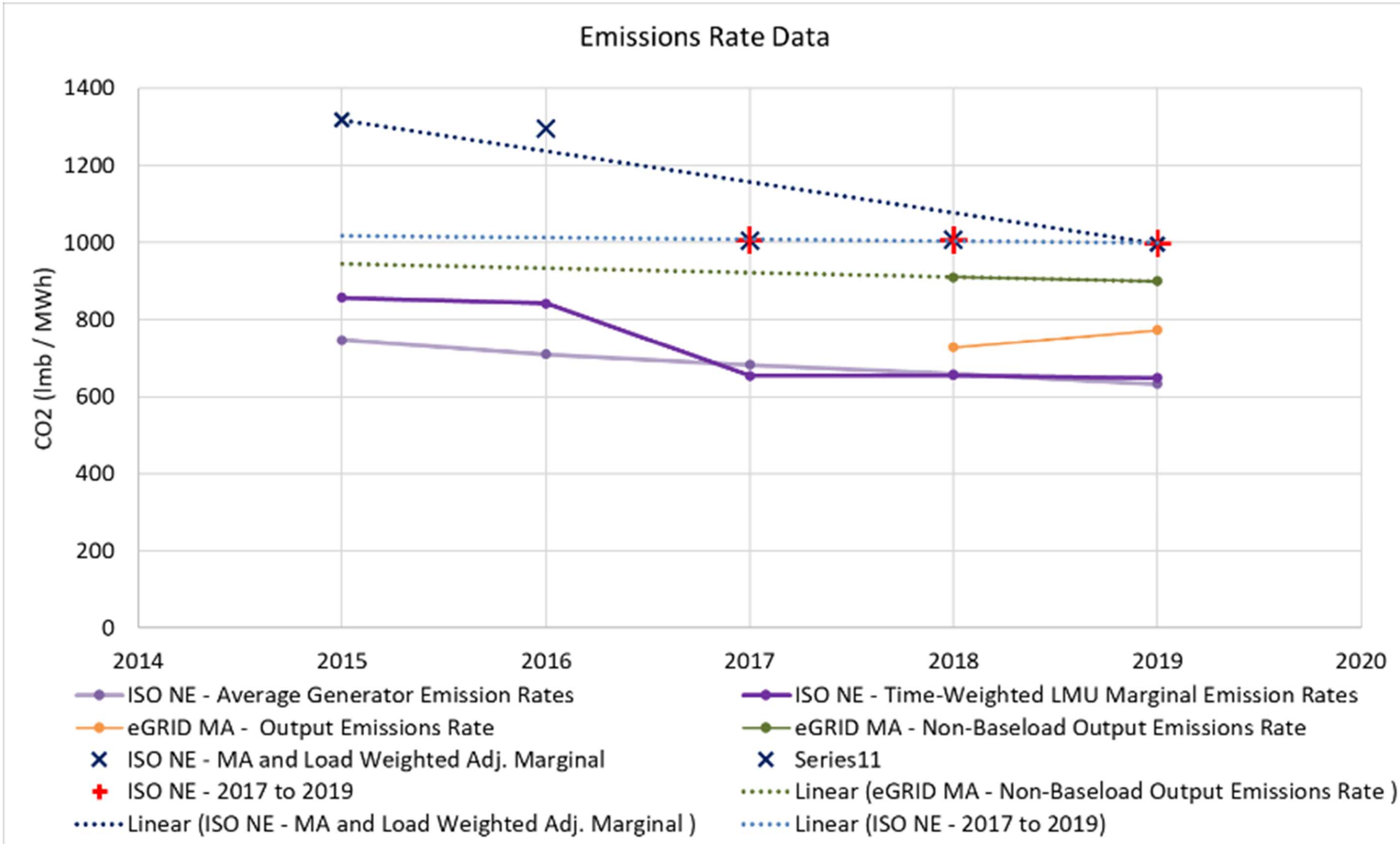


Figure 8. Published Emissions Rate Data and Developed Trendlines

Electric Grid Emissions Models

While historic trends are important to understand the current rate of emission reductions, they don't reflect future changes in energy generation that are expected to result in future reductions in emissions (comparable to dramatic reduction in emissions caused by the closing of the Brayton Point power plant in 2017). To account for future changes in emissions from new renewable generation, the projected MA electric supply from the MA Energy Pathways for Deep Decarbonization Report [8] (Energy Pathways) was used. Figure 9 below shows the projected annual MA electricity supply by source. The rate at which electricity from gas is projected to decline was used as a proxy for modeling the future grid emissions.

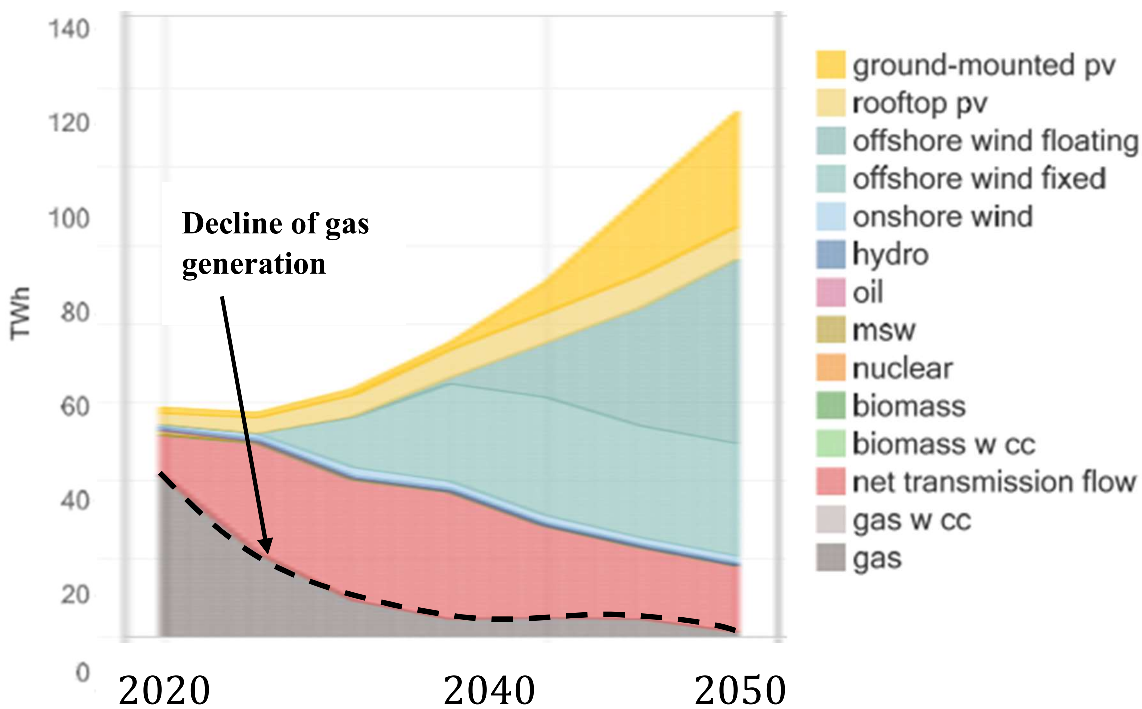


Figure 9. Massachusetts Annual Electrical Supply by Resource Type for All Pathways (Figure 23 of report)

Since generation using natural gas is the primary remaining emitting electric generation source, it is assumed that grid emissions will decrease at the same rate that gas generation does. The modeled emissions reductions, from present day values can be seen in Figure 10. The model includes the following assumptions:

- 80 % reduction in grid emissions by 2030
- Plateau in grid emissions reductions from 2032 to 2043
- Drop in grid emissions from 2044 to 2050 to 8.2 lb CO_2 / MWh. [9]

[8] https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/download
[9] Pg. 2 of Energy Pathways Technical Report

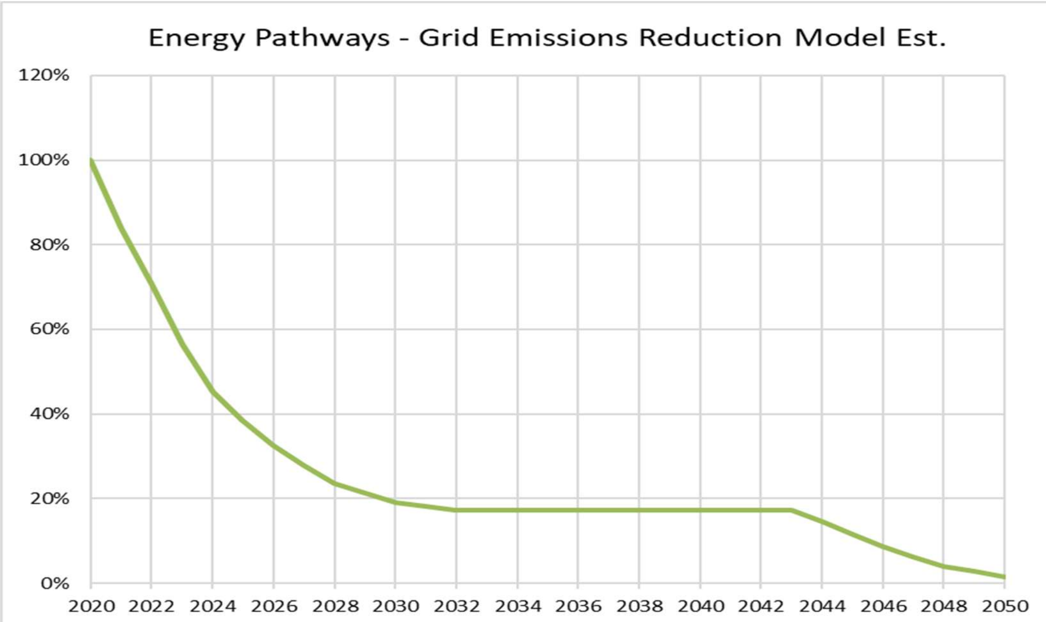


Figure 10. Energy Pathways Grid Emissions Reduction Model

The historical emissions rate data from Figure 8, the Energy Pathways emissions reduction model from Figure 10, and transmission losses of 5.4 % for the eastern grid [10] were used to develop four projections of grid emissions, out to 2050, which are shown below in Figure 11.

[10] https://www.epa.gov/sites/production/files/2021-02/documents/egrid2019_technical_guide.pdf

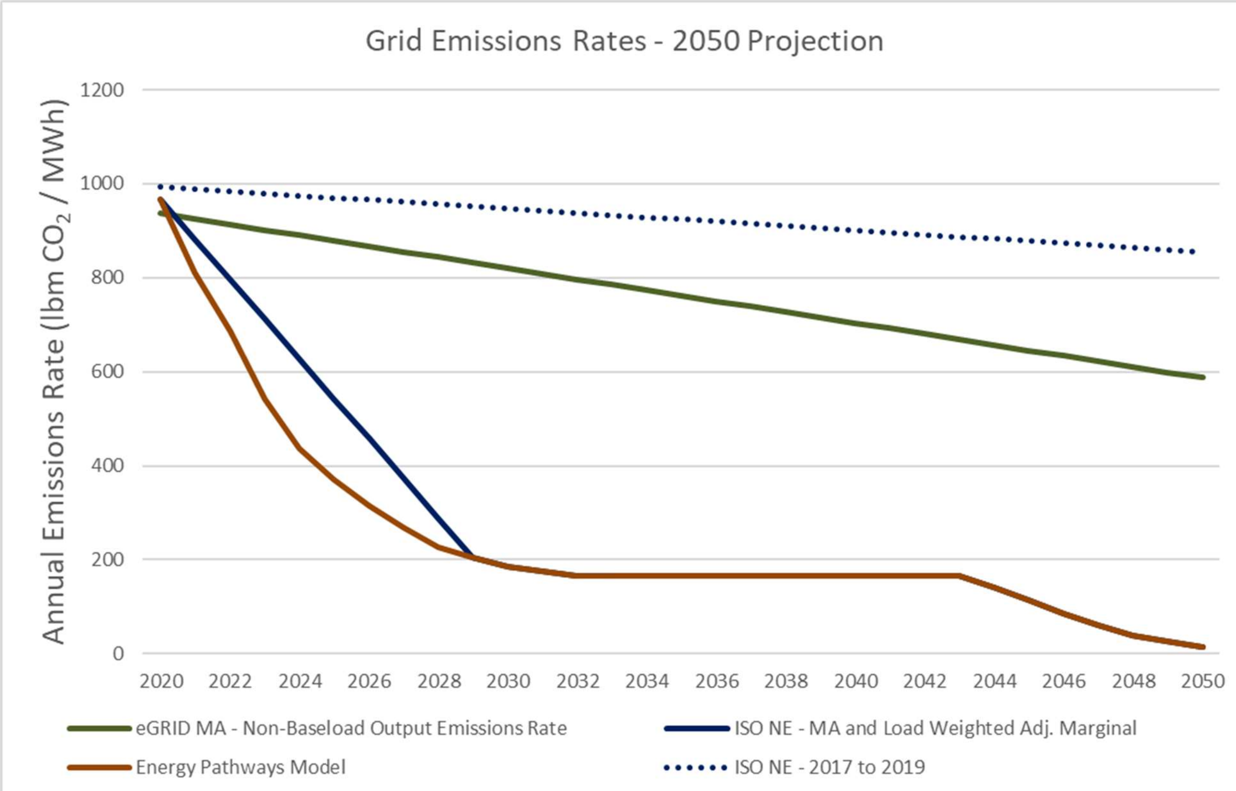


Figure 11. Grid Emissions Projections

There are significant variations between the Energy Pathways model and the various extrapolated historical data trends. Some important observations include:

- The Energy Pathways projection incorporates the thorough and detailed modeling from the report, including deployment of future renewable resources. However the projected grid emissions are representative of average emissions as opposed to marginal emissions.
- The Energy Pathways report projects approximately 5 TWh of electricity production from natural gas in 2050. This resource will operate on the margin due to its operational flexibility resulting in marginal emissions higher than the average grid emissions.
- Adjusted ISO-NE data results in significantly different trends over a 5-year period (2015 to 2019) compared to the three-year period (2017 to 2019); see Figure 8. This is due to a significant drop in emissions associated with closing the 1.5 GW Brayton Point coal plant in MA.
- Adjusted ISO-NE 2017 to 2019 trend has similar slope to eGRID non-baseload emissions trend.
- The Energy Pathways model and ISO-NE 2017 to 2019 trend will serve as upper and lower bounds on future grid emissions. Actual grid emissions will likely fall somewhere between these two trends, depending on the rate of deployment of renewable resources and load shifting (for example, from battery technologies).
- Emissions projections should be updated annually, based on most recently published emissions values, to fine tune the model.

PIPELINE EMISSIONS FACTORS

Performance of a CHP system, and its associated emissions, is a known quantity based on manufacturer ratings and the emissions associated with combusting natural gas. The Energy Information Administration (EIA) published value of 117 lb CO_2 / MMBtu is the widely accepted emissions rate for the combustion of fossil-based natural gas.[11] While pipelines currently carry 100% fossil-based natural gas, it is anticipated that in the future renewable natural gas (RNG) and hydrogen will be blended into the pipeline. This blending of alternative, low carbon fuels (LCF), will reduce the emissions rate of fuel delivered from the pipeline.

Assumptions made for gaseous fuels and their associated emissions include:

- All hydrogen blended into the pipeline is green hydrogen and therefore results in zero CO_2 emissions.
- RNG emissions based on California Air Resource Board (CARB) published data from approved natural gas (RNG) production pathways.
- Across the 142 approved pathways the average lifecycle emissions of RNG was -28.4 lb CO_2 / MMBtu. [12]
- For this study, based on CARB data, emissions associated with RNG combustion were conservatively estimated to be 0 lb CO_2 / MMBtu.
- Source emissions used for fossil natural gas while lifecycle emissions used for both hydrogen and RNG, as discussed above.

The emissions rates, and assumptions, accompanying each gaseous fuel can be found below.

Table 1. Emissions Rates for Approved LCF Pathways – CARB

CO_2e Emissions - CARB LCF Pathways[2] - April 5, 2021		
Fuel Type	**# of Approved Pathways**	**Avg. CO_2e Emissions Rate (lbs / MMBtu)**
CNG	19	110.4
Compressed Natural Gas	61	115.5
Compressed Natural Gas (CNG)	62	-311.1
Total / Average:	**142**	**-28.4**

[11] https://www.eia.gov/tools/faqs/faq.php?id=73&t=11
[12] https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx

Table 2. Fuel Emissions Rates and Assumptions

Fuel	Emission Rate	Notes
Natural gas	117 lbs CO_2/MMBtu	Onsite combustion by CHP or standard boilers. (site emissions, converted to source emissions when pipeline losses included)
Green Hydrogen	0 lbs CO_2 / MMBtu	Produced by electrolysis using renewable electricity. (lifecycle emissions)
RNG	0 lbs CO_2 / MMBtu	Negative net emissions (CARB-approved LCF pathways for CNG, lifecycle emissions)

Once emissions rates were established, the rates at which RNG and hydrogen are produced and blended into the pipeline were projected. Published reports were reviewed to estimate the timeline and quantity of low carbon fuel blending into the natural gas pipeline.

- The Road Map to a US Hydrogen Economy report [13] projects adoption rates for hydrogen blending into gas networks of on average 1.5% by 2030 and 15% by 2050. This report was used to estimate the hydrogen percentage in use for power generation the future.

- A RNG Opportunity for Natural Gas Utilities report, published by MJ Bradley in 2017 [14], focused on the technical potential of RNG production in the northeast. This report estimates the RNG potential in Massachusetts is equal to 10% of the projected total natural gas demand in the state. This report was used to estimate the RNG percentage in the pipeline in 2050.

Both hydrogen and RNG blending rates were estimated to increase linearly to reach the perspective projections in 2035 and 2050. The projected pipeline blending rates can be seen graphically below in Figure 12.

[13] https://www.fchea.org/s/Road-Map-to-a-US-Hydrogen-Economy-Full-Report.pdf
[14] https://mjbradley.com/sites/default/files/MJB%26A_RNG_Final.pdf

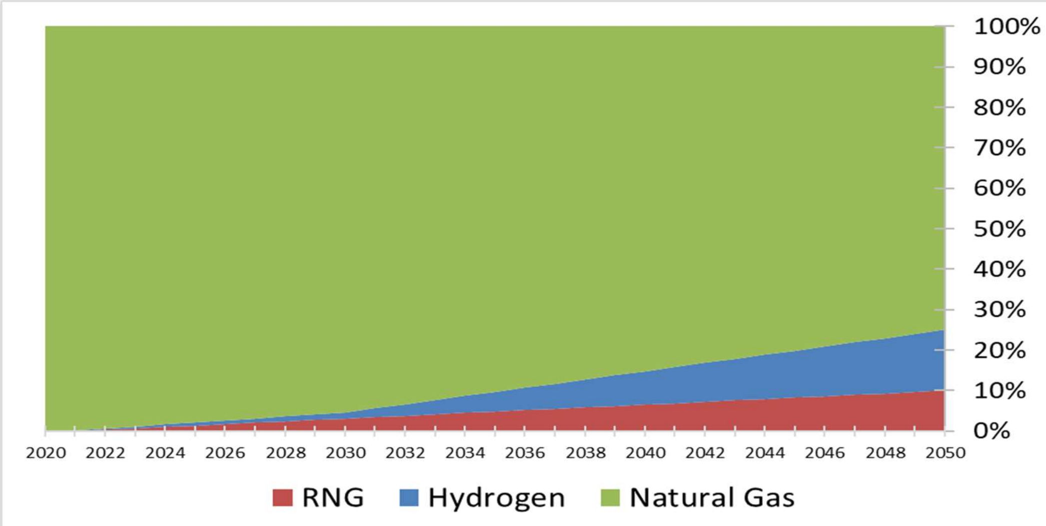


Figure 12. Projected Pipeline Blending of Low Carbon Fuels

Using the established emissions rates from Table 1, LCF blend projections from Figure 12, and pipeline loss of 2.6% [15] the effective emissions rate from pipeline gas was projected out to 2050. This declining emissions rate represents the gradual "greening" of pipeline natural gas as low carbon fuel production and blending ramp up. This is analogous to the way solar and wind deployment have ramped up over time, resulting in emissions reductions from the electrical grid. It is important to note that these projections represent LCF blending into the pipeline which will reduce emissions from any equipment utilizing pipeline natural gas. On a site-by-site basis emissions can be further reduced, and at a greater rate, through the direct production or purchase of low carbon fuels. This LCF direct procurement scenario is discussed in greater detail later in the report.

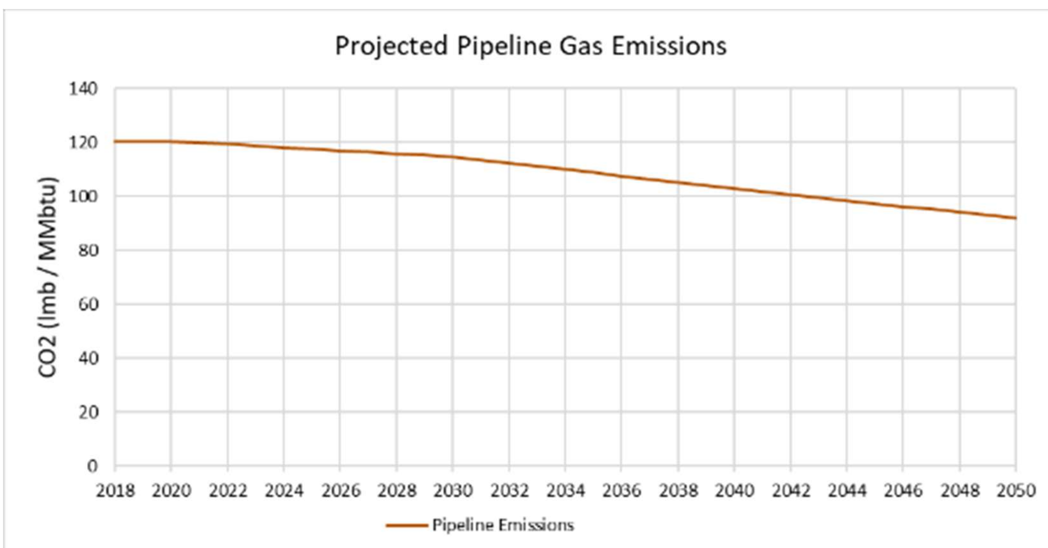


Figure 13. Projected Pipeline Gas Emissions from LCF Blending

[15] https://www.mass.gov/doc/icf-international-report-lost-and-unaccounted-for-gas/download

PERFORMANCE ASSUMPTIONS

Once grid and pipeline emissions rates were established, the performance of the energy systems that uses those fuels needs to be determined. This study evaluated four different-sized CHP systems of varying technologies; 100 kW reciprocating engine (RE), 2 MW RE, 7 MW gas turbine (GT) and 100 MW GT. The technologies evaluated as potential alternatives to CHP include grid electricity and natural gas boiler, on-site solar and natural gas boiler, or grid electricity and heat pump.

Combined Heat and Power Systems

CHP systems are capable of consistently operating at manufacturer full load ratings, provided they are properly sized (ie: the facility has sufficient electric and thermal loads). In this study systems are assumed to be properly sized so that the facility can utilize all the electric generation and a large percentage of the produced thermal output.

CHP system performance was established using performance ratings from the EPA published Catalog of CHP Technologies.[16] In addition to producing power and heat, CHP systems also consume a small amount of power for balance of plant loads such as controls, pumps, ventilation fans, etc. To account for this energy consumption in the performance models a standard parasitic load of 3% of the nameplate rating was assumed for all systems. A table of the CHP system performance used in the emissions study can be seen below in Table 5.

The thermal output from CHP systems is either in the form of hot water (HW) or steam. Smaller systems typically produce HW only while larger systems more commonly produce steam or a combination of steam and HW. The thermal output produced is important when selecting alternative technologies for comparison because thermal resources (HW vs. steam) are not the same.

Some facilities require steam for manufacturing or other process loads (industrial / manufacturing and hospitals) or already have large steam distribution infrastructure (college campuses). Even if facility loads do not explicitly require steam, converting an existing facility from steam to HW is a disruptive and expensive project. Heat pump systems are not capable of producing steam, so there are some facilities for which this alternative technology not a suitable option.

These factors were all considered when determining appropriate alternate technologies for comparison to CHP.

Alternative Technologies

Similar to CHP systems, performance assumptions needed to be established for the alternative technologies. Boiler and heat pump performance assumptions were made using a combination of published resources combined with real world applications and constraints. While on-site solar is one of the alternative technologies assessed, it is a zero-emission resource, so system performance only impacts system energy production and sizing, which can be a challenge as discussed in the next section.

Boilers

There are a wide range of boiler technologies and types; conventional, high efficiency, condensing, hot water, and steam. The boiler type significantly impacts performance as efficiencies can range from 79% for a conventional steam boiler up to 97% for a condensing HW boiler operating with low return water

[16] https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf

temperature operated at partial load. Due to the low return water temperatures necessary for condensing boilers to achieve > 90% efficiency, they were determined not to be an appropriate alternative to CHP in existing buildings. It is appropriate to compare CHP to small to large gas-fired commercial hot water or steam boilers. Average efficiencies for these systems were determined using the DOE Commercial Packaged Boiler Energy Conservation Standards. [17] The average efficiency used for a HW boiler is 84 % HHV while the average efficiency for a steam boiler is 81 % HHV.

Heat Pumps

Similar to boilers, there is a wide range of performance (COP) for heat pump systems. The Northeast Energy Efficiency Partnership (NEEP) [18] has published performance data for over 20,000 systems. In the NEEP data set the rated COP of heat pump systems ranges from 1.75 to 3.63. An assumed COP of 2.5 was selected based on this data set, correlated with experience Frontier Energy has had in monitoring the real world (non-lab) performance of cold climate heat pumps.

Challenges and Constraints

As mentioned earlier in this section, there are several constraints associated with alternative technologies, making them only appropriate alternatives in specific applications. Some of the constraints and benefits that need to be considered include:

- Thermal requirements of a facility (HW vs. steam)
    - The inability of heat pump systems to deliver high grade heat (steam) prevents them from being an acceptable alternative at facilities that have existing steam distribution systems or require steam or high temperature heat for process loads.
- Vulnerability to grid outages
    - CHP systems can provide backup power to facilities in the event of grid outages. This is an important feature of the technology for data centers, hospitals, and critical manufacturing facilities where power outages are unacceptable or would cause significant loss of revenue.
    - While resulting in emissions reductions, electrification leaves a facility vulnerable to utility outages due to extreme weather events, transmission or distribution failures, public safety outages, or supply shortages. When a facility's heating and cooling loads are served by heat pumps, power outages can leave buildings without space conditioning.
- Footprint required for onsite solar
    - Installing rooftop or ground mounted solar can help reduce emissions of residential buildings and even commercial facilities, provided there is sufficient rooftop area or land for the installation of an appropriately sized system.
    - A solar system capable of producing comparable annual kWh's to a CHP system requires significant area (see Table 3 below). Because of the significant space needed for solar, due to low panel efficiencies and annual full load hours, onsite solar is not a realistic alternative for facilities in crowded cities or with large electrical loads.

[17] https://www.energy.gov/sites/default/files/2016/12/f34/CPB_ECS_Final_Rule.pdf
[18] https://ashp.neep.org/#!/product_list/

Table 3. Solar Panel Sizing Comparisons

CHP System	Net CHP Output	Annual Production (kWh)	Required Solar Capacity (kW)	# Panels	Installed Panel Area (ft^2)	Installed Panel Area (Football Fields)
100	97	776,000	517	1,293	29,416	0.51
2,000	1,940	15,520,000	10,347	25,867	588,474	10.22
7,000	6,790	54,320,000	36,213	90,533	2,059,626	35.76
100,000	97,000	776,000,000	517,333	1,293,333	29,423,326	510.8

Assumptions: CHP operated 8,000 hrs / year, solar system operates with 1,500 equivalent full load hours (EFLH), 20% solar system efficiency, 400 watt, 22.75 sq ft panels.

Table 4 below summarizes the topics discussed in this section, including:

- Common applications for the various sized CHP systems.
- Typical use for produced thermal output.
- Appropriate alternative technologies evaluated for each sized system.

Table 4. Typical CHP Applications and Alternative Technologies

	100 kW RE	2 MW RE	7 MW GT	100 MW GT
Typical Applications	Multifamily residential Hotel / lodging Healthcare - small (s)	Education Healthcare Industrial (s – med) Manufacturing (s – med)	Education Healthcare Industrial (s– med) Manufacturing (s – med)	Industrial park Healthcare campus Industrial (lg) Manufacturing (lg) District Energy System
Grid Integration	Behind the Meter	Behind the Meter	Behind the Meter	Behind the Meter and / or Grid Export
Heat Recovery	<u>Hot Water</u> DHW Space Heating (SH)	<u>Hot Water</u> DHW / SH / Process <u>Steam</u> DHW / SH / Process <u>Chilled Water</u>	<u>Hot Water</u> DHW / SH / Process <u>Steam</u> DHW / SH / Process <u>Chilled Water</u>	<u>Steam</u> HP and/or LP Common dist. header Process
Alternative Technologies	Grid & Boiler Solar & Boiler Grid & Heat Pump	Grid & Boiler Solar & Boiler	Grid & Boiler Solar & Boiler	Grid & Boiler Solar & Boiler

CHP and Alternative Technology Performance

The performance assumptions and alternative technology constraints discussed in this section have all been complied into Table 5 below. These values, along with the projected grid and pipeline emissions from the previous section, are used to derive the subsequent emissions calculations and analysis.

Table 5. System Performance Assumptions

	100 kW RE	2 MW RE	7 MW GT*	100 MW GT**
Net Power Output (kW)	97	1,940	6,790	194,000
Electrical Efficiency (% HHV)	27%	38%	30%	30%
Thermal Efficiency (% HHV)	45%	42%	41%	41%
CHP Efficiency (% HHV)	72%	80%	71%***	71%***
Assumed Boiler Efficiency (% HHV)	85%	81%	81%	81%
Assumed Heat Pump COP	2.5	-	-	-

* Assumes co-fired heat recovery steam generator (HRSG)

** Assumes GT w/ co-fired HRSG and backpressure or extraction turbine (typ. for large CHP)

*** Performance stated in EPA CHP Catalog. Actual operation can reach ~78 % HHV

EMISSIONS ANALYSIS AND COMPARISON

This section includes an overview of the emissions calculations for both CHP and alternative systems as well as an evaluation of the present day and future emissions rates. This section will focus on the 2 MW reciprocating engine (RE) unit, as this size is more common than the larger 7 MW and 100 MW GT systems and provides greater emissions reductions than the small 100 kW. Emissions analysis and comparisons to alternatives for the three systems not reported on here (100 kW RE, 7 MW GT, and 100 MW GT) can be found in the appendices.

Emissions Calculations

Table 6 below shows the emissions rate calculations for the 2 MW RE CHP system and alternative technologies. The emissions rate in the table was calculated using the Energy Pathways Model emission rate for 2020. The analysis uses the CHP output (electric and thermal) as the baseline load that must be satisfied by alternative technologies. This allows for a likewise comparison of emissions produced by different technologies serving identical electric and thermal loads.

A runtime of 1-hr was used to simplify the emissions rate calculations. The emissions rate is calculated by dividing the total emissions by the electric production. This is different than an effective electric emissions rate, which is commonly used when evaluating CHP emissions, because the emissions associated with thermal production is included. Changes to the system runtime will result in increased electric and thermal production, gas consumption, and lbs of CO_2 produced, however the calculated emissions rate remains constant for each technology.

Table 6. Emissions Calculations Details – 2020 Energy Pathways Model

	CHP (2 MW Recip.)	Grid & Boiler	Solar and Boiler
Net Power Output (kW)	1940	-	-
Electrical Efficiency	38.0%	-	-
Thermal Efficiency	42.0%	-	-
CHP Efficiency	80.0%	-	-
Runtime (hrs)	1	-	-
Electric Production (MWh)	1.94	1.94	1.94
Fuel Consumption (MMBtu)	17.42		
Thermal Production (MMBtu)	7.32	7.32	7.32
Assumed Boiler Efficiency	81%	81%	81%
Boiler Fuel Consumption (MMBtu)	-	9.07	9.07
Assumed Heat Pump COP	-	-	-
Heat Pump Electric Consumption (MWh)	-	-	-
CHP CO_2 Emission (lb CO_2)	2,038	-	-
Emissions from Electricity (lb CO_2)	-	1,874	0
Emissions from Heating - Gas (lb CO_2)	-	1,061	-
Emissions from Heating - Electricity (lb CO_2)	-	-	1,061
Total Emissions (lb CO_2)	2,038	2,935	1,061
Emissions Rate (lb CO_2 / Bldg. Electric Load MWh)	1,051	1,513	547

The 2020 emissions calculations show that CHP has a lower emissions rate than the grid and boiler alternative in 2020. The installation of on-site solar and boiler would result in the lowest emissions rate if, and only if, adequate land were available to size a solar system for comparable kWh production. For reference, a solar system sufficient to provide this much electricity would require 13.5 acres of nearby usable land. Heat pumps are not included in this comparison because it is assumed the 2 MW CHP system provides steam as a thermal output.

Projected Emissions Comparison

Emissions calculations were performed using the projected grid and pipeline emissions rates and compared to emissions from appropriate alternative technologies annually from 2020 to 2050. Figure 14 compares the emissions rates of CHP and the Grid and Boiler alternative resulting from the various grid emissions models.

Under the most optimistic, emissions model (Energy Pathways), CHP has a lower emissions rate than the Grid and Boiler alternative in the near term, providing emissions reductions, until 2023. The ISO-NE MA and load weighted adjusted marginal emissions model results in CHP providing emissions reductions into 2025. However, comparison to the eGRID MA non-baseload and ISO-NE 2017-2019 emissions models both result in CHP providing greater emissions reductions out past 2050.

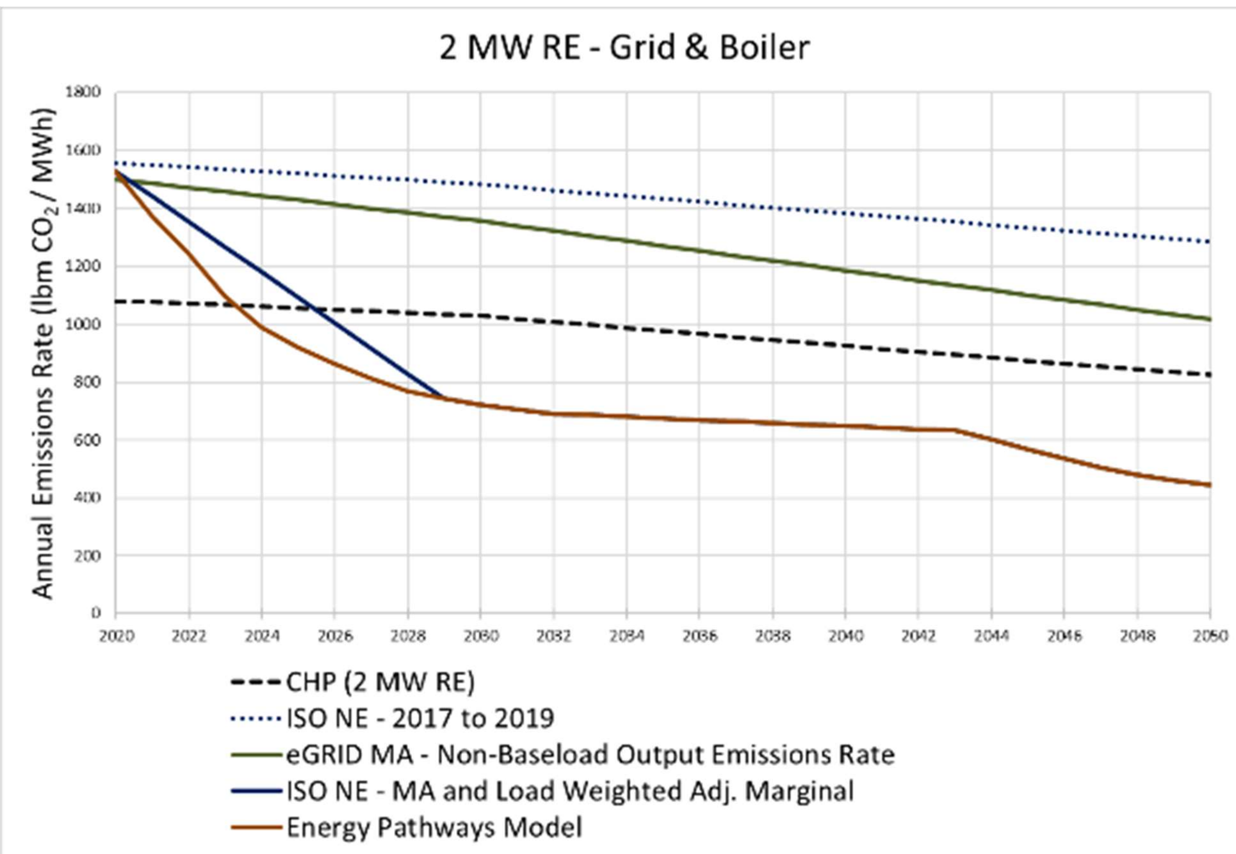


Figure 14. 2 MW RE CHP Emissions Comparison to Grid and Boiler - All Models

Figure 14 shows the significant variation in projected emissions rates and that CHP provides emissions reductions in the short term regardless of the emission model used.

Table 7 below shows a summary of the year CHP provides emissions reductions compared to an alternative technology, for all the emissions models. Solar and boiler is not included in the table because CHP does not provide emissions reductions compared to this alternative under any of the models. Depending on which model the decline of grid emissions follows, CHP also has the potential to provide emissions reductions, compared to a standard Grid and Boiler alternative, out past 2050.

Table 7. Summary of Projected Timeline of CHP Emissions Reductions

Grid Emissions Model	CHP System	Grid & Boiler	Grid & Heat Pump
Energy Pathways	100 kW RE	2022	2021
	2 MW RE	2023	N/A
	7 MW GT	2022	N/A
	100 MW GT	2022	N/A
ISO-NE - MA and Load Weighted Adj. Marginal	100 kW RE	2023	2021
	2 MW RE	2025	N/A
	7 MW GT	2023	N/A
	100 MW GT	2023	N/A
eGRID Non-Baseload	100 kW RE	> 2050	2021
	2 MW RE	> 2050	N/A
	7 MW GT	> 2050	N/A
	100 MW GT	> 2050	N/A
ISO-NE - MA and Load Weighted Adj. Marginal (2017 - 2019)	100 kW RE	> 2050	> 2050
	2 MW RE	> 2050	N/A
	7 MW GT	> 2050	N/A
	100 MW GT	> 2050	N/A

CHP Emissions – Low Carbon Fuel Procurement Scenario

The above emissions projections utilize the conservative LCF pipeline blending rates established in Figure 12, however there is growing interest in directly procuring low carbon fuels. Procurement of RNG or green hydrogen has the potential to significantly reduce emissions associated with individual CHP systems on a case-by-case basis. Figure 15 below models' a 15% increase in facility LCF procurement every 4-years and compares the resulting emissions rate with the emissions rate from the estimated pipeline blending scenario. Direct procurement and combustion of zero emission RNG or green hydrogen would directly reduce CHP emissions in proportion to the percent of RNG or green hydrogen blended with conventional natural gas.

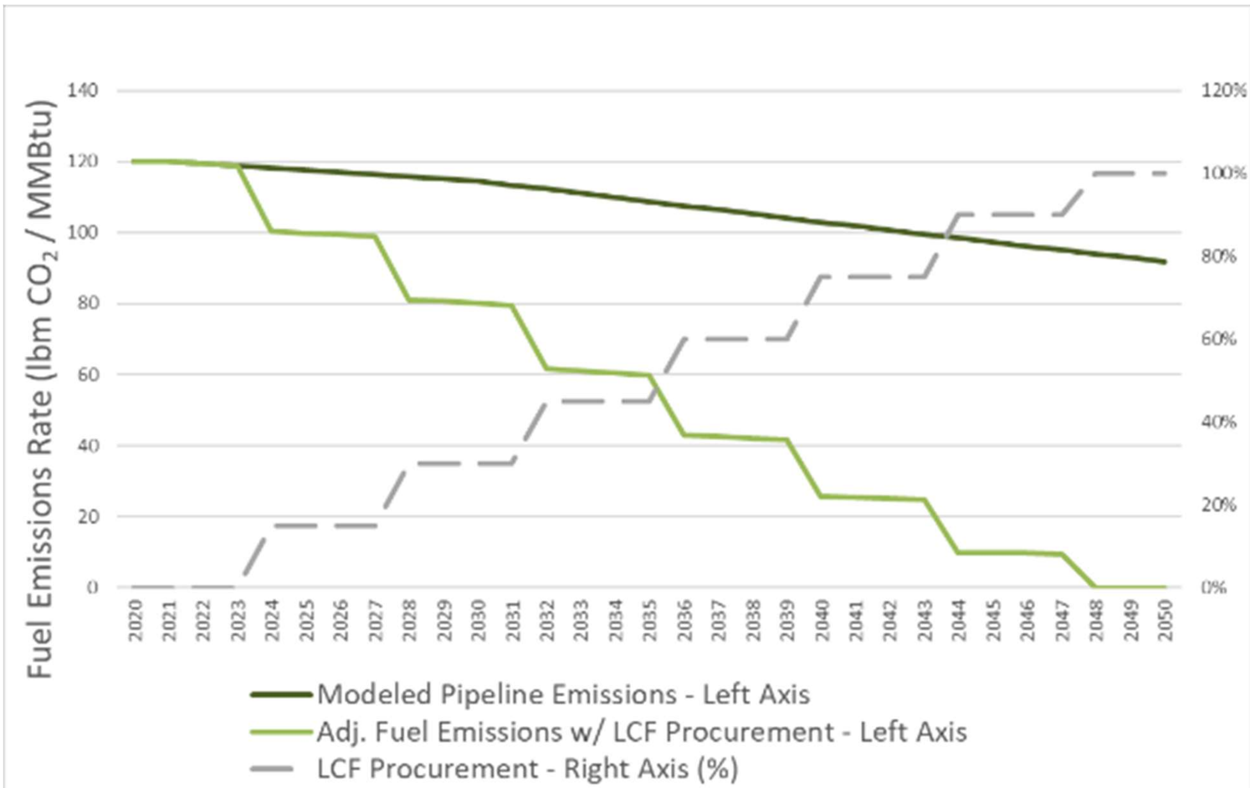


Figure 15. CHP Emissions with LCF Procurement

Figure 16 through Figure 19 below show the resulting emissions for CHP fueled with higher percentages of LCF blends, compared to traditional pipeline fueled CHP and alternative technologies. Compared to the most aggressive Energy Pathways grid emissions model, a 15% increase in LCF procurement every 4-years, would result in CHP system emissions being at parity or lower than the Grid and Boiler alternative, out past 2050. The LCF procurement scenario results in significant emissions reductions compared to CHP operating on pipeline natural gas. Facilities that operate CHP on more than 60% carbon-free fuel would experience emissions reductions compared to all alternative technologies.

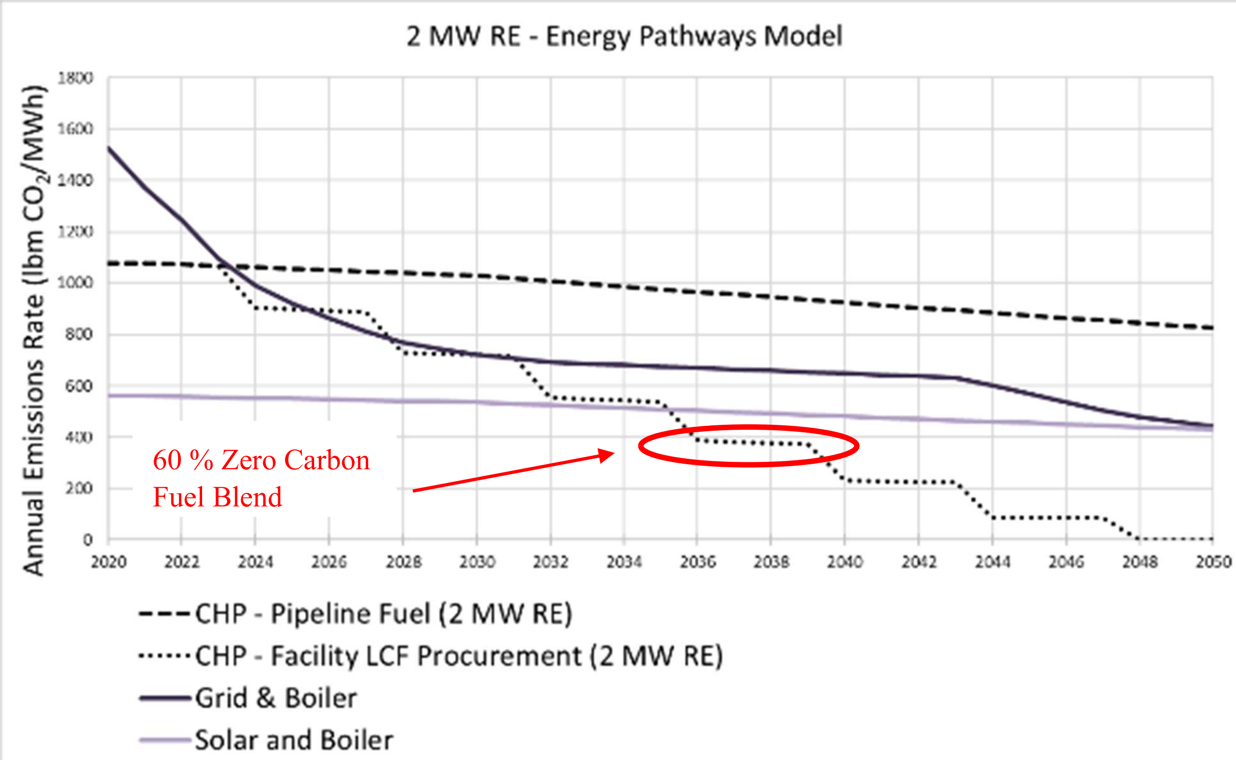


Figure 16. LCF Procurement Scenario - 2 MW RE - Energy Pathways Model

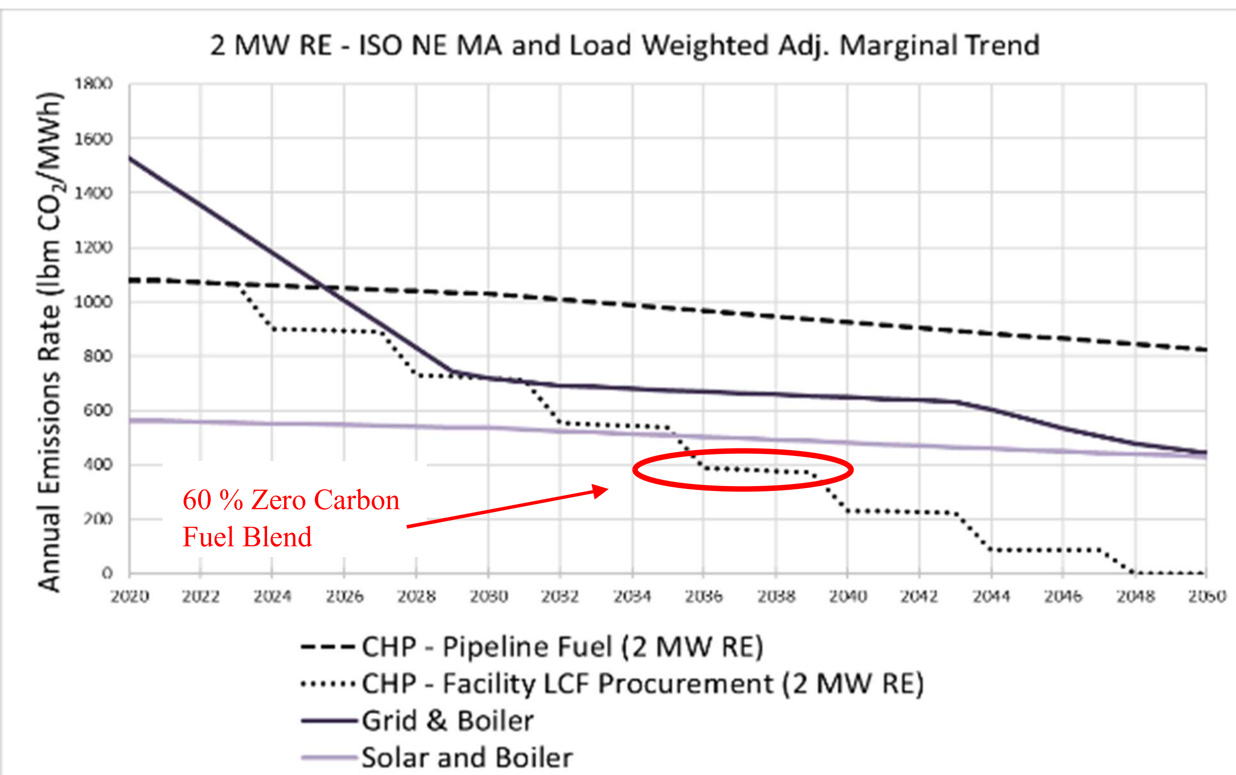


Figure 17. LCF Procurement Scenario - 2 MW RE – ISO-NE MA and Load Weighted Adj. Marginal Trend

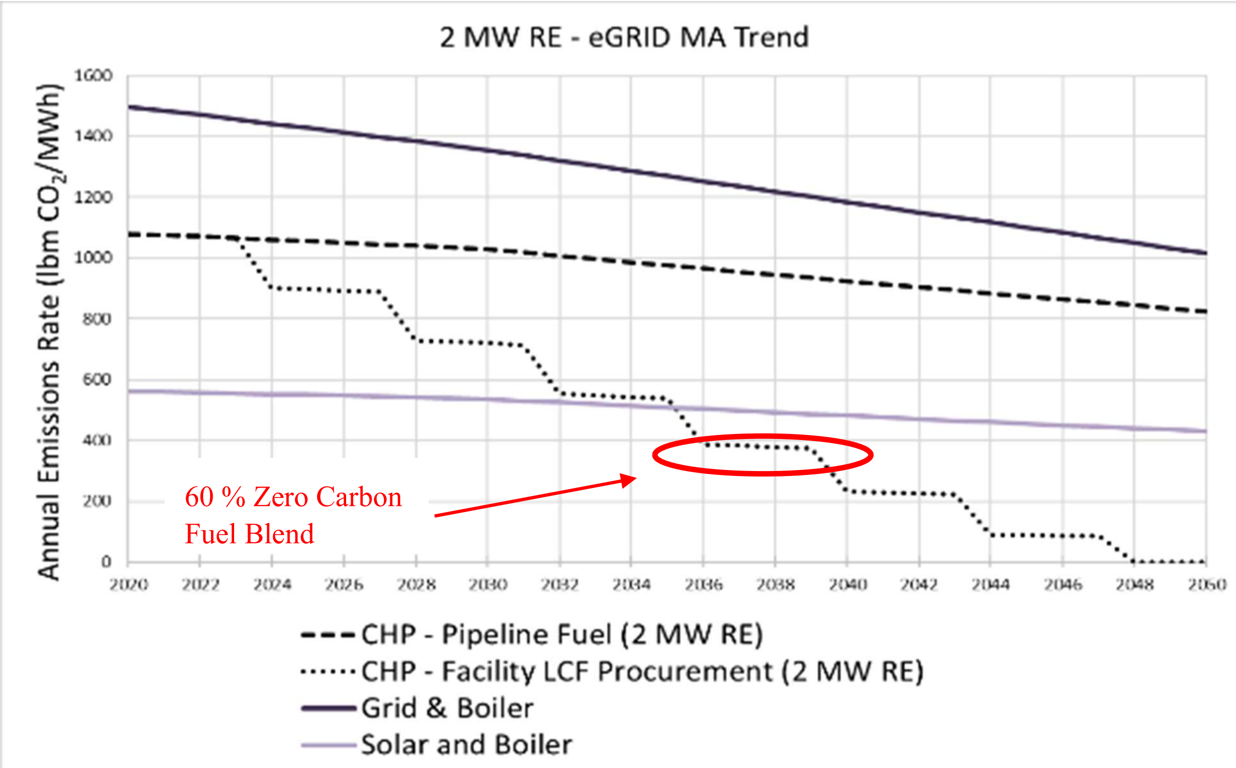


Figure 18. LCF Procurement Scenario - 2 MW RE – eGRID MA Model

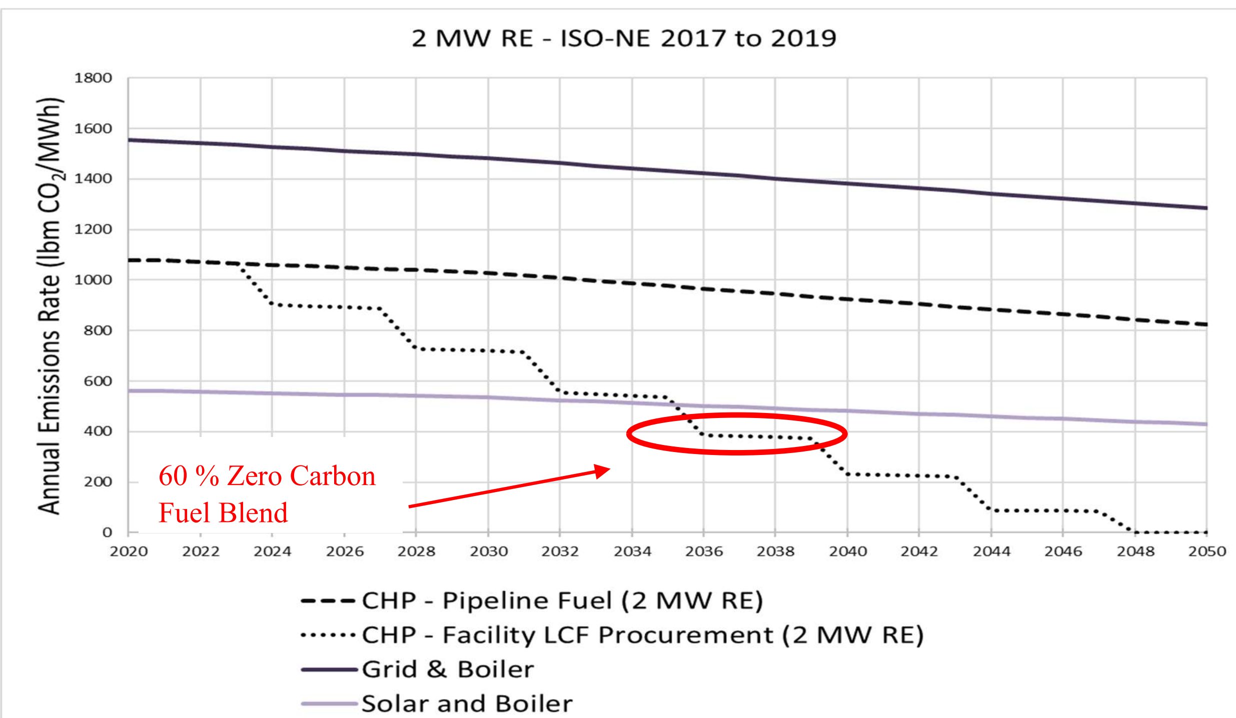


Figure 19. LCF Procurement Scenario - 2 MW RE – ISO-NE MA 2017 – 2019 Model

The use of LCF for stationary power production could allow system owners, operators, and facilities to significantly reduce CO_2 emissions from installed CHP systems. This would allow for both short term, and long term emissions reductions over comparable technologies, independent of the rate in which grid emissions are reduced.

As of late-2020 there are one federal and two state low carbon fuel programs.[19] These include the US Renewable Fuel Standard (RFS), CARB LCFS as mentioned earlier, and Oregon Clean Fuels Program (CFP). The CARB LCFS has been successful on many fronts. It has generated revenue ($2.7 billion in credit trading in 2019), increased LCF production (over 2 billion gasoline gallon equivalent produced of ethanol, biodiesel, renewable diesel, fossil natural gas, bio-methane, and electricity combined in 2020), and driven down the carbon intensity of California's transportation fuel (7.5 % reduction between 2011 and 2020). [20]

The development of a low carbon fuel program in Massachusetts modeled after CARB's LCFS program and expanded to include low carbon fuels for all end uses, including onsite power generation, would help incentivize and drive LCF production. This would help encourage existing and planned CHP systems to reduce their CO_2 emissions, while allowing facility owners and the Commonwealth to maintain or capture the numerous benefits CHP systems provide.

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[19] https://thejacobsen.com/news_items/states-considering-lcfs/
[20] https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

8760 EMISSIONS MODEL

In order to better visualize the impacts of varying grid generation sources on the hourly marginal grid emissions, an hourly model, for all 8,760 hours in the year, was developed. This analysis used published 2019 ISO-NE GenFuelMix 5-minute interval data.[21] 2019 data was used in place of 2020 to exclude impacts of demand reduction due to Covid-19. The data set includes, for each 5-minute interval, the date and time stamp, a fuel category, the generator output (in MW), and a marginal generation flag to indicate whether the generation was on the margin in a particular interval or not. Generation sources that were on the margin were aggregated into average hourly marginal generation by source. A sample of the raw ISO-NE data, for two different hours on January 1, 2019, that was used to determine the hourly marginal generation mix can be seen below in Table 8.

Table 8. ISO-NE GenFuelMix Data Sample

Date	Time	Fuel Category	Fuel Category Rollup	Gen Mw	Marginal Flag
1/1/2019	0:02:10	Hydro	Hydro	1151	Yes
1/1/2019	0:02:10	Natural Gas	Natural Gas	2552	No
1/1/2019	0:02:10	Nuclear	Nuclear	4019	No
1/1/2019	0:02:10	Landfill Gas	Renewables	26	No
1/1/2019	0:02:10	Refuse	Renewables	355	No
1/1/2019	0:02:10	Wind	Renewables	637	Yes
1/1/2019	0:02:10	Wood	Renewables	366	No
1/1/2019	0:02:10	Solar	-	-	-
1/1/2019	0:02:10	Coal	-	-	-
1/1/2019	0:02:10	Oil	-	-	-
1/1/2019	0:02:10	Other	-	-	-
1/1/2019	0:15:59	Hydro	Hydro	1052	Yes
1/1/2019	0:15:59	Natural Gas	Natural Gas	2514	No
1/1/2019	0:15:59	Nuclear	Nuclear	4017	No
1/1/2019	0:15:59	Landfill Gas	Renewables	25	No
1/1/2019	0:15:59	Refuse	Renewables	356	No
1/1/2019	0:15:59	Wind	Renewables	628	Yes
1/1/2019	0:15:59	Wood	Renewables	370	No
1/1/2019	0:15:59	Solar	-	-	-
1/1/2019	0:15:59	Coal	-	-	-
1/1/2019	0:15:59	Oil	-	-	-
1/1/2019	0:15:59	Other	-	-	-

[21] https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/gen-fuel-mix

Emissions rates (lb CO_2 / MWh) for each fuel category were calculated using 2018 ISO-NE RT Marginal Emissions Rate data. [22] Average annual emissions rates were calculated for each emitting generation source. 2018 data was used because this was the last year ISO-NE published this interval data report.

Table 9. Emission Rate (lb CO2 / MWh) By Generation Source - 2018 ISO-NE

Fuel Category	Avg. CO2 Emissions Rate (lbm / MWh)
Coal	**2,299**
Gas	**891**
Oil	**1,762**
Other	**2,514**

Also included in the grid emissions calculation is the T&D losses of 5.4 % for the northeast (as referenced earlier in the report). The calculated hourly marginal generation along with grid emissions rates were used to calculate the hourly grid emissions. The equation used can be found in Equation 2 below.

Equation 2. Marginal Grid Emissions Claculation

$$\textit{Grid Emissions (lb CO2 / MWh)} = [\sum (MG_{FC} * ER_{FC})] / [\sum MG_{FC}] * 1.054$$

Where: MG_{FC} = Marginal generation for each fuel category (MWh)

ER_{FC} = Emissions rate for each fuel category (lb CO_2 / MWh)

1.054 = Grid T&D losses in northeast (5.4 %)

The other part of the model is the effective electric emissions rate from CHP. To establish a CHP emissions model, measured 15-minute interval performance data from a 2.6 MW recip. CHP system, collected under the Massachusetts Save Program, for 2019 was used. This system includes a heat recovery steam generator (HRSG) for steam generation, HW heat recovery for DHW and space heating, and an absorption chiller. It operated continuously throughout the year with an annual capacity factor of 71% and an efficiency of 83.5%.

This emissions rate for a CHP system differs from the emissions rate calculated for the future projections for CHP systems used earlier in this report. This is because, in that earlier case, emissions associated with the thermal component of CHP output were included so a total emissions rate (including both electrical

[22] https://www.iso-ne.com/static-assets/documents/2021/02/2018_rt_marginal_co2_emission_rates.xlsx

and thermal components) was calculated. The emissions rate used in the 8,760 model, which is typically referred to as the "effective electric emissions rate", was used so that emissions associated with the electricity component of CHP output could be compared directly to emissions associated with grid-purchased electricity. The equation used for CHP effective electric emissions can be found in Equation 3 below.

Equation 3. CHP Effective Electric Emissions

CHP Emissions (lb CO_2 / MWh) = (Fuel Emissions – Boiler Offset Emissions) / WG_{CHP} * 1.026

Fuel Emissions = FG_{CHP} * 117 * 1.032

Boiler Offset Emissions = QU_{CHP} * 117 / 81%

Where:

WG_{CHP} = Energy Output from CHP System (MWh)

FG_{CHP} = Fuel Consumed by CHP System (cf)

QU_{CHP} = Thermal output from CHP system (MBtu / h)

1.032 = Higher Heating Value of Natural Gas (MBtu / cf)

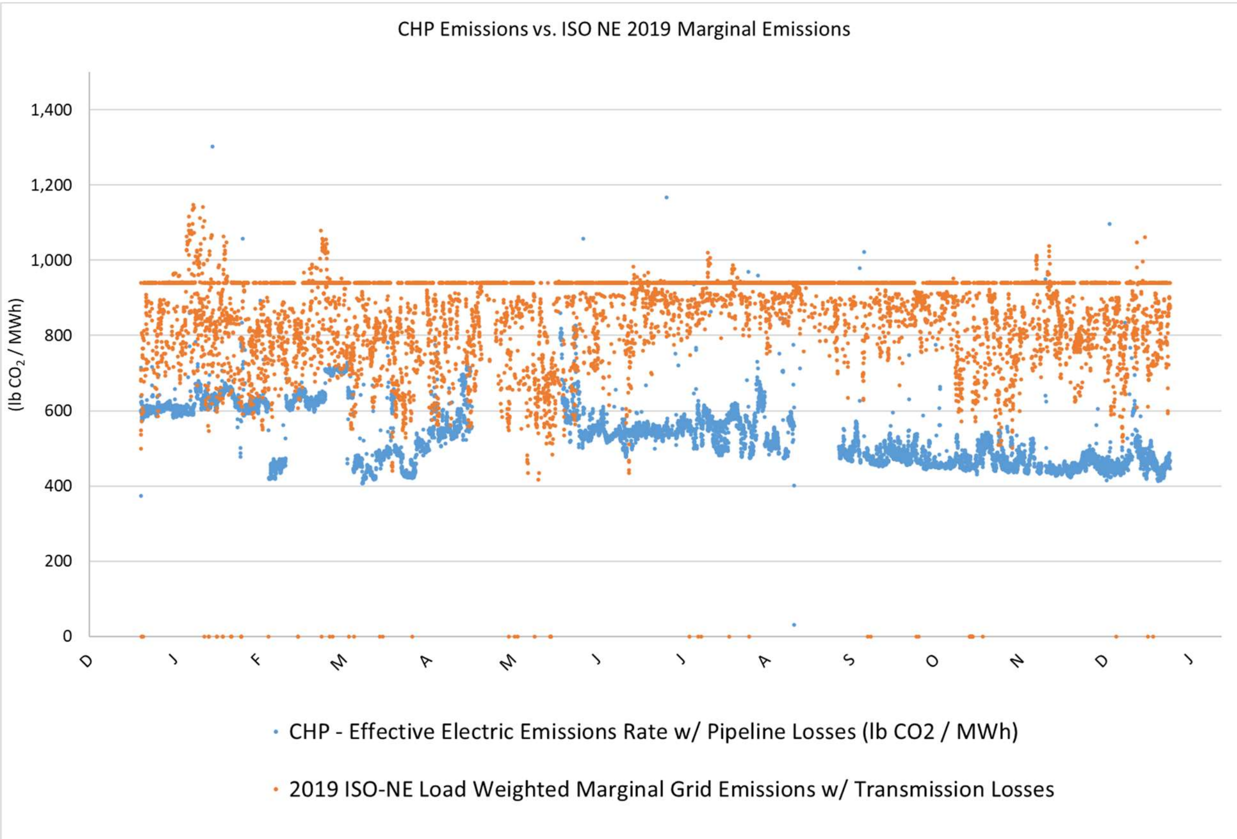
1.026 = Gas Pipeline Losses (2.6 %)

117 = Natural gas emissions rate (lb CO2 / MMBtu)

81 % = Conventional steam boiler efficiency

Grid and CHP effective electric emissions were then calculated for every hour of the year. The comparison of CHP and grid hourly emissions can be seen below.

Figure 20. Hourly (8,760) Model - CHP and ISO-NE Grid Marginal Emissions



The comparison of marginal grid emissions with CHP emissions in this model shows that the marginal grid emissions rate varies significantly throughout the year and is usually higher than the CHP emissions rate. This is due to several grid operating scenarios:

- Marginal grid emissions are low when hydro or wind are on the margin, typically when demand is low.
- Marginal grid emissions are high when oil or other (dual fuel) generation sources operate on the margin, typically when demand is high such as during the summer.
- Marginal generation on the grid is comprised of 100% natural gas nearly 50% of the year (4,305 hrs), resulting in the observed straight line of 939 lb CO2 / MWh emissions: natural gas emissions rate (891 lb CO2 / MWh) * 1.054 (grid losses).

Additional relevant takeaways from this comparison include the following:

- Out of 8,760 hours in 2019, the CHP system analyzed was cleaner than the grid 8,595 hours of the year (that is, 98.1 % of the time).
- A marginal grid emissions rate of 0 lb CO_2 / MWh occurred during only 71 hours (that is, 0.81 % of the time).

- The electricity produced by this CHP system, compared to purchasing power from the grid, resulted in a reduction of 2,394.6 metric tons / year of CO_2 compared to the emissions that would have occurred had the grid been called upon to replace CHP. (This would be the equivalent of removing 521 passenger vehicles from the road.)
- Average emission rates:
  - CHP = 536.1 lb CO_2 / MWh
  - MA Grid Load Weighted Marginal: 862 lb CO_2 / MWh

This 8,760 analysis of hourly marginal grid emissions resulted in an annual marginal emission rate of 862 lb CO_2 / MWh (including T&D losses). This is slightly (14%) higher than the reported 2019 ISO-NE Load-Weighted Marginal Emissions with T&D losses of 758 lb CO_2 / MWh. It is however consistent with the EPA eGRID 2019 published non-baseload emissions rates.

Table 10. Comparison of 2019 Marginal (non-baseload) Emissions Rates

Frontier Energy Calculated 2019 hourly ISO NE Marginal (CO2 lbs/MWh)	2019 ISO NE Load-Weighted Marginal with Grid T&D Losses (CO2 lbs/MWh)[23]	EPA eGrid 2019 NEWE Region Non-Baseload Marginal [24] w/ T&D (CO2 lbs/MWh)	EPA eGrid2019 MA Non-Baseload [24] w/ T&D (CO2 lbs/MWh)
866	758	885	948

If the hourly model is adjusted by 14% to align the resulting annual marginal emissions rate with the published 2019 ISO-NE Load Weighted Marginal with Grid T&D Losses emission rate of 758 lb CO_2 / MWh the annual emissions reductions are reduced only negligibly:

- Adjusted grid emissions reduced the number of hours the CHP system was cleaner than the grid to 8,355 hours (95.4 %) of the year.
- Adjusted grid emissions results don't change the total number of hours (71 or 0.81 % of the year) where the grid emission rate was 0 lb CO_2 / MWh.
- Adjusted grid emissions reduced emissions savings from the electricity produced to 1,629.4 metric tons / year of CO_2. (This would be the equivalent to removing 354 passenger vehicles from the road).

The 8,760 model shows that an average annual marginal emissions rate includes periods when the grid emissions are high (marginal unit is oil or natural gas) as well as periods when grid emissions are low

[23] 2019 ISO New England Electric Generator Air Emissions Report, March 2021: Table 5-7 2019 All LMUS Load Weighted Annual Rate (lbs/MWh) = 719 lbs/MWh *5.4% T&D Losses = 758 lbs/MWh. T&D losses from eGRID2019 Technical Guide, Table 3-6 for Eastern Power Grid

[24] https://www.epa.gov/egrid/data-explorer

(marginal unit is wind and hydro). Regardless of the exact marginal emissions model and average annual marginal emissions rate, this model illustrates the emissions benefits CHP can provide compared to the grid on an hour-by-hour basis.

CONCLUSION

CHP technology should continue to be included in the portfolio of technologies relied upon to achieve carbon emissions reduction. For facilities with low or high pressure steam needs and resiliency requirements, CHP represents the highest efficiency NG-based option. It will serve both electrical and thermal loads with the lowest CO2 emissions. These applications typically include, but are not limited to, hospitals, critical manufacturing, campuses (academic or industrial), and district energy. Onsite solar combined with heat pumps have constraints that make them unsuitable for these applications.

This study shows that a wide variety of CHP systems can provide emissions reductions compared to traditional grid and boiler systems in the short term, independent of grid emissions models. In addition, depending on the emissions reductions actually achieved by the grid in the decades to come, CHP has the potential to provide emissions reductions all the way through 2050. At the same time, emissions reductions can be achieved with even greater certainty by substituting higher pipeline blending rates or direct procurement of LCF's in the operation of CHP facilities. This fuel blending or swapping would enable individual CHP systems to reduce CO_2 emissions to zero beginning in the not-too-distant future.

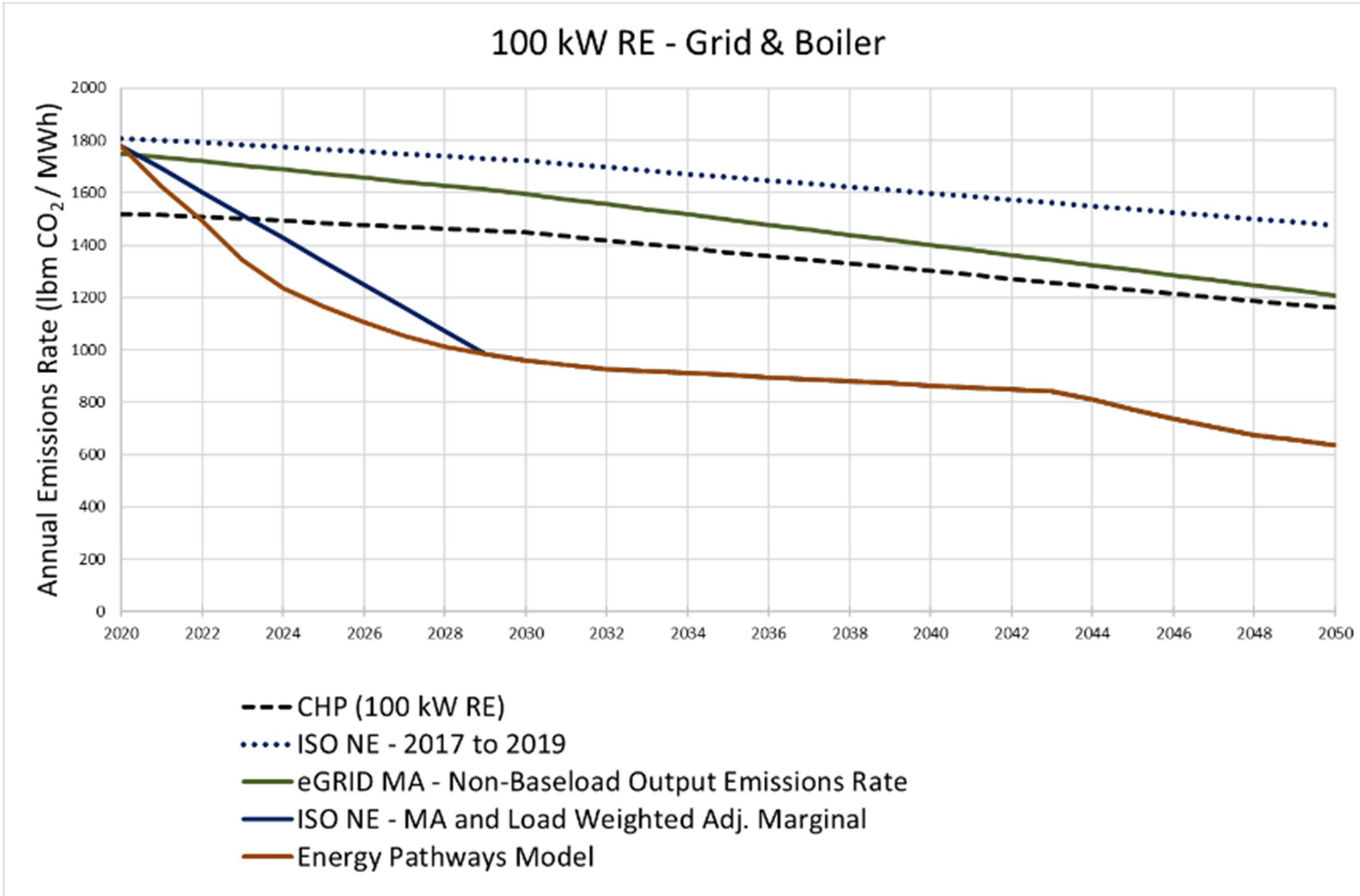
The Massachusetts 2050 Decarbonization Roadmap includes NG for electricity generation in the 2050 grid mix under numerous scenarios. CHP represents one of the most efficient uses of NG and should therefore be included as an emissions reduction technology as long as natural gas is still being combusted.

APPENDIX A – 100 KW RE TABLES AND GRAPHS

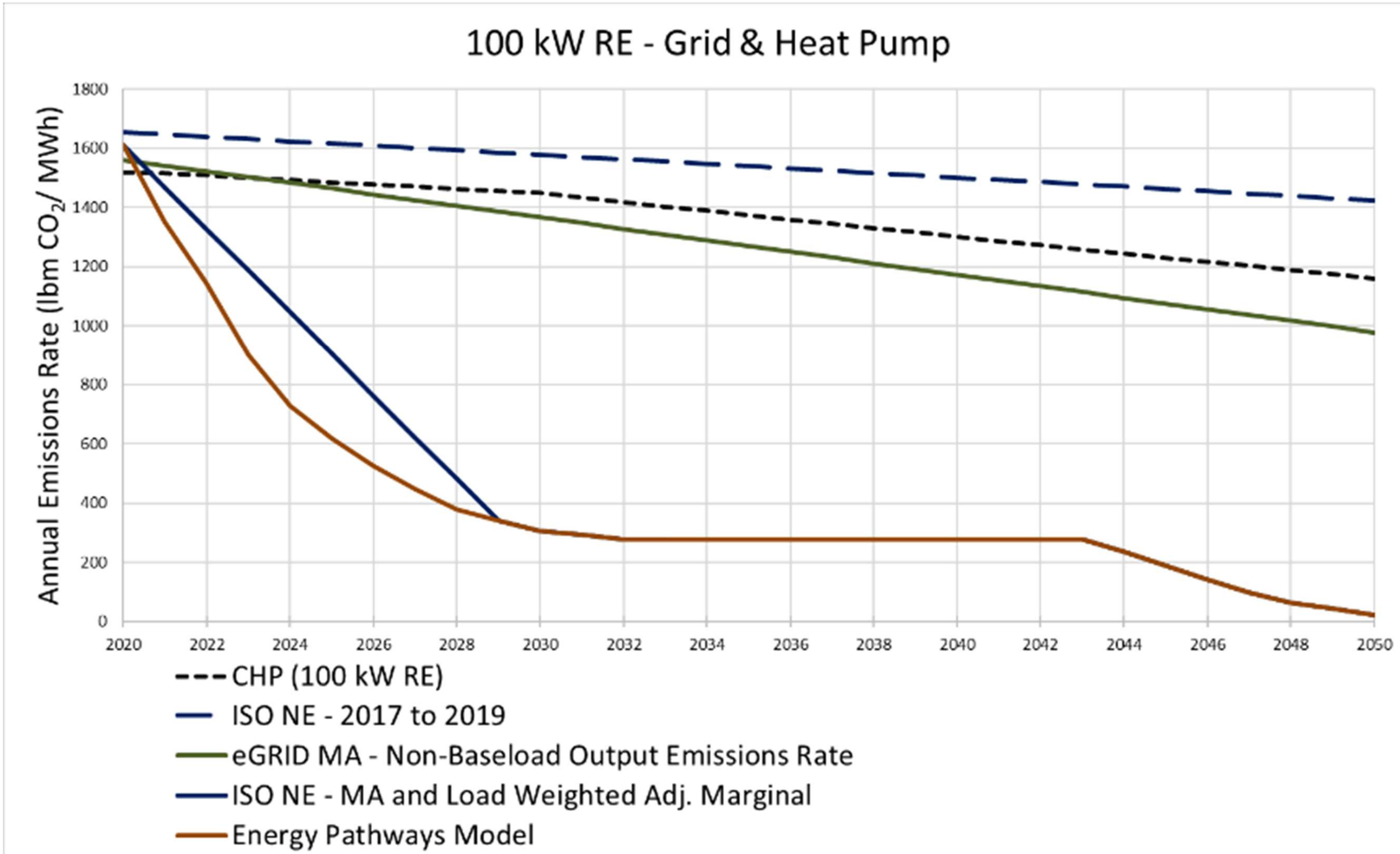
Emissions Calculations Details – 100 kW RE – 2020 Energy Pathways Model

	CHP (100 kW Recip.)	Grid & Boiler	Grid and Heat Pump	Solar and Boiler	Solar and Heat Pump
Net Power Output (kW)	97	-	-	-	-
Electrical Efficiency	27.0%	-	-	-	-
Thermal Efficiency	45.0%	-	-	-	-
CHP Efficiency	72.0%	-	-	-	-
Runtime (hrs)	1				
Electric Production (MWh)	0.10	0.10	0.10	0.10	0.10
Fuel Consumption (MMBtu)	1.23				
Thermal Production (MMBtu)	0.55	0.55	0.55	0.55	0.55
Assumed Boiler Efficiency	84%	84%	-	84%	-
Boiler Fuel (MMBtu)	0.00	0.66	-	0.66	-
Assumed Heat Pump COP	-	-	2.50	-	2.50
Heat Pump Input (MWh)	-	-	0.06	-	0.06
CHP CO_2 Emission (lb CO_2)	143	-	-	-	-
Emissions from Electricity (lb CO_2)	-	94	94	0	0
Emissions from Heating - Gas (lb CO_2)	-	77	-	-	-
Emissions from Heating - Electricity (lb CO_2)	-	-	62	77	0
Total Emissions (lb CO_2)	143	171	156	77	0
Emissions Rate (lb CO_2 / Bldg. Electric Load MWh)	1,479	1,758	1,610	792	0

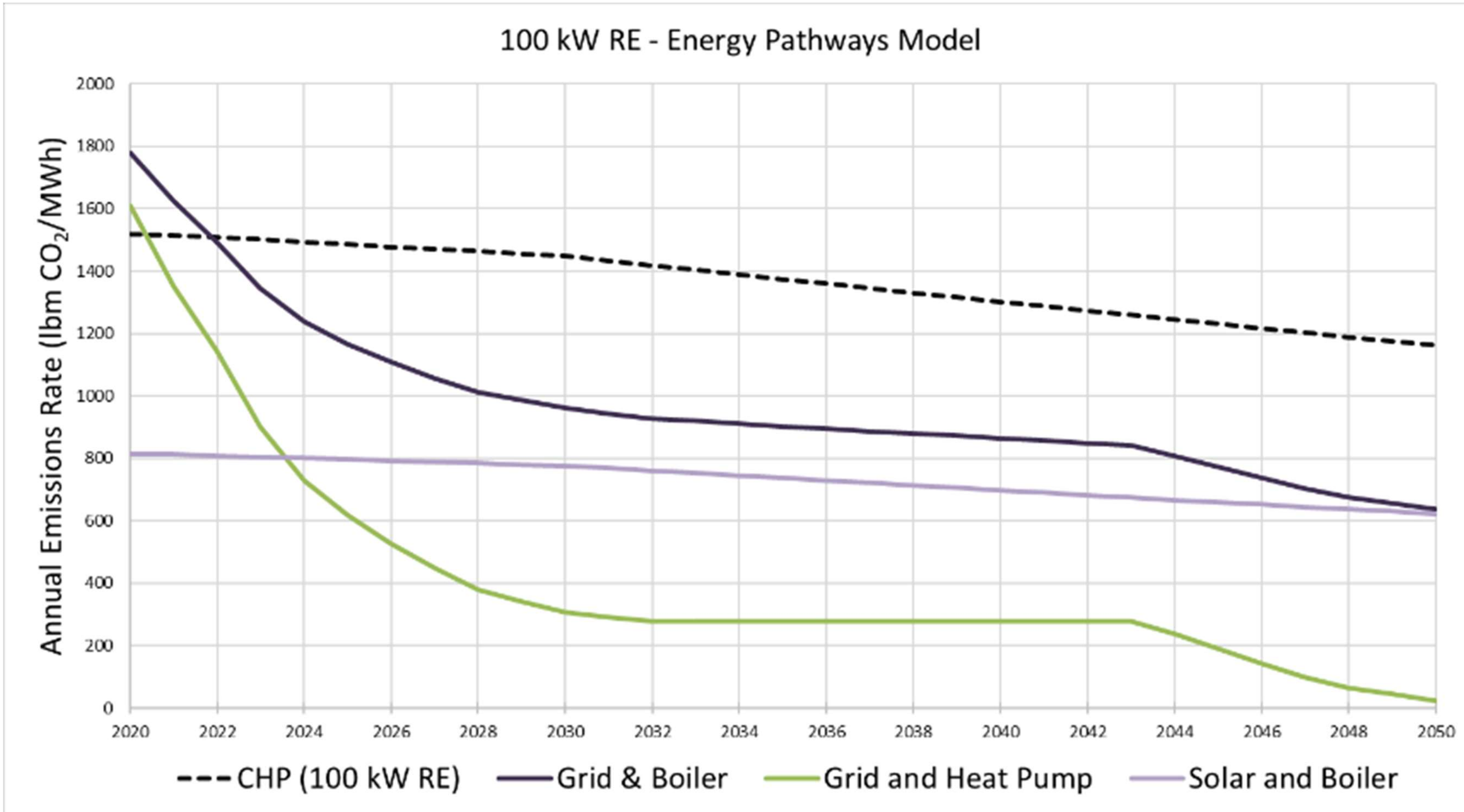
Projected Emissions – 100 kW RE Compared to Grid and Boiler – All Grid Emissions Models



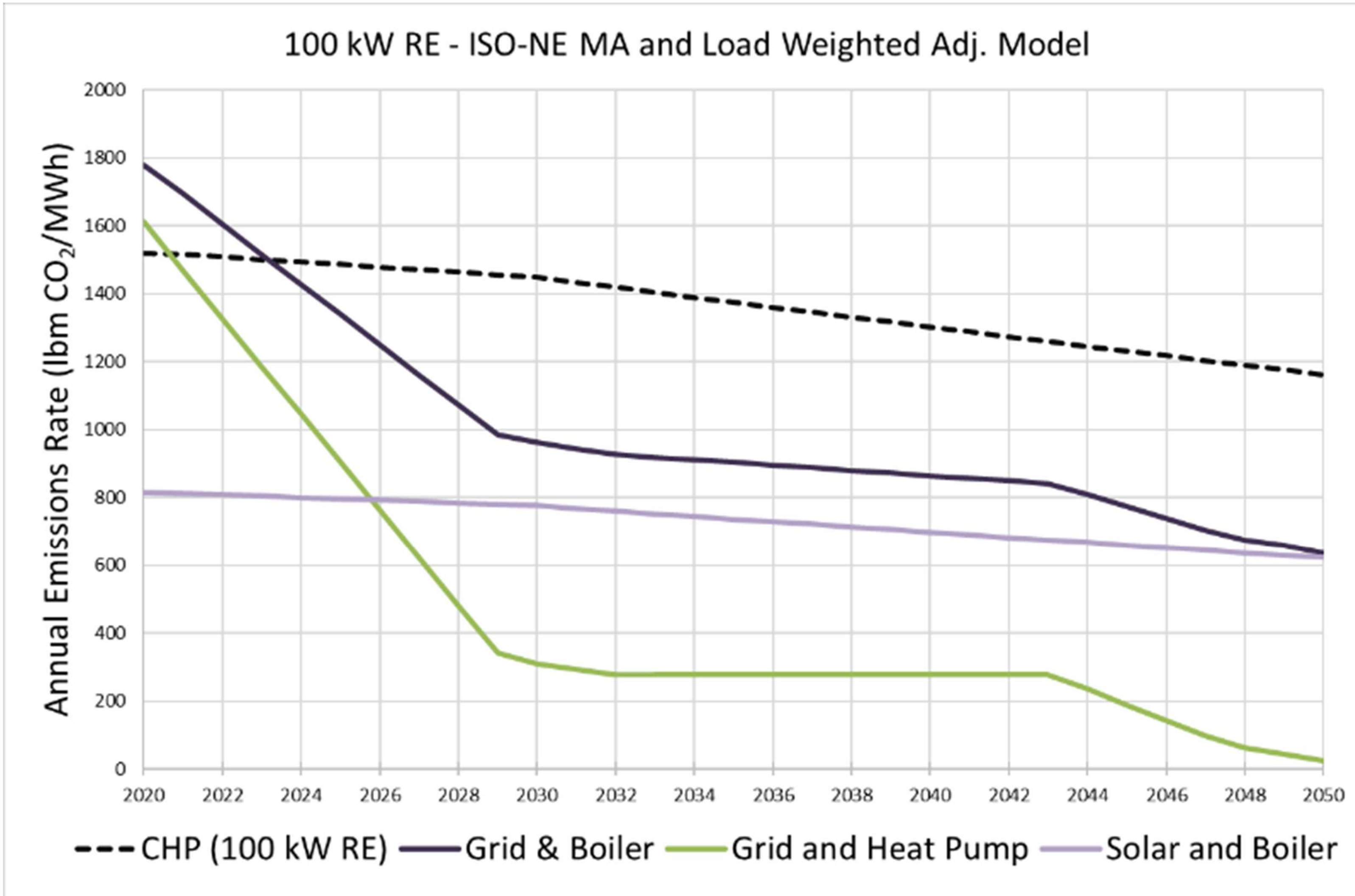
Projected Emissions – 100 kW RE Compared to Grid and Heat Pump – All Grid Emissions Models



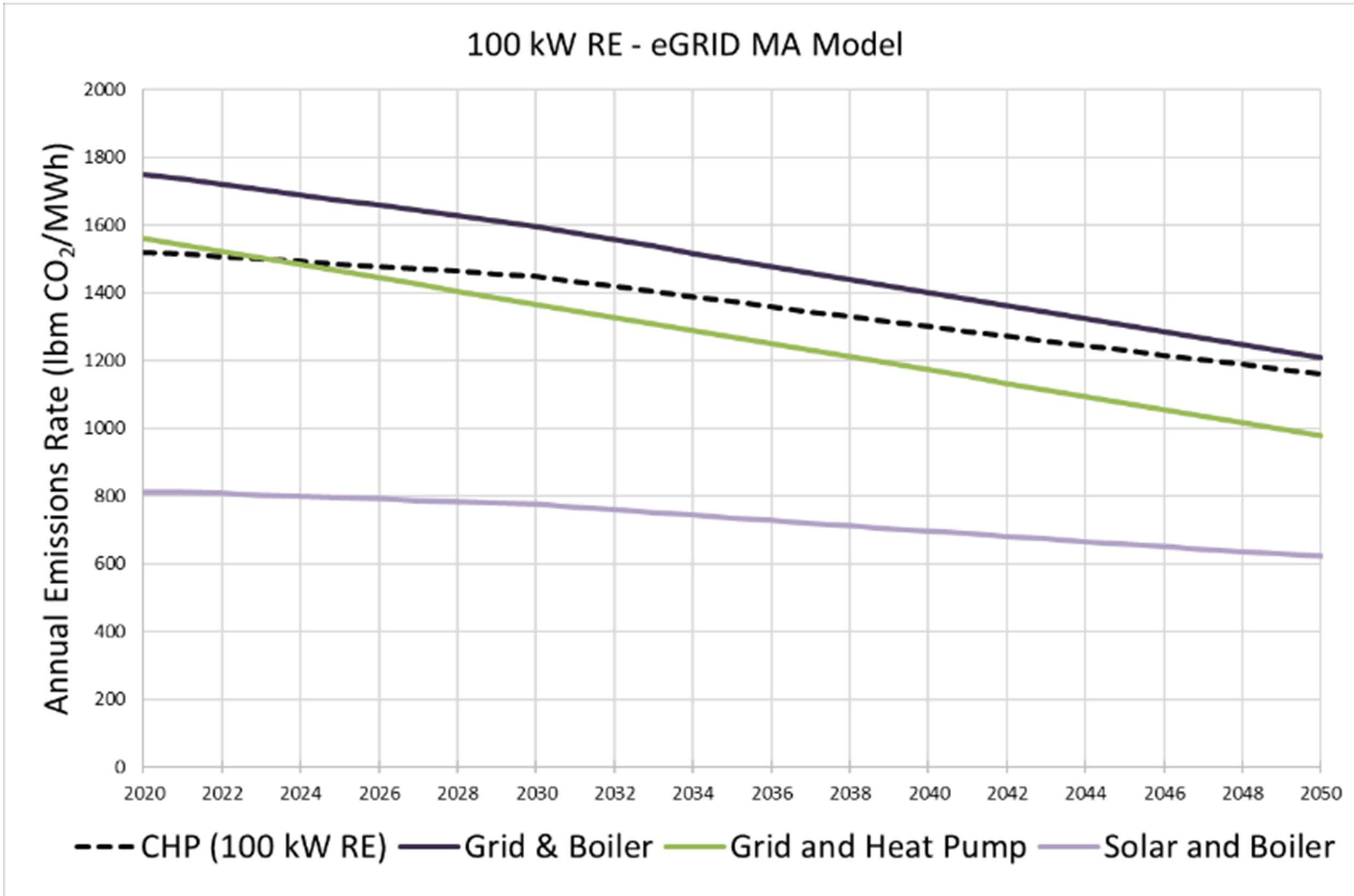
<u>**Projected Emissions – 100 kW RE – Energy Pathways Model**</u>



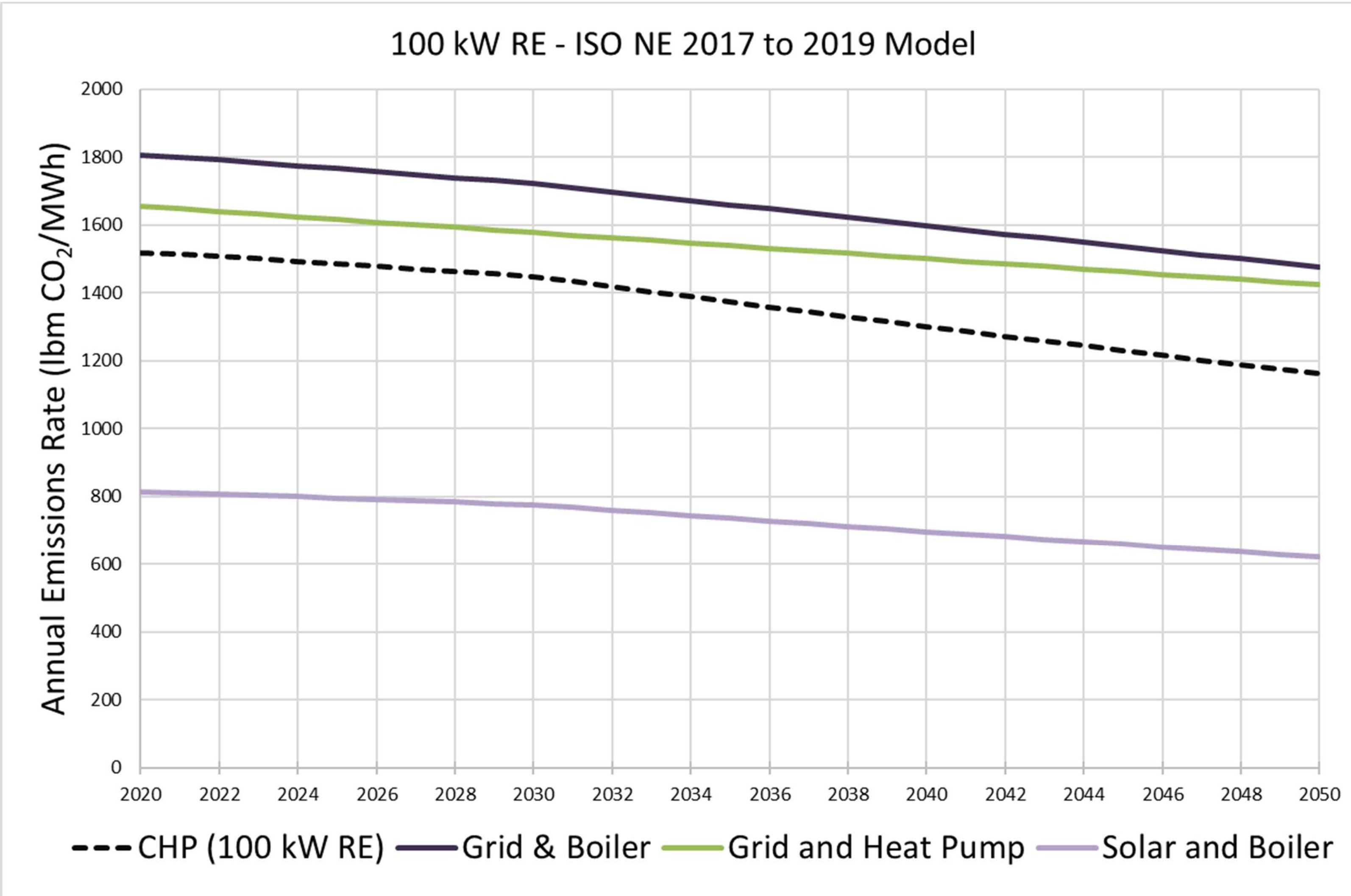
Projected Emissions – 100 kW RE – ISO-NE MA and Load Weighted Adj. Model



Projected Emissions – 100 kW RE – eGRID MA Model



Projected Emissions – 100 kW RE – ISO-NE 2017 to 2019 Model

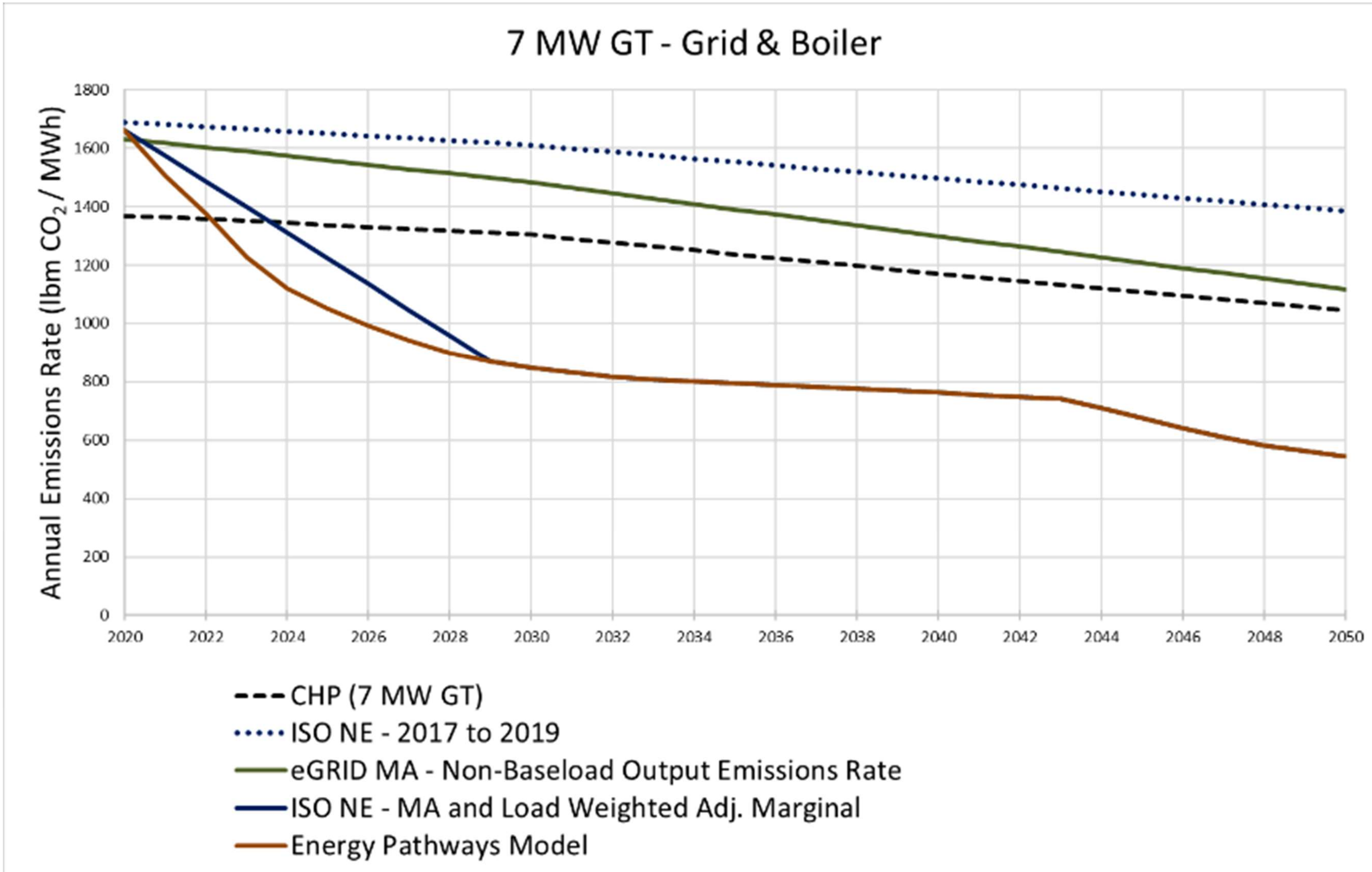


APPENDIX B – 7 MW GT TABLES AND GRAPHS

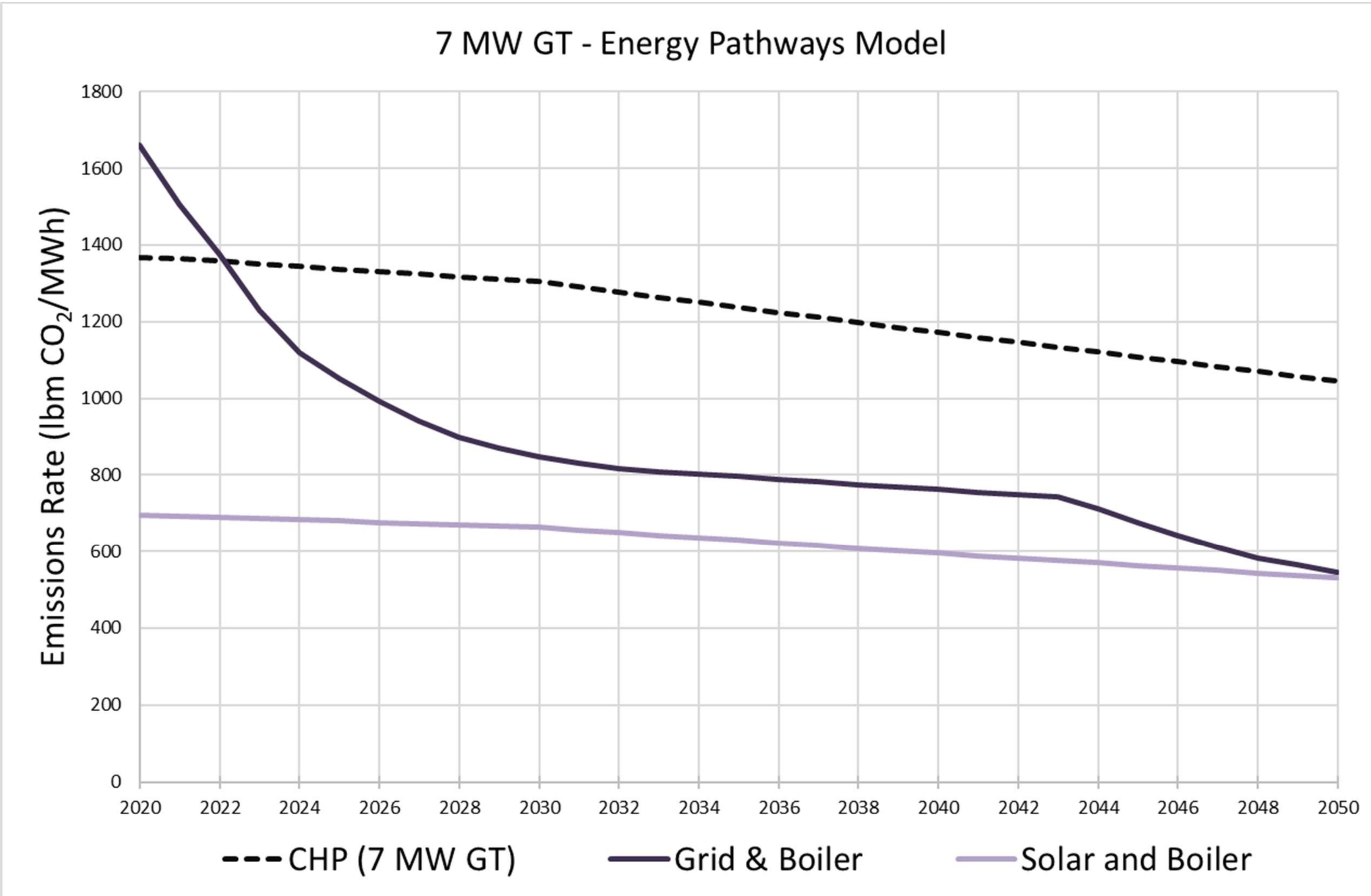
Emissions Calculations Details – 7 MW GT – 2020 Energy Pathways Model

	CHP (7 MW GT)	Grid & Boiler	Solar and Boiler
Net Power Output (kW)	6790	-	-
Electrical Efficiency	30.0%	-	-
Thermal Efficiency	41.0%	-	-
CHP Efficiency	71.0%	-	-
Runtime (hrs)	1		
Electric Production (MWh)	6.79	6.79	6.79
Fuel Consumption (MMBtu)	77.22		
Thermal Production (MMBtu)	31.66	31.66	31.66
Assumed Boiler Efficiency	81%	81%	81%
Boiler Fuel (MMBtu)	0.00	39.25	39.25
Assumed Heat Pump COP	-	-	-
Heat Pump Input (MWh)	-	-	-
CHP CO_2 Emission (lb CO_2)	9,035	-	-
Emissions from Electricity (lb CO_2)	-	6,560	0
Emissions from Heating - Gas (lb CO_2)	-	4,592	-
Emissions from Heating - Electricity (lb CO_2)	-	-	4,592
Total Emissions (lb CO_2)	9,035	11,152	4,592
Emissions Rate (lb CO_2 / Bldg. Electric Load MWh)	1,331	1,642	676

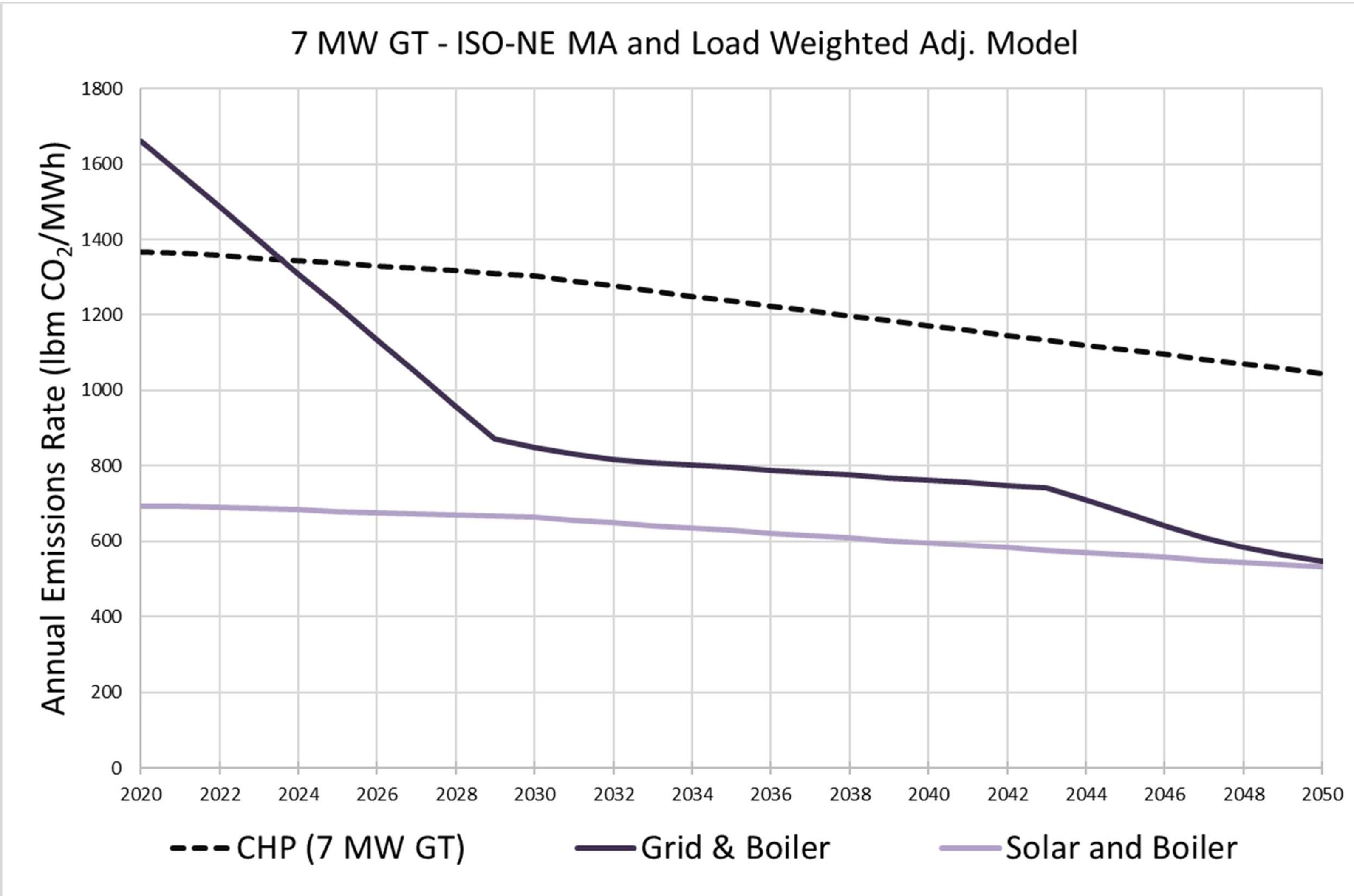
Projected Emissions – 7 MW GT Compared to Grid and Boiler – All Grid Emissions Models



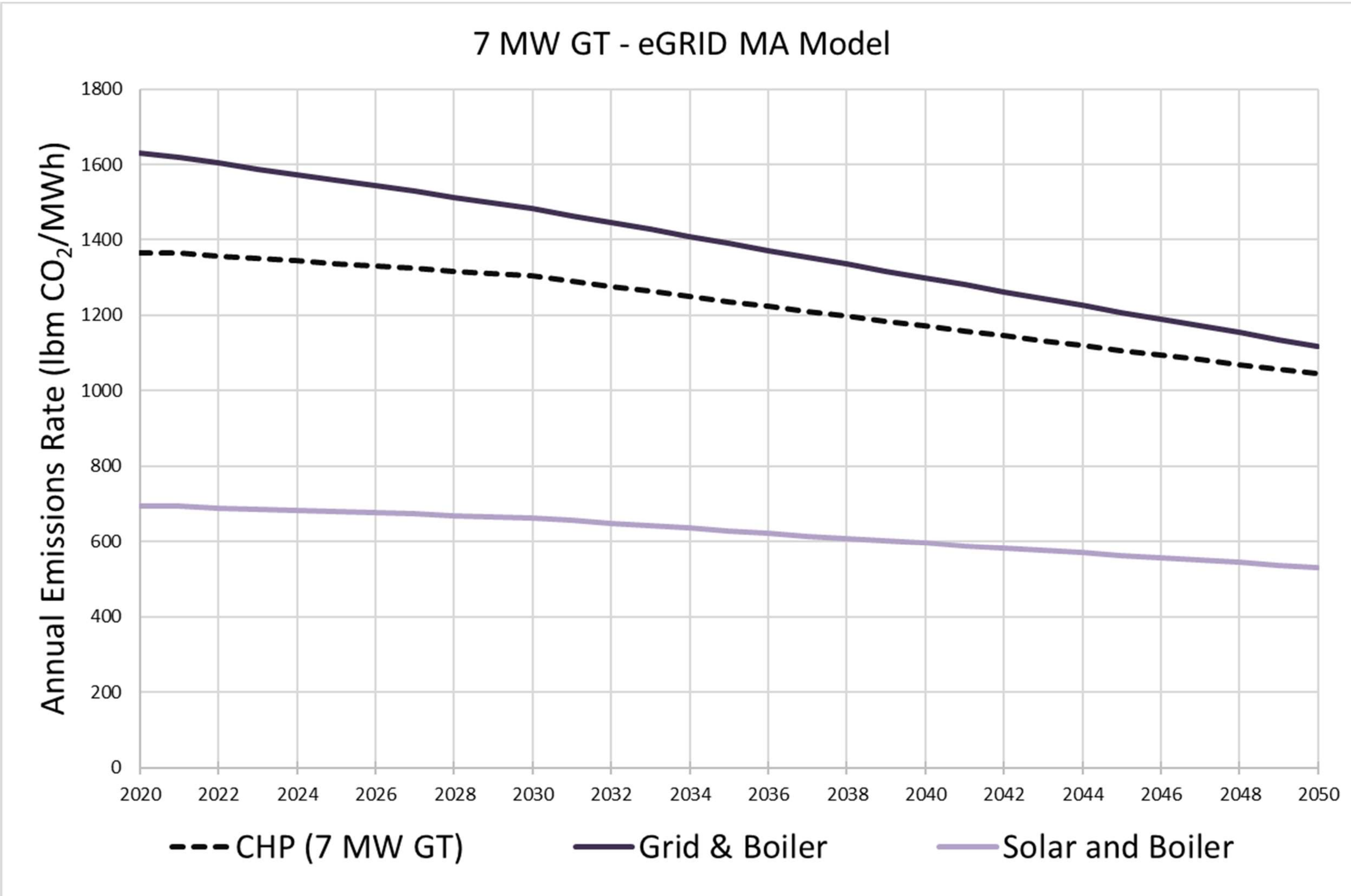
Projected Emissions – 7 MW GT – Energy Pathways Model



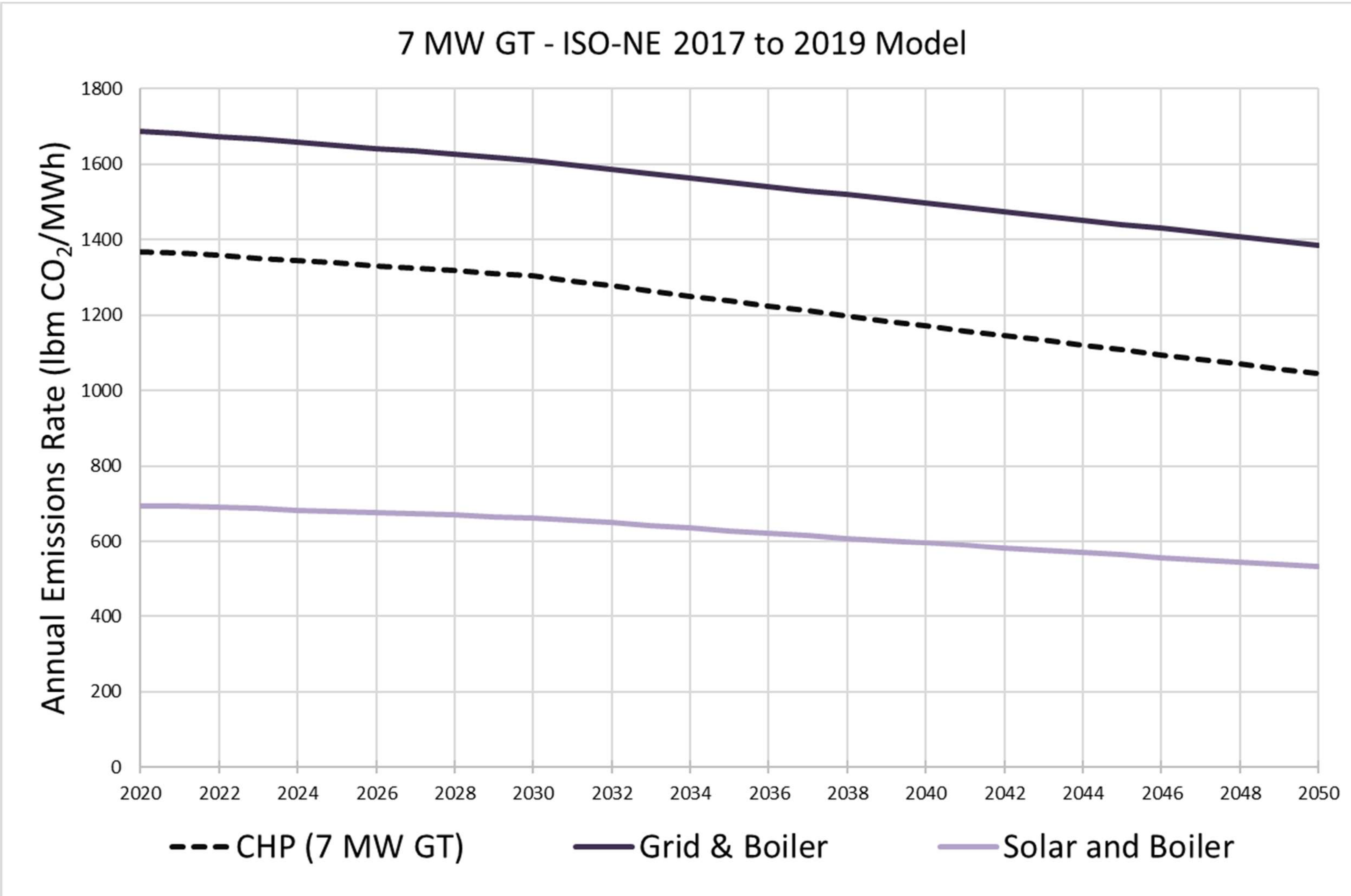
Projected Emissions – 7 MW GT – ISO-NE MA and Load Weighted Adj. Model



Projected Emissions – 7 MW RE – eGRID MA Model



Projected Emissions – 7 MW GT – ISO-NE 2017 to 2019 Model

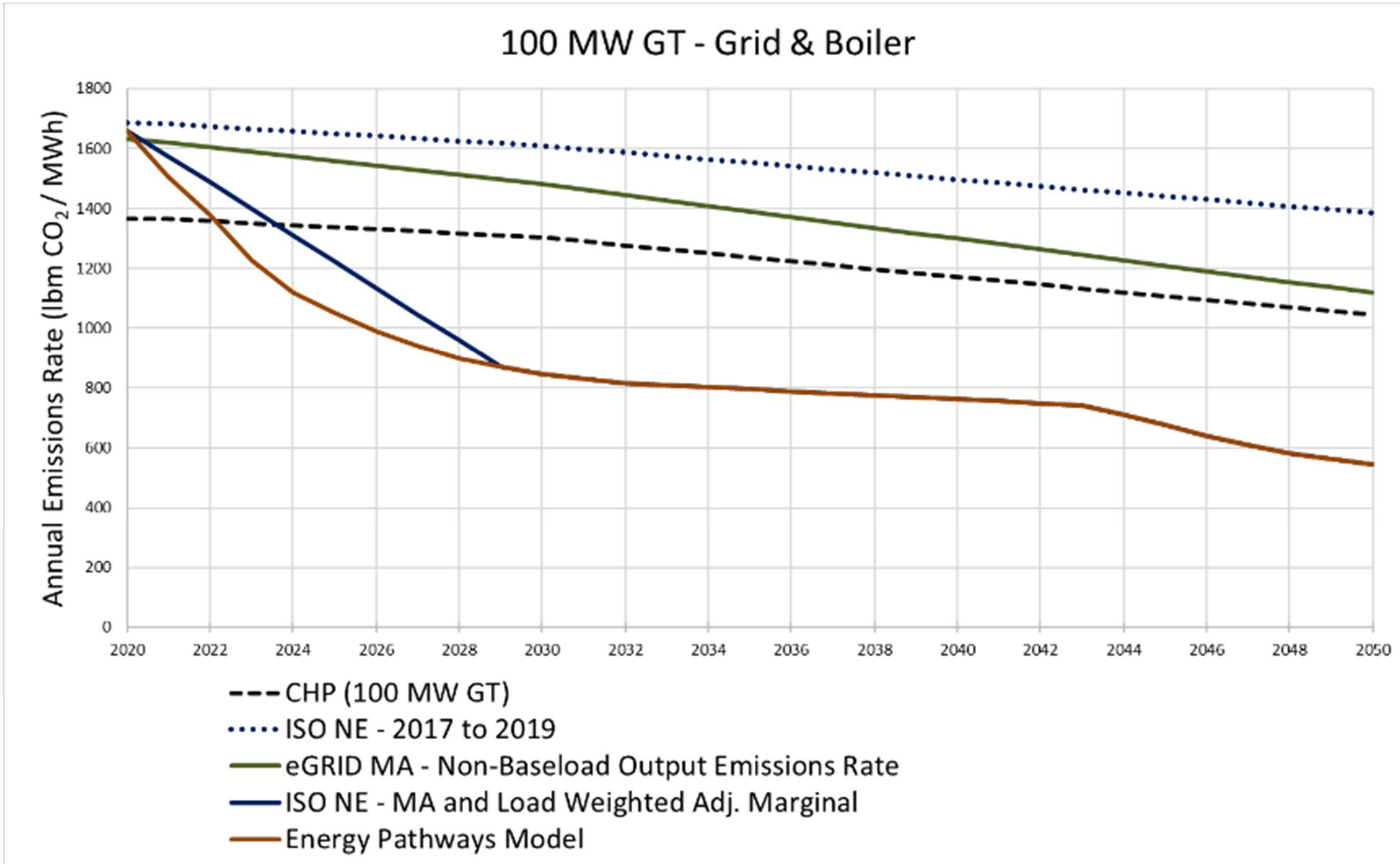


APPENDIX C – 100 MW GT TABLES AND GRAPHS

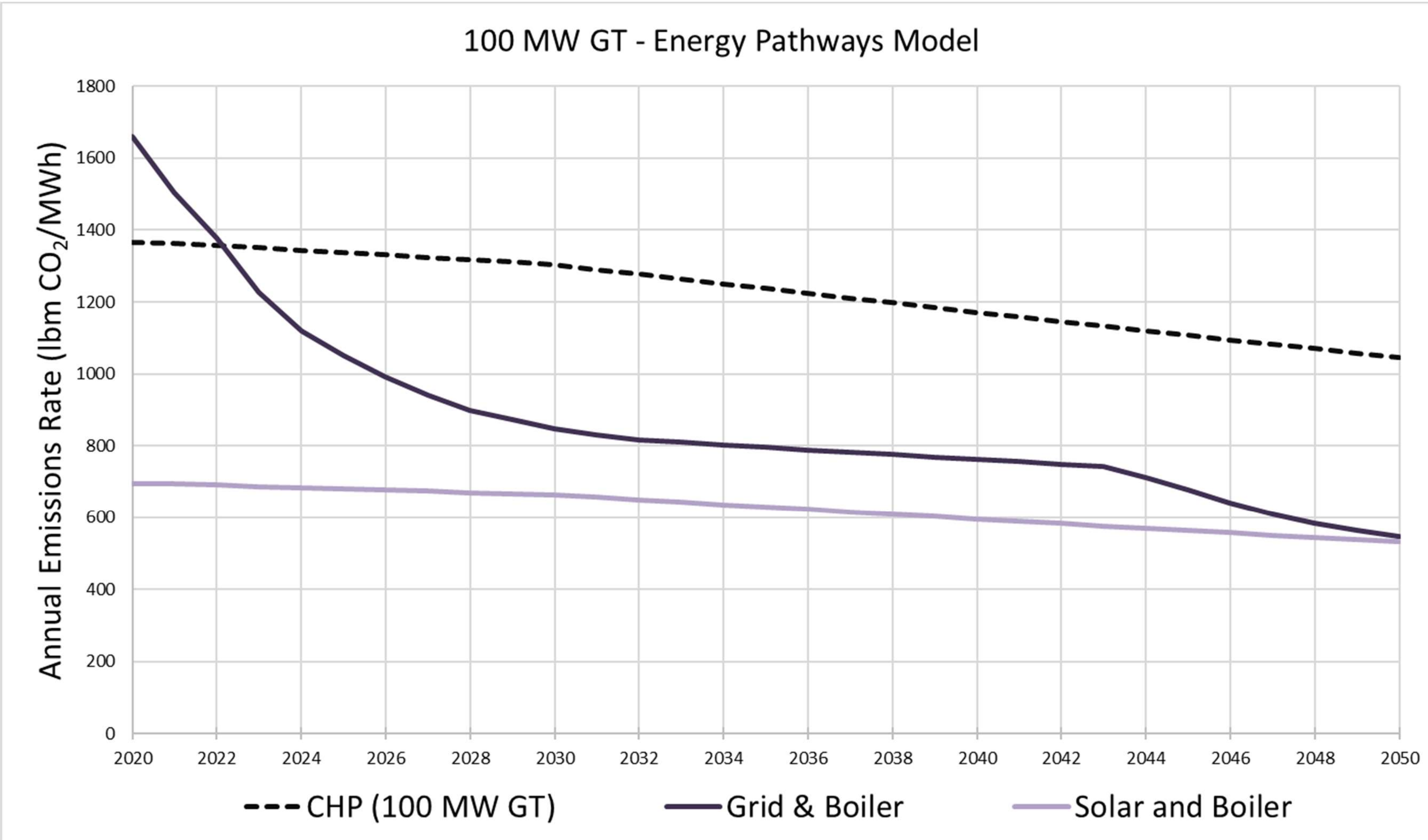
Emissions Calculations Details – 100 MW GT – 2020 Energy Pathways Model

	CHP (100 MW GT)	Grid & Boiler	Solar and Boiler
Net Power Output (kW)	97000	-	-
Electrical Efficiency	30.0%	-	-
Thermal Efficiency	41.0%	-	-
CHP Efficiency	71.0%	-	-
Runtime (hrs)	1		
Electric Production (MWh)	97.00	97.00	97.00
Fuel Consumption (MMBtu)	1,103.21		
Thermal Production (MMBtu)	452.32	452.32	452.32
Assumed Boiler Efficiency	81%	81%	81%
Boiler Fuel (MMBtu)	-	560.72	560.72
Assumed Heat Pump COP	-	-	-
Heat Pump Input (MWh)	-	-	-
CHP CO_2 Emission (lb CO_2)	129,076	-	-
Emissions from Electricity (lb CO_2)	-	93,707	0
Emissions from Heating - Gas (lb CO_2)	-	65,605	-
Emissions from Heating - Electricity (lb CO_2)	-	-	65,605
Total Emissions (lb CO_2)	129,076	159,312	65,605
Emissions Rate (lb CO_2 / Bldg. Electric Load MWh)	1,331	1,642	676

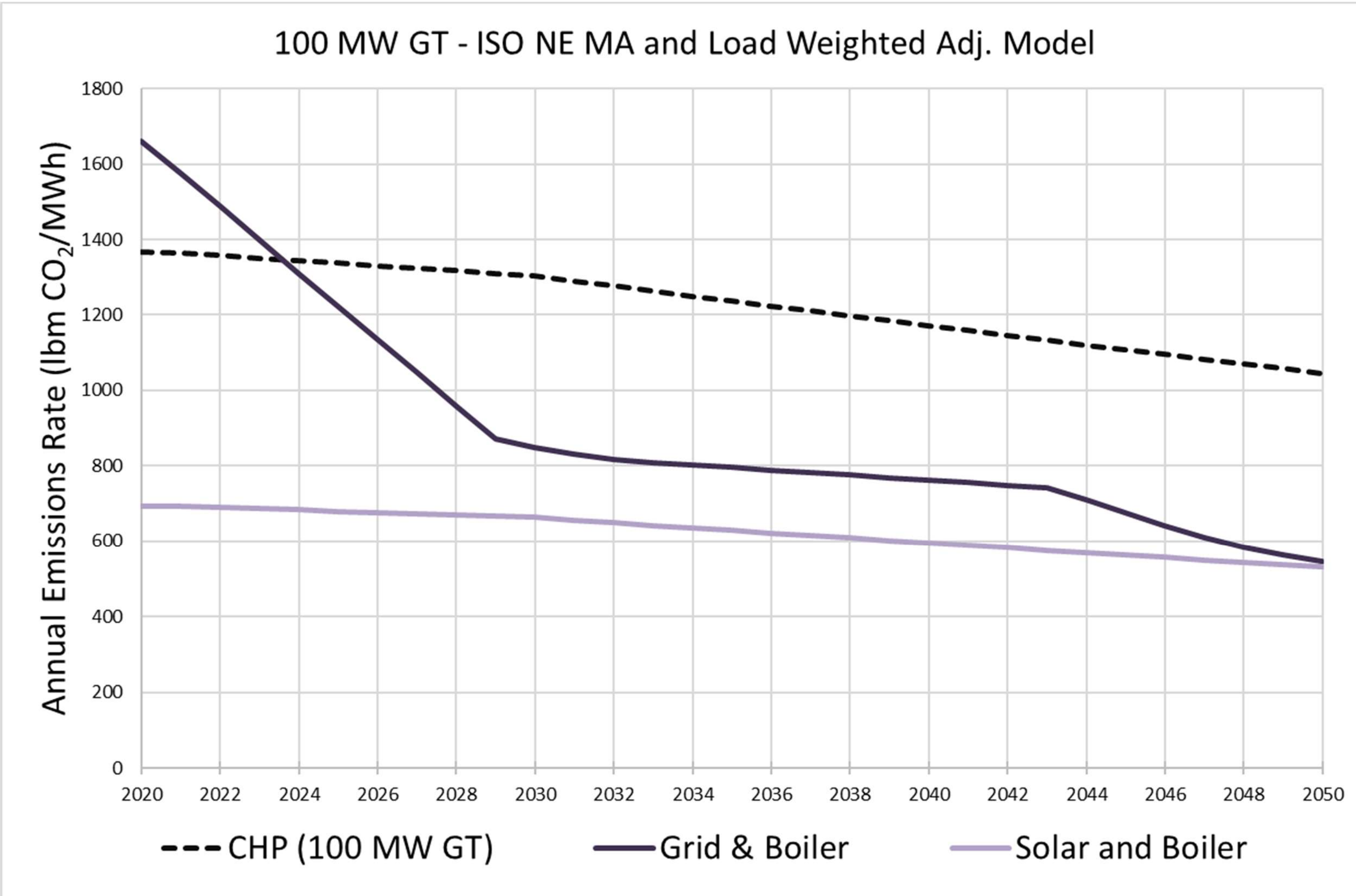
Projected Emissions – 100 MW GT Compared to Grid and Boiler – All Grid Emissions Models



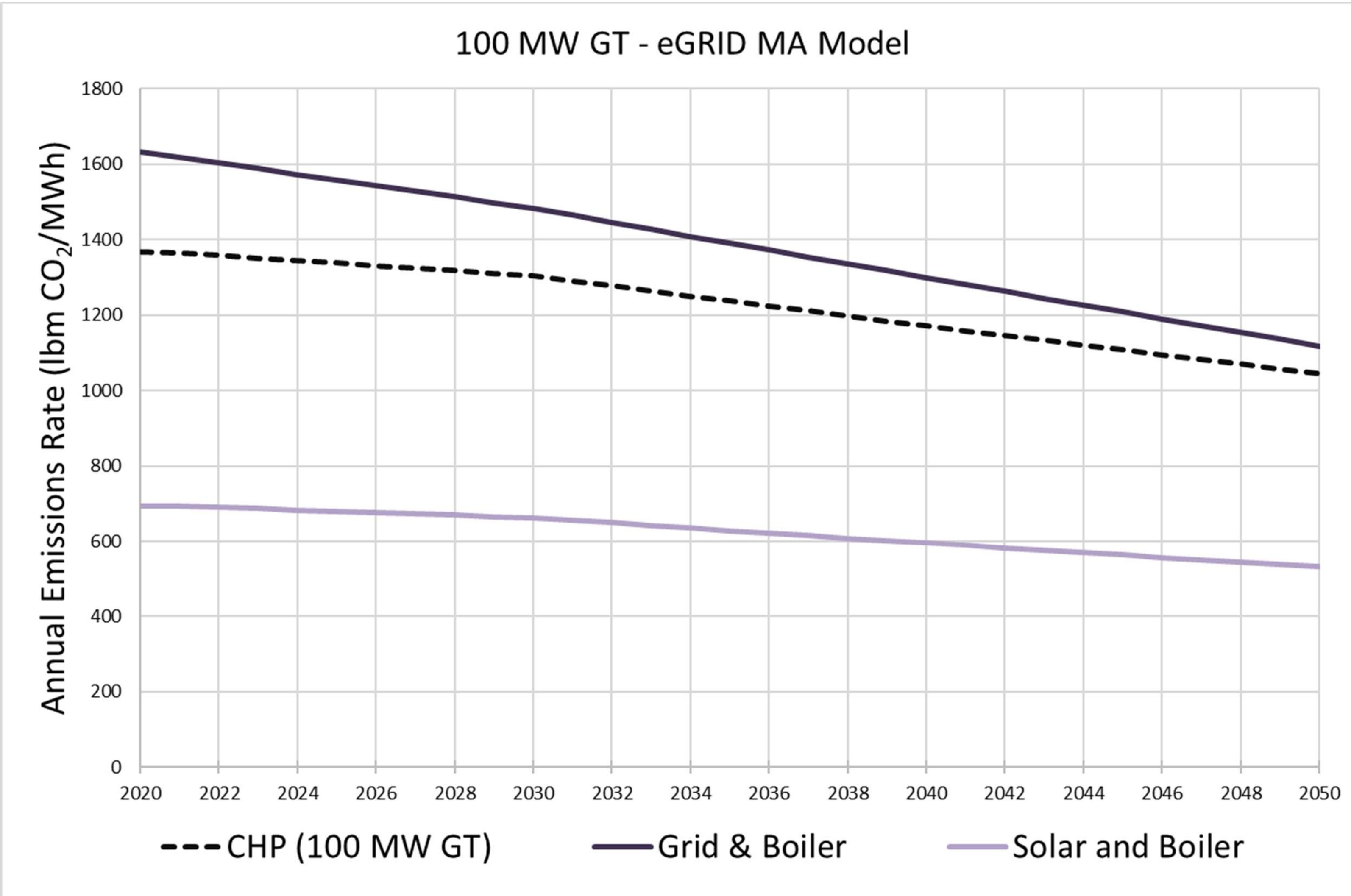
Projected Emissions – 100 MW GT – Energy Pathways Model



Projected Emissions – 100 MW GT – ISO-NE MA and Load Weighted Adj. Model



Projected Emissions – 100 MW GT – eGRID MA Model



Projected Emissions – 100 MW GT – ISO-NE 2017 to 2019 Model