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Electrification of Water and Space Heating in Buildings

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Executive Summary

As state and local governments continue to take the lead in acting to reduce greenhouse gas (GHG) emissions across their economies, policymakers across the United States are focusing on the role that buildings play in meeting climate change mitigation goals.

While public and private sector analyses reach similar conclusions—that reducing the carbon-intensity of buildings must be part of broader policy initiatives toward decarbonizing our economy—transitioning buildings away from utilizing natural gas for space and water heating to electricity exclusively presents significant challenges, from physical infrastructure and electricity grid modernization, to the economics of retrofitting millions of households and commercial buildings.

These challenges are not necessarily insurmountable. However, pragmatic, stepwise solutions—rather than one-size-fits-all—will be absolutely necessary to achieve governmental building decarbonization goals by 2030 and 2050, respectively.

Policymakers and others must take into consideration regional differences, including seasonal and colder climates, as well as the need for high-efficiency gas backup sources for large space and water heating loads, and must create consistent programs and incentives to provide the value proposition to property owners and businesses to make the changes necessary to achieve these goals.

Background

Residential and commercial buildings accounted for approximately 40% of total U.S. energy consumption in 2020[1]; 70 million of those buildings use natural gas, oil or propane on site for space and water heating, as well as cooking. While nearly 87% of building-generated GHG emissions come from space and water heating (Fig. 1), as a percentage of total U.S. GHG emissions, buildings are a smaller overall piece of the decarbonization pie (Fig. 2). Notwithstanding the economy-wide percentages, policymakers and other stakeholders have identified building decarbonization — via the "electrification" of end-use space and water heating installations — as an important and necessary pathway to significantly reduce greenhouse gas emissions from the building sector.

While proponents of electrifying space heating and water heating agree it is needed to achieve the ambitious GHG emission reduction goals put forward by various states and cities, it is important to note that the power sector is currently undergoing a period of unprecedented transformation as it moves away from using fossil fuels for electric generation.

However, while regional and local electricity grids are becoming more efficient at distributing power based on demand and reducing load and integrating "greener" generation sources, such as renewables and natural gas, there are still regional electricity grids that continue to rely on more carbon intensive sources of electricity, such as coal-fired power plants. Hence, policies that accelerate electrification of space and water heating in those regions could result in a net increase of GHG emissions.

Conversely, where electricity is being generated from less carbon-intensive or zero-emission sources, policymakers view increased electrification of various end-uses an increasingly attractive option from an environmental perspective, which is prompting a paradigm shift in business as usual from utilities, policymakers and manufacturers.

Assisting Policymakers in the Energy Transition

Implementing the necessary changes to residential and commercial buildings to reach building decarbonization goals will require a multifaceted and pragmatic approach.

To assist policymakers in analyzing the data in their municipalities to find the best approaches, A. O. Smith has developed an analytical tool that models energy usage, environmental impact and potential electrification proposals. It is designed to quantify the energy use and environmental impact of various policy scenarios across residential and commercial space and water heating solutions in buildings in States and Cities, allowing an informed dialogue on technology choices and cost/benefit analysis to arrive at the best paths forward.

In its inaugural launch, the tool was used to conduct an assessment of various building electrification policy scenarios in California and New York — two states that are moving aggressively to reduce GHG emissions. By comparing the current state of fossil-fueled technologies against each of these transition scenarios, our assessment study takes a deep dive into the impacts that building electrification policies have on GHG reductions.

Based on our findings, the following policy recommendations provide a potential path forward for the increased use of electric and high efficiency gas technologies for space and water heating in the building sectors.

1. High efficiency gas condensing equipment will be important and must serve as a stepping-stone in commercial replacement applications for a managed transition.
2. Hybrid heat pumps with options for gas/electric backup will be necessary for cold climates and space constrained applications.
3. Demand response and energy storage solutions, including thermal storage, will be necessary to decarbonize the grid.
4. New construction should transition to high efficiency heat pumps in water and space heating applications.
5. Consumer education, as well as consistent and long-term funding for GHG reduction financial programs and incentives are going to be essential in aiding consumers in understanding how to make different purchasing decisions and accept new technologies.

Overcoming Barriers to Wider Adoption of Non-Fossil Fuel Technology Approaches

While wider building electrification continues to evolve as a pathway to achieve GHG reduction goals, barriers exist.

There is a clear need to develop economically attractive space and water heating technology solutions to retrofit existing fossil-fuel fired equipment with heat pump applications. For example, in the case of California and New York, more than 90% of residential water heaters are gas fired and the proportion of commercial applications is larger. The total installed cost to the consumers and businesses in certain retrofit applications is substantial. Most existing homes do not have the electric circuitry to power heat pump solutions and as such, significant and expensive electrical panel upgrades in homes will be necessary. In many commercial retrofit applications, the costs will be exponentially larger.

To encourage the widespread adoption of demand response functionality and the use of thermal storage (e.g., using the water heater as a thermal battery and thereby integrating expanded use of renewables for power generation), customers will need to reevaluate their purchasing decision making process as grid-interactive water heating equipment may come with a higher first cost. This educational component should be coupled with an incentive program for customers, builders, and architects to help promote widespread adoption of demand-response functionality and thermal storage to align customers' expectations for the use and utility of their space and water heating equipment and the role the equipment can play in reducing GHG emissions.

There will need to be a tangible and significant enough customer value proposition to transition the market on a large scale. While there are regional differences, fossil fuel fired residential and commercial space and water heating equipment are prevalent in existing buildings. Replacement of the equipment is typically an unplanned event and customers balance replacement decisions on both a first-cost basis and how quickly space and/or water heating needs can be restored. Transitioning from fossil fuel fired products to electric products will—based on regional and space constrained conditions—be more expensive for consumers and businesses; however, following the up-front costs, a positive return on investment is achievable. Therefore, if building decarbonization polices—including electrification — are to be successful, there must be sustained policies that promote high efficiency technology solutions, customer education, and incentives for the purchase and installation of high efficiency equipment.

Advancing Public-Private Partnerships to Increase Awareness and Drive Policy Change

Addressing GHG emissions from buildings should continue to be a focus for policymakers, as well as private industry, when evaluating pathways to decarbonize our economy.

The electrification of buildings will certainly be part of the transition. However, other (and much larger) sector sources of GHG emissions, such as transportation, agriculture and heavy industry must also transition to reach climate change mitigation goals.

Yet, given the considerable focus on things like electric vehicles and renewable power as drivers of change, heat pump technology for water heating in particular still suffers from a general lack of consumer knowledge. It will require a concerted effort that includes public-private partnerships and changes to public policy to successfully deliver the necessary changes to residential and commercial buildings over the ensuing decades.

By analyzing current data to understand the impact of potential decarbonization transition scenarios, pragmatic changes can be implemented in both replacement and new construction applications to reach the 2030 GHG global reduction targets, and be used as a stepping stone to reach the more lofty 2050 goals in the future.

In combination, meaningful headway can be made toward reaching global climate change mitigation goals.

I. Introduction

Decarbonization is the process of reducing gaseous carbon compounds emitted from energy production systems. *Electrification* is the process of converting a system to operate using electricity that would otherwise consume fossil fuels. Policy makers generally consider four “pillars” to decarbonizing the environment (Fig. 1, [1]) of which electrification is one component. Others include energy efficiency and conservation across all sectors, use of low carbon fuels (primarily renewables) and reduction of non-combustion greenhouse gases (GHGs). All four pillars rely on conversion of energy end-uses to low carbon fuel sources and if one pillar falls short of its goals, the reductions need to be accomplished by another.

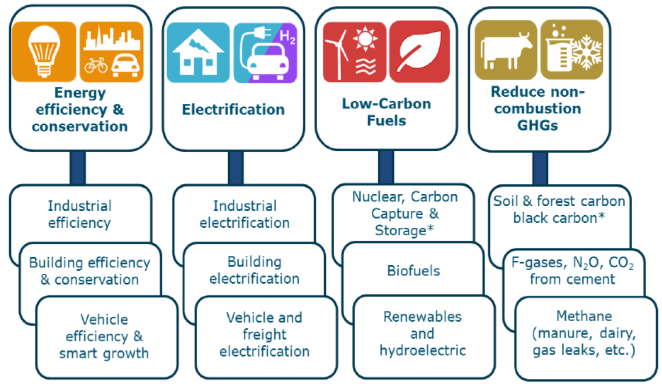

Fig. 1: Four Pillars of Decarbonization [1]

Aggressive electrification of energy end-uses, such as space heating, water heating, and transportation, is needed if the United States is to achieve ambitious GHG emission reduction goals put forward by various states and cities. The power sector is currently undergoing a period of unprecedented transformation due to significant decarbonization of electric generation. Energy efficiency and demand-response technologies are reducing power demand on the grid, while greener sources, such as renewables and even natural gas to displace coal plant generation are reducing the carbon intensity of the electric grid. As a result, electricity is becoming more climate-friendly, with respect to greenhouse gas emissions, in many places. These changes are converging to make the increased electrification of various end-use sectors an increasingly attractive option from an environmental perspective, requiring a paradigm shift in business as usual from utilities, policymakers and manufacturers.

II. What is "Building Electrification"?

Seventy million American homes and businesses use natural gas, oil or propane on-site to heat their space and water, accounting for nearly 90% of the total amount of carbon dioxide generated each year in buildings (Fig. 2). Electrification in buildings involves substituting these fossil-fueled technologies with electric equivalent technologies. Such technologies for the water heating sector and certain of the space heating sector, especially for residential new construction in milder climates, are available today and can easily be implemented without sacrificing consumer satisfaction.

There are also some significant ancillary benefits of building electrification, such as greater flexibility for managing electric loads as well as opportunities to provide additional grid ancillary services. The main barriers to electrification, therefore, do not tend to be technical, but are more economic (fuel prices, lack of grid infrastructure, capital cost of equipment and local climate conditions determining the payback of electric versus non-electric technologies) and market driven (positive consumer perception of gas and lack of education on alternatives). Storage mechanisms can also help in the cost-effective integration of large amounts of renewable energy onto the grid, alleviating situations like the *duck curve*[1] in California.

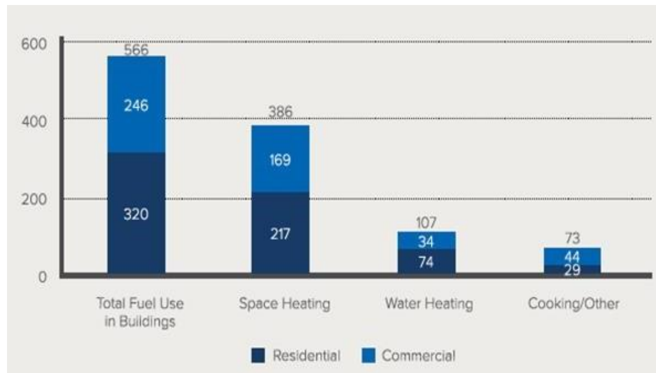

Fig. 2: Million Tons CO_2 Emitted Each Year from Using Fossil Fuels for Combustion in Buildings [2]

Over the past couple of years, various cities and states have implemented, or are considering implementing, ambitious policies for reducing GHG emissions within their respective jurisdictions to achieve "climate change" mitigation policy goals. These policy approaches include reducing or eliminating the amount of fossil fuels used to generate heating (both space and water) and cooling in buildings. As a result, policy makers in these jurisdictions are using state and local statutory and regulatory authority (building codes) as one way to achieve stated policy objectives by requiring conversions from fossil-fuel burning appliances in residences and buildings to ones that use electricity. Other jurisdictions have taken a more cautious approach, allowing gas-fired appliances to continue to be used in certain installations (and under limited circumstances) while still achieving significant GHG reductions.

For A. O. Smith, replacing direct fossil fuel use with electricity for space and water heating provides challenges and opportunities across both the residential and commercial building sectors. The goal of electrification for manufacturers like A. O. Smith is to therefore strategically target the most practical and valuable fuel switching opportunities given current (and future) technology, electricity grid mix, and energy costs for a given jurisdiction. One of the challenging factors is that these variables are fluid, and what is most beneficial to the environment and individuals can change rapidly. Manufacturers like A. O. Smith, therefore, have the challenge of anticipating these changes and implementing a strategy to ensure that the right technologies and products are available to meet our customers' needs, while contributing to the GHG reduction policy goals of various cities and states.

[1] The *duck curve* is a graph of power production over the course of a day that shows the timing imbalance between peak demand and renewable energy production, so named because it resembles the outline of a duck.

III. What Are the Key Components of Electrification Policies?

There are several key components associated with electrification policies that must be considered to make such policies successful in reducing emissions. As mentioned above, these include incorporating measures of load reduction (e.g., energy efficiency or energy conservation), demand response and connected functionality and energy storage. Together these play key roles in any electrification market transition program.

One of the challenges associated with transitioning markets from fossil-fueled based technologies to electric technologies is the increased load placed on the grid due to the switch. Without the combination of electrification with increased energy-efficiency and conservation opportunities, electric utilities will see significant increases in load which may result in infrastructure strain. Policy makers must be mindful of the increasing electric load as they attempt to implement GHG emission policies. For example, simply transitioning from site-based fossil-fuel water heating appliances to electric resistance equivalents would not provide a beneficial form of electrification and would result in increased utility bills for the consumer.

Another key area of concern with increased electrification is grid resiliency, which, coupled with extreme weather conditions, can lead to increased power shortages and even outages. Discrete energy systems or microgrids, consisting of distributed generation sources (CHP, renewables), storage (battery or thermal) and energy management, can limit the impact of such power interruptions, allowing communities to operate in parallel with, or independently from, the main power grid. Such energy systems can also help reduce GHG emissions and need to be included in any analysis.

Due to the potential for increased demand on the grid from electrification, connectivity and demand management functionality of appliances and equipment is essential to managing the electric load added to the grid during certain peak times. Demand management allows the utility to shift the electrical load of the equipment during times when maximum grid capacity has been reached to better manage the load within the utilities' territory during specific time periods. It therefore provides benefits both to the utility by reducing the need to add additional peak generation capacity through costly infrastructure investments and to the consumer by reducing his or her utility bills via implementation of time of use rates.

In addition to demand management, the ability for the residential or commercial building to provide a mechanism for the storage of energy is an important part of the value proposition for achieving electrification policy goals. Energy storage at the local level allows electrical or thermal energy to be stored when excess energy is generated from intermittent renewable sources such as wind or solar. Traditionally, such storage has been done with a battery, although thermal storage in water heaters is a cost-attractive option.

A. What Are GHG-Reduction Goals and Some of the Policy Initiatives Today?

In 2015, one of the largest policies pertaining to GHG reductions, commonly referred to as the Paris Agreement, was adopted; it will be implemented within the United Nations Framework Convention on Climate Change (UNFCCC) starting in the year 2020. The agreement was negotiated by representatives of 196 state parties, of which 185 have become a party signaling their intent to implement such policies. The Paris Agreement's overarching goal is to limit the increase in global average temperature to 1.5°C to mitigate the risks and effects of climate change.

Under the Paris Agreement, each country must determine, plan and regularly report on its contribution to global warming mitigation. In June 2017, U.S. President Donald Trump announced his intention to withdraw the United States from the Paris Agreement. As a result, many cities and states within the US have announced (and are implementing) climate change mitigation policies and strategies, including electrification. Some states, local governments and private-sector businesses have voluntarily pledged to reduce emissions in line with the goals outlined in the Paris Agreement. For example, both New York[2] and California have set a goal to reduce their respective state's GHG emissions by 40 percent below 1990 levels by 2030 and to 80 percent below 1990 levels by 2050. As of early 2019, Washington, Oregon, New Mexico, Colorado, Illinois, Massachusetts, Maryland, California, Minnesota, Michigan, New York, New Jersey, Vermont and the District of Columbia have state or local policy goals regarding GHG emissions reduction which include electrification components. In addition, some of the largest cities are participating in the America Cities Climate Challenge sponsored by the Bloomberg Philanthropies. As part of the challenge, 25 cities have been accepted into a two-year acceleration program with powerful new resources and access to cutting-edge support to help them meet—or beat—their near-term carbon reduction goals. While these are just a few initiatives highlighting the changing landscape with regards to climate change policies, GHG reduction goals are a priority for many policymakers, and it is expected that electrification policies will continue to be implemented over time.

Within the US, California and New York are two states on the forefront of GHG reduction policies, ranking first and third in US state-level gross domestic product (GDP) respectively. Both have low grid carbon intensities—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 generation. Notably, California and New York have largely eliminated in-state coal-fired power generation and both have policies to reduce the role of nuclear power going forward; currently, nuclear generation comprises about 9% of California's and 33% of New York's electricity needs [3]. Worth noting is that in New York City, the legislated closing of the Indian Point nuclear power plant in 2021 is actually projected to increase the carbon intensity of the New York City grid since the shortfall needs to be made up from increased use of natural gas [4].

B. Why Is A. O. Smith Interested in GHG-Reduction Policies?

A. O. Smith, along with its wholly owned subsidiary, Lochinvar LLC, is the largest manufacturer and seller of gas and electric residential and commercial water heating equipment, high efficiency residential and commercial boilers, and pool heaters. A. O. Smith's commitment to innovative, customer-centric and efficient products throughout history has enabled it to become a global leader in delivering water heating and hydronic heating technologies. As a leader in such technologies, the efficiency innovations of our products have a substantial positive impact on our planet. "Innovation Has a Name" is the A. O. Smith motto, and our commitment to innovation results in products that are highly efficient and meet the needs of our customers.

Integral to A. O. Smith's innovation and sustainability initiatives is its investigative efforts into GHG reduction policies. A. O. Smith believes the product solutions needed to compliment these GHG reduction goals will differ by region and market and will have differing impacts. Specific care needs to be given to ensure the consumer utility and satisfaction is maintained for a given application and region, while GHG emission reductions are being obtained. Thus, A. O. Smith has conducted an in-depth modeling study to understand how different technical solutions in the water and hydronic residential and commercial heating markets not only meet customers' needs but also contribute to the overall emission reduction goals in the built environment. The study focusses primarily on the 2030 reduction goals, not only because 10 years is a reasonable product planning lifecycle for water and space heating, but also because it is important to fully understand the impact of potential

[2] Note that New York *City* has a more aggressive target, reducing GHG emissions by 40% below 2005 levels by 2030

transition scenarios that can be implemented today in both replacement and new construction applications as a stepping-stone to reach the more lofty 2050 goals in the future.

This white paper therefore presents several policy scenarios of electrification in buildings in both the state of New York and California in an attempt to help identify a stepwise plan that contributes to achieving the stated GHG emission reduction goals of policymakers, while providing a reasonable pathway toward implementation. The model examines the current state of the art with regard to fossil-fueled technologies being used today and then asks what would happen if various sectors of the residential and commercial building space and water heating loads were switched to alternative lower carbon technologies. It takes into account the current carbon intensity of the grid in each state (generation capacity) and how that carbon intensity varies as demand exceeds supply[3]. Finally, recommendations are put forward that provide a potential path forward for introducing electric technologies in the water heating and space heating sectors in certain end uses.

[3] It should be noted that we do not take into account future trends that would impact these intensities; and shortfall in generation is made up from using natural gas and thus the model presents a conservative step-wise approach to reaching stated GHG emission goals.

IV. Model Methodology

A. O. Smith has recently developed an analytical tool that quantifies the energy use and environmental impact of various policy scenarios across residential and commercial space and water heating solutions in buildings for a given location (state). The input-output model uses hourly accounting of space and water heater loads allowing the user to select a wide range of technologies (and mixes of technologies) for a comparison of two building energy use scenarios (a baseline and a policy scenario) to better understand the environmental impacts of these alternatives.

Many of the existing publicly available methods of estimating GHG emissions use average annual or monthly data to draw high-level conclusions. However, water heating and space conditioning loads vary widely throughout the day with customer usage and ambient temperature changes. Unless fluctuations in renewable generation are small or excess renewables can be stored, this mismatch between generation and consumption causes the carbon content of electricity on the grid to also vary greatly over the course of a day, making annual estimating inaccurate. It has been shown that by 2025, the use of yearly averages could overestimate GHG emissions associated with solar power by >50% when compared to hourly averages in California [5]. Hourly estimation allows the effects of demand response (DR) and energy storage (battery and thermal) to be fully captured and evaluated. Moreover, some of the technologies being considered for transition from gas to electric are heat pumps, whose performance can be greatly affected by ambient temperature changes. It was considered essential, therefore, to develop a model that has the ability to estimate hourly loads for water heating and space conditioning in different climates.

A. Baseline 1990 GHG Emissions

1990 baseline numbers for annual GHG emissions for all states are well documented. The primary sources of GHG emissions generally fall into five distinct "sectors":

1. **ELECTRICITY PRODUCTION (IN-STATE AND IMPORTED):** emissions from the generation, transmission and distribution of electricity

2. **BUILDINGS (RESIDENTIAL AND COMMERCIAL):** emissions from the energy used to power, heat and cool buildings

3. **INDUSTRIAL:** emissions produced from the goods and raw materials we use every day

4. **TRANSPORTATION:** emissions from the movement of people and goods by cars, trucks, trains, ships, airplanes and other vehicles

5. **OTHER:** emissions (methane) from waste and agriculture, natural gas leakage plus the other GHGs such as refrigerants, perfluorocarbons, sulfur hexafluoride, etc.

Segregating GHG inventory into these five buckets in a consistent way between states is fairly straightforward due to standardized ways in which the numbers are reported. Direct emissions for a specific sector occur on-site and include combustion of fossil fuels, leakage of refrigerants or solvents, or management of waste associated to that sector. Indirect emissions occur off-site and include electricity that is centrally generated: this can be listed separately or apportioned to the other four sectors that ultimately use that electricity.

B. Baseline 1990 GHG Emissions for New York and California

Although the model is flexible to allow for any region to be modeled individually, A. O. Smith started by selecting two distinct regions (New York and California) with very different climate profiles. For each region, four discrete segments were evaluated: residential space heating; residential water heating; commercial space heating; commercial water heating. By implementing various policy scenarios, the goal was to investigate which segments within each region have the largest potential impact to help reach specific state GHG emission reduction policy goals.

Residential and commercial buildings make up a large part of the GHG emissions mix—41% and 28% of GHG emissions come from residential and commercial buildings in New York in 2015 [6] and California in 2016 [7], respectively; for cities where transportation and agriculture contributions are limited, this percentage is even higher—58% of GHG emissions come from residential and commercial buildings in New York City [8]. Since this study looks specifically at the impacts of water and space heating in residential and commercial buildings, the GHG emissions pertaining to the building sector only has been used as a baseline. However, this can sometimes prove troublesome: for New York, apportioning the electricity generation consumed by each sector was possible from the NYSERDA data [6]. However, for California, the electricity generation could not be individually apportioned and so the electricity generation includes a small amount for the industrial sector (<10%).

Sector	NY State, 1990		NY State, 2015		California, 1990		California, 2016	
	MMTCO2e	%	MMTCO2e	%	MMTCO2e	%	MMTCO2e	%
Electricity Generation (bldgs. only)	47.3	20	31.9	15	69.0	16	44.6	10
Buildings (Res. & Comm.)	60.6	26	57.4	26	44.2	10	51.4	12
Industrial	35.9	15	15.4	7	146.8	34	124.8	29
Transportation	60.4	25	72.8	33	150.6	35	174.0	41
Other Sources	34.1	14	40.6	19	20.1	5	34.6	8
Total	238.3		218.1		430.7		429.4	

Table 1: New York and California Annual GHG emissions by Sector for Baseline 1990 and 2015 [6]/2016 [7]

Table 1 shows the annual GHG emissions for New York and California for the baseline 1990 and 2015 for New York and 2016 for California (the latest years where reported data are available). The sum of the two numbers in red represent the GHG emissions associated with all residential and commercial buildings for the baseline year 1990. This includes both the on-site combustion and the electricity generation associated with residential and commercial buildings and it is the number that is used when trying to attain a 40% and 80% reduction by 2030 and 2050 respectively for both states.

Table 1 also shows how GHG emissions have changed since 1990 and there are some interesting trends:

1. GHG emissions from electricity generation has reduced significantly in both states due to the transfer from high carbon fuels, such as coal, to lower carbon fuels such as natural gas

2. GHG emissions from buildings has remained relatively flat or gone up due to offsetting effects of larger populations and energy efficiency

3. GHG emissions from industrial has come down significantly in New York due to the move away from high carbon fuels such as oil [6]

4. GHG emissions from transportation has increased in both states due to a higher volume of gasoline vehicles

5. GHG emissions from other sources, such as refrigerants, has also generally increased due to larger populations [9]

C. Model Details for 2017

Fig. 3 shows a schematic of the basic input-output model structure used to estimate current state actual GHG emissions for a given year. As mentioned above, hourly data are used. This can be done for any year for which detailed data are available: the latest year of published data for New York and California are for 2017. The model uses a number of inputs to calculate the total GHG emissions for the building sector, comprising the sum of emissions from the fuel used for combustion of space and water heating appliances, the electricity used to power them and the AC loads.

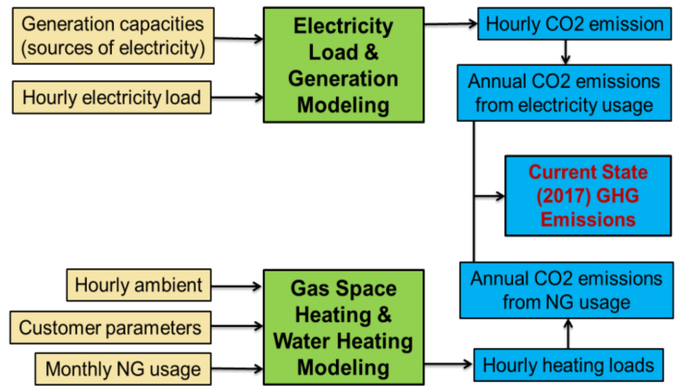

Fig. 3: Model Structure for Current State (2017)

Inputs to the model:

1. **GENERATION CAPACITY AND PRODUCTION (LOAD):** Generating capacity and production are published by fuel source. For New York, this can be found in Power Trends [10] and for CA, this is found from the EIA [3]. For example, in New York, the total generating capacity in 2017 was 38,777 MW, with 34% coming from renewables (nuclear, hydro, wind and solar). The total production in 2017 was 131,183 GWh, or an average of 14,975 MW, with 61% coming from renewables, indicating that the baseload is met with renewables for many times of the year.

2. **HOURLY ELECTRICITY DEMAND DATA:** These data are taken directly from the EIA [11]. To calculate the hourly CO2 emissions from electricity usage, the model assumes an order in which the electricity generation sources are successively initiated to meet the needed load: nuclear, hydro, renewables, coal and natural gas. If the generation at a given point is insufficient to meet the load, then it is assumed the shortfall is made up with additional electricity generation from natural gas. This establishes the carbon intensity of the grid ("greenness" of the grid), which is also calculated hourly based on the generation mix required at every hour.

3. **HOURLY WEATHER DATA:** These are made up of ambient temperature, humidity, wind speed and daily average inlet water temperature. These are taken from a chosen weather station and are needed not only to calculate the space heating load, but also used when calculating the efficiency of the heat pump and the water heating load. Hourly solar and wind generation is also calculated and placed in the generation mix.

4. **CUSTOMER PARAMETERS:** These include total daily hot water usage, draw profiles, and water heater and thermostat set points for both commercial and residential buildings. These are fairly well-established parameters for water and space heating simulation models. The model does not take into account new housing starts, demographic shifts, changes in product mix overtime due to natural forces, changes to grid demand due to externalities (e.g., lighting standards), etc.

5. **HOURLY NATURAL GAS USAGE:** These are also taken from the EIA, but are reported monthly for both residential and commercial buildings. The first assumption is that all the natural gas is used for space and water heating, e.g., any small effect due to cooking is ignored. Since water heating energy usage only changes with inlet water temperature throughout the year, and realizing that there is negligible space heating during the summer, the respective amount of natural gas used for all four segments (residential and commercial space and water heating) can be calculated. Although this is enough to calculate the total GHG emissions from natural gas usage in buildings, it is still desirable to split this up into hourly increments. Assuming typical product efficiencies[4] and capacities, these monthly gas *usage* amounts can be converted into monthly segment *loads* and finally, by assuming typical residential and commercial building sizes, water draw profiles, set points and weather data, hourly gas usage (and hence GHG emissions) can be calculated for each segment.

As mentioned above, the carbon intensity is re-calculated every hour. In general, the carbon intensity of both the New York and California grids has fallen over the past 20 years due to the move away from coal to natural gas and the increasing number of renewables. The carbon intensity in New York, for example, has fallen by more than 50% over the past 15 years. To put this in perspective, the carbon intensity of the New York grid is cleaner than using a 100% efficient gas appliance, i.e.,if the grid has the capacity to meet load, then installing any *new* gas appliance in New York is actually increasing GHG emissions. The California grid in 2017 was not as clean as New York: Fig. 4 shows the electricity generation percent share by fuel source for 2017 for both states and shows the significant amount of renewable nuclear and hydro energy in New York easily overshadowing the large solar and wind renewable contribution in California.

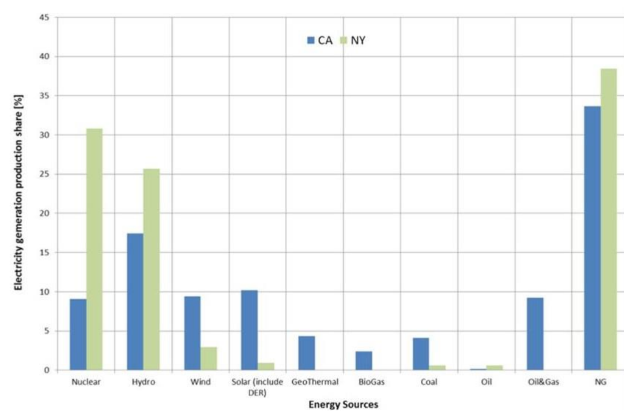

Fig. 4: Electricity Generation % Share by Fuel Source in New York and California in 2017

D. Model Details for Future State Policy Scenarios

Once the data for the *current state* (2017) have been calculated and established (see section 6), the model can be used to investigate the effect of different potential GHG-reduction policy scenarios to see how they can help to reach the required emissions reduction goals in a future state.

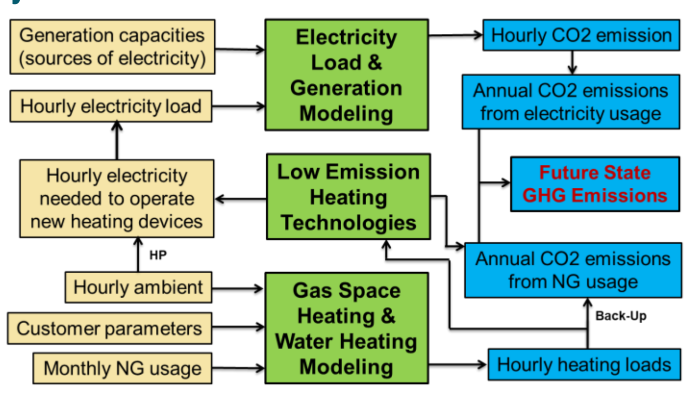

Fig. 5: Model Structure for a Future State Policy Scenario

Fig. 5 shows how the model is restructured for a future state policy scenario. Once the water and space heating loads have been calculated for the current state for each

[4] Product efficiencies are assumed from knowledge of the customer base in a specific location. For residential and commercial space heating, an efficiency of 85% was assumed. For residential water heating, an efficiency of 60% was assumed (non-condensing) and for commercial water heating, an efficiency of 90% was assumed.

segment, then a new low emission heating technology (or mix of them) can be evaluated to meet this load requirement[5]. If the low emission heating technology is simply a higher efficiency gas product (e.g., non-condensing to condensing or gas heat pump), then a new lower total gas usage is calculated to meet the load together with a corresponding lower GHG emission: there is no additional electrical impact to the grid in this scenario.

If the low emission heating technology is electricity based (e.g., electric storage, electric baseboard or, more likely, a heat pump - see section 4), then the interactions become more complex. If the current grid capacity is not sufficient to meet the increase in electrical load from large numbers of electric products replacing current gas products, then the shortfall needs to be made up from other sources of electricity generation, typically imported from other states, and often with higher carbon intensity, especially for a state like New York which already has a very clean grid. Since the model is hourly based, any time there is a capacity deficit in the electricity needed for generation, the difference is met using natural gas. Heat pumps may also need gas or electric backup on the coldest days since their efficiency and heating capacity drop with ambient temperature. The model allows for a cut-off temperature to be chosen, below which either natural gas or electric elements may be used for supplemental heat. Again, being hourly based, the model evaluates technical performance limits much more accurately than monthly or annual models.

A number of interesting policy scenarios can be compared to both the 1990 baseline and 2017 current state numbers:

1. **EFFECT OF IMPROVING CURRENT PRODUCT MIX EFFICIENCY:** Since we know the current gas and electric product mix in a given state, one of the easier policy scenarios to evaluate is the switching of low efficiency gas or electric products to high efficiency (e.g., non-condensing gas to condensing or gas absorption, electric storage to heat pump water heater (HPWH)). Micro-CHP (combined heat and power) is also considered in this section. The reduction in GHG emissions is obtained simply by reducing current load through energy efficiency of same fuel technologies. Market information allows for individual segments to be singled out, such as residential water heating, to provide a straightforward "what is possible" switch with no additional grid strains as well as minimal installation impacts.

2. **EFFECT OF FUEL SWITCHING GAS TO ELECTRIC PRODUCT MIX:** Switching from gas to electric technologies (electrification) for water and space heating seems to be gaining acceptance as a policy scenario. However, simply moving certain segments over to "all-electric" has implications to the grid infrastructure as shown in Fig. 5. The model looks at these scenarios in a realistic way by checking the hourly demand and adjusting carbon intensity of the grid (by assuming use of natural gas to produce electricity) if generation cannot meet load. Additionally, knowing planned power plant shutdowns and proposed increases in intermittent renewables (wind and solar), allows estimation of future grid carbon intensities to be used. Again, one can choose different segments to see the relative effects of residential and commercial water and space heating.

3. **EFFECT OF ADDING ELECTRIC OR THERMAL STORAGE:** Thermal and/or electrical storage can also be included to help balance the mismatch between renewable generation (occurring during the middle of the day and afternoon) and consumption (occurring in the early morning or evening), thereby also lowering the carbon intensity of the grid. One of the big unknowns looking into the future is the amount and pace at which renewables and storage will come online, the latter needed to fully unlock the renewable potential, thereby reducing carbon

[5] For simplicity, it has been assumed that there is no change in population size in a future state. However, this is easily built into the model if desired.

intensity of the grid. The model looks at various storage scenarios, from simple batteries to more complex thermal storage using water heaters and DR options.

Taking all these complex interactions into account, an estimate of the future state GHG emissions can be made and compared to the 1990 baseline and 2017 current state (see section 6). Although it is up to the user to assume a rate of adoption of any future technology mix (and then provide the incentives to achieve this), it does provide some simple guidelines as to which steps should be prioritized. In summary, therefore, the model can be used to help answer some key questions:

- What segments are most likely candidates that policy makers will target to transition first?
- What products in which segments will have the most impact?
- Can the 2030 goal be achieved by switching over to high efficiency same fuel products only?
- What adoption rate is needed in each segment to achieve the 2030 and 2050 goals?
- How much renewable energy and storage will be needed in tandem with high efficiency products to mitigate the additional electrical load necessary to achieve the "electrification" shift?

Before getting into the results of the analysis, it is worth spending some time on the technologies considered.

V. Potential Solutions for GHG Emission Reduction in Buildings in the Next 10 Years

A. Short-Term (available today, <1 year)

1. High-Efficiency Gas Products (Condensing and Gas Absorption/Gas Driven)

The majority of residential gas water heaters (99%) are low-efficiency non-condensing, and one obvious way to achieve an easy reduction in GHG emissions without impacting the grid is to convert these to higher-efficiency products. A couple of options exist here:

a. NON-CONDENSING TO CONDENSING: Rather than wasting energy by sending hot combustion gases up the flue (non-condensing product), condensing technology further extracts heat from the combustion gas and adds this energy into the water by passing these gases through a coil inside the tank. The cold water surrounding the coil collects most of the energy by condensing the water vapor in the combustion gas. Condensing gas water heaters are up to 96% thermally efficient (compared with approximately 80% for non-condensing technology). However, total installed cost is often the issue, especially for the residential market, where first cost is the primary driver in purchasing decision making return on investment for the consumer lengthy. For new construction, condensing products are more attractive since they are less expensive to vent, thereby reducing the overall additional cost burden.

b. GAS DRIVEN HEAT PUMPS: These are similar to an electric heat pump (EHP) in that they transfer energy from a heat source to a heat sink. However, rather than an electric grid-driven compressor, they use a heat source such as natural gas, propane, solar, geothermal or even waste heat to drive the cycle. They come in a number of forms, the simplest being a natural gas internal combustion (IC) engine directly coupled to a compressor driving an EHP. More thermodynamically complex gas heat pumps include adsorption and absorption cycles (explained more below), which use heat to drive a thermal compression process. All three types (gas driven, absorption and adsorption) have similar high thermal efficiencies (up to 140%) and are available on the market today for commercial applications, although the initial costs are high.

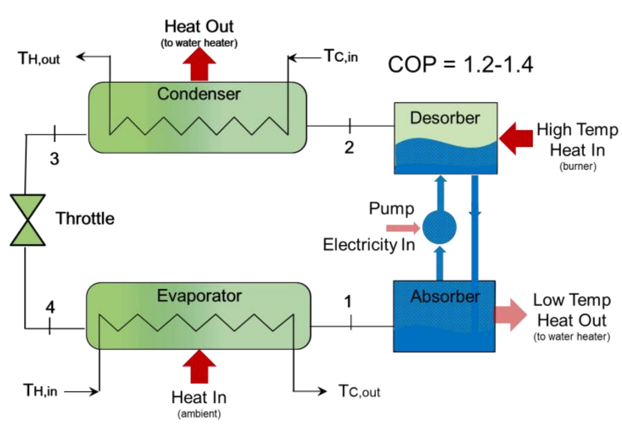

Fig. 6: Schematic Gas Absorption Heat Pump (GAHP)

Gas absorption heat pump (GAHP) water heating has gained a lot of attention over the last few years as one of the most promising emerging gas-fired water heating technologies [12], due primarily to its high thermal efficiency and good performance at lower ambient temperatures. The thermodynamic cycle is complex (Fig. 6), using a fluid pair (typically ammonia-water) in a closed loop continuous cycle to heat water. The condenser, expansion device (throttle) and evaporator are similar in function to those found in a conventional electric HPWH[6]: the ammonia absorbs heat from its surroundings in the evaporator and releases this energy in the condenser. The difference comes from the fact that the vapor from the evaporator is not compressed in a conventional compressor, but rather is exothermically absorbed into water in the

[6] The heat exchangers tend to be more expensive since copper cannot be used with ammonia

absorber, emitting thermal energy in the process. A low-power pump then takes this solution into a desorber at a higher pressure and a heat source is applied to vaporize the ammonia out of the water. The ammonia vapor then passes into the condenser to complete the cycle. The heat exchangers needed to do this thermal compression are fairly complex and designing a GAHP to get consistently high efficiency over a wide range of operating conditions is quite challenging. However, the fact that these heat pumps can use a low cost or free heat source and can operate efficiently at colder ambient temperatures makes them both energy efficient and economical to operate.

Extensive testing of these units over a complete heating season has provided average thermal efficiencies between 120-130% [13]; since gas is, in many ways, more than 3x lower in cost than electricity, then from a fuel cost standpoint, the value proposition of a GAHP is similar to that of an EHP with a COP > 4. Furthermore, as with EHPs, heating capacity and efficiency increase with increasing ambient temperature, indicating that both types of heat pump are well suited to warmer climates.

With decreasing ambient temperature, although the heating capacity and efficiency drop for both electric and gas heat pumps, the decrease is significantly lower for the latter due to the fact that the surrounding air is not the *only* source of heat used by the system (there is a burner in the desorber). This indicates that in a heating dominated climate zone, GAHPs can run in heat pump mode for longer periods than EHPs. It should also be noted that ammonia is a natural refrigerant with a zero GWP, but is toxic, so there are limits to charge quantity if placed indoors.

For New York, Fig. 7 shows the reduction in GHG emissions that can be achieved by using different efficiency gas products mentioned above. A GAHP with an average thermal efficiency of 140%, for example, reduces GHG emissions by 50% and 39% when compared to a non-condensing and condensing gas product respectively. Although GAHP will not provide the deep 80% GHG reductions required by 2050, the technology can certainly be used as a relatively economic transition technology to help reach the 2030 goals.

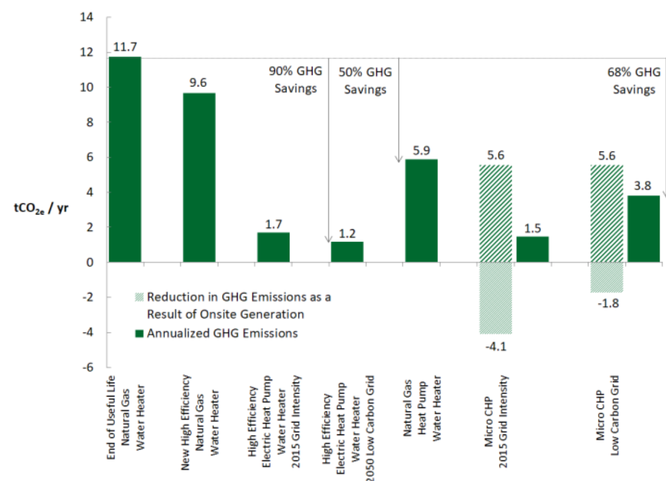

Fig. 7: GHG Reduction for High Efficiency Gas Driven Products

2. Combined Heat and Power (μCHP)

Combined heat and power (CHP) is the concurrent production of useful thermal energy and electricity from a single source of energy. The thermal energy can effectively be used for domestic hot water production, space heating and/or pool heating, while the electricity produced should ideally be used on site to offset a portion of the electricity purchased from the utility. CHP systems are typically combustion turbines or reciprocating engines[7], coupled with a high efficiency generator that is used to produce electric power, in turn connected directly to the building electric service. Heat is captured from the engine and exhaust of the system and if it exceeds immediate needs, it can be stored for later use. Fig. 8 shows a schematic of a micro-CHP system (< 50 kWe) compared to the conventional

[7] Micro-CHP (defined as <50 kWe) are typically fuel cells, IC engines, micro-turbines and Stirling engines

way of producing the same amount of electricity and thermal energy and shows a 50% increase in the overall energy efficiency of the system.

From an energy standpoint, the value proposition for CHP systems is for regions that have high spark spreads[8] and for applications that use a lot of thermal energy. However, the economics of CHP systems depend heavily on how many hours it can operate daily: longer hours mean a shorter payback. The overall efficiency (thermal and electric) of a CHP system of > 90% is much higher than a modern natural gas turbine. From a GHG emission reduction standpoint, since natural gas is being used to produce electricity, then CHP provides a benefit when the carbon intensity of the grid is higher than natural gas, but this benefit will tend to decrease as grid carbon intensities improve over time. Even when grid carbon intensities are already clean, however, significant benefits of CHP remain, such as the reduction of peak loads (demand charges), increased electric resiliency due to islanding from the grid and use as a distributed generation (DG) building block in a microgrid.

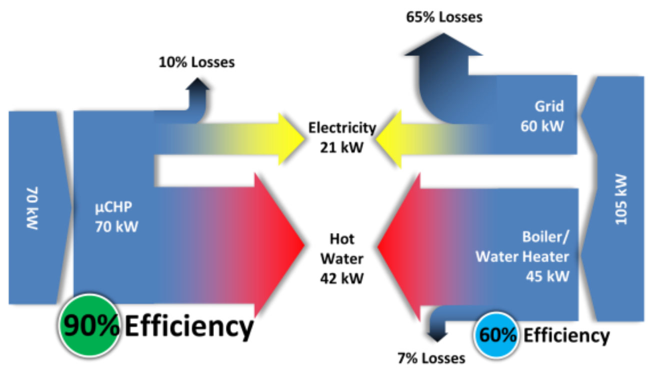

Fig. 8: Schematic Comparing CHP with BAU

Fig. 7 also shows the GHG emission reduction that can be achieved by replacing a gas product with both an electric HP and a micro-CHP system. However, when replacing gas products with electric, the carbon intensity of the grid being used to power the electric product must be considered. For *fixed* grid carbon intensity (New York 2015 in Fig. 7), GHG emissions are reduced by 85% when a non-condensing gas product is replaced with an electric HP[9]. Projecting to future 2050 grid carbon intensity increases this reduction to 90%. Micro-CHP is also shown to be a beneficial GHG reduction technology (85% today versus non-condensing). However, as the grid gets cleaner in the future, the benefit of CHP on GHG emission reduction decreases since the electricity it produces comes from "dirtier" natural gas.

3. Thermal and Electric Energy Storage (Water, Phase Change Material, Battery)

The flexibility that energy storage provides to balance energy consumption and electric generation from the power grid helps to overcome the problem of renewable intermittency and thus make both on-site and utility-scale renewable energy generation more useful. Energy storage can also support microgrids, reduce peak demand, shift demand to provide grid reliability, and reduce electricity costs.

There are a large number of energy storage technologies currently being deployed around the world:

a. SOLID STATE BATTERIES (PRIMARILY LEAD ACID & LITHIUM-ION BATTERIES): a range of electrochemical storage solutions, including advanced chemistry batteries and capacitors.

b. FLOW BATTERIES: batteries where the energy is stored directly in the electrolyte solution for longer cycle life, and quick response times

[8] Spark spread is the ratio of electricity to natural gas price. A spark spread >3 is typically considered to be attractive for CHP.
[9] Note that if many gas products ae converted to electric, then carbon intensity of the grid will not remain fixed as it will depend on the generation mix needed to generate the additional electricity.

c. **FLYWHEELS:** mechanical devices that harness rotational energy to deliver instantaneous electricity

d. **COMPRESSED AIR:** utilizing compressed air to create a potent energy reserve

e. **THERMAL:** capturing heat and cold to create energy on demand

f. **PUMPED HYDRO-POWER:** large-scale reservoirs of energy with water

Although pumped hydro-power has been used for many years as an energy storage mechanism, its widespread adoption is clearly limited. Recently, lithium-ion (Li-ion) batteries and thermal storage seem to be the two most promising technologies being considered for widespread use in GHG reduction scenarios, presumably because of their relatively small size, flexibility, low cost (for thermal storage) and adaptability. Li-ion batteries have been deployed in a wide range of energy-storage applications, ranging from energy-type batteries of a few kilowatt-hours[10] in residential systems with rooftop photovoltaic arrays to multi-megawatt containerized batteries for the provision of grid ancillary services. Since they store energy in the form of electricity, they are also very *useful* in what they can be used for. Battery costs have come down significantly over the years, primarily due to electric vehicle production, allowing for greater amounts of electric storage to be deployed

Thermal energy storage (TES) refers to technologies that make it possible to store hot or chilled water for use at a later time. Water/ice is the medium most often used because it's available, inexpensive and its properties are well understood. Materials with higher energy storage densities per volume (called Phase Change Materials or PCMs), are also gaining acceptance, not only because they take up a smaller volume than water, but also because they can be "tuned" to change phase at any desired temperature. By balancing thermal energy demands between peak and off-peak hours, or even from season to season, TES can assist in the transition to a renewables-based grid. Advantages of TES over battery storage include long term ROI due to their longevity and relatively low cost, around four times lower than a similarly sized battery system.

Storage water heaters make ideal TES devices because they are ubiquitous and already in the vast majority of homes, providing a much lower cost smart grid device than batteries. Utilities are therefore looking at ways whereby renewable solar (PV) or wind energy can be stored as hot water for use later in the day when heating demands are highest. By sending a demand response (DR) signal to potentially millions of connected storage water heaters (residential and commercial), utilities can shift loads during peak periods, instructing them to suspend any electric energy use during a specified time. With enough notice, together with modified control algorithms, these "smart" water heaters can ensure that the customer will not run out of hot water and reduce the load on the grid at peak times. The value for the utility is that they can manage the grid more easily as well as minimize grid infrastructure increases as more electric products go online. For the customer, the value is that they can avoid expensive time-based rates or receive other forms of financial incentives from the utility. Dual use energy storage devices, such as storage type water heaters or batteries in electric vehicles, clearly have a strong value proposition.

4. Air-to-Water and Water-to-Water Heat Pumps

Electric heat pumps (EHPs) are a relatively mature technology, already on the market for many years for space conditioning, and one of the more promising technologies to reduce GHG emissions from buildings. Although not as mature, HPWH are also gaining market acceptance, especially abroad, both

[10] The Tesla Powerwall 2 has a capacity of 13.5 kWh of usable energy storage capacity. It also has a power output capability of 7kW peak and 5kW continuous
https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall 2_AC_Datasheet_en_northamerica.pdf

for residential and commercial applications. Unlike gas products, heat pumps are greatly affected by ambient temperature conditions, choice of refrigerant and size that can impact the efficiency (in cold climates), performance (limited hot water delivery temperature) and customer appeal (slower to recover). These limitations, together with a higher initial cost, have somewhat limited the widespread adoption of heat pumps to date and there is much ongoing research to mitigate these perceived barriers.

An EHP uses electricity to *move energy* from a heat source to a heat sink rather than converting it from a fuel as with combustion heating systems (Fig. 9). An air-to water heat pump extracts heat from an air source (indoor, exhaust, or outdoor air) and delivers it at a higher temperature to heat water (sink). A water-to-water heat pump extracts heat from a water source (geothermal, lake or river) and similarly delivers it to heat water. Each type of heat pump can work either as a stand-alone water heating system, or as a combination water heating and space conditioning (heating and cooling) system.

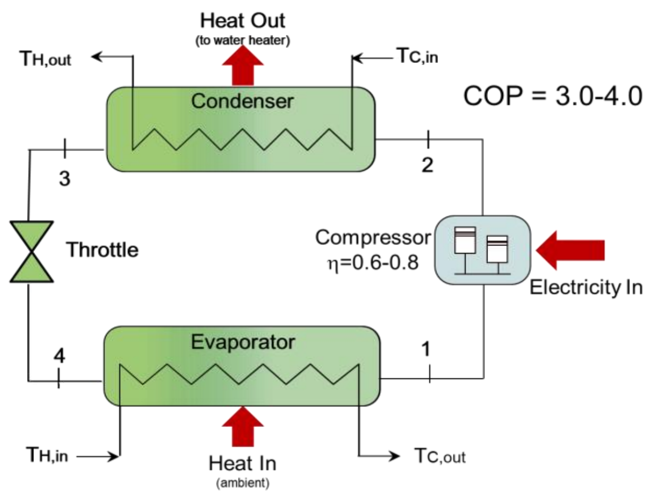

Fig. 9: Schematic of Electric Heat Pump (EHP)

When properly installed, heat pumps can be two to three times more energy efficient than conventional electric resistance water heaters. However, as ambient temperature drops, capacity and efficiency of air-to-water heat pumps suffer due to the heat pump needing to increasingly work harder. Cold climate heat pumps are a key research area today and there are ways to boost performance at colder temperatures (e.g., EVI), though these add expense. Below a certain temperature, it may simply be more economical to use backup heat from either electric elements or natural gas (i.e., a “hybrid” heat pump).

Water-to-water heat pumps (sometimes called ground source heat pumps) use the relatively stable temperature of the earth as a heat source and can therefore maintain higher performance as the outdoor air temperature drops. However, installation is more complex (and expensive) both in dense urban environments and difficult drilling topographies.

In NA, residential air-to-water HP systems (lower capacity) are typically “all-in-one” systems with an integrated water storage tank and condenser wrapped around the tank. One side effect of an integrated air-source HPWH is that it delivers cool exhaust air into the space where it is installed, good for dehumidification and cooling in the summer but may be slightly detrimental in the winter, depending upon local climate. Larger capacity commercial systems tend to be separated or split systems and typically placed outdoors. These can be either *water split*, where the HP system is contained completely in the outdoor unit and water or brine passes to and from the building (called a monoblock), or *refrigerant split* where the HP system is partly installed indoors and partly outdoors with the refrigerant passing to and from the building. The former only requires a plumber for install and can utilize better performing refrigerants, but care needs to be taken to avoid freezing. The latter would additionally require HVAC expertise to install (charged at the site), but are typically less complex and quieter (compressor inside).

B. Medium-Term (TRL > 7, 1-5 years):

1. Reducing Emissions Impacts of Natural Gas

In addition to higher efficiency gas products, there are other lines of research that are looking to reduce the environmental impacts of natural gas:

a. **RENEWABLE NATURAL GAS (RNG):** RNG turns organic waste from sources such as landfills, agriculture, food waste and livestock manure projects into a low-carbon fuel source that is fully interchangeable with conventional, fossil fuel-derived natural gas. Organic waste can be broken down by bacteria in an oxygen-free environment, a process called anaerobic digestion, to produce raw methane, which can be collected and purified into renewable natural gas, essentially pure methane that is interchangeable with conventional fossil-fuel derived natural gas. Once processed, this RNG can be injected into natural gas pipelines, used for transportation fuel, or delivered to homes and businesses.

b. **HYDROGEN AS A FUEL (H2):** When burned, hydrogen produces no GHG emissions, just water and heat. It also has the potential to be distributed using current natural gas infrastructure, making it potentially cheaper than adding to the existing electric grid. Indeed, there are programs underway in the UK to completely convert the city of Leeds' gas network to hydrogen (called H21 [14]). However, appliances using hydrogen still need to be modified not only to account for safety concerns but also to optimize the burners to account for different combustion characteristics of hydrogen (high flame speed and low volumetric density). Perhaps more promising, at least in the short term, is the blending of small amounts of hydrogen with natural gas and using the mixture as a drop-in fuel with existing appliance technology. Most research is looking at starting low by blending up to 5% by volume to confirm it can be considered as a drop-in fuel. The downside of hydrogen is that although it is carbon neutral when used, it is not carbon neutral to produce. Electrolysis of water into hydrogen and oxygen is ongoing, with the hope that a catalyst can be found that allows hydrogen fuel to be cleanly produced.

c. **POWER-TO-GAS (P2G):** P2G is another technology that converts excess electricity generated during periods of low demand or high renewables into hydrogen and oxygen gases from electrolysis of water. The oxygen can be released into the atmosphere or sold for industrial use while the hydrogen can be stored. The stored hydrogen can be blended with natural gas or combined with carbon dioxide to create synthetic methane, which can be used as a replacement for fossil-fuel generated natural gas. P2G technology is still in its infancy with great interest throughout Europe and in some parts of North America.

d. **CARBON CAPTURE AND STORAGE (CCS):** CCS can capture up to 90% of the carbon dioxide created by using fossil fuels in electricity generation and industrial processes. Once captured, the carbon is stored deep underground in depleted oil and gas fields or saline aquifer formations. CCS allows for the continued use of fossil fuels such as natural gas in the generation of electricity while still substantially reducing GHG emissions. However, the technology is still in its infancy, and is expensive with much ongoing research.

2. Improved ATW/WTW Heat Pumps

There is currently an abundance of research ongoing in a couple of key areas with regard to heat pumps to try and extend their operating window and further reduce their impact on the environment.

a. **IMPROVED COLD CLIMATE OPERATION:** There are various technologies that enable heat pumps to be used at lower ambient temperatures without too much loss of efficiency, thereby allowing for longer operating hours. Such methods include defrost mechanisms (reversing flow of refrigerant for a short time to melt the ice off the evaporator), dual compressors (a separate high- and low-pressure circuit in a cascade system) and economized vapor injection (reducing the compressor discharge temperature and extending operating range). However, these methods come at a cost and one needs to balance the pros and cons versus using a gas or electric backup (see *hybrid heat pump* below).

b. **INCREASED HOT WATER EXIT TEMPERATURES:** Commercial gas storage water heaters typically have to be capable of providing 180F water to eliminate any possibility of contamination of Legionella. Boilers also have to operate up to 160F if used with hydronic radiators. Typical refrigerants used today in heat pumps (R-134a, R-410A) cannot meet these high temperatures due to compressor discharge temperature limits. Carbon dioxide is an environmentally friendly refrigerant (GWP = 1) that can provide water temperatures approaching 180F. Although a mature technology in Japan, the thermodynamic cycle is more complex (transcritical versus subcritical), and with its low boiling point, it operates at pressures that are 5-10x higher than other commonly used refrigerants. This brings up both safety and cost concerns, but there is increasing interest in carbon dioxide as a refrigerant and significant research looking at ways to mitigate cost and bring the technology to mass production.

c. **NEW LOW-GWP REFRIGERANTS:** The fluids used in these heat pumps (refrigerants) are potent GHGs. Leakage of these refrigerants into the atmosphere has promoted legislation either in place or pending in many states and regions of the world that propose banning these high-GWP refrigerants in favor of ones that are either zero- or low-GWP. The problem is that many of these replacement fluids are either flammable, toxic, mixtures or operate at very high pressures, adding to safety, complexity and cost concerns. Understanding flammability limits of these proposed replacement fluids is another area of current heavy research.

d. **HYBRID HEAT PUMPS:** In colder climates, it is impractical to have outdoor heat pumps operate over the whole ambient temperature range due not only to drop in efficiency, but also size and cost. Furthermore, it is likely that either gas or electric backup would still be required on the coldest days and need to be sized to meet the highest loads. A hybrid heat pump (or “hybrid boiler”) is an electric heat pump that is sized to satisfy a base load with gas or electric backup to provide cold weather heating/hot water below a certain ambient temperature. For the user, a hybrid system presents less inconvenience than a boiler-to-heat-pump conversion but will inevitably have a higher cost than a replacement gas boiler alone.

C. Other Technologies

1. Fuel Cells

Fuel cells convert chemical energy (typically hydrogen) into electricity in an electrochemical cell. As long as fuel and oxygen are supplied, fuel cells can produce electricity continuously, quietly with near zero emissions (NOx and CO2), depending on the source of hydrogen. Electric conversion efficiencies can reach 55-60%, making them ideal products for distributed generation. Solid oxide fuel cells (SOFC) seem to have emerged as the leading candidate for stationary applications and are already commercialized in small quantities with on-board reformers typically converting natural gas to hydrogen. Barriers to widespread adoption still exist due primarily to cost, on/off cycling durability and long start up times and there is much research being done to address these issues.

2. Other “Not-in-Kind” Thermodynamic Cycles

For heat pumps, the reverse Rankine cycle has been used for close to 150 years. Benefitting from years of research, it is inexpensive, mature, easily adjustable and very controllable, making it the clear technology of choice. Furthermore, breakthroughs in material science and manufacturing have led to new highly compact heat exchangers, more durable compressors and high-performance oils and refrigerants, no doubt keeping this cycle around for many years to come.

With increased attention on the environment and efficiency, however, there are new non-vapor compression HVAC technologies being investigated that are in the early research phase for both cooling and heating. Goetzler et al. [15] did a nice job evaluating 17 viable technology options, ranking them in terms of which had the most potential for energy savings and other non-energy benefits. Without going into more detail here, for heating applications, thermoelastic, magnetocaloric and the Vuilleumier heat pump cycle were evaluated as the most promising.

VI. New York & California Results and Discussion

A. Model Results for Current State (2017)

Fig. 10 shows the hourly electricity load in New York and California in 2017, as published by EIA [11]. Both correlate well with ambient temperature (peaking in the summer) as expected, and there are a couple of interesting things to note:

1. In New York, the demand is relatively flat throughout the year, with only a slight bump in the summer due to the cooling load. As mentioned above, the total grid capacity in New York in 2017 was 38,777 MW, which is more than enough to cover the highest electricity loads shown in Fig. 10 for New York.

2. In California, the bump in electricity demand in the summer is significant, as expected, nearly doubling in value. Clearly, more efficient cooling in California is a priority to reduce the overall needed electrical load. The total grid capacity in California in 2017 was not enough to cover its demand and California had to import electricity from neighboring states during the summer peak.

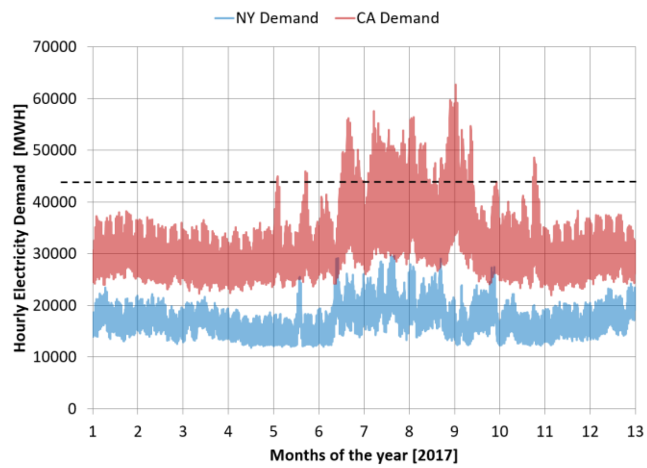

Fig. 10: Hourly Electricity Usage in New York & California 2017

As stated above, the model can break down the GHG emission contribution from the different heating segments of water and space heating and by building type, as shown in Fig. 11.

In New York, the largest segment pertains to residential SH due to the high heating load in winter. Second in New York is commercial water heating, follwed by residential water heating. Commercial space heating is the lowest contributor, presumable because there is significant district heating in place today, i.e.,there isn't much decentralized combustion used for commercial space heating. In California, on the other hand, since the annual space heating loads are significantly less, the larger contributors are commercial and residential water heating. It seems clear that for A. O. Smith, the segments of residential and commercial water heating would be those to prioritize.

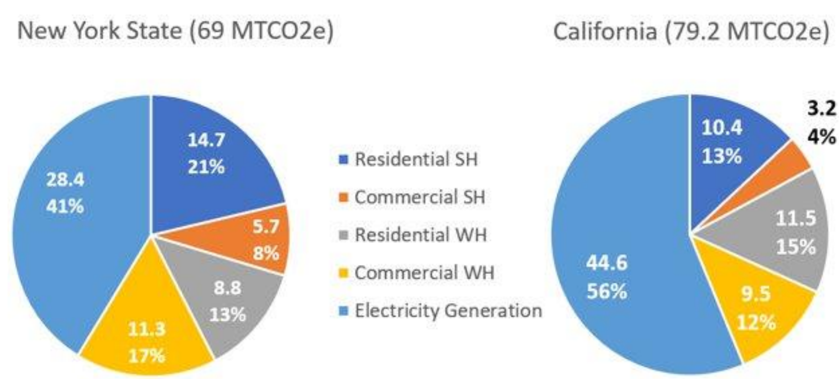

Fig. 11: GHG Emissions by Heating Segment in New York & California in 2017

B. Policy Scenarios Analyzed

As mentioned above in section 4.4, the model can now be used to ask "what if" type questions. A series of policy scenarios were chosen, shown in Table 2. Scenarios 2-4 looked at changing the current product efficiency mix, moving to 100% condensing technology, then additionally converting 50% of commercial water heating to either GAHP or micro-CHP. The effect of using renewable natural gas can also be easily evaluated by a simple multiple of the different carbon intensities of the fuel. Clearly there is minimal impact to the grid in these three policy scenarios (adding CHP will actually reduce load).

EFFECT		EXPLANATION
2017 – BAU	1	2017 Current State GHG Emissions
improving current product mix efficiency	2	Scenario 1, plus all gas product to high-efficiency (92%) condensing
	3	Scenario 2, plus 50% comm. WH to GAHP (120%)
	4	Scenario 2, plus 25% comm. WH to μCHP (90%)
fuel switching gas to electric product	5	Scenario 1, plus all res. WH gas product to indoor HPWH
	6	Scenario 5, plus all comm. WH gas product to split HPWH (NG < 20°F)
	7	Scenario 6, plus all res. SH to split ASHP (NG < 20°F)
	8	Scenario 7, plus all comm. SH to split HPWH/ASHP (NG < 20°F)
improving grid intensity	9	Scenario 6, (res. & comm. WH) plus improved 2030 grid intensity
	10	Scenario 8, (all WH & SH) plus improved 2030 grid intensity

Table 2: Policy Scenarios Analyzed

Scenarios 5-8 look at incrementally changing each heating segment in turn from gas to electric to enable the impact of each segment to be fully understood. For these scenarios, the current grid *generation mix* is maintained: as more load comes on to the grid (replacing gas products with electric), the difference between calculated hourly load and generation capacity is made up from natural gas. This increases the carbon intensity of the grid as more electric products are utilized and decreases the benefit seen in GHG emissions reduction. As mentioned above, since it is impractical to have outdoor heat pumps operate over the whole ambient temperature range, it was assumed that hybrid heat pumps, already available in Europe, would be used, with a heat pump cut-off temperature at 20°F. Finally, Scenarios 9 and 10 look at a future state with assumed lower carbon intensity (greener grid): this has been estimated from known reported changes to generation infrastructure (closure of nuclear power plants, projected increases in wind and solar, etc). The following sections look at New York and California separately.

C. New York Results

Although GHG emission reduction is the goal, the cost of increasing the needed grid infrastructure is often seen as major barrier. An interesting question is the size of grid that would be needed if the entire water and space heating load were converted to electricity (storage water heating and electric space heat). Although in reality this is unrealistic since heating loads would be HP and/or gas (see next plot), Fig. 12 does show a worst-case scenario where the required load in New York would be about three to four times the current load and about twice the current generation capacity due to the winter heating load requirements, something that would seem to be economically challenging even if it were technically feasible. Even in the summer, with all water heating moving to electric storage, the current grid size would be challenged on certain days.

For heating, based on the long stretch of very cold temperatures seen in the Midwest and Northeast in 2019 and the low temperature limits of air source heat pumps[11], it seems reasonable that natural gas will continue to have a significant part to play, even if only in a backup role in a hybrid HP. Fig. 13 shows the same plot as Fig. 12, but using hybrid heat pumps with natural gas backup below 20°F for space heating and HPWH for water heating. It can be seen that in the winter, the load has almost been significantly reduced and is below the generation capacity of the state except for a few days. For the summer, the load is only slightly higher than the AC load due to the high efficiency of the HPWH.

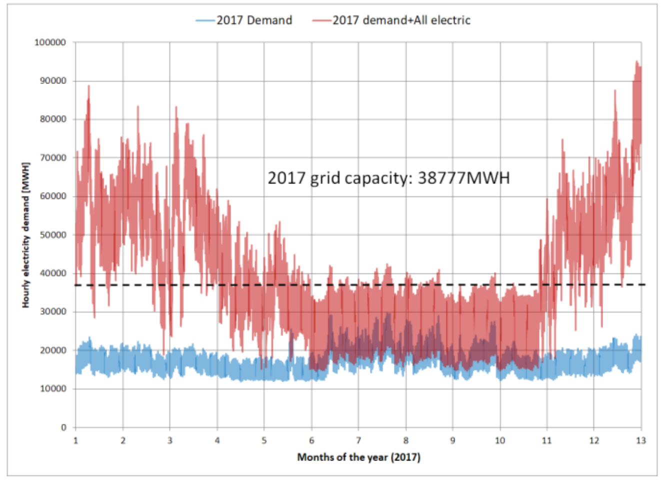

Fig. 12: New York Grid Size if All Building Heating Loads Were Moved to Electric

1. SCENARIOS 2-4

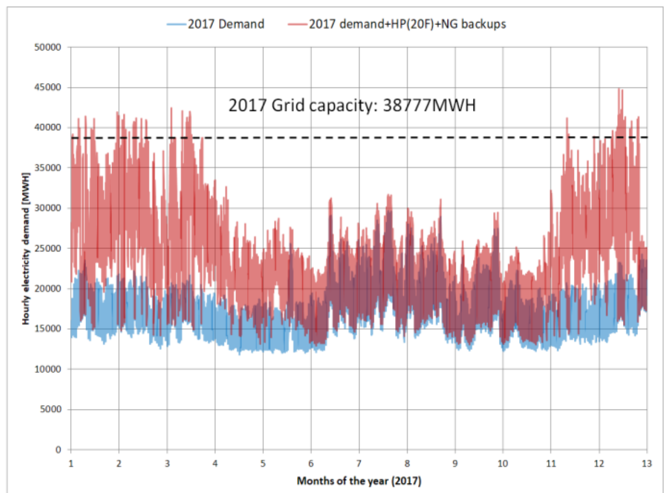

Fig. 13: New York Grid Size if All Building Heating Loads Used Hybrid HP (Down to 20°F with Gas Backup)

Fig. 14 shows the effect of improving the current gas product efficiency mix in New York. The blue and yellow colors in the figure refer respectively to the GHG emission contribution from building combustion and building electricity. The numbers under each column refer to the scenarios provided in Table 2. The GHG contributions from gas in Scenario 1 are further split into the four segments of residential and commercial water and space heating. Finally, the 2030 and 2050 goals are shown on the right-hand side of the figure and it can be seen that in 2017 (Scenario 1: 2017 current state), as indicated by the dashed 2030 target line, New York has not quite met its 2030 goals (40% reduction below 1990); however, it is close, due primarily to natural gas replacing coal for electricity generation.

Scenario 2 shows the effect of changing all products to high efficiency condensing gas (92%) and therefore shows no change to the electricity portion. Scenario 2 provides an overall reduction in GHG emissions (over current state) of about 4%, a relatively small impact since most of these products are already high efficiency (with the exception of residential water heating). Scenario 3 looks at further replacing 50% of all commercial water heating to gas absorption, using an average annual total efficiency of 120% based on field data [16]; this provides an additional 7.5% reduction over current state. With over 11% reduction in GHG emissions over current state (2017), Scenarios 2 and 3 show that there is merit for retrofit applications to move from low efficiency to high efficiency gas products.

[11] Geothermal heat pumps do not suffer from low temperature limits, however tend to not only be significantly more expensive to install but also difficult to install in many locations due to underlying bedrock, for example

However as stated earlier, for new construction, adding even a high efficiency gas product would not help reduce GHG emissions since the grid in New York is already so clean.

Rather than replace 50% of commercial water heating with GAHP, Scenario 4 shows the effect of replacing commercial water heating applications with a 25 kW micro-CHP product. When operating, the combined efficiency of the micro-CHP system is about 90% (see Fig. 8). Producing power on-site and using the waste heat for hot water (or space heating) is clearly beneficial from a GHG emission standpoint over using natural gas for electricity at a central plant and wasting the heat. The model calculates the net GHG emission benefit assuming a certain percent of commercial water heaters are converted over to micro-CHP.

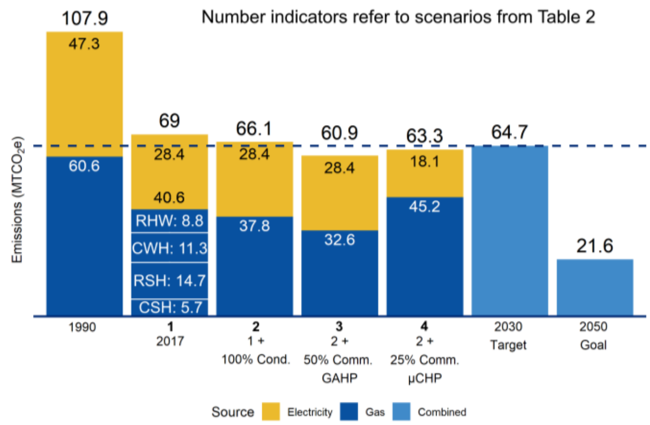

Fig. 14: Effect of Improving Current Gas Product Mix Efficiency on GHG Emissions in New York

It was mentioned above that these devices are thermally led, i.e., they produce electricity only when there is a thermal load. In addition, to provide an economic value proposition, these systems need to operate a minimum of 16 hours/day, and due to the non-uniform water draw profile of most commercial buildings, require storage. For this study, therefore, it was assumed that only 50% of commercial buildings would provide a suitable application for micro-CHP: together with a 50% market penetration, the model therefore assumes a 25% replacement of conventional commercial water heaters for Scenario 4. Fig. 14 shows that Scenario 4 provides a smaller decrease in GHG emissions cf. Scenario 3 (about 4%) but only assumes a 25% penetration. Furthermore, there are a couple of things regarding CHP systems that would further reduce GHG emissions:

1. They are typically used for baseload water heating only: for a typical commercial water heating profile in New York, due to the non-uniformity of the draw profile, such a system can account for about 70% of the water heating load (used in this analysis), the remainder coming from natural gas. If the water heating load was more uniform (e.g., multifamily or dorm rooms), then a CHP system would operate for more hours/day and provide a higher percent of the overall load

2. If space heating load were also supplied by the micro-CHP system, then the number of buildings and the operating hours would both increase

As mentioned earlier, producing electricity on-site (distributed generation) has significant benefits in addition to simply reducing GHG emissions, such as lower demand charges, increased electric resiliency (islanding from the grid) and use as a building block for microgrid systems.

2. SCENARIOS 5-8

Fig. 15 shows the effect of switching each heating segment (residential water heating, commercial water heating, residential space heating and commercial space heating) sequentially from gas to electric HP in New York (Scenarios 5-8). HP efficiencies used in the model vary with ambient temperature and are current state-of-the-art values. For residential WH, the HPWHs are indoor units and hence operate for all ambient temperatures. However, account is made for the additional heating needed to offset the cooling effect from the HP. For all the other segments, gas backup is assumed below 20°F[12] so even when all segments are electrified (Scenario 8), there is still some gas required. It can be seen that as each segment is "electrified" (yellow bars) due to the need to supplement the electricity generation with natural gas, GHG emissions from electricity use increase, as expected. Due to the high heating loads in New York, the figure shows that residential SH provides the biggest incremental increase (7.4%); commercial WH (5.0%) and residential WH (3.8%) also provide significant incremental reductions. Assuming gas backup below 20°F (requiring a grid capacity that is no larger than today (see Fig. 13), Fig. 15 shows that there is potential for more than an 18% reduction in building GHG emissions for New York over current state (2017) if all four segments were electrified. Scenario 9 (all water heating) and 10 (all water and space heating) show the effect of further improving the grid intensity in New York by 31% (2017 to 2030, per state plans), providing a possible *additional* 16% reduction from buildings—enough for 2030 targets, but clearly still not enough to meet the 2050 goal without further action.

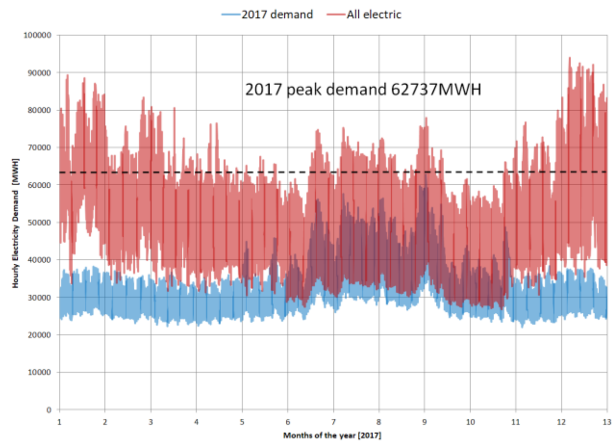

Fig. 16: California Grid Size If All Building Heating Loads Were Moved to Electric

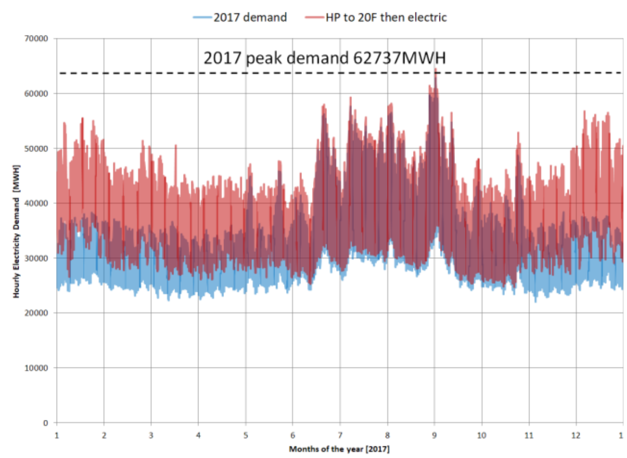

Fig. 17: California Grid Size if All Building Heating Loads Used Heat Pump

C. California Results

As with New York, Fig. 16 shows the needed grid size in California if the entire water and space heating load were converted to electricity (storage water heating and electric space heat). Although in reality this is again unrealistic, it shows that the required load in California is about two to three times the current load and only 50% higher than the current generation capacity. Note that although the load is seasonably well balanced, it is still the winter heating loads that slightly dominate in terms of peak demand, although the current grid capacity is also undersized in the summer.

Fig. 17 shows the same plot as Fig. 16, but uses heat pumps for space heating and HPWH for water heating. Since temperatures do not get too low in California, negligible backup is needed. It can be

[12] It is possible to go to lower ambient temperatures with heat pumps today. However, cost and size of the unit increases exponentially, providing diminishing returns compared to gas backup. A value of 20°F seems to be a reasonable cut-off temperature for most products on the market today, providing a compromise between size, cost and availability.

seen that the load has been significantly reduced below the generation capacity of the state for all seasons and the grid is actually very well balanced over the year.

1. SCENARIOS 2-4

Fig. 18 shows the effect of improving the current gas product efficiency mix in California. Similar to before with New York, the brown and orange colors in the figure refer respectively to the GHG emission contribution from building combustion and building electricity and the numbers under each column refer to the scenarios provided in Table 2. The GHG contributions from gas in Scenario 1 are again further split into the 4 segments of residential and commercial water and space heating and the 2030 and 2050 goals are shown on the right-hand side of the figure. Like New York, it can be seen that in 2017 (Scenario 1: 2017 current state), as indicated by the dashed 2030 target line, California has not yet met its 2030 goals.

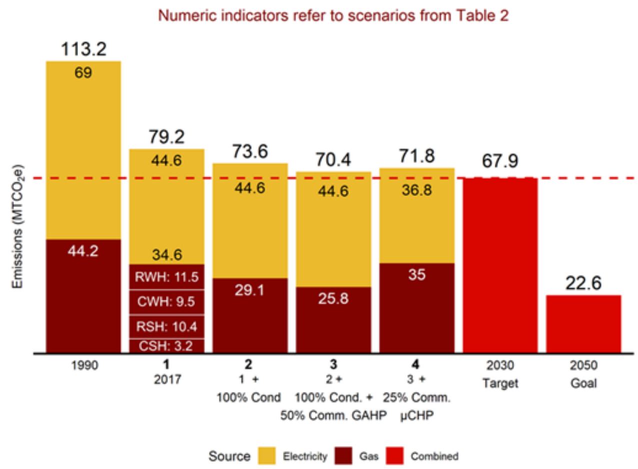

Fig. 18: Effect of Improving Current Gas Product Mix Efficiency on GHG Emissions in California

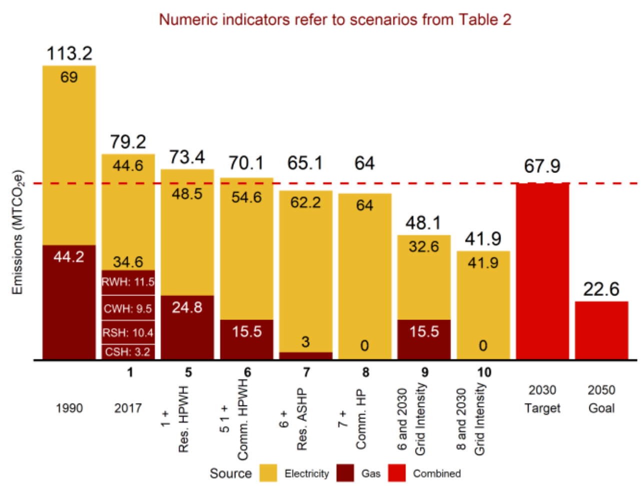

Fig. 19: Effect of Fuel Switching and Greener Grid on GHG Emissions in California

The scenarios discussed here are the same as those discussed above for New York and only results will be given here. Scenario 2 (100% condensing) provides an overall reduction in GHG emissions (over current state) of about 7%, a relatively small impact like New York since most of these products are already high efficiency (with the exception of residential water heating). Scenario 3 (replacing 50% of all commercial water heating to gas absorption), provides an additional reduction over current state of 4%. With over 11% reduction in GHG emissions over current state (2017), Scenarios 2 and 3 show that there is also merit in California for retrofit applications to move from low efficiency to high efficiency gas products.

Using the same reasoning as above for New York, Scenario 4 again shows the effect of replacing 25% of commercial water heating applications with a 25 kW micro-CHP product. It can be seen from Fig. 18 that Scenario 4 provides a smaller decrease in GHG emissions cf. Scenario 3 (about 2%), but again, only assumes a 25% penetration. Furthermore, the same tangible and intangible benefits mentioned above for New York when using micro-CHP would also be true for California.

2. SCENARIOS 5-8

Fig. 19 shows the effect of switching each heating segment sequentially from gas to electric in California (Scenarios 5-8). As before with New York, HP efficiencies used in the model vary with ambient temperature and are state-of-the-art. Also, for residential WH, the HPWHs are indoor units and hence operate for all ambient temperatures. Unlike New York, there is negligible backup needed for the other segments, as seen in Scenario 8. Since the heating load in California is much lower than New York, the figure shows that electrification of the residential WH load provides the largest opportunity for reduction of GHG emissions (7.3%). Electrifying residential SH and commercial WH provide an additional 10.5% opportunity for GHG emission reduction. Overall, if all four segments were electrified, Fig. 19 shows that there is potential for a nearly 19% reduction in building GHG emissions for California over current state (2017). Scenario 9 (all water heating) and 10 (all water and space heating) show the effect of improving the grid intensity in California by 36% (2017 to 2030, per state plans), providing an *additional* 28% reduction from buildings possible—again, enough for 2030 targets, but clearly still not enough to meet the 2050 goals without further action.

VII. New York and California Recommended Solutions and Barriers

From A. O. Smith's perspective, there are several key takeaways from the analysis that will help states and cities reach their GHG emission reduction goals:

A. Residential and commercial water heating are the primary A. O. Smith targets for GHG reductions in buildings.

B. High efficiency gas is important and should serve as a stepping-stone in replacement applications for a managed transition.

C. New construction should transition to high-efficiency heat pumps in water and space heating applications.

D. Demand response and energy storage solutions, including thermal storage, will be absolutely necessary to decarbonize the grid.

E. Hybrid heat pumps with options for gas/electric backup will be necessary for cold climates and space constrained applications.

F. With these new product solutions, consumer education and GHG reduction programs are going to be essential in aiding consumers in understanding how to make different purchasing decisions and accept new technologies.

However, there are some key barriers to overcome to achieve these GHG reduction goals:

A. Residential water heaters are a commodity today and an unplanned replacement, which skews the market towards less efficient purchases due to first-cost bias. Replacing a low efficiency gas product to a high efficiency gas product will be more expensive up-front for the consumer but provide a payback over multiple years. There will have to be some other customer value proposition for this market transformation to happen on a large scale, such as incentives, leasing options with shared cost/savings, or favorable utility rates.

B. Since >90% of residential water heaters are gas fired in New York and California, it will become necessary to find an economically attractive proposition to retrofit these existing gas products with a high efficiency EHP for electrification to be successful. The issue is not so much the cost of the replacement unit itself, but more the total installed cost to the consumer in certain applications. For example, many older homes do not have the electric circuitry to power the EHP with its 4.5kW backup element. A significant and expensive wiring upgrade throughout the house is a major reason why the uptake of these units has been slow in the retrofit market.

C. To encourage the widespread adoption demand response functionality and the use of thermal storage (i.e., using the water heater as a thermal battery and thereby encouraging the use of renewables for power generation), consumer purchasing decisions need to be altered such that the value of larger water heaters is well understand even though they come with a higher first cost. This education should be coupled with an incentive program (financial or otherwise) for the customer and builder to help promote widespread adoption and use of demand response functionality and thermal storage with the understanding that the primary goal remains customer satisfaction levels must be met at all times.

References

[1] California Energy Commission, "Deep Decarbonization in a High Renewables Future," CEC-500-2018-012, June 2018.

[2] S. Billimoria, L. Guccione, M. Henchen, and L. Louis-Prescott, "The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings," Basalt, CO, 2018.

[3] EIA, "State Electricity Profiles," 2019. https://www.eia.gov/electricity/state/

[4] The City of New York, "New York City Roadmap to 80x50," 2016.

[5] J. A. de Chalendar and S. M. Benson, "Why 100% Renewable Energy Is Not Enough," *Joule*, vol. 3, no. 6, pp. 1389–1393, Jun. 2019.

[6] NYSERDA, "New York Greenhouse Gas Inventory: 1990-2015 - Final Report," Albany, NY, 2018.

[7] California Air Resources Board, "California Greenhouse Gas Inventory for 2000-2016 - by Sector and Activity," *California Greenhouse Gas Emission Inventory - 2018 Edition*, 2018. https://ww3.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_sector_sum_2000-16.pdf

[8] The City of New York Mayor's Office of Sustainability, "City of New York Inventory of New York's Green House Gas Emissions in 2015," 2017.

[9] D. Brack, S. O. Andersen, and X. Sun, "National Hydrofluorocarbon (HFC) Inventories: A summary of the key findings from the first tranche of studies," Paris, France, 2016.

[10] NYISO, "Power Trends: New York's Evolving Electric Grid," Rensselaer, NY, 2017.

[11] EIA, "U.S. Electric System Operating Data," 2019. https://www.eia.gov/realtime_grid/?src=data#/status?end=20180803T12

[12] W. Goetzler, M. Guernsey, and M. Droesch, "Research and Development Roadmap for Emerging Water Heating Technologies," Washington D.C., 2014.

[13] M. Garrabrant, R. Stout, C. Keinath, and P. Glanville, "Experimental Evaluation of Low-Cost Gas Heat Pump Prototypes for Building Space Heating," in *16th International Refrigeration and Air Conditioning Conference*, 2016, pp. 1–8.

[14] https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf

[15] W. Goetzler, R. Zogg, J. Young, C. Johnson, "Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies," DOE Building Technologies Office, March 2014.

[16] C. Keinath, M. Garrabrant, "Performance of Commercial Sized Gas HPWHs at a Commercial Laundry Facility," ACEEE Hot Water Forum, March 2019