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Title: Case Studies of Future Residential Natural Gas and Electrification Scenarios in Leading Low-Carbon Regions

Introduction and Background

There is active worldwide dialogue and action on policies aiming to reduce greenhouse gas (GHG) emissions as a means of alleviating potential future global warming effects. This is particularly advanced in several developed economies, such as Germany and the United Kingdom (U.K.). In the United States (U.S.), there are no comprehensive federal policies to reduce GHG emissions, though strides in reducing carbon dioxide (CO_2) emissions have occurred in the past decade – stemming mainly from natural gas displacing coal power generation.

Some U.S. states have established or are formulating more aggressive low-carbon emission policies. These state-level policies generally start with a supply-based policy requiring, and often subsidizing, low or zero-carbon power generation sources. Further consideration is underway on demand-side policies such as using electricity to displace traditional fossil fuel applications. Examples include electric vehicles – in place of traditional liquid fuels – or using electricity for space and water heating in homes and businesses – in lieu of natural gas.

Within the U.S., California and New York are two U.S. states on the forefront of GHG reduction policies. Notably, these two states are major economic entities, ranked first and third in U.S. state-level gross domestic product (GDP). California's GDP is nearly comparable to the U.K., while New York's GDP is similar to Canada's. Table 1 provides comparative electricity information on two European countries and these two U.S. states.

Table 1: Comparison of Electricity Use and Emissions Rates in Select European Countries and U.S. States (2016)

	Electricity Use (billion kWh)	Average Electricity Emission Rate (g CO2/kWh)	Average Residential Electricity Price (/kWh)
Germany	481	474	$0.368 (U.S. $)
United Kingdom	304	243	$0.242 (U.S. $)
California	257	239	$0.1739 (U.S. $)
New York	197	233	$0.1758 (U.S. $)
U.S. Average	--	484	$0.1255 (U.S. $)

Sources: US Department of Energy, Energy Information Administration (DOE EIA); UK.GOV; Climate Transparency: Brown to Green: The G20 Transition To A Low-Carbon Economy (2017; Germany)

California and New York have low power generation sector CO_2 emission rates – about half of the average U.S. – due in part to legacy nuclear and hydroelectric power generation plants and more recent construction of wind, solar, and natural gas power capacity. Notably, California and New York have largely eliminated in-state coal-fired power generation. The UK has CO_2 emission rates similar to California and New York, while Germany's emission rates are conspicuously higher – mainly due to continued reliance on coal for power generation. Like Germany, California and New York have policies to reduce the role of nuclear power; currently, nuclear generation comprises about 9% of California's and 30% of New York's electricity needs.

Generally, higher electricity prices are seen in regions aggressively transitioning toward low-carbon power generation. Residential electricity prices in California and New York are about 35-40% more than the U.S. average; in the UK and Germany, home electricity prices are 93% and 193% higher than average U.S. residential electricity prices. Figure 1 shows trends in Europe, with a correlation between higher per-capita use of wind and solar resulting in higher electricity prices in Germany, Denmark, and Spain. A downward trend in wind and solar prices may help to lower future electricity price impacts. Electricity prices are often lower where legacy low-carbon hydropower or nuclear generation plants constitute a large portion of the electricity supply, such as Norway and France.

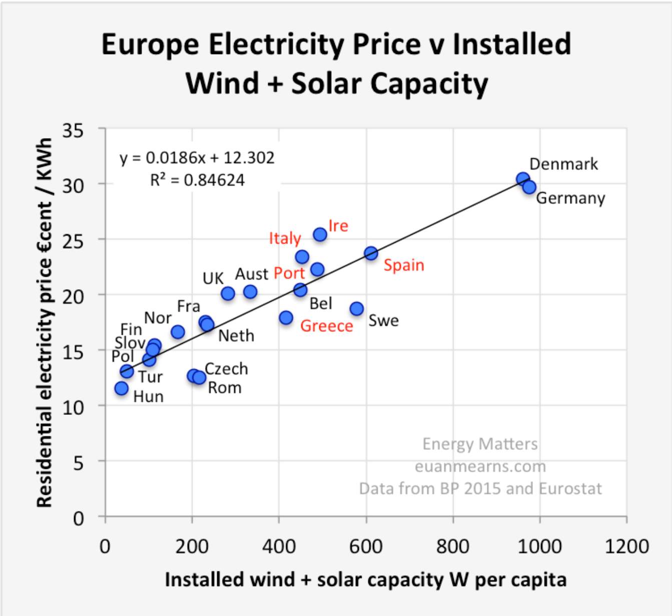

Figure 1: European Trends for Wind and Solar Per Capita Use and Electricity Prices

Carbon abatement cost analyses – that is, costs per unit of CO_2 equivalent (CO_2e) emission reduction – are often used as policy tools to assess greenhouse gas emission reduction options. These are costs society or consumers pay when GHG reduction policies are implemented. As shown in Figure 2, these costs presently range up to \$15-\$30/metric ton of CO_2 reduced in leading countries such as the U.K. and Germany.

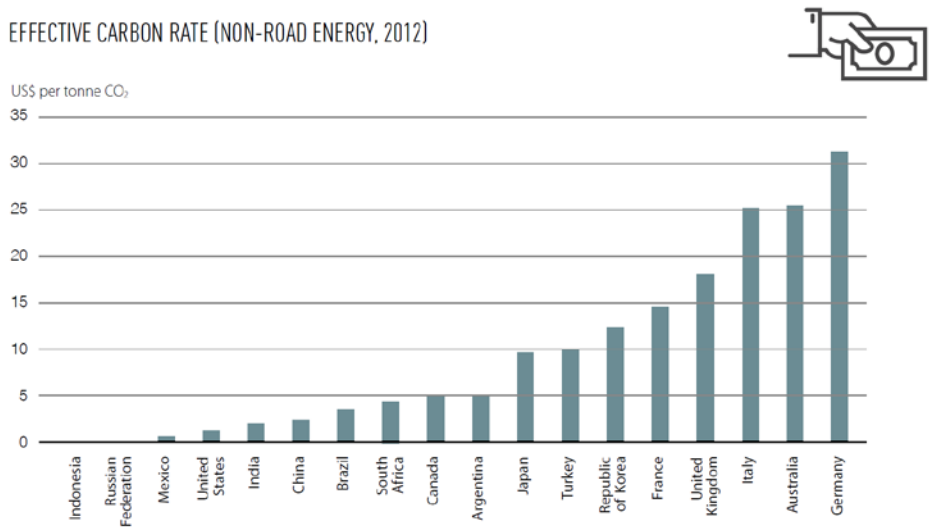

Figure 2: Effective Carbon Abatement Cost of Public Policies in Different Countries (Source: Climate Transparency)

Objectives

This research is intended to quantify the energy use, environmental impact, and cost-trade-offs of potential governmental policy scenarios for residential energy use in California and New York. Specifically, the analysis focuses on the role of natural gas and electricity in traditional home applications: space heating, water heating, cooking, and clothes drying. In these energy use scenarios, we explore the potential implications for consumers and society, with an emphasis on the cost and constraints of residential electrification.

The analysis explores in additional implications and considerations associated with electric space heating. Understanding peak energy use, particularly during severe cold temperature periods, is an important consideration for a major transition from an established energy model (i.e., using natural gas pipelines with large-scale natural gas storage) to a potential new scenario that significantly increases seasonal electricity use. The paper highlights real-world performance of cold climate electric heat pumps, distributed home solar PV systems during winter months, and issues associated with large-scale energy storage.

Cost metrics used in this analysis include annual consumer energy costs, installed capital cost for home appliances, and carbon abatement cost (in $/CO_2e$ metric ton). Energy use includes site and total primary energy. Along with various GHG emissions such carbon dioxide and methane, the analysis software includes conventional emissions on a site and source basis (e.g., NO_x, SO_x, and particulate matter).

Methods

In 2017, GTI developed an analytical software platform called the Energy Planning and Analysis Tool (EPAT). The publicly available EPAT software (epat.gastechnology.org) provides regional U.S. estimates of site and full-cycle energy consumption, capital, and operating costs for several residential energy applications (e.g., space heating, water heating, cooking, clothes drying, and other home energy uses). The software allows the user to select a wide range of residential technologies for a pair-wise comparison of two home energy use scenarios: baseline and alternative. The pair-wise analysis can be repeated with different assumptions to craft a range of scenarios.

The EPAT software uses a library of information from published and publicly available data sources pertaining to typical residential energy equipment and appliances (e.g., capital cost and efficiency). Default values can be modified to support specific equipment analyses. EPAT also includes published regional residential energy prices (e.g., for natural gas, electricity, propane, etc.) or energy costs can be specified by the user. Home energy use attributes built into EPAT are mainly derived from the U.S. Department of Energy's Residential Energy Consumption Survey. The software strives to represent real-world operating attributes, such as the seasonal performance of air-source electric heat pumps.

A key EPAT software feature is the use of full-fuel-cycle, or primary, energy consumption and emissions. For example, state-level (or local) power generation characteristics are based on real-world operating plants in different regions of the U.S. The software can be customized to enable scenarios with modified electricity generation portfolios. Full-fuel-cycle emissions of natural gas are also included, capturing upstream energy used to produce and deliver natural gas to homes as well as full-fuel-cycle emissions such as methane.

This analysis includes a baseline scenario using current residential natural gas consumption in California and New York along with alternative energy use scenarios. The baseline scenario uses a proxy estimation of the homes in these two states currently using natural gas (Table 2). Total state-level residential natural gas use and CO_2 emissions, available from DOE EIA, were used to calibrate the baseline home population.

Table 2: Baseline Scenario Home Natural Gas Populations for California and New York

	California	New York
Single Family Detached Homes	7,200,000	2,200,000
Single-Family Attached Homes	750,000	340,000
Multi-Family (2-4 units)	800,000	950,000
Multi-Family (5+ units)	2,200,000	1,750,000
Total Residential Gas Use	432 TJ (409 bcf)	443 TJ (420 bcf)
Total CO_2 Site Emissions	24 MMT	25 MMT

Table 3 shows key attributes used in the baseline and alternative scenarios for space and water heating; these are the largest natural gas uses in homes. Equipment options are standard baseline Energy Star equipment for space and water heating, while cooking and clothes drying were conventional minimum efficiency natural gas or electric appliances. For the next-generation natural gas energy efficiency option in California, we selected a combination natural gas heat pump device that meets both space and water heating needs. This system was suitable due to the lower space heating requirements in California compared to New York homes and matches the efficiency performance attributes but with lower costs than two separate gas heat pump space heating and water heating devices used in New York.

Table 3: Residential Energy Use Scenarios

	Space Heating	Water Heating
Baseline Natural Gas Options	80% efficiency non-condensing furnace	Conventional storage water heater (Energy Factor, EF, 0.62)
Electric Energy Efficiency Options	HSPF 8.4 electric heat pump	Electric heat pump water heater (EF 2.0)
Mature Natural Gas Energy Efficiency Options	96% efficiency condensing furnace	95% efficiency tankless (EF 0.95)
Next-Generation Natural Gas Energy Efficiency	New York: 140% efficiency gas absorption heat pump (COP 1.4)	New York: 130% efficiency gas absorption heat pump (EF 1.3)
	California: 140% efficiency combination space and water heating gas absorption heat pump (COP 1.4)	

For both the mature and next-generation natural gas efficiency scenarios, we use a complementary scenario of 15% renewable natural gas (RNG, or bio-methane) blended with conventional natural gas. RNG provides a 15% CO_2 emission reduction, with higher natural gas cost. The RNG commodity energy cost was \$10/MMBtu (\$9.48/GJ) – over twice the commodity cost of conventional U.S. natural gas – plus delivery charges.

For the theoretical electrification scenario, the analysis assumes 100% electric heat pumps use for space and water heating in the natural gas homes converted to electricity. In practice, this is an optimistic scenario given that about 30% of U.S. homes currently using electric heating employ heat pumps; further, newer electric heat pump water heaters are an especially small fraction of the market.

The all-electric scenario incorporates a modified power generation mix that reflects future changes in the use of low and zero-carbon power generation sources, while also considering the intense winter-peaking impact of shifting current natural gas space heating loads to electricity (Table 4). Most of the new peak electric load (65%) occurs only during winter months and would be met by non-baseload generators, assumed to be primarily dispatchable natural gas power generation. With this real-world consideration, the future power generation mix shown in Table 4 was used to supply the new electric loads. This future mix has similar CO_2e emission rates to the existing mix in these two states (the California data factor in the planned shutdown of California's last nuclear power plant and in both states reflect a large winter seasonal demand mainly met by natural gas power generation).

Table 4: Current and Future Scenario California and New York Power Generation Mix

	Current Power Generation	Future Power Generation
California	Natural gas: 60.4% Coal: 0.4% Nuclear: 8.8% Hydro: 8.7% Non-Hydro Renewable: 21.7%	Natural gas: 59.5% Hydro: 16.8% Non-Hydro Renewable: 23.7%
New York	Natural gas: 25.9% Oil, Coal: 6.1% Nuclear: 30.6% Hydro: 30.4% Non-Hydro Renewable: 7%	Natural gas: 60% Nuclear/Hydro: 20% Non-Hydro Renewable: 20%

Idealized scenarios using 100% baseload wind and solar power generation are largely impractical in meeting the severe shorter-duration winter space heating demand, especially given the low output from solar PV systems in winter months.

Results

Energy and Environmental Comparison of Residential Natural Gas and Electric Scenarios

Table 5 and Table 6 show the results of the natural gas and electricity scenarios in California and New York State, respectively. These results show significant annual energy costs increases if policy mandated a switch from the current natural gas appliances to an all-electric home. Annual energy costs for California energy consumers would go up at least 45%, while New York energy consumers would see their energy bills increase by 90%. In practice, energy costs could be higher because not all homes switched from natural gas to electricity will use electric heat pumps due to their high first cost. Further, higher peak electric demand would likely require system-wide investments that could increase electricity prices.

The all-electric residential scenario could achieve CO_2e emissions reductions, but the consumer and societal costs are high. The carbon abatement costs are about \$200/metric ton CO_2e in California and an especially high \$434/metric ton CO_2e in New York, compared to the current natural gas baseline. These are nearly ten times greater than typical CO_2e emission abatement costs shown in Figure 2. The carbon abatement costs through electrification would be even higher if (1) electricity prices go up or (2) if electric heat pumps are not used in 100% of the converted homes. Because of the appreciably higher annual energy costs, the all-electric scenarios have negative benefit cost ratios of -1.96 in California and -7.89 in New York. There is never a payback for energy consumers in an all-electric scenario, with the consumer cost implications increasing substantially in cold-weather regions.

Table 5: California Home Natural Gas and Electricity Scenarios

	Current Natural Gas Baseline	All Electric Heat Pump Scenario (Future Mix)	Using Mature Natural Gas Technologies	Mature Gas Technologies & 15% RNG	Next-Generation Gas Heat Pumps	Natural Gas Heat Pumps & 15% RNG
Annual Energy Costs (\$, billion/yr)	\$4.95	\$7.20	\$3.81	\$4.03	\$3.21	\$3.40
Annual Source Energy (Trillion Btu/yr)	464	512	354	354	290	290
Annual CO_2 Emissions (MMT/yr)	24.7	12.9	18.6	15.8	14.4	12.3
Annual CO_2e Emissions (MMT/yr)	28.0	14.2	21.0	17.9	16.3	13.8
Equipment Capital Cost (\$, billion)	\$48.76	\$56.3	\$62.2	\$62.2	\$90.0	\$90.0
Annual Capital Cost (\$, billion/yr); 15 Year Simple Amortization	\$3.25	\$3.75	\$4.15	\$4.15	\$6.00	\$6.00
\$/metric ton CO_2e	--	\$199	-\$35	-\$2	\$87	\$85
Benefit/Cost Ratio (ΔEnergy/Annualized Capital Costs)	--	-1.96	1.28	1.02	0.63	0.56
Simple Payback (Years)	--	Never	11.8	14.6	23.7	26.6

Table 6: New York State Home Natural Gas and Electricity Scenarios

	Current Natural Gas Baseline	All Electric Heat Pump Scenario (Future Mix)	Using Mature Natural Gas Technologies	Mature Gas Technologies & 15% RNG	Next-Generation Gas Heat Pumps	Natural Gas Heat Pumps & 15% RNG
Annual Energy Costs ($, billion/yr)	$5.36	$10.17	$4.29	$4.49	$3.41	$3.57
Annual Source Energy (Trillion Btu/yr)	462	443	366	366	277	277
Annual CO_2 Emissions (MMT/yr)	24.9	14.3	19.7	16.7	14.4	12.2
Annual CO_2e Emissions (MMT/yr)	28.2	15.7	22.2	18.9	16.3	13.8
Equipment Capital Cost ($, billion)	$25.2	$34.4	$33.6	$33.6	$61.2	$61.2
Annual Capital Cost ($, billion/yr); 15 Year Simple Amortization	$1.68	$2.29	$2.24	$2.24	$4.08	$4.08
$/metric ton CO_2e	--	$434	-$88	-$35	$37	$42
Benefit/Cost Ratio (ΔEnergy/Capital Costs)	--	-7.89	1.91	1.55	0.81	0.75
Simple Payback (Years)	--	Never	7.9	9.7	18.5	20.1

Natural gas pathways can offer appreciable CO_2e emission reductions with lower costs to consumers and society – including being on par with electrification scenarios in terms of percent CO_2e emission decreased. Wider adoption of mature natural gas energy efficiency products could reduce consumer natural gas costs by 20-25%, with a net negative CO_2e abatement cost of -$35/metric ton in California to -$88/metric ton in New York. Net negative CO_2e abatement costs are net benefits to consumers and society. Mature natural gas energy efficiency products have positive benefit/cost ratios of 1.28 in California and 1.91 in New York. Using 15% RNG with mature high-efficiency natural gas products results in emission levels that begin to approach electric conversion scenarios, but at more attractive societal costs of -$2 to -$35/metric ton CO_2e in California and New York, respectively.

In the longer term, natural gas heat pumps and 15% RNG can achieve comparable CO_2e reductions to electricity, with lower societal costs ($35-$85/metric ton CO_2e). Next-generation natural gas heat pumps have positive benefit/cost ratios, but their values fall below 1.0 – indicative of longer payback periods. This reflects the current high equipment costs, typical of early market entry pricing for emerging technologies.

Figure 3 illustrates the findings. Near-term low-risk, less-costly carbon emission reductions of 20-35% are possible using available natural gas energy efficiency products in homes; the upper range is achieved by blending RNG. All-electric homes in California and New York could reduce CO_2e emissions by 40-50%, but only if heat pumps are used in all households. This pathway has high societal costs of $200/metric ton CO_2e in California to over $400/metric ton CO_2e in New York. Comparable levels of CO_2e emission reduction (40-50%) are possible with next-generation natural gas heat pumps. Maximum reductions are achieved by blending RNG and using natural gas heat pumps.

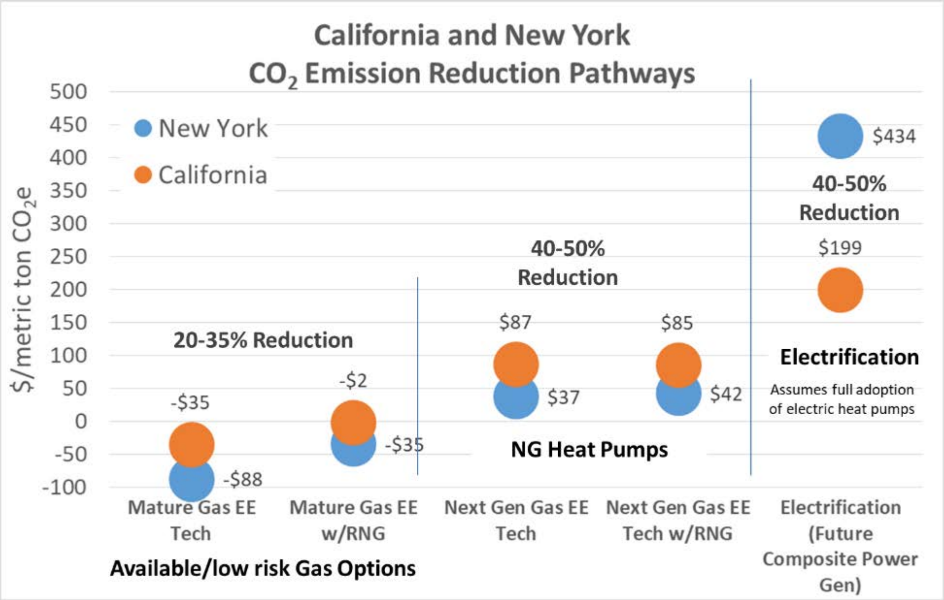

Figure 3: Natural Gas and Electric Residential Carbon Abatement Costs

Operational Considerations Of An All-Electric Home Scenario

There are a significant issues and real-world limitations when considering a large-scale shift from residential natural gas use to electricity, including:

- What are the implications to the electric generation, transmission, and distribution system when heating-dominated natural gas loads are electrified? What is the magnitude of the peak day electricity demand increase? What are the potential electric price impacts?
- What is the real-world performance of air source electric heat pumps in cold temperatures? How would electric heat pumps impact consumer energy costs and comfort, particularly in severely cold temperatures?
- How do home solar PV systems perform during winter months?
- What are the energy storage considerations of an all-electric scenario?

In the following, we touch on several of these questions.

In terms of electric heat pumps and cold weather conditions, Figure 4 illustrates the significant sensible space conditioning differences between cold weather heating loads and summer cooling loads. The temperature differential for heating, particularly in northern climates, is substantially larger than required for cooling.

Winter Heating from 0°F to 70°F …is like… **Summer Cooling from 145°F to 75°F**

Figure 4: Graphical Comparison of Heating and Cooling Energy Requirements

Beyond temperature differential, power demand requirements for electric space heating are more challenging due to the diminishing cold-temperature performance and heat-delivery capacity of electric heat pumps. Figure 5 shows the precipitous drop in electric heat pump efficiency during cold weather. In addition, snow accumulation and periodic defrosting of heat pump coils can impact electric heat pump performance and efficiency (Figure 6). Water condensing from the outdoor ambient air and freezing on electric heat pump outdoor coils is a common winter occurrence, particular in regions with higher humidity levels. Defrosting cycles typically use electric resistance heating or reverse operation that further diminishes real-world electric heat pump performance and efficiency at cold temperatures.

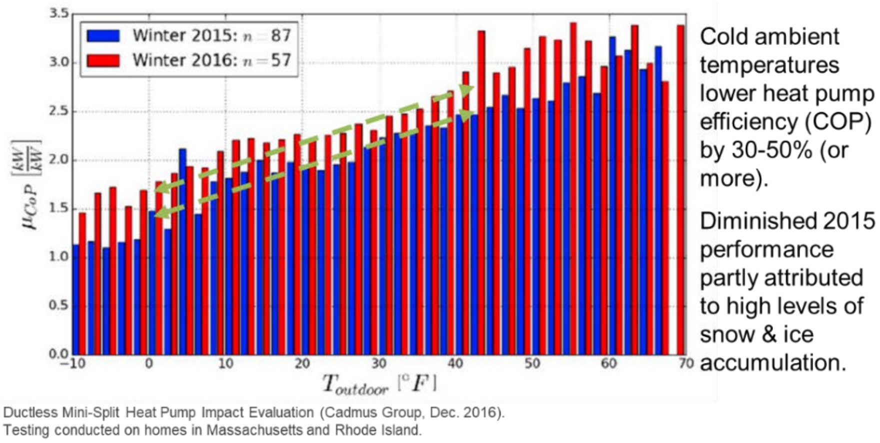

Figure 5: Cold Climate Electric Heat Pump Performance

Figure 6: Impact of Snow Accumulation (left) and Ice Formation (right) on Electric Heat Pumps

Shifting from natural gas to electric space heating results in dramatic increases in residential peak electricity use and is highly concentrated during the winter. This is a major technical and economic challenge. Figure 7 and Figure 8 show changes in monthly residential electricity use with residential electrification in California and New York. This is based on recent monthly data on current residential electricity use (shown in orange) along with the additional monthly electricity required if all current California or New York residential gas use were shifted to electricity (darker blue). These figures also show the additional electricity use if only 50% of homes used electric heat pumps and 50% used electric resistance heating (this incremental electricity use is shown in light blue).

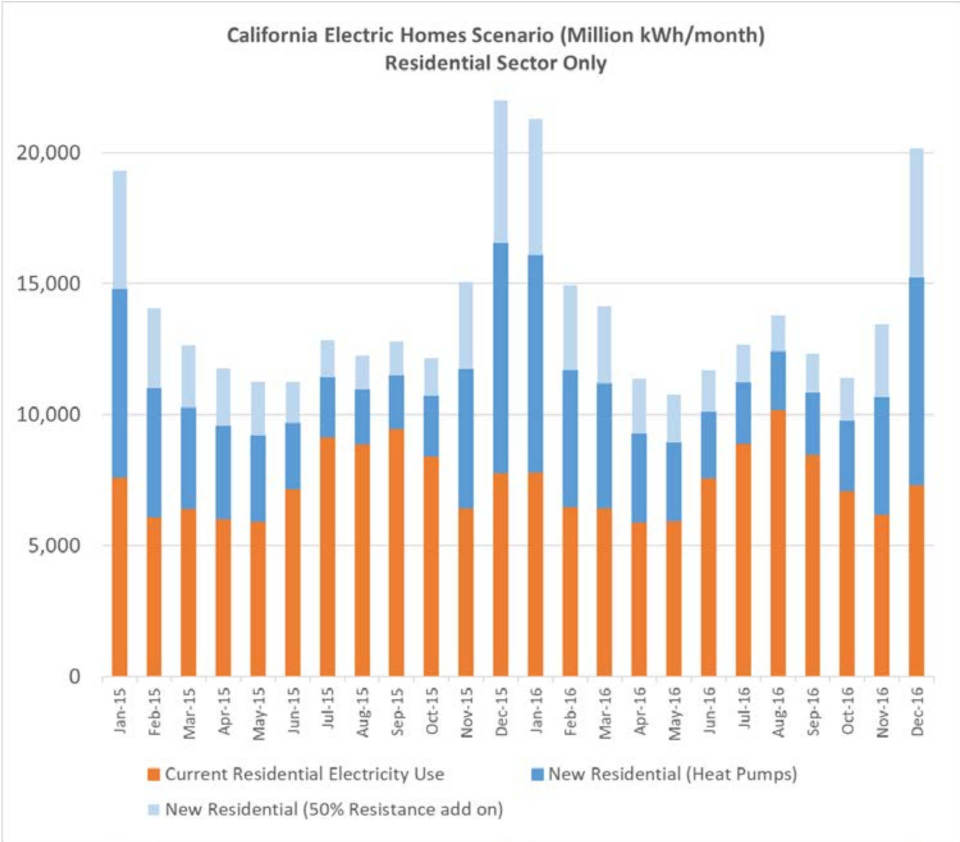

Figure 7: Impact On California Monthly Residential Electricity Use

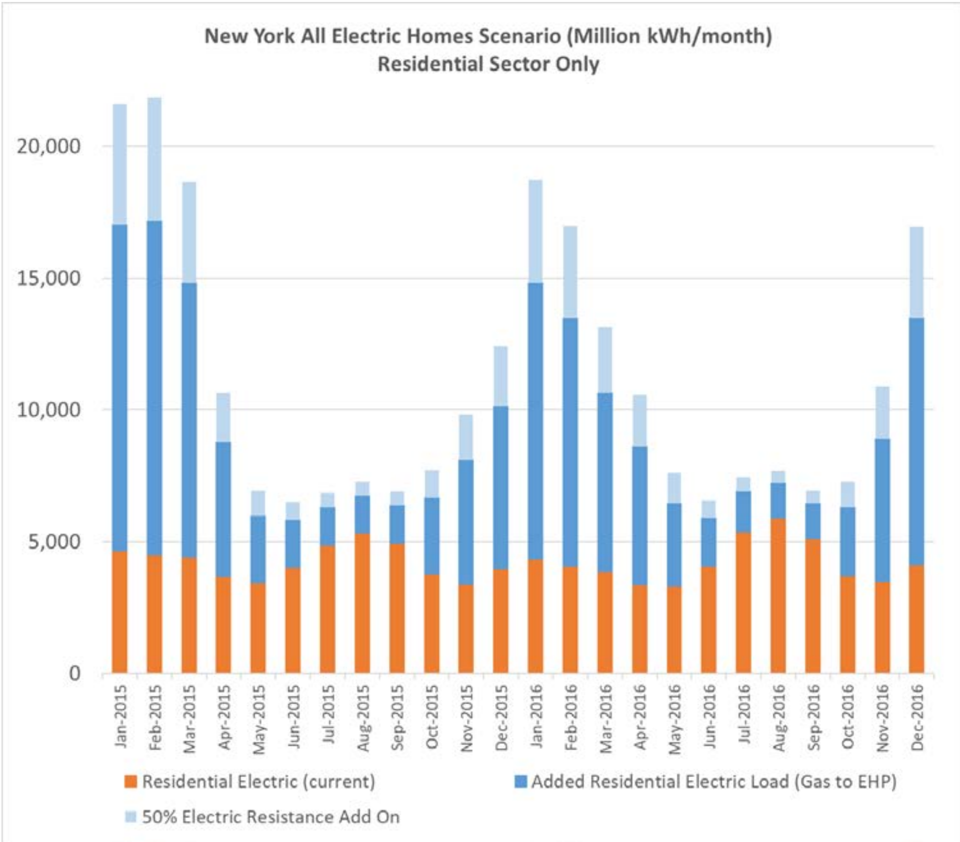

Figure 8: Impact On New York Monthly Residential Electricity Use

On a peak day or hourly basis during the coldest times of the year, the relative increases in peak electricity demand would be even greater than illustrated in these graphs. Figure 9 shows results from GTI's building simulation of electric space heating in two different homes with varying building envelope construction. The figure illustrates the effect of declining electric heat pump efficiency at colder temperatures. Older homes built to less-stringent building codes would require substantially more electricity to meet peaking heating loads. The figure overlays the performance of solar PV systems in southern and northern climates. In colder northern regions, residential solar PV systems would rarely meet the hourly power demands for space heating, much less other home loads or produce adequate excess power to recharge battery storage systems.

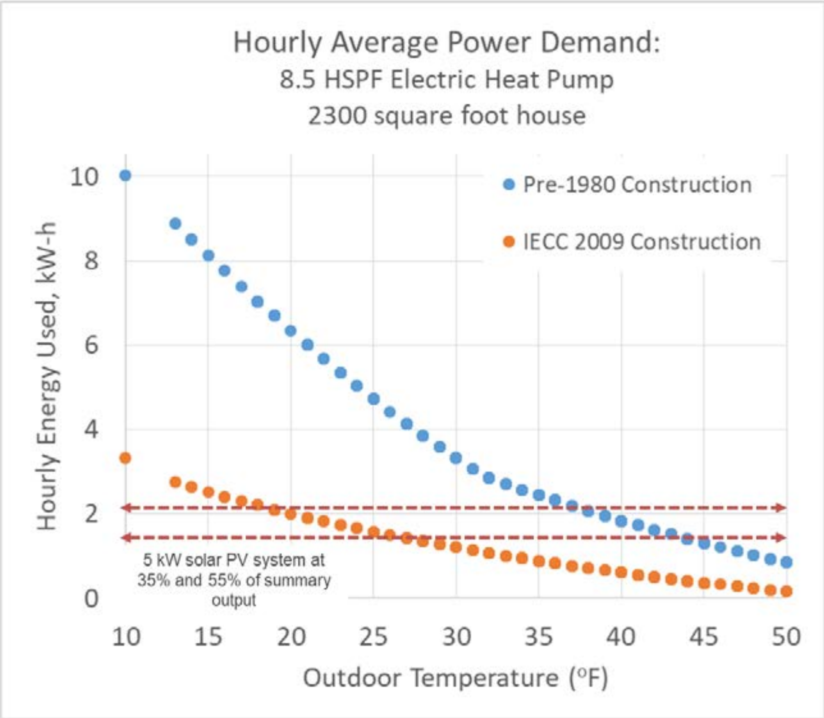

Figure 9: Example Impact of Temperature On Home Electric Heating Power Requirements for Older and Newer Homes

Electrification policies often include the notion of using solar photovoltaic (PV) systems – particularly at the home level. The challenge of shifting from natural gas heating to solar PV is the notably diminished performance of solar systems during the winter months. Figure 10 shows data from NASA on solar PV systems in different U.S. locations during each month of the year. In southern regions during winter months, solar PV systems produce about 50-55% of their summer output; in northern zones, wintertime solar PV output can drop to 30-35% of summer levels. The drop in solar PV performance during winter months is due to shorter days and typically greater cloud coverage; snow accumulation on solar PV systems can further diminish performance.

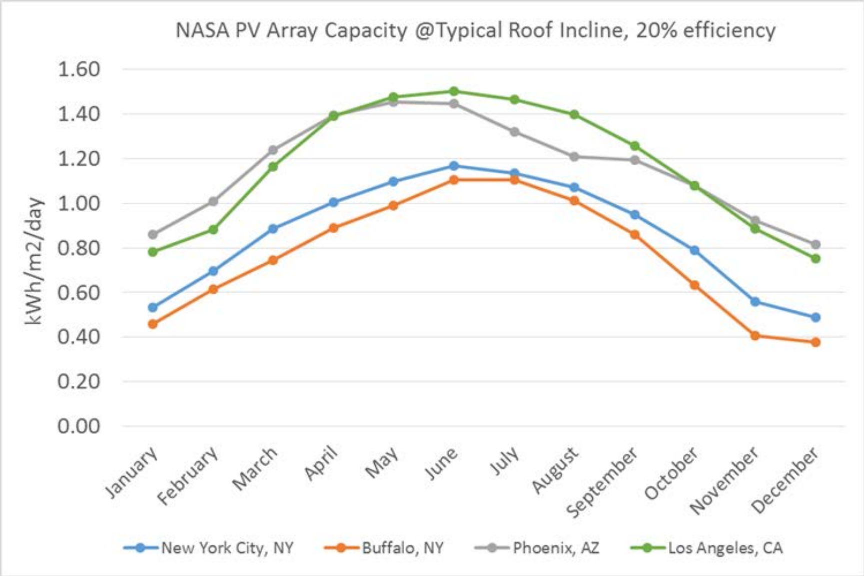

Figure 10: Comparison of Monthly Solar PV System Output

Energy storage is a major area of differentiation between natural gas and electricity use. In the U.S., there are extensive natural gas storage infrastructure, mainly in underground formations. The U.S. natural gas industry uses off-peak periods of April-October to store natural gas in these large-volume storage locations, with the objective of withdrawing massive natural gas volumes during peak cold periods. Figure 11 shows U.S. DOE EIA data on natural gas underground storage, highlighting weekly amounts injected or withdrawn. Recent years have seen two incidents of record levels of natural gas storage used during extreme cold periods – 288 bcf (304 TJ) in January 2014 and 359 bcf (379 TJ) in January 2018. This represents massive amounts of energy available over a short period of time. In context, delivering 359 bcf from natural gas storage in one week is equal to about 638 GW. In contrast, total U.S. electric energy storage capacity is about 24 GW, mostly large pumped hydro facilities.

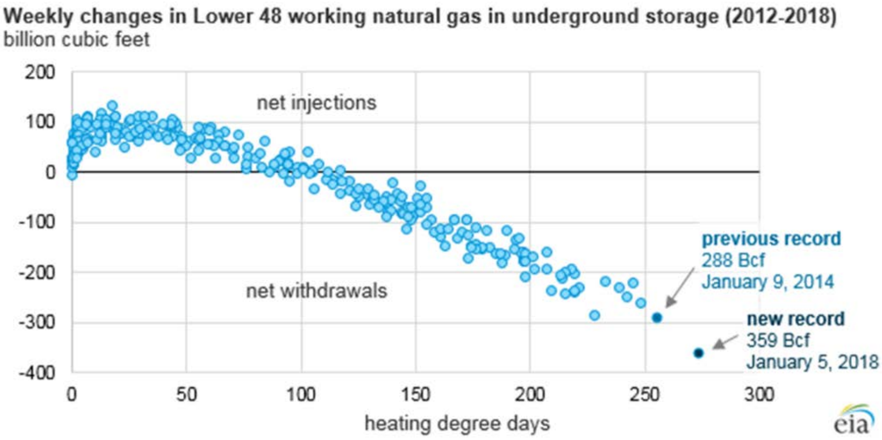

Figure 11: Impact of Heat Degree Day on Gas Storage Usage

The notion of battery energy storage is gaining traction in some regions. The idealized view of battery energy storage often differs from the reality of the cost, performance limitations, and material intensity of batteries. Figure 12 shows one example of a large-scale battery energy storage facility. While batteries are seen as viable options for providing ancillary grid services such as frequency regulation, their cost-effectiveness as bulk energy storage systems is not established. Relying on batteries to deliver bulk electricity during extreme cold periods, when battery performance declines, seems an unlikely alternative to proven, cost-effective large-scale natural gas storage.

Figure 12: Example Large-Scale Battery Energy Storage System

Conclusions

There are growing efforts to explore options to reduce GHG emissions as a means of avoiding potential future global warming impacts. Some policymakers are advocating expanded use of low- or zero-carbon emission power generation sources, coupled with using electricity to displace traditional fossil fuel uses such as liquid fuels for vehicles and natural gas for home space heating, water heating, cooking, and drying.

Using a comprehensive analytical software called the Energy Planning Analysis Tool (EPAT), GTI examined potential future scenarios of high-efficiency natural gas equipment and renewable natural gas along with electrification in two leading low-carbon power generation regions of the United States – California and New York State.

As summarized in Table 7, the findings show all-electric homes are a much more expensive carbon abatement approach – from $200 to over $400/metric ton of CO_2e emissions reduction in California and New York, respectively. The benefit/cost ratio of all-electric homes are negative, due to the large increase in annual consumer energy costs through electrification. The economics are even less favorable if electric heat pumps are not adopted in 100% of homes or if electric price increases are required to finance major power generation, transmission, and distribution system upgrades. Home electrification is particularly costly in cold weather regions such as New York.

Table 7: Current and Future Scenario California and New York Power Generation Mix

	All-Electric Heat Pump Scenario	**Mature Natural Gas Scenario**	**Next-Generation Natural Gas Scenario**
California			
% CO_2e Reduction	-49%	-25% (-36% RNG)	-42% (-51% RNG)
CO_2e/metric ton Cost	$199	-$35 (-$2 RNG)	$87 ($85 RNG)
Benefit/Cost Ratio	-1.96	1.28 (1.02 RNG)	0.63 (0.56 RNG)
New York			
% CO_2e Reduction	-44%	-21% (-33% RNG)	-42% (-51% RNG)
CO_2e/metric ton Cost	$434	-$88 (-$35 RNG)	$37 ($42 RNG)
Benefit/Cost Ratio	-7.89	1.91 (1.55 RNG)	0.81 (0.75 RNG)

In contrast, the direct use of natural gas offers several cost-effective scenarios for appreciable reductions in CO_2e emissions by (1) expanding the market penetration of mature natural gas energy efficiency equipment, (2) developing and deploying natural gas heat pumps for space and water heating, and (3) blending renewable natural gas with conventional natural gas to reduce the carbon intensity of natural gas supply.

This analysis highlights several limitations with implementing an all-electric home scenario, particularly in cold climates. These include the diminishing performance of electric heat pumps at cold temperatures, the substantial decline in home solar PV system output during winter months (which is exacerbated in northern regions), and the severe increase in peak electric demand that would come about with an electrification scenario. In terms of meeting peak space heating demand, system-level natural gas storage is substantially more cost-effective than electricity storage with batteries.

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U.S.DOE-EIA Electricity Use Data: https://www.eia.gov/electricity/data/browser/

U.S.DOE-EIA Electricity Price Data: https://www.eia.gov/electricity/data.php#sales

U.S.DOE-EIA State Carbon Emissions Data: https://www.eia.gov/environment/emissions/state/

United States Environmental Protection Agency, USEPA 2017 Emissions & Generation Resources Integrated Database. http://www.epa.gov/cleanenergy/energy-resources/egrid/