Building Electrification Policy and Combined Heat and Power Relevance

Why Electrification Policy is Generally Counterproductive to its Carbon Reduction Goals

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Introduction

To reduce carbon emissions, climate change advocates are encouraging municipalities to enact “building electrification” policies, the promoting through local building codes that certain types of facilities adopt all-electric heating systems. Inherent in the building electrification concept is that most of the electricity be supplied, if not now, then in the foreseeable future, by carbon free sources (wind, solar, hydro, etc.). Thoughtfully applied to specific geographic regions and building types, electrification can be a sound policy with real climate change benefits. The replacement of an efficient natural gas water heater with the best electric counterpart, however, can increase a building’s carbon footprint if the electricity is from high carbon sources. Careful examination of the policy’s impact reveals this shortcoming to be true in most power grids as they exist today and likely well into the future. This is because natural gas heating appliances are very efficient (up to 90%) while “effective grid efficiencies” are much lower, typically about 40%. This means that countrywide adoption of building electrification could turn out to be counterproductive to its intended benefits.

In this paper, we will review building electrification policy toward showing specific conditions where electrification effectively reduces greenhouse gas emissions and where it does not. Moreover, we will show that cogeneration (or combined heat and power/CHP) will always produce improved carbon emissions relative to building electrification because electric grids, even those projected many decades into the future, will require some fossil fuel power to manage the variability of renewable sources; it is this residual, non-renewable portion of the electric grid, called the marginal component, which cogeneration systems offset. Sound climate change policy should be aimed at expanding renewable electricity sources where electric power is the only option (i.e. for lighting, residential AC, etc.) or where it is most impactful (e.g. electric automobiles which replace engines operating at less than 30% efficiency). When it comes to heating, cogeneration should always be encouraged, as the electricity generated will reduce production from the last residual electricity generated by the fossil fuel power plants. Electric heating systems cannot match the carbon benefit as they will only add to the power required from these inefficient plants, effectively negating their benefits. We believe that electrification will gain modest adoption where it makes sense – to residential housing in moderate temperate regions, and where the grid is highly saturated by renewable sources with ample battery storage. This is a narrow slice of CHP markets.

The US Power Grid[1]

Domestic grid power is sourced from a wide variety of technologies which have varying degrees of carbon emissions, typically expressed in pounds of carbon as CO_2 per megawatt-hour of electricity generated (lb/mWh). The US Department of Energy or DOE (see footnote 1) publishes annualized state electric power statistics in two categories:

- *Average Grid Sources*: A state's "average carbon emissions" for the grid is defined as the total carbon (as CO_2) emitted by the state's electricity production divided by the total electric power generated. Renewable sources such as wind, solar, and nuclear power have no carbon emissions while fossils fuels generate CO_2 relative to their combustion chemistry and inversely proportional to their efficiency. Hence a grid's average emissions are a blend, weighted to each source's relative contribution.
- *Marginal Grid Sources*: These are the subset of power sources that make up the difference between grid supply and demand. This assures that customers receive steady, uninterrupted power. Marginal sources are invariably fossil fuel plants that can be modulated quickly while the output of "must take" sources, such as wind or solar, ebb and flow.

The DOE statistics for a very "clean" state, California, are shown in Figures 1 and 2.The first, the average electricity grid sources for 2018 (the latest available), shows the California grid receiving power from a variety of sources that on the whole result in an emissions rate of 420 lb/mWh. On the other hand, the marginal electricity source is almost exclusively natural gas plants (95.3%) with an overall emissions rate of 871 lb/mWh.

The marginal emissions rate is an essential concept to policy makers in that it accurately measures the benefit of alternative sources of electricity. When a solar power system initiates operation, it has significant carbon benefit because it causes the carbon intensive sources, the marginal natural gas turbines, to dial back their output. The other "must take" sources, that are sharing the grid with the new solar system, are not impacted; they continue producing as much electricity as possible during any given period. No solar power system displaces other carbon free sources; the exception is the rare circumstance of the most heavily solar powered state, California, where the combined "must take" sources exceed the grid's use requirements[2]. Figures 3 and 4 list grid emissions rates for a collection of states[3] under the two categories: grid average and marginal. New York State and California have the lowest average grid emissions, with New York utilizing significant hydro and nuclear sources, and very

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[1] The data presented in this paper relating to grid statistics are sourced from the Environmental Protection Agency webpage: Emissions & Generation Resource Integrated Database (eGRID) for 2018 (https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid). eGrid is prepared by the Energy Information Agency, US Department of Energy (DOE), a US federal government agency.

[2] Excess solar production occurred about eight days (or about 2 percent of the time) in California in the latest source we found on the topic: "California invested heavily in solar power. Now there's so much that other states are sometimes paid to take it," (https://www.latimes.com/projects/la-fi-electricity-solar/).

[3] We have selected states where, due to both significant population and higher electric/low natural gas rates are viable cogeneration markets. Kansas is also shown as it is typical of many Midwest states, which are not shown, that are very high carbon emitters being largely comprised of fossil fuel sources, much of it coal.

little wind (3%) and solar power (0.2%). California has a more balanced renewable portfolio, highlighted by a significant solar contribution (13.8%).

Figure 1
California "Average" Electricity Grid Sources

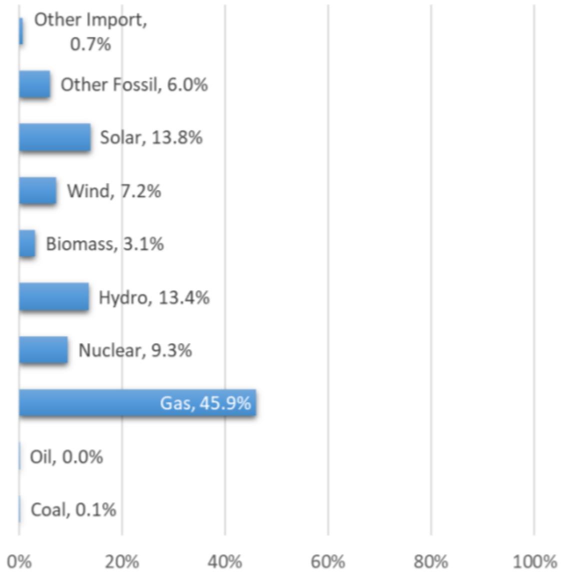


Figure 2
California "Marginal" Electricity Grid Sources

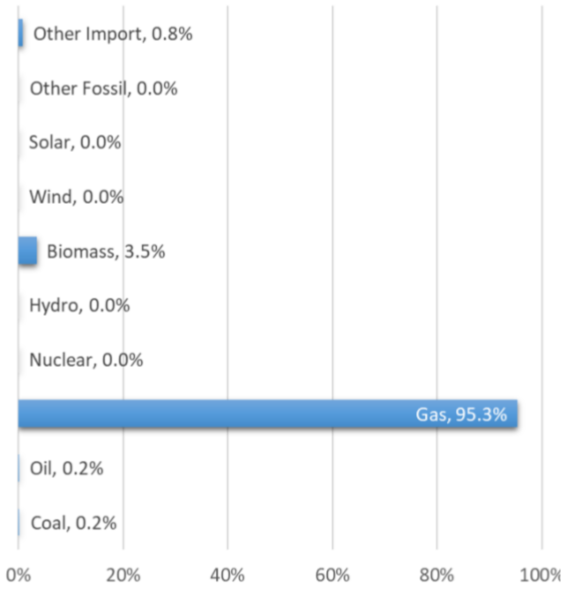


Figure 3 - Average Grid Carbon Emissions Rate for Various States (lb/mWh)

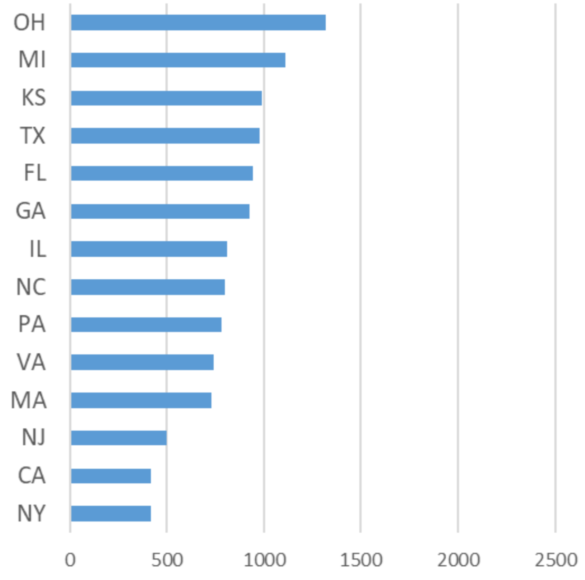
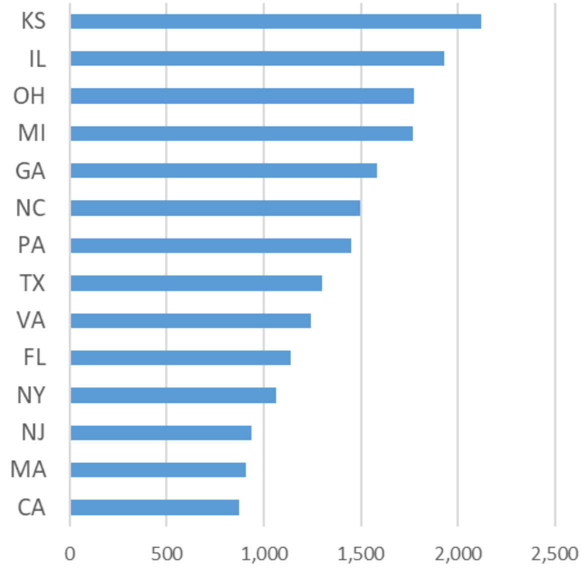


Figure 4 - Marginal Grid Carbon Emissions Rate for Various States (lb/mWh)

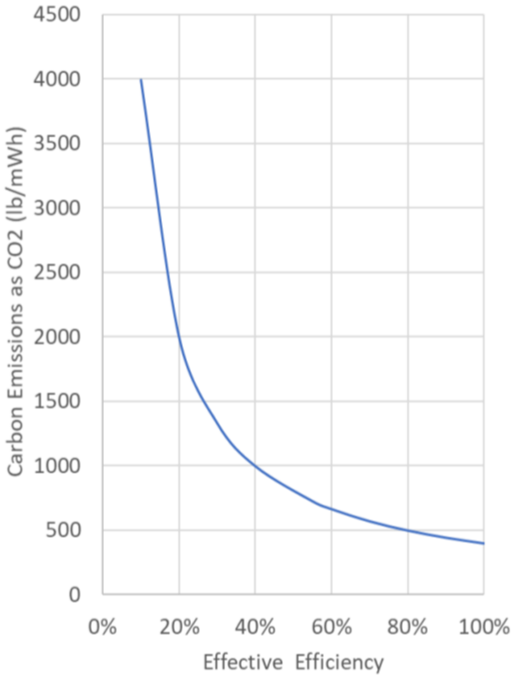


Effective Grid Efficiency

A useful concept in this discussion is "effective grid efficiency," a measure relating carbon emissions, a somewhat abstract parameter, to one that is more relatable. For any combustion-based power source, the carbon emissions (as CO_2) are directly related to efficiency for the specific fuel used. Since natural gas is the most common fuel used in heating and marginal power generation, this paper will utilize this fuel as the basis for the effective grid efficiency parameter. Figure 5 shows this relationship for natural gas power generation. As shown, the carbon emissions decrease with higher efficiency, with the important benchmark of 40%, a typical power station efficiency, having carbon emissions of 1,000 lb/mWh of electricity produced. Moreover, the "average power generation" carbon emissions from Figure 3 represent a range of effective efficiencies from 100% (New York @ 450 lb/MWh) to 30% (Ohio @ 1350 lb/MWh). For California, as with New York, its grid carbon emissions are interpreted as the blend of power sources, both with and without carbon emissions that collectively are the equivalent of having a natural gas power source with 100% efficiency. On the other hand, the marginal power generation sources for the states shown in Figure 4 have an effective efficiency range of 45% (California) to 19% (Kansas). In this case, California's value is consistent with Figure 2; that is, the marginal fuel is mostly natural gas power at about 40% efficiency with a slight boost from the biofuels. Kansas, on the other hand, relies on 80% of its marginal power from coal (not shown here but in the DOE database) which has greater carbon emissions for an equivalent combustion energy.

Having converted the carbon emissions to the "effective grid efficiency," it is possible to relate the impact of electrification on carbon emissions in easily understood arguments. For example, if it is proposed that an electric resistant water heater replace its natural gas counterpart, the negative carbon impact is evident; the replacement would increase marginal power production at a 40% effective efficiency. The result would be a process decrease from 90%, the natural gas heater efficiency, to 40%, the grid efficiency multiplied by the resistant water heater's point of use efficiency, about 100%. If the very best electric heating technology were used, an electric heat pump with an efficiency of 200%[4], the resulting process efficiency would double to 80%, still leading to higher carbon emissions than the existing natural gas

Figure 5 - Carbon Emissions as CO2 vs. Efficiency for Natural Gas



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[4] Electric heat pumps have high efficiencies or COPs (coefficients of performance) only in warm climates. Operation in cold ambient conditions will result in much lower COPs which greatly detracts from both their financial and carbon emission benefit. See Appendix A for a detailed discussion of heat pump water heating efficiencies and data supporting our typical COP as 2.0 in CHP markets (commercial/industrial).

water heater. Water heating that utilizes the cogeneration process is preferable to electrification because cogeneration electricity offsets the inefficient marginal power sources while producing hot water with only a small increase in natural gas use relative to the gas water heater whose operation it replaces.

We will expand on the carbon impact comparison of these heating technologies in a later section of this paper. It is worth noting here that we are limiting our detailed analysis to carbon emissions while not addressing the other major, unfavorable aspect of electrification – its financial burden. Per unit of energy electricity costs is three times that of natural gas. As such, an electric resistance water heater will triple an owner's water heating cost. An electric heat pump heater will halve the electricity use but only at a significant first cost premium of 3-4 times that of its electric or natural gas counterpart, while still having a higher operational cost than the gas unit.

Future Marginal Power Sources

The major counterargument to the assertion put forth in this paper – that electrification policies would often be detrimental to their carbon reduction goals – is that marginal fossil fuel power production will be eliminated by widespread use of energy storage – batteries, water electrolysis and various mechanical strategies[5]. Storing the energy for later release when the renewable sources are unavailable would enable electric grids to have greater renewable saturation- while decreasing the need for marginal power from fossil fueled plants. Under this scenario, both the average and marginal grid emissions would substantially decrease thus justifying electrification policy.

It is evident, therefore, that a projection of the rate of fossil fuel phaseout for marginal power generation is essential for assessing electrification policy. If these marginal fossil fuel plants are supplanted by storage technology in relatively short order, electrification policy should be considered. On the other hand, if these fossil fueled plants continue to operate in the long term, then electrification becomes expensive and counterproductive. The best methodology for making this assessment, in our opinion, is to review projections for natural gas use by those most qualified and invested in the outcome, the large multinational extraction corporations and the Department of Energy.

Figure 6, taken from BP's 2018 global energy outlook[6] for all applications, shows both global renewable energy and natural gas consumption increasing through 2040. Declining sources are oil and coal. The 2020 EIA projection[7], Figure 7, is more on point for this discussion as it provides a similar projection but further into the future (2050) and for energy sources directly applied to electricity production in the US. In this projection, the proportion of US electricity sourced from renewables will increase, as will the proportion generated by natural gas at the expense of nuclear and coal, very similar to BP's global outlook. However, BP's projections have very significant global increases in renewables, about 3-fold,

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[5] Electrolysis is the manufacturer of hydrogen from water using, in this case, renewable electricity. In most storage schemes, the hydrogen can be used to power a fuel cell generating electricity for the grid when the renewable resource is not producing electricity.

[6] See https://www.dailyoilbulletin.com/article/2018/9/4/analysis-energy-supply-and-the-future-of-the-oil-a/

[7] From the "Annual Energy Outlook 2020" prepared by U.S. Energy Information Administration, Office of Energy Analysis (EIA) U.S. Department of Energy (https://www.eia.gov/aeo)

through 2040, contrasting sharply with the EIA domestic projection, a 100% renewable increase though the longer period (30 years, to 2050). We consider the global vs. domestic forecasts for renewable growth as understandable since the former is currently at a much lower starting point (5%) where growth would be expected to be more rapid.

Viewing the US renewable projections another way, the EIA expects a modest 3% annual growth in renewable energy over the next 30 years. This strongly supports the conclusion that the long term marginal power future will be largely unchanged; highly saturated regions of renewable sourced power may exist, but they will be relatively modest in their scope, while electricity on the margins will continue to be supplied by fossil fuels, albeit more dominated by natural gas as coal use diminishes and oil use flattens.

Figure 6 – BP Global Projections for Energy Sources through 2040[6]

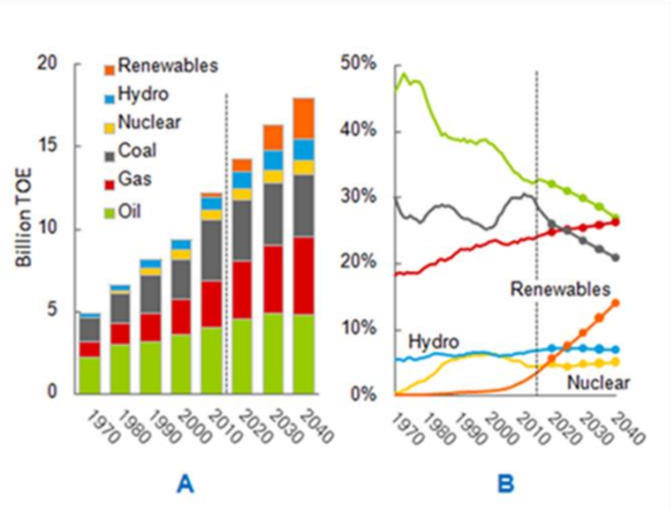
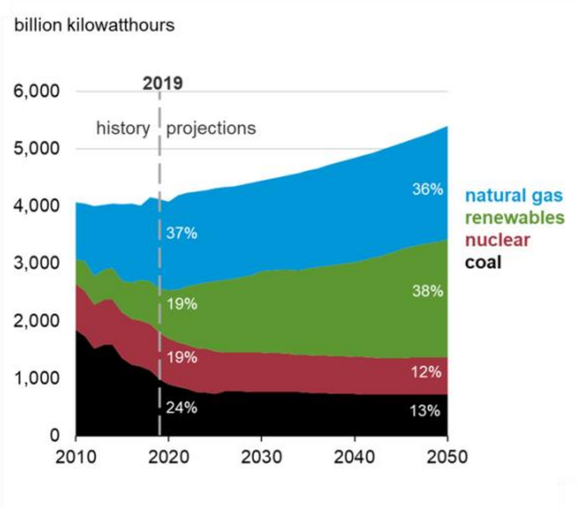


Figure 7 – EIA Projections for US Electricity Energy Sources through 2050[7]



Detailed Analysis of Electrification's Impact on Varying Grid Types

A generalized analysis of electrification strategy relative to natural gas options, which includes CHP, is presented in Figure 8. Shown in the chart are the carbon emissions for a base case of producing 100 kW of electricity and 6.4 therms of hot water[8] for varying effective grid efficiencies and utilizing four different heating methods:

- Cogeneration or Combined Heat and Power (CHP)
- a conventional natural gas water heater
- an electric heat pump water heater powered by the electric grid[9]
- a resistance electric heater powered by the electric grid

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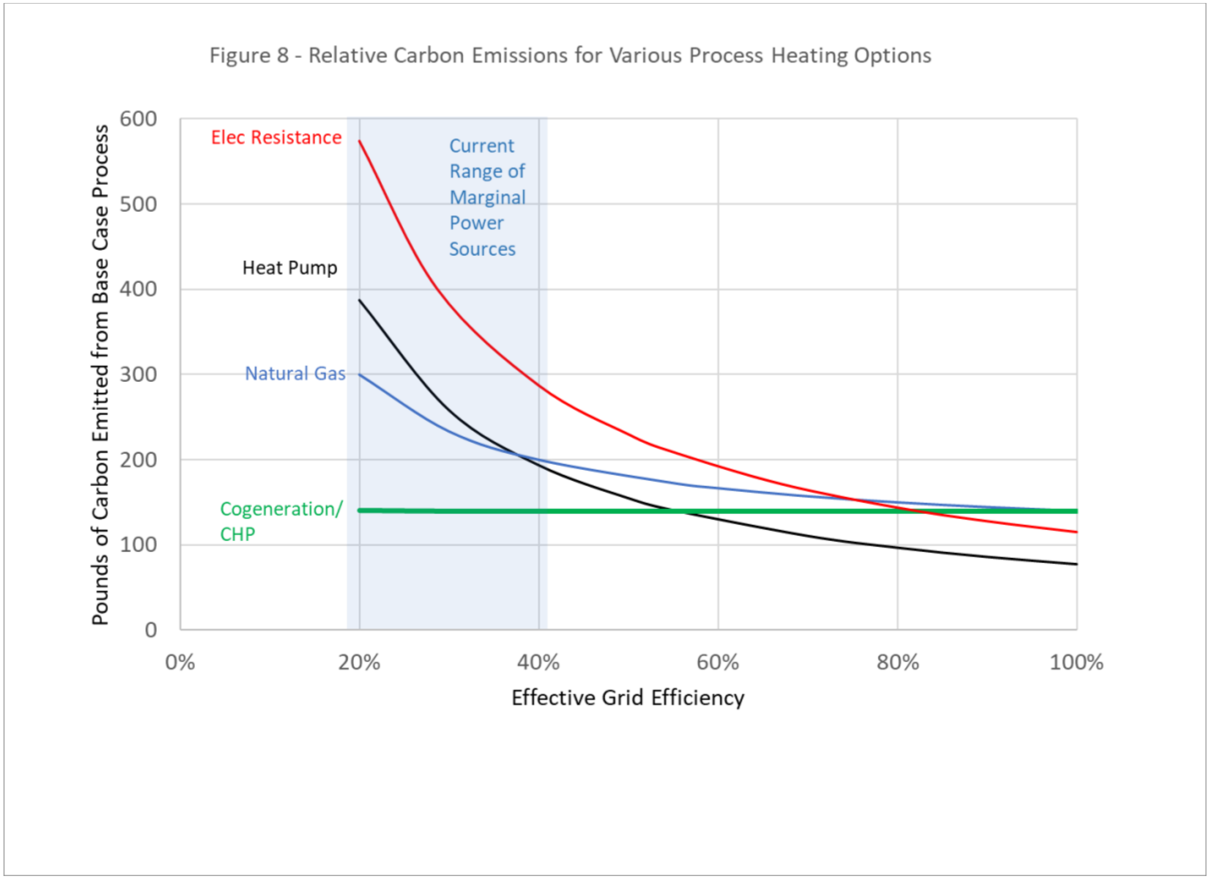
[8] The base process used here is the energy output rate of a single InVerde e+ cogeneration system.

[9] For the COP of the water heater we have used 2.0 which is the midrange value for processes where cogeneration/COP is applied. See Appendix A for detailed discussion of this topic.

As shown, where grid efficiencies are in the range of current marginal power sources, the lowest carbon emitting process is cogeneration followed in order by natural gas heating, electric heat pump heating and finally by electric resistance heating. As the grid becomes more efficient, the electric technologies close the gap with the heat pump system achieving parity with cogeneration when the grid becomes 60% efficient (or at a carbon emissions rate of 700 lb/mWh). As the grid approaches 100% effective efficiency, the four processes begin converging on emissions rates in the range of 90-140 pounds.



Conclusions

- CHP (Combined Heat and Power) will remain the benchmark for low carbon emissions heating well into the future, offsetting marginal power sources (fossil fuel plants). No major power source will eclipse CHP until major reductions are made in the carbon emissions of the marginal sources. This seems unlikely even through 2050 per the DOE/EIA projection (Figure 7).
- Given the current effective efficiency (or carbon emissions rate) of electrification, mandating it is substantially counterproductive. This would increase overall carbon emissions even in the most decarbonized states (New York and California) by 50% for the best electric technology (heat pumps) and 200% when compared to electric resistance heaters.
- The carbon benefit from electrification will increase as grid power sources improve, but only if the improvement extends to the marginal power sources. These are not likely to improve unless

large gains are made in market penetration of energy storage technology. We see the recent DOE projections as compelling reason to anticipate otherwise (see Figure 7).

- Undoubtedly, electrification will be effective policy in some cases, but these will be limited to regions with ample financial resources and moderate weather conditions. Electrification will extend mostly to new residential construction (i.e. California) where moderate weather allows greater reliance on solar sources and provides heat pumps with the warm ambient temperatures required for high efficiency (COP) operation. Financial resources are likewise important since electrification uses inexpensive resistance heating (as opposed to more expensive heat pumps). Electrification will increase carbon emissions until marginal power sources decarbonize to the level of an 80% effective grid efficiency.
- Electrification policies will go awry if they focus on disabling natural gas connections and discouraging the development of gas heating technologies (including CHP) while failing to require the installation of high efficiency heat pumps. If this is the case, which seems likely, then the policies will backfire on a large scale, causing carbon emissions attributed to heating to double in both the short and long term.
- It is unlikely, in our opinion, that electrification will extend beyond a narrow slice of markets like California. In areas having significant heating loads and less viable renewable sources (i.e. the Northeast), electrification will prove uneconomical. This is especially so in existing commercial and industrial facilities where renovation to incorporate heat pump heating would be inefficient due to the cold climate and higher process heating temperatures. Further, the increased electric supply required for electric heating would be highly problematic as most grid transmissions in CHP markets are already constricted.
- Lastly, our analysis shows that electrification is a poor use of resources in mitigating carbon emissions. As presented in Figure 8, the carbon emissions of the four heating processes are vastly different today, significantly favoring natural gas technology in general and CHP particularly. Most importantly, and even with the most optimistic forecast for grid decarbonization, electrification's benefits are minimal when the technologies converge around the same carbon emissions value – 90 to 140 pounds. This small benefit comes less from electrification than the already high efficiency of natural gas technologies, especially CHP.

Appendix A – Heat Pump Water Heating COP Range

Heat pumps operate over a wide range of efficiencies or rather coefficients of performance (COPs) which complicates the discussion on the subject. Adding to the confusion is that (pro/con) advocates of gas versus electric technology often selectively present COP values that assist in making their case. Negative advocates probably overemphasize lower source temperature COPs while advocates do likewise but to opposite temperature conditions. For example, heat pump water heater literature from manufacturers present tepid water heating temperatures (~100°F) as the basis of their reported COP's. It is usually difficult to find performance data for moderate water heating temperatures (~130°F) and harder still to find data for the higher temperatures common in commercial hydronic heating systems

(~140-160°F). The other critical temperature in a heat pump COP is that of the source from which heat is being drawn. The further these two temperatures are spread apart, the lower the COP. As such, pro-electrification advocates argue their policy case utilizing elevated COP values without properly stipulating that their attainment requires optimal conditions that would not generally occur.

Large commercial buildings (hotels, assisted living homes, dormitories, condominiums, and hospitals) are the heart of the CHP market. In almost all cases, domestic hot water is centralized with storage tanks for buffering usage rates. Storage tanks are usually warmer than residential heaters, typically 125 to 140°F, since the water is distributed across large distances. Hydronic space heating in these larger settings are typically higher, in the range of 140 to 160°F. Industrial processes (dehumidification, sanitation, etc.) are likewise done at high temperatures, often approaching 180°F.

For this paper we are utilizing test data from NREL (the National Renewable Energy Laboratory) applied to commercially available water heating heat pumps. This data is from a highly reliable source and is complete in that it covers favorable and unfavorable temperature conditions.

The pertinent NREL information is presented in Figure A.1[10] and Figure A.2[11]. The first shows manufacturers' data for a heat pump water heater over a broad range of water tank temperatures and ambient temperatures. As one would expect, COPs decline as these temperatures diverge. If we examine the range of temperatures typically encountered in commercial/industrial applications (the blue shaded area) the COP range is between 3.0 to well under 1.0. The midpoint is about 1.25.

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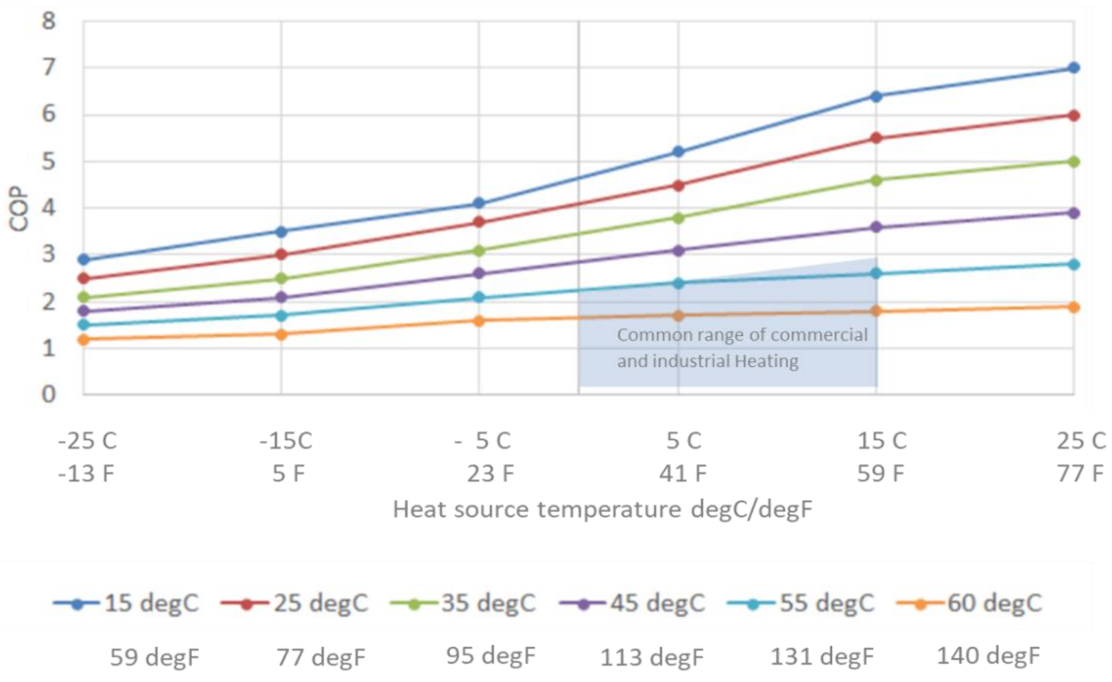
[10] Janne, Hirvonenhttps & Kai Sirén (2017). High Latitude Solar Heating Using Photovoltaic Panels, Air-Source Heat Pumps and Borehole Thermal Energy Storage (See https://www.researchgate.net/publication/326114264_High_Latitude_Solar_Heating_Using_Photovoltaic_Panels_Air-Source_Heat_Pumps_and_Borehole_Thermal_Energy_Storage).

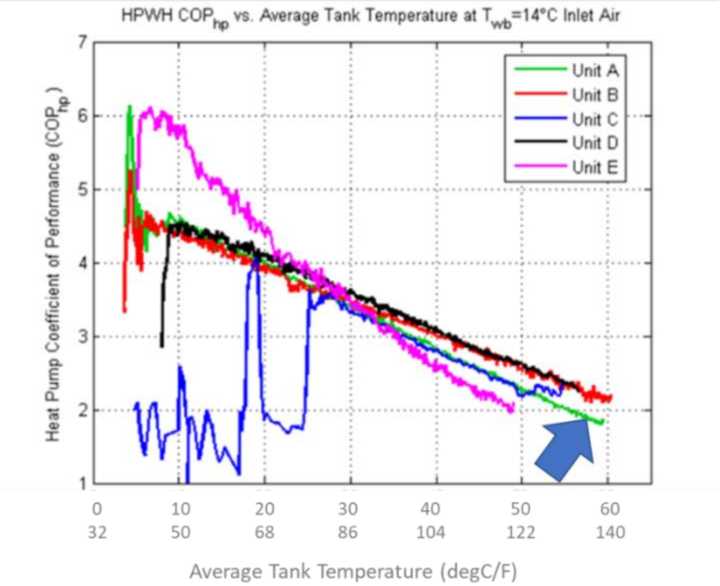
[11] Sparn, Bethany & Hudon, Kathleen & Christensen, Dane. (2011). Laboratory Performance Evaluation of Residential Integrated Heat Pump Water Heaters. 10.2172/1025650 (See https://www.researchgate.net/publication/255027740_Laboratory_Performance_Evaluation_of_Residential_Integrated_Heat_Pump_Water_Heaters)

Figure A.1[10] - COP of the air-to-water heat pump with different load-side inlet temperatures. Based on model NIBE-2120.



The second chart, Figure A.2[11], presents test data of six commercially available heat pump water heaters at a single source temperature[12] of 14°C (57°F). That is, the tests were done at a simulated ambient outdoor temperature of 57°F, which is a reasonable annual average temperature in most of our markets. The data of all the test heaters converges to about 2.0 (see blue arrow in the chart) and less for water heating temperatures at the lower end of those encountered in commercial/industrial markets (125-135°F).

Figure A.2[11]



In our analysis, we have selected a heat pump water heating COP of 2.0, which we believe is fair, if not generous, for higher latitude CHP markets. Still, we would concede that certain markets have ambient conditions that could justify higher COPs, such as recreational pool heating and combined heating and air-conditioning applications. For CHP markets consisting of commercial buildings, in which potable and hydronic heating systems have been designed for higher temperatures,

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[12] The heat pump must use an outdoor source for its heat in most cases. Using heat from an indoor space would effectively air condition the space and simply add heat load to the space heating system.

retrofit with heat pump technology would be costly and probably impractical. On the other hand, in new residential construction and in warmer areas, heat pump technology can show high COPs and have a carbon benefit, although a muted one since the extra electric heat load will be borne by marginal sources characterized by a low effective efficiency.