Decarbonizing residential space and water heating: The case for electrification

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Abstract
In order to meet ambitious carbon reduction goals, direct combustion of fossil fuels in homes will need to largely cease. The largest portion of this reduction will likely come from energy efficiency, but efficiency alone will not be sufficient. This paper looks specifically at California and builds the case for why energy efficiency with electrification of heating is the most likely path to achieve the large carbon emission reduction needed from this sector. We examine alternative decarbonization strategies, such as solar thermal, biogas, synthetic natural gas, and electrification and show why electrification is likely to be the most promising path. While electrification may be the most promising path in California, it is not necessarily the most promising path in all regions. We discuss the benefits of electrification and its limitations.

Motivation
In 2014 about 5 % of total US greenhouse gas (GHG) emissions, or 345.1 million metric tons of CO_2-equivalent, came from combustion of fossil fuels in the residential sector,[1] with about 69 % of this coming from space heating and 22 % from water heating.[2] In California, a similar fraction of state-wide GHG emissions (6 %) is the result of direct combustion of fossil fuels in the residential sector.[3] California has ambitious goal of reducing carbon emission 80 % below 1990 levels by 2050, and in order to meet this goal all aspects of the energy system will need significant changes. Impressive progress has already been made: a rapidly expanding share of renewables in electricity generation, exciting advancements in electric vehicles and lower carbon fuels, and almost 40 years of pioneering energy efficiency policy.

Technical potential studies show that meeting aggressive 2050 emission reduction goals is possible in California, the US, and Europe, but these studies consistently include substantially reducing or eliminating direct emissions from residential space and water heating as a necessary measure.[4, 5, 6, 7] In order to achieve a goal of emissions getting to 80 % below 1990 levels by 2050, it is likely that emissions from buildings will need to decrease by even more than 80 %. Reductions in other sectors

1. EPA. 2016. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014." http://www.epa.gov/climate/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2011.pdf.

2. DOE. 2012. "2011 Building Energy Data Book."

3. ARB. 2015. "California Greenhouse Gas Inventory for 2000–2013."

4. Wei, Max, James H Nelson, Jeffery B Greenblatt, Ana Mileva, Josiah Johnston, Michael Ting, Christopher Yang, Chris Jones, James E McMahon, and Daniel M Kammen. 2013. "Deep Carbon Reductions in California Require Electrification and Integration across Economic Sectors." *Environmental Research Letters* 8 (1): 14038. doi:10.1088/1748-9326/8/1/014038.

5. Williams, James H., Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow, Snuller Price, and Margaret S. Torn. 2012. "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity." Science 335 (6064): 53–59. doi:10.1126/science.1208365.

6. Long, Jane, Miriam John, Jeffery Greenblatt, Max Wei, Christopher Yang, Burton Richter, Bryan Hannegan, and Heather Youngs. 2011. "California's Energy Future-The View to 2050." https://escholarship.org/uc/item/2tb1c1mv.pdf.

7. European Climate Foundation. Roadmap 2050. http://www.roadmap2050.eu/reports.

like air travel, trucking, and industry may be more difficult and costly than decarbonizing buildings.

In 2009, approximately 80 % of households served by five major utilities in California used natural gas as the primary fuel for space heating and water heating, and those households used an average of 354 therms (37 GJ) of natural gas per year for all uses.[8] Natural gas heating dominates today in California because of the relative prices of retail electricity and natural gas, and because of the additional capital costs that come with solar water heating, heat pumps, or decarbonized pipeline gas infrastructure.

Historically, the residential space and water heating sector has received little attention in climate policy relative to larger emissions sources like electricity generation and transportation. While decarbonizing this sector is a necessary part of a broader strategy, it requires understanding consumer preferences and how, when, and why they adopt new technologies. Changing how we heat space and water requires irreversible decisions. For example, investing in decarbonized gas infrastructure might lock us in to that pathway for decades, while moving away from gas would impact investments in natural gas infrastructure and force us to rethink subsidies for gas-efficient appliances. As customers electrify heating and less gas is sold, the delivery cost of each unit of gas would increase to cover the fixed costs of maintaining gas infrastructure. Greater electricity consumption, particularly if new heating loads are flexible, could increase load factors of electricity infrastructure leading to lower electricity prices. Widespread fuel switching could potentially lead to a death spiral where gas costs rise and customers continue to switch away from gas.

Political and institutional barriers exist that will make the energy system slow to change. Gas utilities, particularly those that are separate from electric utilities, would strongly resist policies that reduce their earnings. Customers would surely also resist either being disconnected from a gas supply or having to pay exorbitant rates to cover infrastructure costs. Choosing another path, such as decarbonized gas, would require large infrastructure investments in facilities that can produce biogas or synthetic methane. If such investments are made, they may encourage continued gas use for space and water heating. We need to decide which path is better – though different optimal paths may exist in different locations. Since the building stock is slow to change, policies need to be put in place soon. In order to avoid stranded investments, maximize cumulative emissions reductions, and achieve carbon reductions at the lowest cost, policy and planning is required now to drive investment in lower carbon alternatives and to plan for infrastructure changes. In this paper, we compare different strategies that could achieve emissions reductions in the residential sector.

Strategies to decarbonize space and water heating

Four primary options exist to reduce emissions from the residential space and water heating sector: Energy efficiency, Solar thermal, Decarbonized pipeline gas (injecting biogas, synthetic methane, and/or hydrogen produced from renewable electricity into the natural gas system), and Electrification (switching from gas furnaces and boilers to heat pumps that use low carbon electricity). These options come with different services, costs, speeds, scales, and implications for market participants. Developing effective policy to meet emission reduction goals must take into account the attributes of the various alternatives. This paper evaluates the options, and concludes that electrification of heating, with improved energy efficiency, will be the preferred path to meet emission reductions goals of the residential space and water heating sector in California. Strategies for other regions are also discussed.

ENERGY EFFICIENCY

Energy efficiency alone will be insufficient to reduce emissions by 80 % or more by 2050. Even aggressive efficiency improvements that save 2 % per year would only reduce emissions by 50 % over the next 35 years. Such a rate of efficiency improvement would be far greater than we have seen in the recent past. Over the last 35 years we have seen a decrease in energy intensity (energy use per dollar of GDP) of 50 % in the United States, but much of this has been due to structural changes in the economy. Nadel et al. estimate that 60 % of this decrease in energy intensity came from energy efficiency and that over the next 35 years a reduction of energy use by 40–60 % could be cost effective through more efficient equipment, zero net energy buildings, industrial improvements, deep building retrofits, and advanced vehicles.[9] Wei et al. estimate that energy efficiency could lead to 43 % emission reduction in California. We will need to look beyond efficiency to meet deep decarbonization goals. After also accounting for additional demand, energy efficiency alone is unlikely to get us even halfway to our 2050 emissions goal.

SOLAR THERMAL

Similar to energy efficiency, solar thermal options like solar watering heating (SWH) or even passive solar design for space heating are similar to energy efficiency measures because they simply reduce demand for other fuels to provide an energy service. A typical solar fraction of solar water heating is in the 0.5 to 0.7 range which means that 30–50 % of another fuel is used after installing a solar hot water system. Of course, it is possible that a larger system could be installed that would increase the solar fraction, but such a system would be uneconomic because it would produce unusable heat at certain times of year or cause overheating of the system.

SWH has supporters because of the higher thermal efficiencies compared to solar photovoltaic (PV) panel efficiency (~40 % vs 15 % efficient), and it matches supply and end uses in energy quality.[10] It also is a relatively low-tech solution that potentially is also low cost. But given technology advancements and major cost reductions in PV, the case for solar water heating is diminishing. Furthermore, the efficiency difference is somewhat misleading, since they deliver different forms of energy. Electricity is far more valuable than heat. The electricity that a PV system could produce can be used in a heat pump water heater (HPWH). A heat pump could have a coefficient

8. KEMA. 2010. "2009 California Residential Appliance Saturation Study." http://www.energy.ca.gov/2010publications/CEC-200-2010-004/CEC-200-2010-004-ES.PDF

9. Nadel, S., N. Elliott, and T. Langer. "Energy Efficiency in the United States: 35 Years and Counting." ACEEE. June 2015.

10. Lovins, A.B. 1976. "Energy Strategy: The Road Not Taken." Foreign Aff. 55: 65.

of performance (COP) of 3 or more, tripling the system efficiency and putting the PV on par with SWH[11]. A 2009 Itron study found that the average cost of SWH systems cost $6,358 with an average levelized cost of saved energy of $2.52/therm ($23.86/GJ) for systems that displaced gas and $0.104/kWh for systems that displaced electricity, assuming a 25-year life with no additional maintenance issues over the life of the system.[12] We believe that zero maintenance of a SWH system for 25 years is far too optimistic. In practice, it will require periodic inspections and maintenance. As part of the study, they also compared these installed costs with other market data in Hawaii, Oregon, Northern Europe, China, and India. Average costs in all regions other than China and India were similar (within about $1,000). Costs in China and India were found to be less than one tenth the cost in California. This may be due to smaller systems and lower labour costs. If very large cost reductions for SWH are possible (and they outpace cost reductions in PV systems) then SWH may play an important role in decarbonizing. But today, the economics clearly favour PV+HPWH systems in California.

Solar water heating systems would certainly have an impact on reducing emissions, but they might not be the most effective use of funds. Let us consider a few scenarios. First, if the consumer has an electric resistance hot water heater, they could switch to a heat pump and gain about the same energy savings at half the cost, with the average installed cost of HPWH being around $3,000. If they already have a HPWH, the value of the energy savings that would come from a SWH would be cut by a factor of 2 or more—leading to a cost of saved electricity twice as much as what was found in the Itron study. If a heat pump were already installed, the economics of adding solar water heating would not be favourable, as the cost of saved energy would be far higher than the cost of energy. On the other hand, if SWH were installed first, the economics of switching from a resistance water heater to a heat pump would not be favourable because the energy savings that the HPWH could provide would be much smaller. The order of events matters a lot.

The biggest drawback of SWH is that they simply do not reduce emissions enough. If the goal is to eliminate residential emissions from natural gas combustion, then cutting only two thirds of those emissions from water heating still leaves us far from our goal. Policymakers should be cognizant of the impact that SWH could have in the future. While SWH might reduce emissions today, choosing SWH could lock in remaining emissions further into the future by changing the future economics of electrification. Instead of spending $6,000 on a SWH system, a homeowner could choose to spend $3,000 on a HPWH and $3,000 on a 1 kW PV system[13]. This would provide a greater climate benefit. That PV system could produce 1,555 kWH/year in San Francisco[14], or 159 therms (17 GJ) of heat delivered with a COP of 3. The average Pacific Gas and Electric customer used 183 therms (19 GJ) for water heating, which assuming an 80 % efficient hot water heater, is 146 therms (15 GJ) of delivered water heating energy. In other words, the $6,000 spent on a HPWH+PV system would be net zero energy, while the SWH would only cut energy by about ⅔. While HPWH+PV might be zero net energy, it would not necessarily be zero emissions since not all consumption would come directly from the PV.

The above analysis may come across as very bearish on SWH, but it is possible that in some scenarios it could be a part of the mix. Solar fraction can vary widely between northern and southern California, ranging from 0.55 to greater than 0.85.[15] SWH in areas with very high solar fractions could be a part of a smart decarbonizing strategy, particularly with cost reductions – though those areas will also have more productive PV systems as well.

A variety of decarbonization options, like SWH, will be important to hedge risk of other strategies not delivering on their potential to decarbonize the water heating sector. SWH are an old, proven technology, and can deliver emissions reductions. Because of their high cost, they should not be the first choice for decarbonizing water heating. For space heating, SWH could be useful in buildings that use hot water to distribute heat, and it could also be useful in new construction with hydronic heating systems, but the transition cost of existing buildings would be cost prohibitive.

Photovoltaic thermal hybrid solar collectors (PVT) generate both electricity and heat. The system efficiency is higher because the PV can operate more efficiently when cooler, and some energy that is not converted to electricity is captured as heat. With cost reductions, PVT systems could also potentially decarbonize heating cheaper than PV + HPWH. Further research, development, and deployment is needed to drive costs down.

DECARBONIZED PIPELINE GAS

Another decarbonization option is to leave heating systems in the building stock alone, but distribute fuels that have lower lifecycle carbon emissions. The biggest advantage of this strategy is that it requires no action on the part of consumers. Motivating consumers to take action when it comes to energy use has been challenging and well documented in the energy efficiency gap literature, and this would be another case where a large number of consumers would need to take coordinated actions to reduce carbon emissions. Experience with energy efficiency investments show that consumers are hesitant to respond, have high hurdle rates to make efficiency investment, only invest with very short paybacks – and often do not get the expected savings. Decarbonized pipeline gas overcomes these barrier, and of the four strategies to decarbonize space and water heating, only decarbonizing pipeline gas can be achieved through central planning. Along with this benefit, decarbonizing pipeline gas would also be preferable for natural gas utilities because it would allow their business to survive while meeting deep decarbonization goals – though they would also likely resist a full transition away from natural gas.

11. Solar energy is converted to electricity with 15 % efficiency, but the system efficiency of solar energy to heat is 45 % (15 % × 3) because of the 300 % efficient heat pump.

12. Itron. 2009. "California Center for Sustainable Energy Solar Water Heating Pilot Program: Interim Evaluation Report."

13. Assuming a $3/W installed PV cost. The total installed cost of residential PV systems in 2015 was $4/W on average in the US, and $1.7/W in Germany. Barbose, Galen L., and Naïm R. Darghouth. 2016. "Tracking the Sun IX: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States."

14. National Renewable Energy Lab. 2016. PVWatts Calculator. http://pvwatts.nrel.gov/

15. Cassard, Hannah, Paul Denholm, and Sean Ong. 2011. "Break-Even Cost for Residential Solar Water Heating in the United States: Key Drivers and Sensitivities." NREL 303: 275–3000.

Three main options fall into this category of fuel: biogas, hydrogen, and synthetic methane. Biogas can be produced using biomass put through an anaerobic digestion or thermochemical process. Hydrogen can be produced using excess renewable electricity to electrolyze water to generate hydrogen. This hydrogen can then be mixed in to the natural gas system at fractions up to 10 % or put through a methanation process to create synthetic methane[16]. The cost of all three options is very high today, and the resources needed to produce all three low carbon fuels will likely be scarce in the future.

If decarbonized gas were used to reduce emission from space and water heating end uses in California, it would most likely come predominantly from biogas. A recent study looking at the costs of decarbonizing using an electric only or mixed case (which included decarbonized gas) found that costs were comparable for both options.[17] This study relied on California receiving a population-weighted share of all biomass produced in the United States in a best-case scenario of biomass production.[18] The other environmental impacts of such a high level of biomass production were not accounted for.

Given that the biomass supply will be constrained (particularly if we want to avoid the worst environmental side effects of increased biomass productions) there will certainly be better uses for it than space and water heating in California. Some existing end uses, like industrial process heat, heavy duty vehicles, and aviation will be more challenging to decarbonize, so biomass resources would have a bigger impact for those end uses.

Biomass could be used more efficiently and with lower emissions if it were converted to electricity. A ton of biomass can be converted to about 9.5 GJ of biogas or 6.5 GJ of electricity through combustion. Combustion provides three benefits. First, 6.5 GJ of electricity is more valuable for heating than 9.5 GJ of biogas.[17] When used in a heat pump a GJ of electricity delivers 2–3 GJ of heat. One GJ of biogas on the other hand might only deliver 0.95 GJ of heat. Second, combustion of biomass is about a third of the cost per ton than conversion to biogas. So, you get 1.5–2 times as much heat per ton of biomass at ⅓ the cost. Finally, combustion of biomass, together with carbon capture and storage allows for negative net emissions.

If, biogas was produced at all for space and water heating, it would be better used in colder climates. Most parts of California have low heating demands, which means that if heating systems were electrified there would not need to be very large increases in electricity infrastructure. This would not necessarily be the case in very cold climates where power systems would need to be much larger to support electric heating systems.

Another way to reduce emissions of residential natural gas combustion is to replace natural gas with synthetic methane or hydrogen that has been produced with low-carbon electricity, known as power to gas (P2G). Generating hydrogen or synthetic methane from excess renewable electricity production could be a flexible load that could be used to deal with intermittency of wind and solar generation. It would also have the potential to seasonally store energy from renewables in the natural gas infrastructure both directly and by displacing other fossil gas usage by varying amounts over the year. Rather than curtailing renewables during times of over production, this energy could be used to produce other fuels. Energy+Environmental Economics estimates that with a 50 % Renewable Portfolio Standard and diverse resources, there would be 1,300 hours of overgeneration per year, generating 5,400 GWh.[19] The disadvantages of a synthetic methane/hydrogen pathway are many. The line of questioning goes as follows: What would be required to make investment in synthetic methane production attractive? If this investment were made, how would that infrastructure be used, and with what implications on emissions? What is scale of the emissions impact that this investment could have? If synthetic methane were produced, how would it be used?

With many hours of overproduction, other flexible demands would likely step in to use the free electricity. Relying only on excess generation hours is not feasible because it would lead to low utilization of expensive electrolyzers. Unfortunately, the system efficiency of synthetic methane production is very low, particularly when we compare it to other options. Converting electricity to hydrogen is 50–70 % efficient, with methanation of that hydrogen (converting H_2 to CH_4) resulting in an additional 20 % loss.[20] Some hydrogen could be potentially mixed directly into natural gas networks, though it is uncertain what the allowable fraction would be or how much leakage would occur of small H_2 molecules. The system efficiency of the path from electricity to gas to heat looks particularly bad when we compare it with using electricity directly through a heat pump. It will be for policy makers to decide if the behavioural and political benefits of this strategy outweigh the system efficiency penalty and costs.

As seen in Figure 1, for every 100 units of electricity in, a power to gas conversion pathway would create about 45 units of heat. However, those same 100 units could create 250 units of heat when used directly in a heat pump. Power to gas does have the advantage of storing energy – potentially very large amounts, over long seasonal timescales – so that generation and consumption do not have to happen at the same time. But a factor of five difference in system efficiency will be hard to overcome.

Both biogas and synthetic methane come with the risk of leakage and the global warming that results when methane leaks into the atmosphere. While natural gas has been regarded as a bridge fuel from coal to renewables, some suggest that when accounting for leakage, it may not have any emissions benefit.[21]

16. Melaina, M. W., O. Antonia, and M. Penev. 2013. "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues." National Renewable Energy Laboratory.

17. Energy+Environmental Economics. 2015. "Decarbonizing Pipeline Gas to Help Meet California's 2050 Greenhouse Gas Reduction Goal." https://ethree.com/documents/E3_Decarbonizing_Pipeline_01-27-2015.pdf.

18. Perlack, Robert D., Laurence M. Eaton, Anthony F. Turhollow Jr, Matt H. Langholtz, Craig C. Brandt, Mark E. Downing, Robin L. Graham, et al. 2011. "US Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry." http://lib.dr.iastate.edu/abe_eng_reports/16/.

19. Energy+Environmental Economics. 2014. "Investigating a Higher Renewables Portfolio Standard in California." https://ethree.com/documents/E3_Final_RPS_Report_2014_01_06_with_appendices.pdf.

20. Götz, Manuel, Jonathan Lefebvre, Friedemann Mörs, Amy McDaniel Koch, Frank Graf, Siegfried Bajohr, Rainer Reimert, and Thomas Kolb. 2016. "Renewable Power-to-Gas: A Technological and Economic Review." *Renewable Energy* 85 (January): 1371–90. doi:10.1016/j.renene.2015.07.066.

21. Brandt, A. R., G. A. Heath, E. A. Kort, F. O'Sullivan, G. Petron, S. M. Jordaan, P. Tans, et al. 2014. "Methane Leaks from North American Natural Gas Systems." Science 343 (6172): 733–35. doi:10.1126/science.1247045.

Decarbonized gas can provide a role in future energy system – but that should not distract us from focusing on rapid effort to electrify residential space and water heating. P2G's ability to use intermittent resources and diversification of low carbon carriers are real benefits, but unlikely to serve all of our current natural gas demands. While diversification might lower risk, diversifying with P2G with high/uncertain costs and uncertain biomass availability might be higher risk overall.

ELECTRIFICATION

Electrification of the residential space and water heating sector would mean transitioning existing natural gas furnaces, boilers, and water heaters to electric resistance or heat pump systems. Resistance water heaters are much less efficient but much lower cost. It is possible that in some space heating applications, with very few hours of operation, these would be suitable. But in most cases heat pump systems would most be more economical, particularly in areas with higher electricity costs.

There is much promise with electrification of heating loads, though we must also recognize the challenges or unintended consequences of this transition. Today, air conditioning systems use refrigerants with very high global warming potential (GWP). One common refrigerant, R-410a, has a GWP of over 2,000. A typical home air conditioning unit might have 5 kg of refrigerant. If we assume that a heat pump has a similar quantity of refrigerant and that all of this refrigerant escapes over the 15-year life of the unit, then the climate impact from refrigerant leakage alone would be 70 % of the CO_2 emissions from burning natural gas even if the heat pump is using only clean electricity.[22] Without paying attention to refrigerant leakage, most of the potential benefit of electrified heating could be lost. New heat pump technologies are becoming commercialized that use CO_2 as the refrigerant, though these systems are still expensive.

It might go without saying, but encouraging electrification prematurely could have negative consequences if the electric grid is not yet clean enough. When the marginal generator during times of space/water heating is above a 32 % efficiency natural gas generator, we would be better off switching to a heat pump with an EF of 3 vs a 96 % efficient natural gas furnace. California is already there, but not all of the US is.

Other concerns about heat pumps are that they perform worse at colder outdoor temperatures. New cold climate space conditioning heat pumps are emerging that have COPs well over 2 even at below freezing temperatures.[23] Heat pump water heaters also are noisier than other water heaters, so consumers may need to adapt – though very quiet heat pumps are also on the market. There is also some transition cost for some houses if an upgrade to the electrical service is required. This upgrade should be coordinated with other activities, such as installing electric vehicle charging.

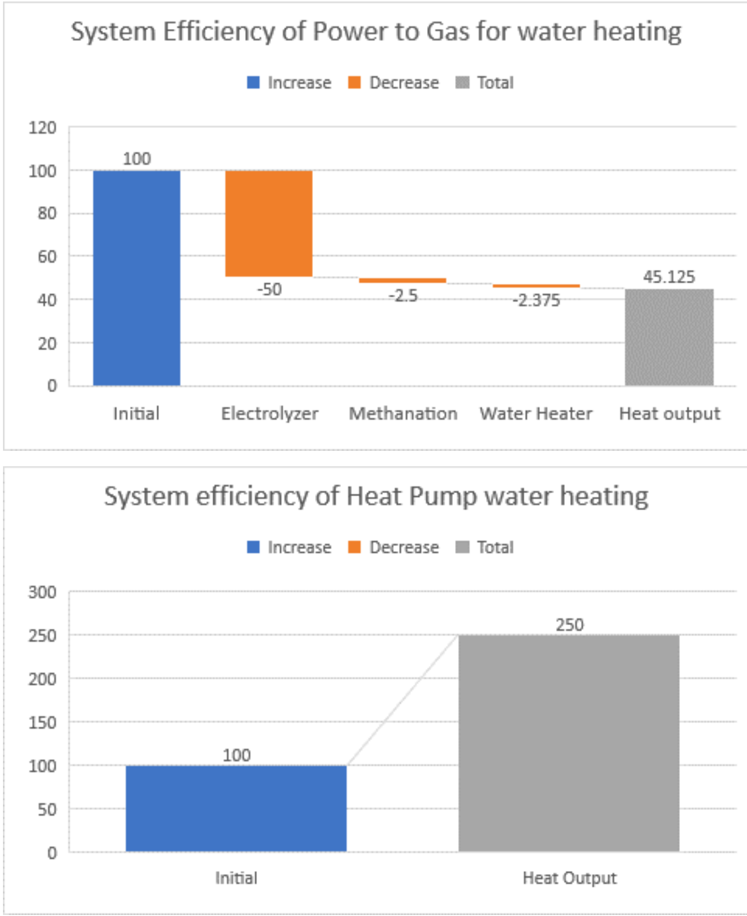

Figure 1. Comparison of system efficiency of electricity to heat via two pathways: synthetic methane and a heat pump water heater.

While electrification of space and water heating has a shorter time scale storage/flexibility potential, it does not have the same seasonal storage attributes of synthetic methane. The seasonal storage benefit of renewable electricity through hydrogen or synthetic methane might be real but, we can potentially separate this benefit from the decision of whether to electrify residential space and water heating. If the economics were favourable for seasonal storage we could still save that energy as gas, and then use it in a fuel cell or generator and use electricity in a heat pump and come out ahead in terms of total system efficiency.

The heat pump is the key piece of the residential heating decarbonization puzzle. If consumers are offered a reliable, durable, affordable, and high-performing heat pump then electrification is the clear path to decarbonize space and water heating because of the triple efficiency gain compared to resistance heating. Without heat pumps, decarbonization goals will be more difficult to achieve and will rely on solar water heating or decarbonized gas, with existing forced air systems being served by decarbonized gas, and hot water heating served by solar water heaters.

While electrification has promising climate benefits, the economics today in California are challenging. Figure 2 shows what the breakeven relative gas and electricity prices would need to be to choose a gas water heater with an energy factor (EF) of 0.67 over a HPWH of EF 2 (for solid line) or 3 (for dotted line). Currently, with all residential electricity rates (vertical lines) and gas rates (horizontal lines) for Pacific Gas and

22. Assuming that 200 therms (21 GJ) of natural gas are used for space heating annually and produce emissions of 5 kg CO_2/therm, resulting in 1,000 kg CO_2/year with natural gas heating. The emissions from leakage of 0.34 kg/year of R-410a, with a GWP of 2,088, would result in the equivalent emissions of 710 CO_2/year. Electricity is assumed to be emission free in this scenario, but if it were not then the heat pump could lead to higher emissions when leakage is accounted for. Natural gas leakage is also an important issue, and is not accounted for in this example.

23. http://www.neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump

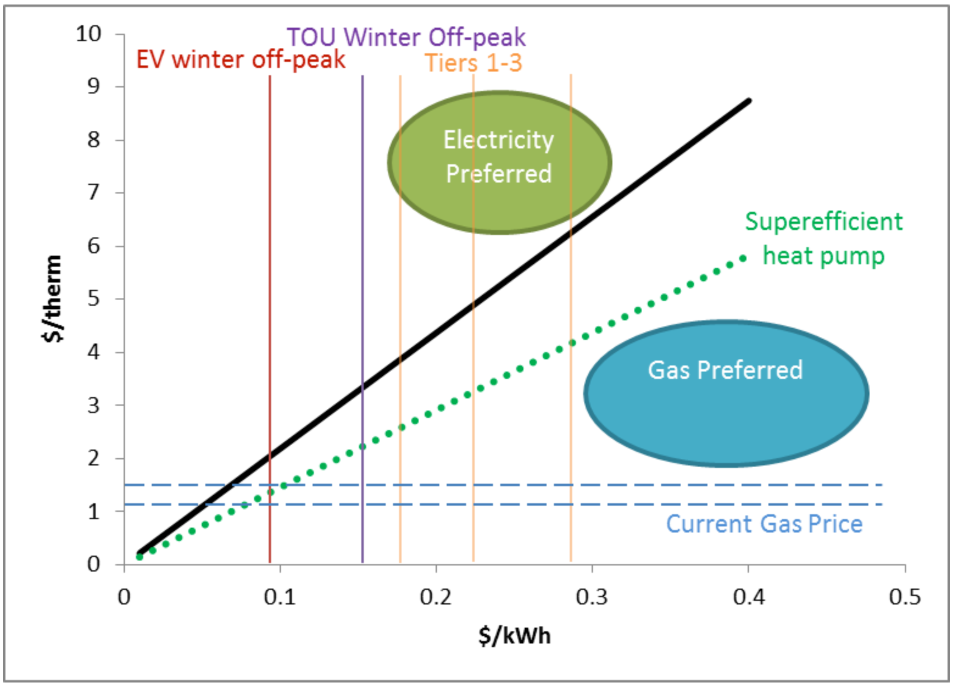

Figure 2. Regions of fuel prices where natural gas and electric heating would be preferred, given a specific set of gas and electric heating technologies (67 % efficient gas appliance vs 200 % efficient (300 % in superefficient case) electric appliance. Vertical lines represent current electricity rates in northern California, and horizontal lines represent current gas prices. With current rates, gas heating is strongly preferred.

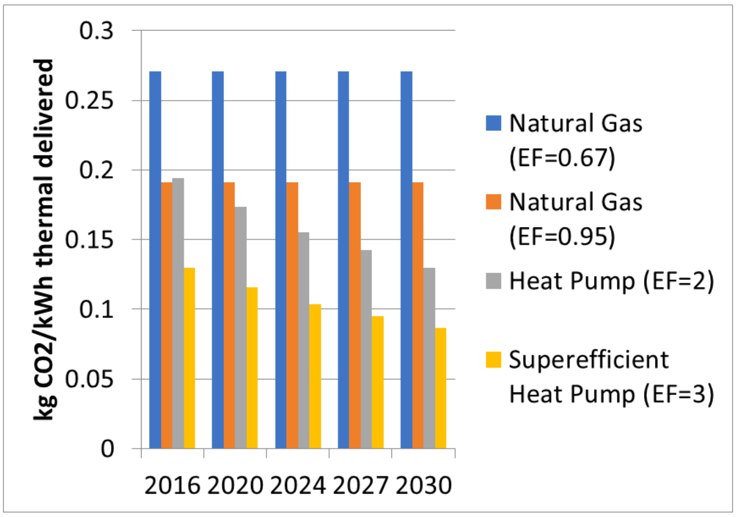

Figure 3. As a greater share of electricity comes from renewable generation, the emission reduction of electrification increases. Switching to a heat pump delivers immediate and increasing emissions reductions. Emissions from four different technologies with different energy factors (EF) are shown.

Electric we are in a gas-preferred region (in terms of operating cost). With a special Electric Vehicle rate, combined with a more efficient heat pump, the operating costs would be similar. If policymakers decide that electrifying heating is necessary to meet climate goals, changes would need to be made to electricity and/or gas rates.

Finally, the climate benefits that electrification provides in California are real and increasing as illustrated in Figure 3. Switching from a gas water heater to a HPWH today provides an immediate climate benefit (except possibly switching from the most efficient gas on-demand water heaters to the least efficient heat pumps). But that benefit will increase over time. Since electricity is going to get cleaner over the coming decades because of renewable portfolio standards, the emissions benefit will increase. Choosing a more efficient gas water heater or furnace will have the same benefit year after year, but choosing to electrify will create a larger and larger emissions reduction each year. Money spent on more efficient gas appliances may be better spent on electrification. Similarly, the environmental benefit of an additional PV system on the grid will decrease over time, as the electricity that it is displacing gets cleaner and cleaner. However, the benefit of electrification increases. While politically challenging, electrification deserves the full attention of policymakers if we are serious about meeting deep decarbonization goals.

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