Emissions Abatement from Electrification of Residential Natural Gas: Technical Case Studies and Policy Implications

by

KARL H. KOESSER

University of Wisconsin-Madison

Department of Mechanical Engineering

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Introduction

With the current effects and future risks of climate change becoming increasingly apparent, municipalities throughout the US are beginning to enact more stringent environmental regulations in the absence of meaningful federal policy. One of the more recent campaigns is to ban natural gas hookups in new residential buildings. This started with Berkeley, California in July 2019 and has expanded to over 50 municipalities enacting or considering similar laws.[1] With so many potential greenhouse gas abatement options available, this paper aims to quantify and contextualize the financial, energy, and emissions efficiencies of natural gas bans in relation to other existing or potential policies.

From the list of municipalities enacting gas bans, Berkeley, CA and Brookline, MA are selected as case studies. These locations have considerably different climates and therefore will allow more robust analysis of the thermodynamic performance of electrified homes vs traditional fossil fuel options. One in four US homes are already electric-only (primarily in the South), and most environmental policy studies indicate that this percentage must be significantly expanded in order to meet emissions reduction goals.[2] NREL finds that "Achieving the full electrification potential of end uses explored in the transportation, industry, and buildings sectors results in over a 72% reduction in fossil fuel combustion for these end uses by 2050 relative to the Baseline scenario—a reduction of approximately 33 quads of fossil fuel consumption. The transportation sector accounts for the large majority of this reduction (63%), followed by buildings (31%) and industry (the remaining 6%)." Final energy efficiency of end-use processes increases by over

[1] Municipal Natural Gas Bans: Round 1 (Turner, 2020): http://blogs.law.columbia.edu/climatechange/2020/01/09/municipal-natural-gas-bans-round-1/
[2] One in four U.S. homes is all electric (EIA, 2019): https://www.eia.gov/todayinenergy/detail.php?id=39293

40%.[3] An aggressive, multi-sector approach is necessary, but this paper will focus on electrification of the building sector only.

Figure 1 below provides a simple snapshot of the climate profiles of the two case study locations. The Methodology section that follows on the next page describes this paper's approach to examining the merit of residential gas bans in these locations.

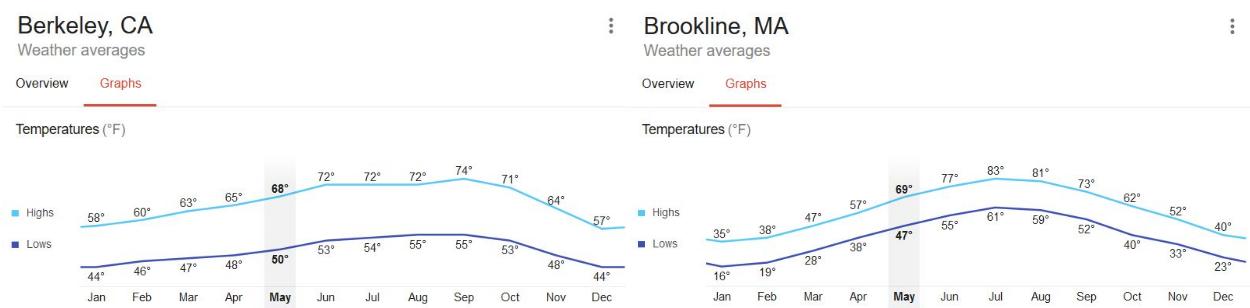

Figure 1: *Simple climate data for the two case study locations.* ***Source:*** *Google reproduction of NOAA data.*[4]

[3] Electrification and Decarbonization (NREL, 2017): https://www.nrel.gov/docs/fy17osti/68214.pdf
[4] National Centers for Environmental Information (NOAA, 2020): https://www.ncdc.noaa.gov/

Methodology

In order to study the effects of residential natural gas bans in the two case study locations, new home construction software with energy, economic, and emissions calculation capabilities was needed. The Building Energy Optimization Tool (BEopt) from the National Renewable Energy Laboratory (NREL) was selected for this purpose, utilizing version 2.8.0.0, the latest iteration available as of Spring 2020.[5] BEopt enables analysis of retrofits and new home construction using intuitive building design, appliance specifications, utility and weather data, and realistic building materials and practices. It is often used for the study of extensive energy-saving measures and net-zero buildings, such as in Gregory Marsicek Jr.'s 2012 thesis on the feasibility of solar and heat pump systems to reduce conditioning energy consumption.[6]

However, the intention of this report is not to change numerous parameters about a home in order to optimize the energy efficiency. Instead, the idea is to isolate the effects of residential electrification mandates by only changing the space and water heating equipment versus a traditional gas reference. This benchmarking is made more convenient by the Department of Energy (DOE) Building America Program for research and innovation in "residential building energy performance, durability, quality, affordability, and comfort."[7] Their codes and practices are built into NREL's BEopt, so upon opening the software, the project type "Building America" with application type "New Construction" is selected. For this analysis, a single family home is constructed for study, as seen in Figure 2 and explained below.

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[5] BEopt Download (NREL, 2020): https://beopt.nrel.gov/downloadBEopt2
[6] Feasibility of Solar/Heat Pump Systems for Reducing Conditioning Energy Consumption (Marsicek, 2012): UW-Madison Department of Mechanical Engineering Thesis Collection
[7] Building America (DOE, 2020): https://www.energy.gov/eere/buildings/building-america

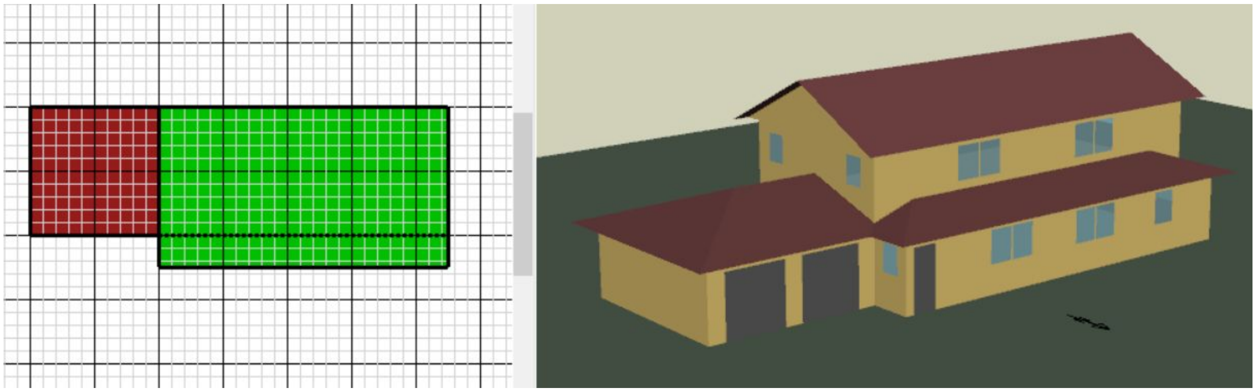

Figure 2: *Single-family new home model in BEopt "Geometry screen." Image by author.*

BEopt provides convenient modeling features for sketching the floorplan of a home and designating areas as main living space, finished and unfinished attics, garages, basements, and more. The home created for this project is a 3 bedroom, 2.5 bathroom with 2 stories, a 2-car garage, and 2,025 total finished square feet. The first level has a 4:12 pitched, hip type, truss-cantilever structure, with the upper roof having a 6:12 gable type (same structure). All attics are unfinished and there is no basement. The front of the house faces north, and the window and door placement was automatically generated and left unchanged. This same layout is used in both the Berkeley, CA and Boston, MA case studies.

The next step is to switch from the "Geometry screen," where the floor plans are drawn, to the "Site screen," where weather files, utility and emissions rates, and economic parameters are set. On the following page, a screenshot of the values used for the Berkeley, CA case study is presented in Figure 3 and explained below (along with values used for Brookline, MA).

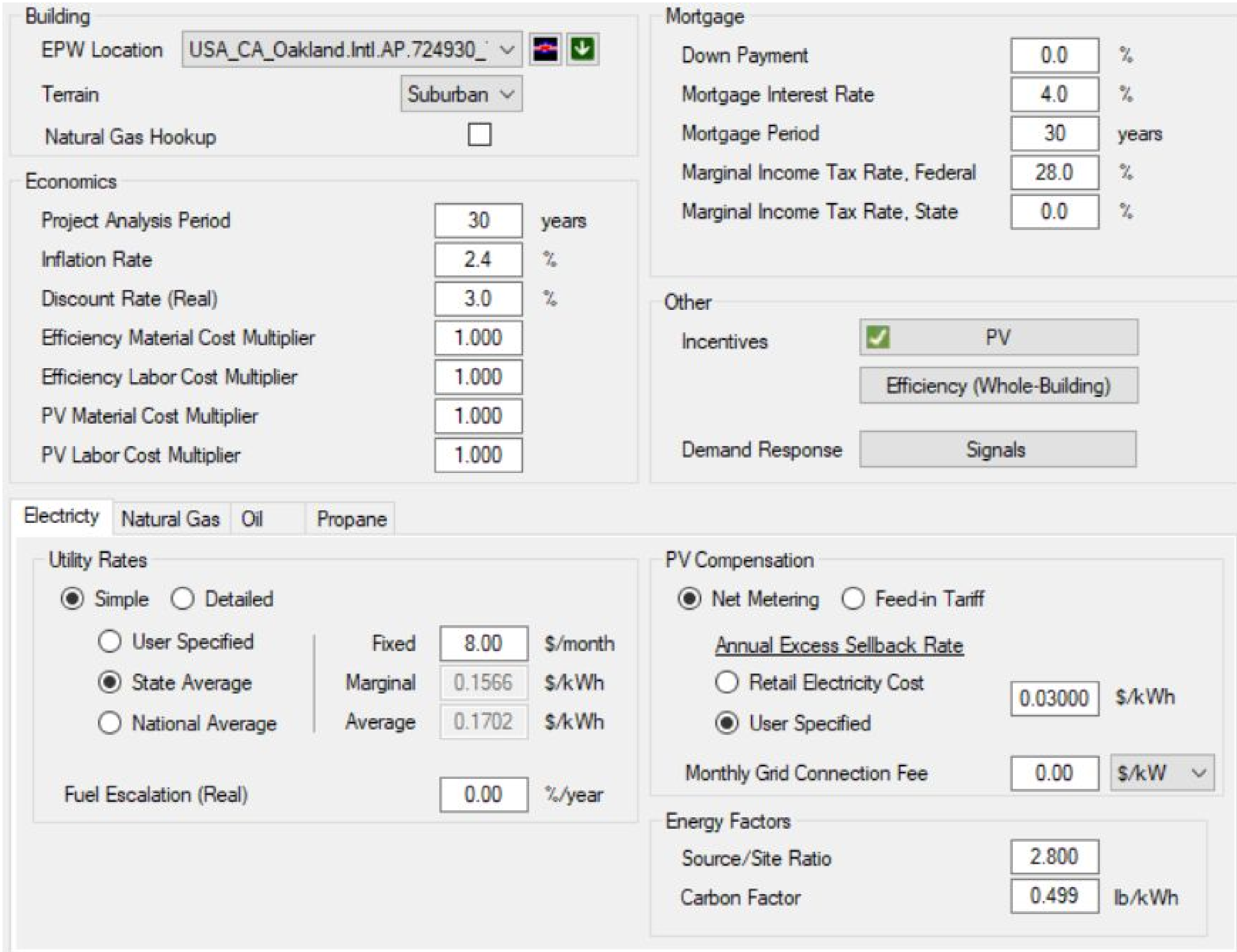

Figure 3: *BEopt "Site screen" for selecting weather, utility, and economic inputs. Image by author.*

The "EPW location" dropdown allows the selection of weather and solar data files. For the Berkeley case study, the closest and most recent file was at Oakland International Airport, filename USA_CA_Oakland.Intl.AP.724930_TMY3.epw. For Brookline, the file used was USA_MA_Boston-Logan.Intl.AP.725090_TMY3.epw. The default "Suburban" terrain was retained in both cases, and the "Natural Gas Hookup" box was unchecked - this makes the *reference* an electric-only home with no gas hookup at all, and the alternate-option designs created for the study will be the conventional fossil type. Economic parameters were left on their default values shown above, as were PV compensation and incentives since those two were not relevant to the study.

Some of the energy factors for electricity and natural gas, however, were updated. Both energy sources have a “Source/Site Ratio” and “Carbon Factor;” the former takes into account the difference in energy produced at the source vs arrived at the site (home) due to generation and delivery losses, and the latter is the greenhouse gas emissions per unit of energy. All of the BEopt default values for these parameters are national averages from ANSI/ASHRAE Standard 105-2014, Appendix J. More recent source/site ratio values were obtained from the 2019 Energy Star PortfolioManager Technical Reference: 2.8 for electricity and 1.05 for natural gas, both of which are lower than the defaults (3.15 and 1.09, respectively).[8] New carbon factors for electricity were obtained from the latest Environmental Protection Agency (EPA) “Power Profiler,” taken at eGRID subregion granularity - 0.4987 lb/kWh for Berkeley (CAMX region) and 0.5276 lb/kWh for Brookline (NEWE region).[9] This was a very important adjustment, as the national-average default was three times higher at 1.53 lb/kWh due to significant regional differences in generation mixes. Note that carbon factor values are in pounds of “CO_2-equivalent (CO_2-eq),” indicating that the global warming potential of other greenhouse gas emissions such as CH_4 and N_2O have been taken into account in addition to CO_2. More recent data for carbon factors for natural gas (CO_2-eq) and source/site ratios disaggregated by location were not readily available; the former was left as the default 14.15 lb/therm, and the latter was changed to new national averages as described above.

[8] PortfolioManager Technical Reference (Energy Star, 2019): https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf

[9] Power Profiler (EPA, 2020): https://www.epa.gov/sites/production/files/2020-01/egrid2018_summary_tables.xlsx

Utility rates for electricity and natural gas were left at the default State Averages for multiple reasons. While the "Detailed" electricity rates option allowed lookup of time-of-use and tiered energy plans for specific utility regions, BEopt did not offer the same granularity for natural gas, despite such seasonal and baseline rate designs being used in both Berkeley[10] and Brookline.[11] Due to the energy usage of the benchmark homes, using special electricity rates but not special gas rates would skew results significantly against non-fossil alternatives due to the punitively higher prices at higher consumption rates. For this reason, as well as the fluid nature of some of these rates and charges year to year, the default state averages are used.

Finally, the "Options screen" allows the user to customize the building materials, appliances, and other factors for the project. The Building America "B10 Benchmark" home is automatically generated with options realistic to the chosen site location. The "My Design," tab, which is used in this analysis for creating the traditional fossil conditioning loadout, is then assessed to ensure all options are the same as the reference *besides* the space conditioning and water heating equipment. A summary of these constant parameters, which are slightly different between case study *locations*, are presented on the following page in Table 1.

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[10] Gas Rate Finder (PG&E, 2020): https://www.pge.com/tariffs/GRF.SHTML
[11] Massachusetts Gas Delivery Rates (National Grid, 2020): http://gasrates.nationalgridus.com/ne/index-rates-afternov.jsp

Table 1: *Building options for each case location. Options are held constant between the fossil and all-electric cases, with the only differences being in the space and water heating equipment. Table by author.*

Option	Berkeley, CA	Brookline, MA
Wood stud	R-13 Fiberglass Batt, 2x4, 16 in o.c.	
Wall sheathing	OSB	OSB, R-5 XPS
Exterior finish	Vinyl, light	
Interzonal walls	R-13 Fiberglass Batt, 2x4, 16 in o.c.	R-13 Fiberglass Batt, 2x4, 16 in o.c., R-5 XPS
Unfinished attic	Ceiling R-30 Cellulose, Vented	Ceiling R-38 Cellulose, Vented
Roof material	Asphalt shingles, Medium	
Foundation slab	Uninsulated	2ft R10 Perimeter, R5 Gap XPS
Floor mass	Wood Surface	
Exterior, partition, and ceiling mass	1/2 in. Drywall	
Windows	Low-E, Double, Non-metal, Air, L-Gain	Low-E, Double, Non-metal, Arg. M-Gain
Air leakage	7 ACH50, 0.5 Shelter Coefficient	
Ducts	15% Leakage, R-8	
Water heating distribution	Uninsulated, TrunkBranch, Copper	
Lighting	34% CFL Hardwired, 34% CFL Plugin	
Refrigerator	Top freezer, EF = 17.6	
Cooking Range	Electric	
Dishwasher	318 Rated kWh	
Clothes Washer	Standard	
Clothes Dryer	Electric	

The main, base cases to be analyzed involve the following space and water conditioning equipment in both locations - see Table 2 below (for sizing, see the Results section).

Table 2: *Space conditioning and water heating selections for the main, "base" analysis scenario. Table by author.*

Equipment Type	**Electric "B10 Benchmark"**	**Fossil "My Design"**
Space Conditioning	SEER 13, 7.7 HSPF air-source heat pump ● Single stage ● 11.4 EER [kBtu/kWh] ● Cost: $2,566 ● 15-year lifetime	SEER 13 central air ● Single stage ● 11.1 EER [kBtu/kWh] ● Cost: $2,143 ● 16-year lifetime 78% AFUE gas furnace ● Open flue ● Cost: $1,941 ● 20-year lifetime
Water Heating	"Electric benchmark" water heater ● Energy factor: 0.9 ● Cost: $460 ● 13-year lifetime	"Gas standard" water heater ● Energy factor: 0.59 ● Recovery efficiency: 0.76 ● Cost: $636 ● 13-year lifetime

A secondary design scenario with better equipment is performed in the Analysis section in order to examine the effects of more capital-intensive, but higher-efficiency options. Note that the "Reference" dropdown must be changed from "B10 Benchmark" to "User-defined" in order to edit the default benchmark equipment options. Once again, all building options besides the conditioning equipment are held constant between electric and fossil designs in a given case location. The options selected in the high-efficiency scenario are summarized in Table 3 on the following page.

Table 3: *Space conditioning and water heating selections for the secondary, "high efficiency" analysis scenario. Table by author.*

Equipment Type	**Electric "User-Defined" Reference**	**Fossil "My Design"**
Space Conditioning	SEER 18, 9.3 HSPF air-source heat pump ● 2 stage ● 14.5 EER [kBtu/kWh] ● Cost: $3, ● 15-year lifetime	SEER 18 central air ● 2 stage ● 15.2 EER [kBtu/kWh] ● Cost: $2,759 ● 16-year lifetime 95% AFUE gas furnace ● Closed flue ● Cost: $2,626 ● 20-year lifetime
Water Heating	"Electric premium" water heater ● Energy factor: 0.95 ● Cost: $404 ● 13-year lifetime	"Gas premium" water heater ● Condensing, closed flue ● Energy factor: 0.82 ● Recovery efficiency: 0.9 ● Cost: $1,725 ● 13-year lifetime

The results of the base scenario are discussed in the Analysis section that follows, with a comparison to the secondary high-efficiency scenario at the end.

Analysis

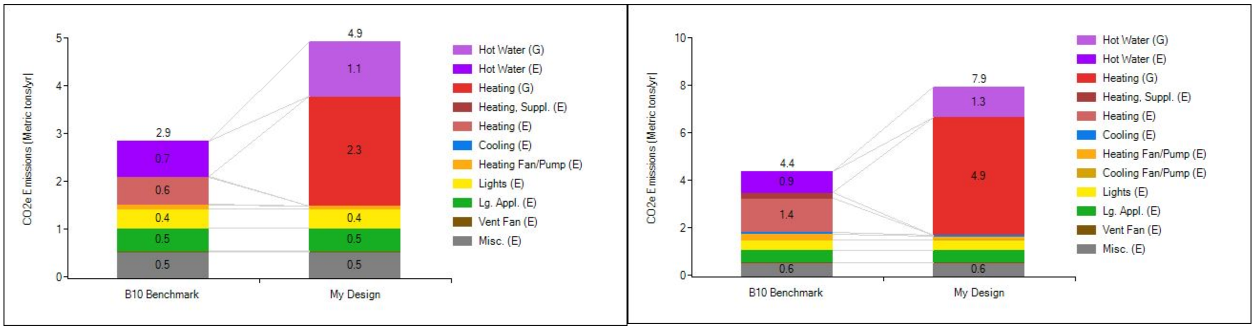

Figure 4: *CO_2-eq emissions differences between the electric B10 benchmark and a fossil design. Berkeley's results are on the left and Brookline's results are on the right. Image by author.*

As shown in Figure 4 above, the electric B10 benchmark resulted in significantly lower greenhouse gas emissions vs a fossil design in both case locations - a 41% decrease in Berkeley (2 tons/year, left) and a 44% decrease in Brookline (3.5 tons/year, right). The electric benchmark also had a lower present value of fixed costs (upfront, replacement, and residual value) vs the fossil design in both cases: \$2,497 lower in Berkeley and \$2,156 lower in Brookline. However, these benefits came at the expense of utility bills, shown in Figure 5 below.

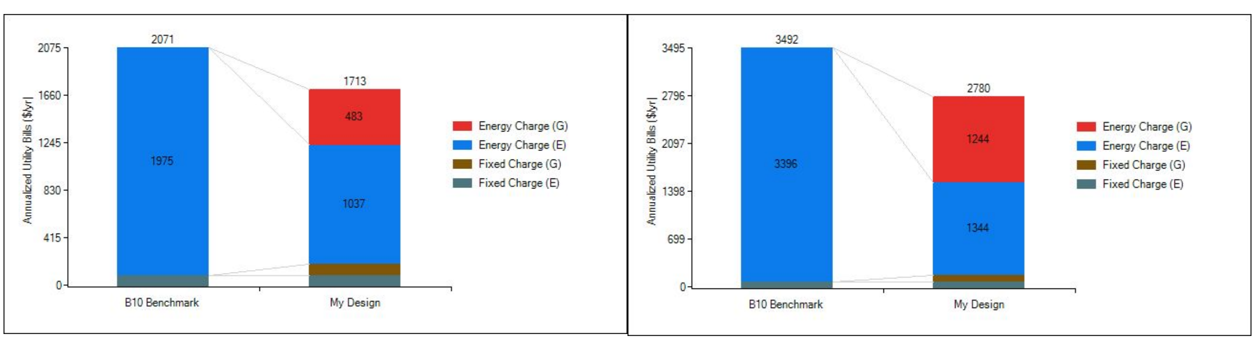

Figure 5: *Utility bill results in Berkeley (left) and Brookline (right). Image by author.*

Annualized utility bills were 21% higher ($358/year) in Berkeley and 26% higher ($712/year) in Brookline. While humans are significantly more sensitive to up-front, near-term costs (hence the insidiousness of climate change), this increase in utility bills is considerable enough that it could dissuade people from going all-electric if it weren't mandated - a quick calculation shows the $2,497 lower present value in Berkeley would be eroded by the increased utility bills in 7 years, and only 3 years in Brookline. A new-construction homeowner might find this unsatisfactory, but the incentives of landlords and real estate developers (and to some degree, utility companies) may be different, as they pay the capital costs while their customers pay the utility bills (however, depending on how salient utility bills are to prospective buyers/renters, this could affect sales). These bills can obviously be significantly impacted by other energy efficiency measures, and in the Discussion section, factors such as relative abatement cost, carbon pricing, building codes, and other considerations will be explored.

For energy, the electric benchmark resulted in approximately half the site usage vs the fossil design in both locations, as shown in Figure 6 below.

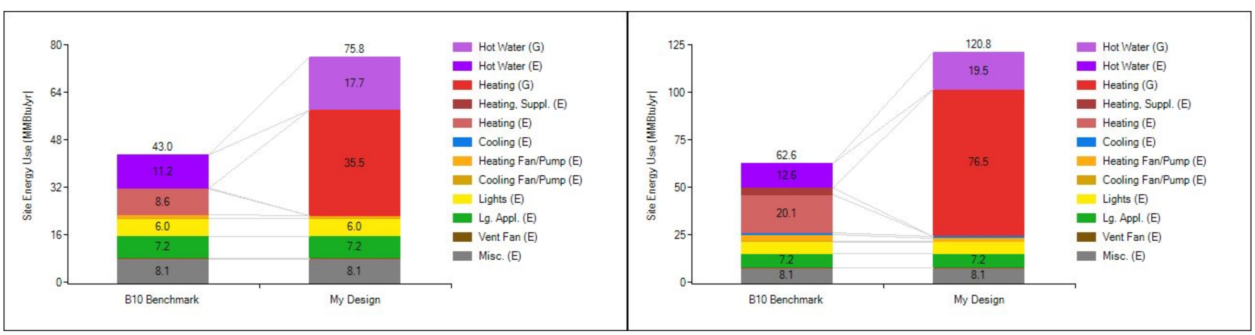

Figure 6: *Site energy use in MMBtu/year for Berkeley (left) and Brookline (right)*

However, due to the much lower source/site ratio for natural gas, the source energy usage was nearly identical between all-electric and fossil designs in both cases. This source usage could be significantly reduced by installing solar panels - and indeed, sun-rich California has mandated that all new homes must have personal or community solar as of January 1st, 2020, in addition to other statewide building codes requiring better insulation, air filtration, and incentives for battery storage (let alone other municipalities joining Berkeley in banning gas).[12] This holistic, multi-pronged approach coupled with significant decarbonization of the electricity grid is a model that other states must examine if the world is to meet its drastic, but necessary emissions reduction goals.

HVAC capacities are autosized by BEopt based on calculations consistent with ACCA Manual J sizing. Values in kBtu/hr for each case and design are shown in Figure 7 below. For reference, 1 ton is equal to 12 kBtu/hr, so the capacities in tons for each case are 3.6 and 6.4 for Berkeley and Brookline, respectively.

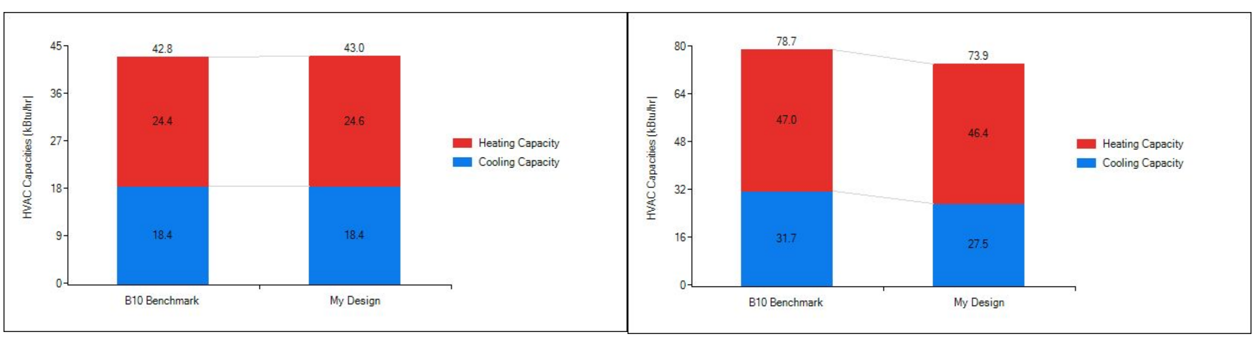

Figure 7: *HVAC capacities in the Berkeley (left) and Brookline (right) cases. Image by author.*

[12] CA Solar Mandate and Gas Bans (SF Chronicle, 2020): https://www.sfchronicle.com/business/article/California-solar-mandate-gas-bans-take-effect-in-14931617.php

As described at the end of the Methodology section, an additional design comparison was performed for each case location by using more efficient SEER 18 conditioning equipment, a 95% AFUE furnace for the fossil designs, and higher performance electric and fossil water heaters. The results vs the original cases are summarized in Table 4 below, with green shading indicating an outcome in favor of electrification, red against, and yellow relatively the same.

Table 4: *Selected results for both the base and high-efficiency design studies for each case. All values are expressed as how the electric design performs relative to the fossil design. Indicators shaded green are in favor of electrification, red against, and yellow are relatively similar. Simulated in BEopt by author.*

Parameter (units)	**Base Designs**		**High-Efficiency Designs**	
	Berkeley, CA	**Brookline, MA**	**Berkeley, CA**	**Brookline, MA**
GHG emissions (tons CO_2-eq/year)	-2.0	-3.5	-1.7	-2.3
GHG emissions (change)	-41%	-44%	-40%	-36%
Present value of fixed costs (change)	-$2,497	-$2,156	-$4,974	-$4,647
Utility bills ($/year)	+$358	+$712	+$334	+$840
Utility bills (% change)	+21%	+26%	+21%	+35%
Breakeven of upfront savings vs increased utility bills (years)	7.0	3.0	14.9	5.5
Site energy (MMBtu/year)	-32.8	-58.2	-25.7	-39.7
Site energy (% change)	-43%	-48%	-39%	-40%
Source energy (MMBtu/year)	+4.8	+10.1	+4.2	+19.4
Source energy (% change)	+4%	+6%	+4%	+13%

Discussion

The main factor of interest for this analysis is to determine the impact and cost-effectiveness of residential natural gas bans on greenhouse gas emissions. If it does not truly reduce emissions, then it is not worth doing from a climate standpoint; if it works, but the abatement is expensive, one could argue there are more efficient, "lower-hanging fruit" abatement options that could be pursued first (or instead). As shown previously in the Analysis section, gas bans are certainly effective at reducing emissions (36-44%) while also reducing up-front and maintenance costs. However, the significantly increased utility bills (21-35%) cause these savings to break even with the fossil design after anywhere from 3-15 years (see Table 4). In order to put a value on the cost of greenhouse gas abatement, Equation 1 below will be used to calculate what "carbon price" would need to be added in order to make this breakeven point occur 10 or 20 years after installation.

$$Carbon\ price\ \left[\frac{\$}{ton\ CO_2eq}\right] = \frac{Utility\ Bill\ Increase\ \left[\frac{\$}{year}\right] - \frac{Upfront\ Savings\ [\$]}{Breakeven\ [years]}}{Reduction\ in\ Carbon\ Emissions\ \left[\frac{ton\ CO_2eq}{year}\right]}$$

Equation 1: *Finding the abatement cost as a function of electric/fossil breakeven point. Formula by author.*

The results of this calculation are presented for each case and performance tier in Table 5 on the following page, where negative values would indicate it *pays* to abate carbon and positive values indicate a *cost* the consumer bears to reduce emissions with an unsatisfactory breakeven.

Table 5: *Greenhouse gas abatement cost in dollars per ton of CO_2-eq for each scenario as a function of desired breakeven time. Calculations by author.*

Breakeven time	**Base Designs**		**High-Efficiency Designs**	
	Berkeley, CA	**Brookline, MA**	**Berkeley, CA**	**Brookline, MA**
10 years	$54	$142	-$96	$163
20 years	$117	$173	$50	$264

These values are then compared to the greenhouse gas abatement costs of other potential solutions, as shown in Figure 8 below.

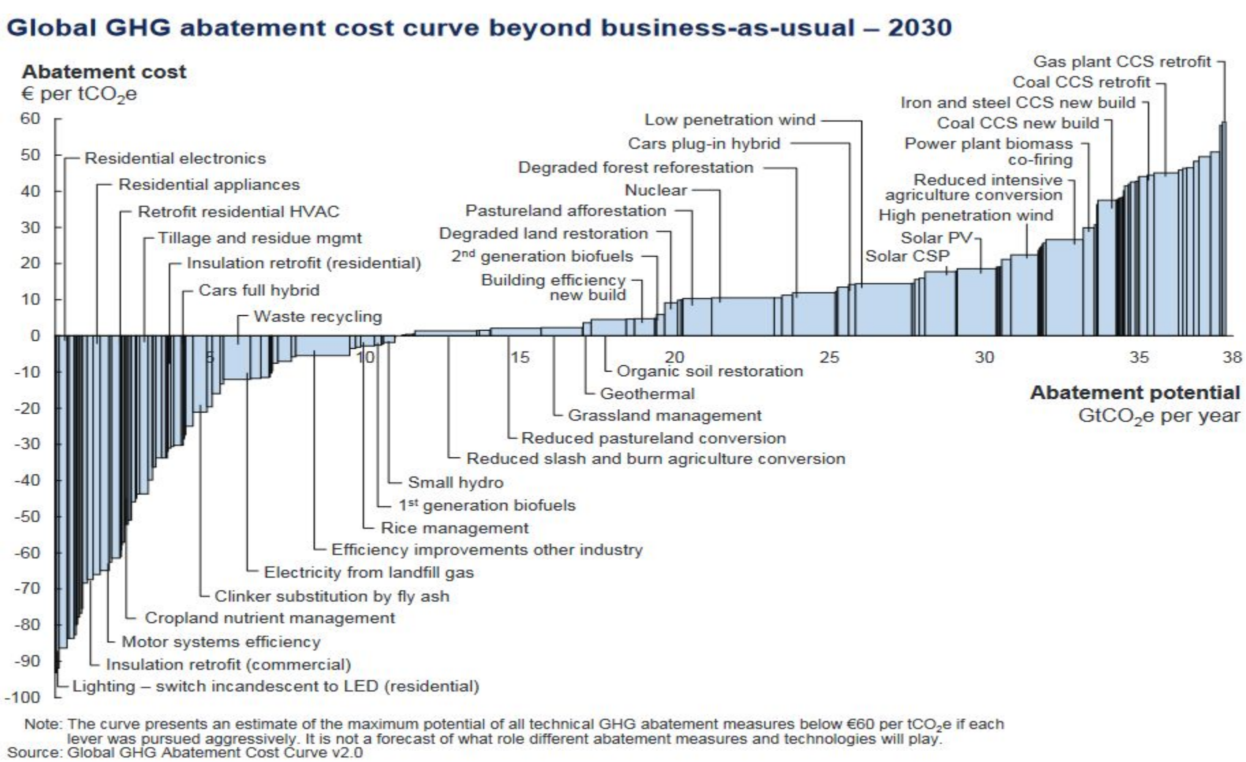

Figure 8: *Greenhouse gas abatement cost curves in 2030 for various solutions, when pursued aggressively.* ***Source:*** *Analysis by McKinsey and Company, 2010.*[13]

[13] Pathways to a Low-Carbon Economy (McKinsey, 2010): https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Pathways%20to%20a%20low%20carbon%20economy/Pathways%20to%20a%20low%20carbon%20economy.ashx

In Berkeley, it actually pays to reduce emissions with high-efficiency electrification if the homeowner's "indifference point" is a decade - to the tune of $96/ton. This is comparable to some of the most cost-effective options in McKinsey's report, such as LED lighting and residential electronics. All other scenarios have a positive abatement cost, particularly in Brookline where the weather is more extreme and the energy prices are higher. Note that both California[14] and Massachusetts[15] participate in (different) cap-and-trade programs with prices of $15-18 and $5-6 per ton, respectively. A nationwide carbon price assessed as far upstream as possible would be more effective and efficient, as the price signal would be economy-wide and felt by everyone. In order to protect US business competitiveness, encourage global pricing adoption, increase political popularity, and fix the regressive nature of energy taxes, it is recommended that both a carbon tariff/rebate system be implemented at the border and a carbon dividend to US households be implemented along with the carbon pricing scheme.[16]

So if electrification is not the most cost-effective abatement option, are Berkeley and Brookline making an unwise choice in banning natural gas and missing out on low-hanging fruit? In a word, no. Both California and Massachusetts already have a number of aggressive policies for improving things like building and transportation efficiency. For example, California has already embraced the top solution (LED lighting) by requiring all bulbs manufactured or sold in the state after January 1st, 2018 to have a minimum efficiency level of 45 lumens per watt, which essentially bans incandescent bulbs.[17] They also have had statewide energy efficiency standards for buildings since 1976, the latest iteration of which mandates solar for all new homes

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[14] Auction Information (CARB, 2020): https://ww3.arb.ca.gov/cc/capandtrade/auction/auction.htm
[15] Auction Results (RGGI, 2020): https://www.rggi.org/auctions/auction-results
[16] Making Carbon Pricing Work for Citizens (Klenert, 2018): https://www.nature.com/articles/s41558-018-0201-2
[17] CA to Get New Bulb Standards (NRDC, 2017): https://www.nrdc.org/experts/noah-horowitz/california-get-new-light-bulb-efficiency-standards-jan-1

and lays out a number of "energy and water efficiency requirements (and indoor air quality requirements) for newly constructed buildings, additions to existing buildings, and alterations to existing buildings," meaning many existing homes will require retrofits to meet new standards (tailored to local conditions) if owners choose to make any renovations.[18] Massachusetts is also no slouch, with their building codes incorporating the latest Energy Star 3.1 certification, as well as laying out optional, performance-based "Stretch Codes" above the base requirements - Brookline and the majority of other municipalities have opted-in to these.[19]

Also note that McKinsey analysis is from 2010; since then, some technologies such as solar and wind have fallen in price much faster than even the most optimistic expert predictions. While significant education and incentives are still required for the solutions with negative abatement costs (due to consumer inability to recognize or capture the value of things such as energy efficiency), the more-expensive system-wide changes on the right side of the curve are also very important and necessary to drive deep decarbonization. With a cleaner electricity grid, nearly all activities become inherently less carbon intensive, particularly when coupled with electrification measures such as EVs and the building codes under study. As far as political feasibility is concerned, powerful utilities that serve both electricity and gas should embrace electrification for the increased business, particularly if energy efficiency measures are being mandated as well - something the industry is often hesitant or even militant towards.[20]

Noteworthily, new-home electrification becomes considerably more cost-competitive when you consider the avoided cost of installing and maintaining gas lines, which is not

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[18] 2019 Building Energy Efficiency Standards (CEC, 2018): https://ww2.energy.ca.gov/publications/displayOneReport_cms.php?pubNum=CEC-400-2018-020-CMF
[19] Building Energy Code (Mass.gov, 2017): https://www.mass.gov/info-details/building-energy-code
[20] How Utilities Stall Progress on Alternative Energy (Wheeling, 2019): https://psmag.com/environment/how-utilities-stall-progress-on-alternative-energy

considered in BEopt and so far has not been included in the analysis. While many utilities will run main lines from the street to a home for free, the cost of running gas lines to various systems and appliances quickly reaches many thousands of dollars.[21] Indeed, a 2018 study by the Rocky Mountain Institute (RMI) examining the economics of electrification in four cities - one of which was Oakland, CA - found that heat pumps in the Bay Area are universally more cost-effective in new construction, even before considering time-of-use electricity plans.[22] This was largely due to both the avoided costs of gas lines and the reduced cost and complexity inherent to heat pumps, which serve the purpose of furnaces and air conditioners in one unit.

The RMI report also notes the massive risk of fugitive emissions from natural gas production and distribution. Precise emissions are hard to quantify/locate and are still shrouded in uncertainty,[23] but numerous studies (such as this very recent one in Nature)[24] indicate that fugitive emissions are vastly higher than reported, with some estimates being so high as to nearly eliminate the entire climate benefit of switching from coal to gas.[25] In addition to this risk, continuing to incentivize and build gas pipelines further entrenches the "carbon lock-in" path dependence the world already experiences.[26] Current fossil fuel infrastructure alone is more than enough to blow past Paris climate targets.[27] Minimal buildout of new fossil fuel infrastructure and expedited shutdowns are required to prevent lock-in and stranded assets, most notably with

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[21] Gas Line Installation and Repair Costs (HomeGuide, 2020): https://homeguide.com/costs/gas-line-installation-cost
[22] The Economics of Electrifying Buildings (RMI, 2018): https://rmi.org/insight/the-economics-of-electrifying-buildings/
[23] Methane Tracker 2020 (IEA, 2020): https://www.iea.org/reports/methane-tracker-2020/methane-from-oil-gas
[24] Preindustrial CH_4 indicates greater anthropogenic fossil CH_4 emissions (Hmiel, 2020): https://www.nature.com/articles/s41586-020-1991-8
[25] Greater focus needed on methane leakage from natural gas infrastructure (Alvarez, 2012): https://www.pnas.org/content/109/17/6435
[26] Assessing carbon lock-in (Erickson, 2015): https://iopscience.iop.org/article/10.1088/1748-9326/10/8/084023
[27] How Much Global Warming Is Fossil Fuel Infrastructure Locking In? (McKenna, 2019): https://insideclimatenews.org/news/01072019/climate-change-lock-in-fossil-fuel-power-plants-paris-goals-nature-study

coal.[28] In a statement in opposition to the Brookline natural gas ban, a National Grid spokesperson noted that pipelines could play a role in the clean energy future by transporting biogas.[29] While this is potentially true (as well as for other options like hydrogen), the existing infrastructure is already plentiful and in need of maintenance, not expansion. Continuing to build aggressively with an uncertain and risky future is unwise and dangerous, especially in locations where electrification is already better.

Finally, the health and safety implications of natural gas bans add significant, but difficult to quantify co-benefits. Growing bodies of research indicate that the indoor air pollution caused by combustion appliances drastically exceeds levels that are considered safe according to air quality standards - many of which are increasingly considered to be set too high.[30] Adding to this is the peace of mind of no risk of gas explosions - particularly in places like earthquake-prone California.

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[28] Quantifying operational lifetimes for coal power plants under the Paris goals (Cui, 2019): https://www.nature.com/articles/s41467-019-12618-3

[29] Brookline Is Still Cooking With Gas, But Has Banned Fossil Fuels For Heating (Gellerman, 2019): https://www.wbur.org/earthwhile/2019/11/20/brookline-fossil-fuel-ban-heating-oil-natural-gas

[30] Gas stoves can generate unsafe levels of indoor air pollution (Roberts, 2020): https://www.vox.com/energy-and-environment/2020/5/7/21247602/gas-stove-cooking-indoor-air-pollution-health-risks

Conclusion

In order to assess the merit of residential natural gas bans for new homes, the two cities Berkeley, CA and Brookline, MA were selected as case studies, as they were two of the first to enact such bans and reside in considerably different climate zones. NREL's BEopt software was used to model the energy and emissions performance of a single-family detached new home with 3 beds, 2.5 baths, a 2-car garage, and 2,025 finished square feet. The main analysis compared a fossil-equipped system to an all-electric Building America B10 benchmark home, where all building factors were held constant except for the space and water conditioning equipment in order to isolate their effects. A secondary analysis upgraded the SEER 13 conditioning equipment to SEER 18 for both fossil and electric cases in order to observe the results' sensitivity to using more efficient and capital-intensive options (fossil furnaces were upgraded from 78% AFUE to 95% AFUE, and both electric and fossil water heaters were switched to premium options). HVAC capacities were autosized by BEopt, and economic, utility rate , and weather data were left on pre-programmed, locational values. Source/site ratios and carbon factors were updated to more recent DOE and EPA figures.

Results showed significant greenhouse case abatement from electrification, ranging from 36-44% reduction vs traditional fossil options. The present value of up-front and maintenance costs was also reduced by $2,156-$4,974 due to heat pumps replacing both the air conditioner and the furnace. However, electrified homes saw significantly higher (21-35%) annualized utility bills, removing the upfront electrification savings in as little as 3 years (Brookline, low-efficiency case) to as many as 15 years (Berkeley, high-efficiency case).

GHG abatement costs were found by calculating the carbon price that would be necessary to push the breakeven with fossil generation to 10 or 20 years post-installation. These prices ranged from -$96/ton (Berkeley, high-efficiency, 10-year breakeven) to $264/ton (Brookline, high-efficiency, 20-year breakeven), with a mean of $108 and median of $130 per ton. In general, the more extreme weather and higher energy prices in Brookline led to less economical outcomes vs Berkeley.

These carbon prices were compared to the abatement cost curve of other solutions, ranging from about -$100/ton for LED lighting to a cap of $60/ton for gas plant CCS. While the analysis showed natural gas bans are less economical than most other solutions in most scenarios, many of the cheaper energy efficiency options are already being addressed by building codes and other policies in the case study locations. In such locations, gas bans are therefore a logical next step in a holistic approach to mitigation, particularly when considering the infrastructure lock-in and vastly underreported fugitive emissions inherent to gas production and distribution. Electrification becomes significantly more attractive when the costs of gas line installation/maintenance and harder-to-quantify health benefits from indoor air quality improvements are considered.

Policy recommendations from this report include:

- Strengthening existing building codes, particularly by expanding retrofits, passive house design, electrification, and demand-side management
- An economy-wide carbon price with rebates to citizens and a border adjustment
- Reducing the carbon intensity and consumption of energy with renewable portfolio standards, time-of-use rates, and expedited fossil generation shutdowns (especially coal)
- Providing innovative financing options for residential energy projects and drastically increasing awareness and knowledge of heat pumps by homeowners and contractors
- Driving down prices of decarbonization technology further via economies of scale from public purchasing of equipment, concurrently reducing government building emissions.