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Scenarios to decarbonize residential water heating in California

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ABSTRACT

This paper presents the first detailed long-term stock turnover model to investigate scenarios to decarbonize the residential water heating sector in California, which is currently dominated by natural gas. We model a mix of water heating (WH) technologies including conventional and on-demand (tank-less) natural gas heating, electric resistance, existing electric heat pumps, advanced heat pumps with low global warming refrigerants and solar thermal water heaters. Technically feasible policy scenarios are developed by considering combinations of WH technologies with efficiency gains within each technology, lowering global warming potential of refrigerants and decreasing grid carbon intensity. We then evaluate energy demand, emissions and equipment replacement costs of the pathways. We develop multiple scenarios by which the annual greenhouse gas emissions from residential water heaters in California can be reduced by over 80% from 1990 levels resulting in an annual savings of over 10 Million Metric Tons by 2050. The overall cost of transition will depend on future cost reductions in heat pump and solar thermal water heating equipment, energy costs, and hot water consumption.

1. Introduction

California is an important test bed for national and international climate policies having already implemented some of the most ambitious climate regulations in the country. California Assembly Bill 32 (AB 32) was passed in 2006 and mandated that statewide emissions in 2020 should not exceed those in 1990. For the year 2050, California Executive Order (EO) S-3–05 sets an ambitious goal to reduce the economy wide emissions by 80% below the 1990 level. More recently in 2016, California's climate commitment has been strengthened by the passage of California State Bill 32 (SB 32), requiring that annual greenhouse gas (GHG) emissions in 2030 be 40% below 1990 level. Moreover, in 2016, the state set a 40% reduction target for hydrofluorocarbon (HFC or "F-gas") refrigerants in 2030 from 2012 levels (CA SB 1383).

In 2014, California's statewide GHG emissions were led by the transportation sector at 37% of overall emissions, followed by the industrial, electricity, building heating, and agriculture sectors at 24%, 20%, 11%, and 8%, respectively. For the state to achieve an economy-wide emissions reduction of 80% of 1990 level by 2050, a first order goal would be to achieve 80% emissions reduction in emissions from each sector, although some sectors and end-use applications may be more difficult to decarbonize than others. For example, heavy-duty transportation and high temperature industrial heating are typically viewed as relatively more difficult to decarbonize than the electricity sector.

Decarbonizing the building heating sector follows the general paths of achieving high energy efficiency in the building shell (e.g., attic, wall, floor insulation), installing energy efficient appliances and decarbonizing the energy supply (e.g., transitioning to lower carbon electricity sources) and/or lower carbon fuels for equipment with onsite combustion (e.g., directed biogas for space heating or water heating). Coupling decarbonized electricity supplies with fuel substituting of heating demand from natural gas to electricity has great potential for building decarbonization (Wei et al., 2013a; 2013b; Munuera, 2013; Dennis, 2016). In Europe, the effects of electrification of buildings and efficiency retrofits such as heat pumps on emissions reductions have been highlighted in several studies (MacLean, 2016; Kelly, 2016; ETIP-SNET, 2017). The role of decarbonized pipeline gas fuels and electrification of end-uses to achieve deep-decarbonization in California has been examined by E3 (2015). Given the limited bio methane availability in the state, the E3 scenario assumes the share of methane derived from solid biomass blended into the pipeline increases. However, there is uncertainty in the costs associated with biomass

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Abbreviations: HP, Heat pump; HPWH, Heat pump water heater; NGWH, Natural gas water heater; INGWH, Instantaneous natural gas water heater; ERWH, Electric resistance water heater; PWH, Propane water heater; AdvHP, Advanced water heater; SThWH, Solar thermal water heater

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supply, gasification and methanation costs (E3, 2015).

While California's existing decarbonization policies address sectors such as light duty vehicles and electricity generation, policies do not directly address fuel substituting in buildings. In fact, for many regions in California without large-scale industries, transportation and building heating are already the two largest sources of GHG. Here we focus on building heating electrification with much lower carbon electricity supply as the primary pathway for building decarbonization. In order to develop more actionable plans and potential policies in decarbonizing buildings, a comprehensive analysis of scenarios for each of the building heating subsectors is required.

Residential water and space heating sectors made up about 34% and 25%, respectively, of total building end-use natural gas consumption in 2014 (CA IEPR, 2015; RAAS, 2009). With tighter building shells and a warming climate, energy demand for space heating may decrease in the future. Thus, the focus in this paper is on residential water heating, and we present a detailed lifecycle comparison of available water heating technologies and develop technically feasible policy scenarios to reduce 2050 emissions by over 80% below 1990 level.

Several studies have established the cost effectiveness and emissions savings of heat pump-based water heating (Franco et al. (2010); Northwest Energy Efficiency Alliance (NEEA (2015); Nadel (2016); and SMUD (2012)). In addition, performing active demand response can help in reducing costs of electric resistance and HP-based water heating (Patteeuw et al., 2015). The U.S. National Energy Modeling System (NEMS) models a range of water heaters amongst other household appliances to project residential energy consumption by fuel type and end-use (United States Energy Information Agency (US EIA), 2014). An earlier report by the Sacramento Municipal Utility District (SMUD, 2012) projects scenarios for decarbonization building heating and transportation in the Sacramento municipal district. To achieve an 80% emissions reductions, this study recommends building electrification and the adoption of heat pump based water heater (HPWH) to begin before 2030. Our model is a more detailed statewide model than earlier work. It includes a wider range of water heating technologies and considers refrigerant global warming potential (GWP) and GHG emissions due to refrigerant leakage. We develop technically feasible scenarios with gradually phasing in electrification of water heaters. Further, the portfolio of future stock of water heaters includes advanced heat pump technology and solar thermal with heat pump back up.

While a couple of the scenarios developed here reduce 2050 emissions by over 80% below the 1990 level, the 2030 emissions fall short of the 40% reduction target. However, the 2030 emissions target can be achieved with a 25% reduction in hot water demand from current levels. Our estimates of the net present value of the incremental cost of these pathways is not onerous, an estimated 7–30% higher than the business as usual case (Table 5). This analysis demonstrates that fuel substituting to electricity without the forced retirement of existing equipment cannot wait beyond 2020 for California to achieve the 2050 emissions goals.

The paper is structured as follows: Section 2 provides a background on the status of water heating sector in California and water heating technologies. Assumptions on equipment costs, fuel and maintenance along with other assumptions on current and future appliance efficiencies, fuel carbon intensity, and refrigerant GWP can be found in Section 3. Section 3 also provides an overview of the model methodology. Section 4 presents analysis and results. Finally, Section 5 presents conclusion and some policy implications.

2. Background

The vast majority (about 90%) of California's households use natural gas for water heating, resulting in annual GHG emissions of about 14 million tons (Table 6) (RAAS, 2009; CA-IEPR, 2015). Efficiency gains in water heaters, lower GHG intensity fuel sources and lowering hot water consumption can all help bring down these emissions. Electrification of heating accompanied with the adoption of market ready high efficiency electric heat pump (HP) technologies can lower the emissions further depending on the carbon intensity of the grid (Nadel, 2016; SMUD, 2012). California's Zero Net Energy (ZNE) action plan incentivizes high energy efficiency building designs and end-use appliances with the goal for all new homes to be 100% ZNE by 2020 (California Zero Net Energy, 2015) and there is active interest in all-electric new homes. But mandating existing homes to be retrofit, or replace appliances with non-conventional heating equipment could be expensive and difficult. With this backdrop, a careful analysis of multiple aspects of available and emerging technologies should be undertaken to avoid locking in expensive assets which might be sub optimal in the long run. Further estimates are also required to determine appropriate timing of potential transitioning to alternative technologies based on life cycle costs and carbon savings.

Given the uncertainty in estimating the 1990 emissions from residential water heating, we assume it is very similar to 2016 emissions with the efficiency gains in natural gas water heater (NGWH) standards compensating for the WH stock growth. Hence, in lieu of 1990, the reference year for future year GHG targets, we henceforth will use 2016 as the base year for comparison of future emissions. For an 80% reduction below 2016 (estimated 1990) level, the annual emissions due to this sector has to drop to 2.8 Million Metric Ton of CO_2-equivalent ($MMTCO_2e$) by 2050.

Replacement considerations of the existing appliance fleet include fuel choice, carbon intensity of the fuel, storage tank or tank-less for natural gas based heating, first costs to the consumer, life-cycle costs, contractor education and awareness, consumer awareness and preferences, etc. In this section, we discuss some important factors in water heating technologies.

The current efficiency standards of the most prevalent storage NGWH is 0.675, a 20% improvement over the past standard of 0.62 (United States Department of Energy (2008); California Energy Commission (2014). A more energy efficient natural gas option is an instantaneous or tank-less NG WH (INGWH), with an efficiency factor of 0.82 and above. INGWH partially achieves this higher efficiency by avoiding standby losses, and 0.82 is set as the minimum standard for natural gas water heaters in CA Title 24 building code (CA-BEES, 2016). INGWH have a higher installed cost due to the need to deliver higher instantaneous energy than conventional NGWH.

Among the electric WHs, electric resistance WH (ERWH) have the largest market share. The current energy factor (EF) standards of electric WH are 0.96 for ERWH and 2.0 for heat pump water heaters (HPWH) and correspond to storage tanks of under and over 55 gallons, respectively (CEC, 2015). The adoption of heat pump water heaters (HPWH) can clearly result in considerable reduction in energy and emissions compared to ERWH. Note that HPWH can reduce ambient temperature by 2–6°F when in operation, increasing space heating demand. Hence the location of installation of HPWH – conditioned or unconditioned space matters; however, we do not take this into account in this paper. Moreover, if the ambient temperature drops below ~45°F, HPWH will switch to electric resistance mode, reducing the efficiency of the unit (Shapiro and Puttagunta, 2016). However, California's mild weather for the most part precludes this situation. HPWH can save more energy than non-condensing and condensing gas water heaters if power comes from efficient natural gas combined-cycle or renewable energy based power plants (Nadel, 2016). Sanden has begun marketing $SANCO_2$, a heat pump with CO_2 as refrigerant in North America (Sanden, 2016). Similarly, solar thermal water heaters (SThWH) can play an important role in mitigating energy demand and emissions and have been adopted widely in several countries (e.g., Israel, China and Germany). California's favorable solar resource can help SThWH meet over 70% of the hot water demand (Cassard et al., 2011). In spite of a long history of receiving state subsidies, these have a negligible market share in California with capital costs about 5–10

Table 1
Water Heater Technologies - Energy Factors and Cost Assumptions.

	NG	ING	ER	HP	Advanced HP	STh +ERWH or (+HPWH)
2016 EF	0.675	0.82	0.95	2.0 (Refrigerant with GWP = 1430)	3.5 (Refrigerant with GWP =1)	2.4 (or 5.0) solar fraction = 70%
Capex ($)	850 [a]	900 [a,c]	300 [a,c]	1400 [a,c]	4500 [g]	6500 + Capex of backup [c,f]
Install/retrofit/fuel switch ($)	500 [a]	500 + 900 (retrofit)	500 [b]	500 +500 (fuel switch)	500	1500 [c]
Annual O &M ($)	0	85 [a]	0	16 [a]	16	25 [a]
Avg. Lifetime (years)	13 [e]	20 [e]	13 [b]	13 [b]	13	20 [a]

(d)Nadel, 2016,
[a] UE EIA 2015,
[b] Franco et al (2010),
[c] SMUD 2012
[e] CA-BEES, 2013, and
[f] CSI, 2016,
[g] NW-EcoBuilding, 2016

times that of conventional NGWH or ERWH (Table 1).

Overall due to low natural gas (NG) fuel prices, NGWH heaters remain the cheapest option for consumers on a lifecycle cost basis. The capital cost of ERWH is the lowest, but nonetheless, lifecycle costs favor HPWH over ERWH. (Fig. 3, and Shapiro and Puttagunta, 2016). Further, electrified storage WH like ERWH, HPWH and SThWH can play a major role in demand response designed to reduce peak demand and/or provide energy storage services to the grid. This is particularly important, with increased intermittent renewable based electricity generation coming on-line (SMUD, 2012; NEAA, 2014).

3. Model overview

The model starts with the current natural gas dominated business as usual ‘frozen’ scenario with current appliance efficiency standards held fixed into the future and where the electricity generation meets 50% renewable portfolio standards by 2030 per California law SB 350. Water heaters are replaced only on natural retirement and the transition to alternative technologies is phased in gradually over time. The technology-fuel type and efficiency of the replacement WH are dependent on the particular scenario. Each subsequent scenario incrementally adds possible future policy assumptions over and above the previous one, progressively bringing down GHG emissions.

Our stock turnover model takes into account the following five key factors that influence the emissions from the use of water heaters:

1. The carbon intensity of the fuel source.
2. Heating equipment energy efficiency given by energy factor (EF)[1] and existing federal and state energy efficiency appliance standards
3. The timing of fuel substituting e.g., starting in 2020 vs. 2030
4. GWP of refrigerants and emissions from refrigerant leakage
5. Hot Water Consumption

We model six broad categories of available water heating technologies that will constitute the portfolio of WH stock in any given year: natural gas storage water heater (NGWH), instantaneous or tank-less natural gas WH (INGWH), electric resistant WH (ERWH), propane WH (PWH), air source heat pump WH (HPWH), advanced heat pumps (AdvHP) with CO_2 (GWP = 1) as refrigerant, and solar thermal water heaters (SThWH). For simplicity, and in line with data from appliance studies, we assume the mortality rate of all water heater technologies follows a Weibull probability distribution. (Lutz et al., 2011a, 2011b; United States Energy Information Agency (US EIA), 2014).

Some of the future policy considerations we consider are the following: gradually reducing grid carbon intensity to meet the 2050 goal of 80% GHG emissions reduction, gains in WH efficiencies every decade, and switching to refrigerants with lower GWP for heat pumps. The high GWP (over 1400) hydrofluorocarbons (HFCs) based refrigerants in appliances such as heat pumps have to be phased down to lower GWP alternatives to comply with SB 1383 and the recent amendment to Montreal Protocol (US EPA-GWP, 2016). Advanced HP with CO_2 refrigerant (called “Eco-Cute”), has been marketed in Japan for decades (E3T, 2016). For solar thermal water heaters, we compare backup options of electric resistance (STh+ER) and heat pump (STh+HP). The high cost of solar thermal technologies and advanced heat pump technologies can potentially be mitigated if sized appropriately for both space and water heating. These “combo” systems marketed in Europe (International Energy Agency, Solar Heating & Cooling Program IEA-SHC, 2013a, 2013b) are not considered here. Gas-based HPWH are also not considered since they represent only an incremental efficiency gain from INGWH and are not sufficient to meet the long-term climate targets.

In 2016, the base year for the model, the residential WH stock comprises of 90% NGWH, 6% ERWH and 4% PWH with an average age of 8 years. For comparison, the weighted average age of water heaters in the western region in 2009 was estimated to be 9 years (RECS, 2013). Annual energy and emissions depends on the vintage years of the stock and the corresponding energy and emissions factors assumed for those years. The first five scenarios use only WH technologies which are included in today's federal standards – NGWH, INGWH, ERWH, PWH and HPWH. Each subsequent scenario builds on the previous ones, with additional assumptions incremental to previous ones. Each scenario thus achieves an incremental reduction in GHG emissions. In the fuel substituting scenarios, electrification of the stock is phased in gradually, with a certain percentage of the retiring NG or propane stock fuel switched to electricity. In the sixth scenario, ‘Advanced Technology scenario’, new homes built after 2020, in compliance with ZNE goals, choose to adopt advanced HPWH or Solar thermal WH with heat pump backup while the retiring existing stock make their replacement choice based on economics.

3.1. Energy factor

For NGWH, prior to 2016, the efficiency of a stock depends on its vintage year; and EF follows the Department of Energy's water heater standards. (United States Department of Energy, 2010, CEC, 2016). With this assumption, we arrive at an estimated weighted average EF of 0.62 in 2016 for the NGWH stock. Assumptions for current and future efficiency standards and adoption years for various technologies can be found in Table 2. These assumptions are based on 2016 California Building Energy Efficiency Standards and the Department of Energy's appliance standards (California Building Energy Efficiency Standards,

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[1] Energy Factor is the ratio of energy output from the water heater to the total energy delivered to the WH.

Table 2
Energy Factor Assumptions for Stock Turnover Model.

WH Technology	Time Horizon	Energy Factor Assumption[a]
Natural Gas	2016	0.62 (weighted avg. EF of existing stock)
	2016–2020 (a)	0.675
	2020–2030	0.77
	2030–2050	0.85
Instantaneous Natural Gas	2016–2030	0.82
	2030–2050	0.95
Electric Resistance	< 2020	0.96
	> 2020	0.96
Heat Pumps	< 2020	2.0 with Refrigerant GWP =1430
	2020–2030	2.5 with Refrigerant GWP = 4
	2030–2050	3.5 with Refrigerant GWP = 4
Advanced HP	2016	3.5 with Refrigerant GWP = 1

[a] Energy factors, GWP of refrigerants and the years of adoption of standards assumed here are based on US DOE Energy Star (2016), CA-BEES, (2013) and US EIA, 2016, Baxter et al. (2016).

2016; Department of Energy, Energy Star, 2016; US EIA, 2016).

3.2. Refrigerants

Currently HPWH market is dominated by units using hydrofluorocarbon (HFC) based refrigerant, R-134a with a GWP of around 1430 (US Dept. of Energy, 2016). With the goal of an eventual phase-down of HFC refrigerant (US EPA, 2016), one potential refrigerant, R-1234yf, with a GWP of 4 has emerged. Results from initial tests of R-1234yf in lieu of R-134a in General Electric's HPWH indicate that a more optimized R-1234yf design may closely match the performance of R-134a (Baxter et al., 2016). Consistent with this, our model assumes heat pumps have refrigerants with a GWP of 1430 till the year 2020 after which a refrigerant with a GWP of 4. We assume an average heat pump will contain a 0.75 kg of refrigerant (Baxter et al., 2016). Table 3 below gives refrigerant's lifecycle leakage assumptions. We assume that the efficiency factor of the appliance and refrigerant leakage are the same for both refrigerant types. The refrigerant in advanced HP (AdvHP) is CO_2 and hence has a GWP of 1. The refrigerant used in the HP backup in STh +HP will depend on the adoption year.

3.3. Fuel carbon intensities and costs

For natural gas and propane, a fixed carbon intensity of 6.1 kg/therm and 5.7 kg/gallon, respectively, is assumed throughout the time horizon (PGE-CC, 2016). We arrive at the carbon intensity by projecting a 'business-as-usual' electricity demand of 370,000 GWh for the year 2050, by extending the 2026 projections of California Integrated Energy Policy (CA IEPR, 2015) and using electricity sector's emissions from the California Air Resources Board (2000, 2016). The carbon intensity of grid-supplied electricity decreases continuously from the 2016 level of 0.28 kg/kWhe to 0.203 in 2030 to 0.06 in 2050 as per California climate legislation (CA-SB350, CA-AB 32, 2016). Note that with the EFs assumed in Table 1 below, HPWH have much lower GHG emissions than NGWH using average emissions factors and slightly lower emissions using a marginal emissions factor corresponding to a natural gas generator. As the grid becomes cleaner (lower carbon), the grid emissions factor for HPWH is expected to drop. Demand response with HPWH can in the future also shift demand to times of high solar PV output.

Table 3
Refrigerant leakage assumptions.

Average amount of Refrigerant in a heat pump[a]	0.75 kg
Average leakage in installation	0.05%
Average annual leakage[b]	2%
End of life loss rate[b]	100%

[a] Baxter et al. (2016), US EPA (2015), GHG (2015).
[b] Gallagher et al. (2013).

Current retail price of natural gas is roughly 4.5 times cheaper than electricity at $0.04 per kWh (or $1.138 per therm) while the average retail electricity price in the residential sector is $ 0.175 per kWh (US EIA, 2016). Our goal in this paper is to present the relative merits of each of the technology and fuel choices. Given the uncertainty in future fuel prices and to keep the analysis simple, we assume an annual retail price for all the three fuel sources to increase at an annual rate of be 2%. In Table 5 we present upper bounds of costs assuming the retail electricity prices increase at an annual rate of 5%.

3.4. WH cost assumptions and learning

Cost assumptions for WH technologies (Table 1) are based on several studies including building sector appliance and equipment costs given by US Energy Information Administration (United States Energy Information Agency (US EIA), 2015; Franco et al., 2010; and SMUD, 2012). For an NG or propane based WH to switch to electricity, we assume an average electric upgrade cost of $500 over and above the installation cost. A switch from storage based NGWH to instantaneous NG WH will incur an installation cost of $900 because of additional gas infrastructure requirement on-site to provide higher energy to heat up water quickly.

NGWH and ERWH have millions of units deployed and their cost and operations are perhaps better understood with little room for price drop. However, INGWH and HPWH have low market share and less operational data. A gain in market shares of INGWH and HPWH could result in economies of scale in manufacturing and learning by doing bringing down the installed costs. On the other hand, energy efficiency improvement could result in higher costs. However, Desroches et al. (2013) show that the manufacturing costs decreased by 40% for doubling of efficiency for split air-conditioners during 1999–2011; similarly, for room A/Cs they estimate a price decrease of 33% for an efficiency gain of 30%. Conversely, equipment efficiency improved by over 30% at the same price over about a decade. Assuming similar price dynamics for water heating technologies, as a simplified proxy to continuous technology and manufacturing improvements, we assume that the price of HPWH, INGWH, and NGWH remain constant, even as performances increase per Table 2 each decade. Another way of interpreting this assumption is that this defines a cost-performance target for INGWH and HPWH across the next several decades.

While solar thermal water heaters are well understood and economically viable in several countries, the system cost can be over $7000 in California with low adoption rates (California Solar Initiative, 2016). California Solar initiative's (CSI) thermal program rebate combined with the 30% federal residential renewable energy tax credit will bring down the installed cost (California Solar Initiative, 2016). However, with uncertainty in future policy and unclear impact of subsidies on adoption rates, we assume capital and installation costs of $6000 and $1500, respectively. An additional cost of a backup technology is assumed. For AdvHP an installed cost of $5000[2] is assumed (NW-EcoBuilding, 2016). While all technologies are assumed to have a fixed installation cost of $500, SThWH technologies have an installation cost of $1500.

For AdvHP and SThWH technologies, we assume a learning rate of 10%; that is for every doubling of cumulative capacity installed, the price drops by 10%. For comparison, learning rates between 10% and

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[2] $5000 is the cost for a combination -space and water heating equipment, after Oregon rebate. We are assuming this as the cost without rebate for water heating.

20% for gas and electric water heaters are estimated in appliance price forecasting in United States Department of Energy (2011). For both these technologies we assume a floor price, below which the installed cost cannot fall. While advanced HP technology might have technical challenges that might keep the floor price high, solar thermal water heaters have seen large-scale global adoption and should have a lower floor price. However, labor and overhead costs have room to decrease with experience, as in solar photovoltaic systems (Chung et al., 2015). Noting the difficult in predicting future prices, we assume a floor price of $2500 for the total installed cost for both AdvHP and STh+HP.

3.5. Other assumptions

Lutz et al. (2011a) and Parker et al. (2015) in their studies estimate the average daily demand of hot water for an average household with 3 occupants as being around 50 gallons. Further the Parker et al., study indicate that the demographics of the household and the number of occupants are highly correlated with the hot water usage. In California, natural gas demand to meet the annual hot water consumption of a single and a multi-family home on average, are not statistically different; while annual electricity demand of a multi-family home is only 50% of that of a single-family home (RAAS, 2009). However, with significant market share, the results for NG based WH perhaps is likely to have a higher statistical significance. With this backdrop, our model assumes an average of 50 gallons of daily hot water demand per household, without distinguishing between single-family and multi-family usage. The temperature of the inlet water is increased by 75 °F for delivery in the model as suggested in Lutz et al. (1998). Lifetimes of all water heaters are assumed to have an average life of 13 years, except for SThWH and INGWH, which are assumed to operate on average for 20 years (Lutz et al., 2011b; US EIA, 2015).

4. Results and discussion

In Section 4.1, we compare energy usage, emissions and the costs associated with the various water heating technologies. In Section 4.2, we describe scenario assumptions that lead to lower emissions in 2050 and that can be achieved by the adoption of supporting policies. We then compare the emissions and costs associated with each of the scenarios. Note that these scenarios are meant to be illustrative and to provide a range of options and possible technology and potential costs for decarbonizing the residential water heating sector.

4.1. Comparison of water heating technologies

The annual energy consumption by a water heater is assumed to be fixed for a given appliance over its lifetime assuming a daily average hot water demand of 50 gallons. The average annual energy consumption of WH technologies are compared in Fig. 1. Three different HPWH technologies (HP1, HP2, AdvHP) with different energy factors and refrigerant types are compared. For the solar thermal water heater, two different backup heating technologies are considered: electric resistance backup (STh+ER) and HP (STh+HP) backup. We do not include the impacts of ambient air temperature cooling in the case of HPWH.

Fig. 2 and Fig. 3 compare emissions and life cycle costs of the five technologies for three different installation years at varying energy factors. Here the carbon intensity of the electric grid is gradually reduced and the 2050 emissions are 80% below the 1990 level. The annual emissions of a WH will depend on the amount of hot water consumption, the efficiency of the appliance, GWP of the refrigerant and refrigerant leakage assumptions, and the carbon intensity of the fuel source in that year. For HPWH and STh+HP, the solid color in the bottom of the bars represents the emissions from fuel source and the top hatched (‘**’) part represents the emissions due to refrigerant leakage. Here we can see the emissions drop with the improvement in appliance efficiencies as per the timeline given in Table 2, dropping of

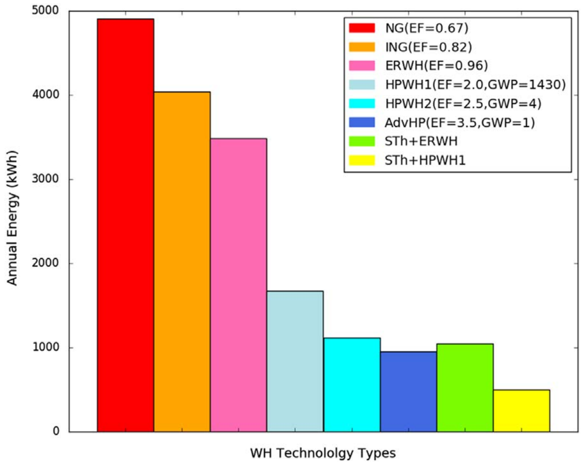

Fig. 1. Annual Energy Consumption of WH Technologies.

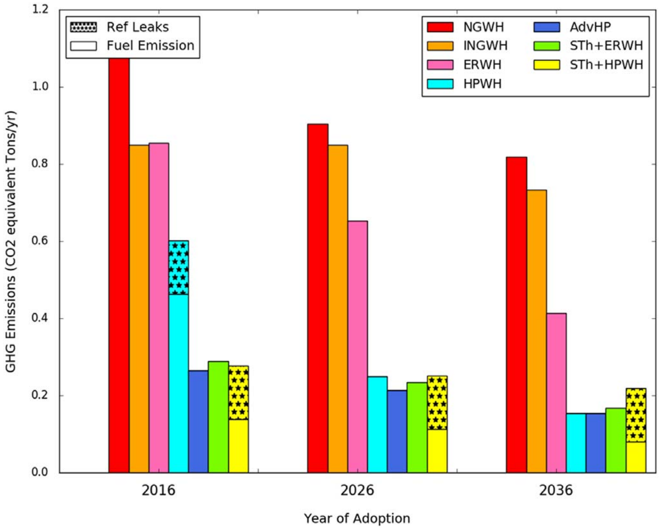

Fig. 2. Average Annual Emissions from source fuel (solid color) and refrigerant leakage(**).

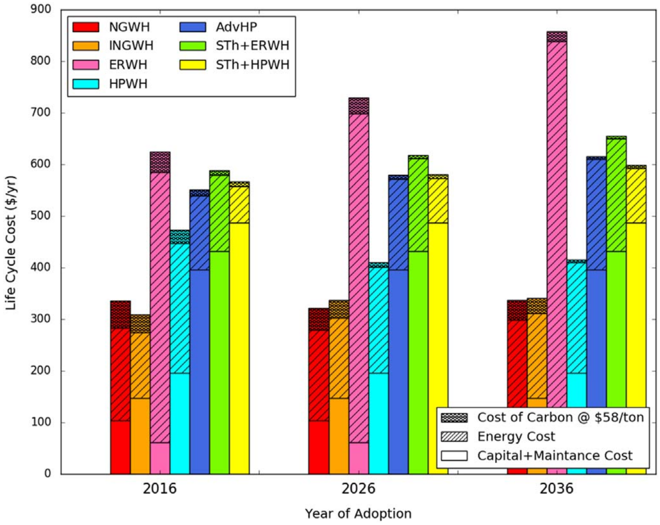

Fig. 3. LCC of WH Technologies – Capital & Maintenance Cost (solid color), Energy Cost (//), Carbon Cost (**) at $58/ton.

carbon intensity of the grid and the lowering GWP of the refrigerant.

The total lifecycle costs (LCC) of operating a water heater consists of the initial capital cost, installation cost, any upgrade costs (e.g., electrical panel upgrade), annual maintenance cost and replacements costs, annual fuel or energy costs. In Fig. 3, the solid color bars are the annualized cost of capital, installation, and maintenance cost and the shaded ('//') section is the average annual energy cost. The hatched ('**') tip of each bar is the average annual social carbon cost assuming a carbon tax of \$57.50[3] per ton of emission is levied (SC GHG, 2016). We observe that energy costs remain fairly flat for NGWH, INGWH, HPWH and STh+HP, as energy price increase (2% annually) is compensated by efficiency gains. However, energy costs increase marginally with higher energy costs every decade for ERWH and STh+ER,

4.2. Scenarios for WH adoption

Table 4 below describes the assumptions of six scenarios of WH stock turnover over the years 2016–2050. As illustrations, Figs. 4, 5 and 6 present the evolution of the state's residential WH stock, annually, under the assumptions of the scenarios, 'NG + Energy Efficiency', '2020 Electrification' and 'Advanced WH Technologies', respectively.

4.2.1. Key results of the WH stock turnover scenarios

We observe that the following factors all have to occur for deep emissions reduction: (i) electrification phase- in by 2020, (ii) gains in appliance efficiency standards, (iii) decrease in GWP of refrigerants, and (iv) decrease in grid carbon intensity. By adopting the '2020 Elec_Low GWP' scenario that includes all four factors, GHG emissions can be reduced by 82% below 2016 levels. This is accomplished with the widespread adoption of electric heat pump technologies. Increased adoption of advanced HP and solar thermal water heater from 2020 onwards can help lower the emissions further to 87% below 2016 levels. We do not consider a "forced-adoption" case that would require the replacement of existing stock with new equipment before existing equipment end-of-life. Such a forced replacement could in principal move out the latest year for electrification or solar WH phase-in, but would result in greater stranded equipment costs, would not provide the equipment manufacturing industry time to ramp up production, and would be a greater discontinuity to electricity load for grid planners and utilities. We present below key take away from each of the scenarios presented in the last section.

4.2.1.1. Frozen. Increasing efficiency units are not sufficient to compensate for the stock growth and annual GHG Emissions will increase to 16.4 million tons by 2050, a 14% increase from 2016. The total energy demand in 2050 will be 77.3 Billion kWh (95% from natural gas usage) and 18% above current annual usage. The net present value (NPV) in 2016 of the total replacement cost (capital and installation costs but excluding maintenance costs) of retiring stock of WHs between the years 2016 and 2050 is estimated to be \$25 billion.

4.2.1.2. NG + EE. The annual GHG emissions in 2050 will be 13 $MMTCO_2e$, a 10% reduction from the 2016 levels primarily driven by the adoption of higher efficiency INGWH. This scenario will result in a total energy demand of 61 billion kWh in 2050. The lower carbon intensity of the grid does not play a significant role since only 5% of the WHs are electric. The NPV of replacement cost in this scenario will be slightly higher at \$26 billion, with the larger adoption of INGWH.

4.2.1.3. Electrification. By 2050, around 64% of the WH stock will have adopted HPWH in this scenario. However, with electrification starting in 2030, the emissions in this scenario do not meet the sectoral target. In 2030, the emissions will be 13.2 million tons and by 2050 will reduce by 50% from 2016 levels to 7.0 million tons. The total energy demand will drop substantially from previous scenarios to 33 billion kWh with NPV of replacements costs in 2016 at \$29 billion.

4.2.1.4. Electrification. With electrification phasing-in in 2020, emissions in 2030 will reduce to 11.8 million tons and to 5.0 Million tons by 2050, a 66% reduction from 2016 levels. In 2050, close to 90% of the WH stock will be electric and will account for 66% of the total energy demand of 21.7 billion kWh. The NPV of equipment replacement cost of this scenario is \$33.1 billion.

4.2.1.5. Elec + low GWP. The drop in GWP brings the GHG emissions in 2050 to 2.45 Million tons, a reduction of 82% from 2016 levels. The energy demand will remain the same as in the previous scenario. We assume no change in capital costs for these HPWH with lower GWP refrigerants, hence the cost of replacement in the scenario remains the same as the previous case.

4.2.1.6. Advanced technology. In this scenario, emissions in 2050 drop to 1.8 $MMTCO_2e$, an 87% drop from 2016 levels. The energy demand in 2050 is at 15.9 billion kWh. With the initial high capital cost assumptions, the replacement cost for the scenario is considerably higher at \$43 billion than the rest of the scenarios. However, the NPV of all costs including, replacement, energy and carbon is only 2% higher than the frozen scenario or 10% higher than the 'NG+EE' scenario.

4.3. GHG emissions trajectories

Fig. 7 shows the GHG trajectories accompanying each of these six scenarios; the adoption of two of the scenarios (2020 Elec + GWP and Adv Tech) can bring down the emissions by over 80%. Fig. 8 shows the contribution of each of the four factors (green bars) resulting in the net reduction of 82% in the 'Low GWP' case. The top two curves represent the emissions in frozen' and reduction in NG+EE' scenarios relative to 2016 level. Just phasing in electrification in 2020 is not sufficient and must be accompanied by improved energy efficiency, lowered carbon intensity of grid and lower GWP refrigerant. Reducing daily hot water consumption by 25% can bring the emissions further down to 87% below 2016 level, similar to the AdvTech scenario.

The last column of Table 5 shows the cumulative GHG emissions resulting from the scenarios presented above. The cumulative emissions reduction to 2050 in the '2020 Elec+GWP' relative to the frozen case can be seen to be over 200 MMT CO_2e. The overall additional costs to 2050 of equipment replacement and energy due to the adoption of this scenario is \$3.6 billion over the frozen case (first two columns of Table 5), corresponding to a cost of \$18 per ton of CO_2 savings. Similarly, the 'Adv Tech' scenario reduces cumulative emissions by 224 MMT CO_2e and has a cost of \$33 per ton of CO_2 savings. Reducing hot water demand by 25% in the '2020 Elec+GWP' case results in cumulative emissions savings of 282 $MMTCO_2e$, and a cost of -\$47 per ton of CO_2 savings. For example, lower hot water consumption can be achieved through efficiency improvements in washing machines and dish washers (Portland Water, 2016; US DOE, 2012).

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[3] A fixed carbon cost of \$57.50/ton through 2016–2050 at our model's discount rate approximates the cost schedule of CO_2 (3% discount rate case) in the Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis- Under Executive Order 12866- August 2016.

Table 4
Assumptions on Scenarios of Stock turnover of WHs.

Scenarios	Assumptions on Stock	Other Assumptions
Frozen	Retiring NG and Propane based stock will be replaced by same fuel based technology, but with 2016 efficiency standards. ERWH will be replaced by HPWH of EF of 2.0. All new homes will adopt INGWH of EF 0.82 (CA-BEES, 2016).	2030 Grid emissions are 40% lower than 1990 levels (CA-SB 32) Grid emissions from 2030 to 2050 will be held fixed. No efficiency gains from 2016 to 2050. No reduction in GWP of refrigerants used in HPWH.
NG+ Efficiency Efficiency (NG+EE)	No fuel substituting. Of the retiring NG stock: 25% will be replaced by INGWH and 75% by NGWH. All new homes get INGWH.	GHG Emissions from the grid continue to drop after 2030. The 2050 emissions drop to 80% below 1990 levels. Efficiency improves every decade as per Table 2. No GWP improvement as in the frozen case.
2030 Electrification	Electrification gradually phased in 2030. Starting 2030, retiring non-electric WHs in the existing homes and new homes will switch to electric HPWH, ramping to 60% the retiring stock in 2040; 100% by 2050.	Same as NG + EE Scenario
2020 Electrification	Electrification gradually phased in 2020. Starting in 2020, retiring old heaters and new homes start adopting electric HPWH. 60%, 90% and 100% of the retiring stock will adopt electric HPWH by 2020, 2030 and 2050, respectively.	Same as NG + EE Scenario
2020 Elec + Low GWP	Same as 2020 Electrification Scenario	In addition to last scenario, 2020 on the GWP of refrigerant drops to 4 from 1430.
Advanced Technology	Percentage of retiring existing stock choosing to electrify same as above. 3 electric WHs available for replacement for retiring stock: HPWH, STh+HP and AdvHP: 80% choose cheapest, 15% 2nd cheapest and 5% the most expensive. From 2020, new Homes will adopt either STh+HP or AdvHP.	Solar Thermal water heater has a HPWH as a backup. With learning by doing, installed costs of these Solar Thermal WH and AdvHP technologies will drop over time.

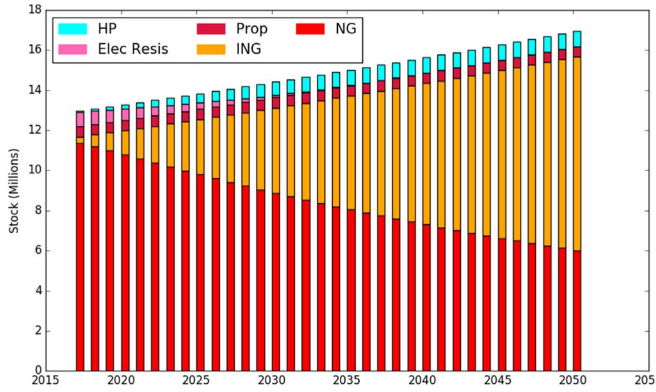

Fig. 4. WH stock under 'Natural Gas + EE' Scenario.

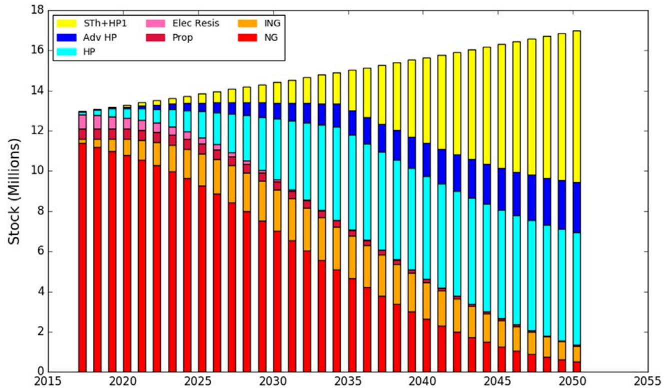

Fig. 6. Advanced WH Technologies Scenario.

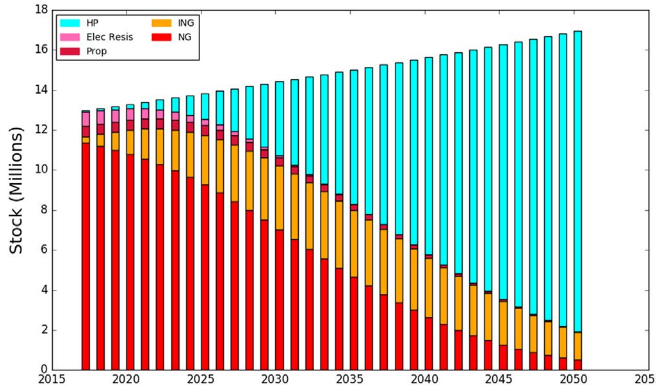

Fig. 5. Water Heater Stock in the 2020 Electrification Scenario.

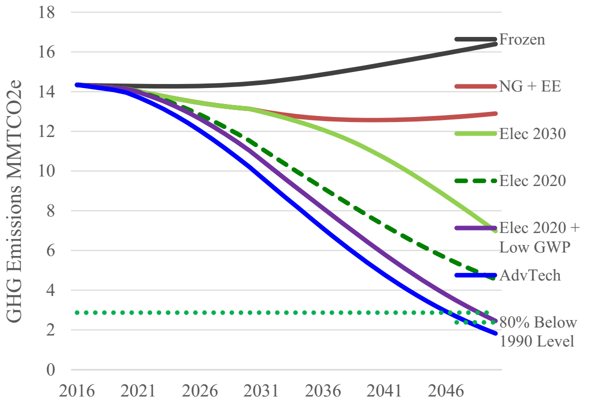

Fig. 7. GHG Emissions trajectories for each Scenario.

4.4. Energy demand

Moving from the frozen scenario to the 'Low GWP' scenario, we see the emissions drop primarily due to electrification and the adoption of high efficiency electric HPWH. Fig. 9 shows the total energy demand in the year 2050 from each of the scenarios. With efficiency gains in natural gas based WHs, the NG demand as well as the electricity demand in the 'NG+EE' scenario drops from the frozen case. We can see that from this scenario on, natural gas demand shrinks and electricity demand increases though at a slower pace. The fourth and fifth bars are identical, as the only difference is the GWP of the refrigerant which only affects the emissions. The 6th bar is the result of 25% lower hot water usage. The total energy demand in the 'Adv Tech' scenario is 17% lower than the Low GWP case and hence results in lower emissions. The solar thermal system with efficient HP backup results in the lowest energy demand and emissions. While the high up-front capital costs of these technologies are a barrier to widespread adoption of these, long term energy consumption should be an important consideration.

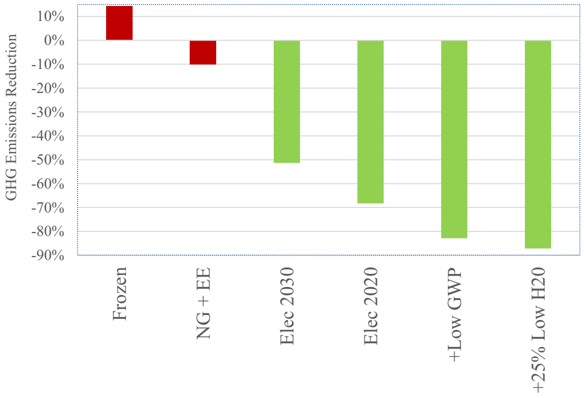

Fig. 8. Step wise Emissions Reduction in 2050 from 2016 under '2020 Elec+Low GWP' scenario.

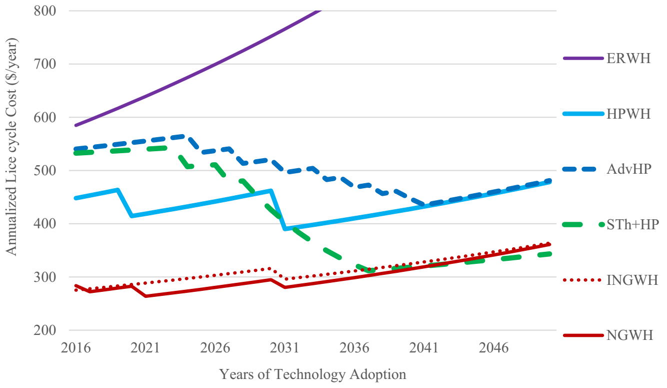

Fig. 10. Life Cycle Cost comparison of installing WH technologies under the Advanced Tech. Scenario.

Table 5
Net Present Value of Costs in 2016 for Expenditure in 2016–2050.

	NPV of Energy Cost ($billions)	NPV of Replacement Cost ($billions)	NPV Carbon Cost (@$58/ton) ($billions)	Total NPV Cost ($billions)	Cumulative GHG emissions (MMT CO_2e)
Frozen	75.7	24.7	15.8	116.2	524
NG+EE	68.1	26.0	14.4	108.5	463
2030 Elec	68.6	28.8	13.8	111.2	419
2020 Elec	70.9	33.1	12.7	116.8	360
'2020 Elec with Low GWP'	70.9	33.1	11.8	115.8	321
'2020 Elec with Low GWP' With 25% low H20	54.0	33.1	9.1	96.0	242
'2020 Elec + Low GWP' With Elec price increases at 5%	96.0	33.1	11.8	141.0	321
'2020 Elec+ Low GWP' with high HPWH price[a]	70.9	41.0	11.8	124.0	321
Adv Tech	65.0	42.8	11.0	119.0	300
'Adv Tech' with High Elect price increases at 5%	83.0	42.8	11.0	137.0	300

[a] In this case, the capital cost of HPWH increases commensurate with efficiency gains assumed in 2020 and 2030.

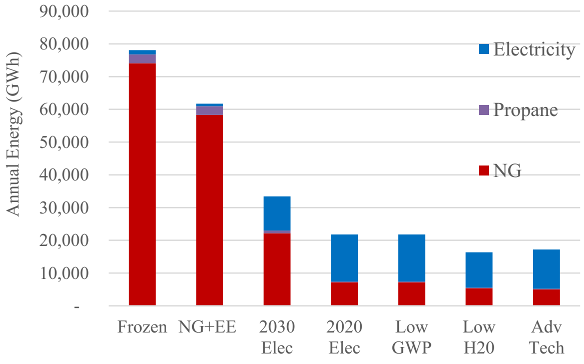

Fig. 9. Total Energy Demand in 2050 under Different Scenarios.

4.5. Economic impact of adoption scenarios

The 'Adv Tech' scenario assumes that new homes built after 2020 choose either AdvHP or STh+HP meet their hot water need. This helps kick-start the cumulative installation of these two technologies. Over time, with increased cumulative adoption, the capital cost will drop with learning. Fig. 10 compares the lifecycle cost of installing each of the WH technologies over the entire time horizon under the 'Adv Tech' scenario. The upward slopes in all cases are due to fuel price increase at an annual rate of 2%. The efficiency gains bring down the energy costs in the years 2020 and 2030 for NGWH, INGWH and HPWH. Learning rate assumptions are responsible for cost reductions in the long run for AdvHP and STh+HP. As expected, NGWH and INGWH are the least expensive due to low fuel costs and lower capital costs. In spite of the lowest capital cost ERWH is expensive on a lifecycle basis due to high energy costs. The high capital cost of INGWH, spread over the assumed 20-year lifetime, is not so onerous.

HPWHs adopted after 2030 will have an EF of 3.5 which is equivalent to the EF of AdvHP, and with the decline in capital costs of AdvHP due to learning, by 2040 these two have the same LCC. This is justified, as they are essentially the same technology. With high solar fraction of 70% in California the annual operating energy cost of STh+HP in the early years will be roughly half of that of AdvHP and one-third of that of HPWH. Moreover, with low energy consumption, STh+HP's LCC costs are fairly immune to rising electricity price. Further, the high capital cost of STh+HP is amortized over 20 years as against 13 years for AdvHP, hence STh+HP starts with a slightly lower lifecycle cost than AdvHP. The majority of owners of retiring water heaters will chose the cheapest of the HPWH, AdvHP and STh+HP. With low LCC STh+HP gains a higher market share than AdvHP. This in turn triggers higher adoption rates for STh+HP, leading to further decline in price due to learning. By 2031, STh+HP breaks even with HPWH and by 2037 the LCC of STh+HP drops below natural gas based heating options.

Table 5 compares net present values of energy cost, appliance replacement cost (capital cost and installation cost) and carbon cost. Energy costs outweigh equipment replacement costs in all scenarios. While the 'Low GWP' scenario has lower capital cost, the Adv Tech scenario has lower energy cost. The 'Low GWP' scenario has a 7% higher cost than the NG+EE case. A 25% lower hot water consumption, will reduce overall cost by 16% in the 'Low GWP' case, making it lower cost than the NG+EE case. All the analysis is based on NG and electricity prices increasing at 2% annually. However, if the electricity price were to increase at a steeper rate because of the higher renewable mix (E3, 2015; Cooke et al., 2015), at 5% electricity annual increase in the '2020 Elec + Low GWP' scenario, the NPV of energy cost increases to $96 billion compared to the $71 billion at the baseline 2% increase rate. In our assumptions thus far, we have assumed that HPWH capital costs stay fixed even with efficiency gains. If the capital costs of HPWH were to increase at the same rate as the efficiency gains assumed, then the total replacement cost of equipment in the 'Low GWP' case will be 24% higher at $41 billion. With higher electricity prices, the NPV of energy cost in the 'AdvHP scenario' will increase to $83 billion. The three shaded rows in Table 5 provide upper bounds of potential cost of bringing down the emissions. Compared to the NG+EE case, these cases range from 14% to 30% higher NPV.

5. Discussion

None of the above scenarios meet California 2030 target of 40% emissions reduction in the residential water heating sector. For example, in the 'NG+EE' scenario, the share of storage based NGWH drops to 60% by 2030 while the more efficient instantaneous INGWH's share goes up to 30%, resulting in a modest 7.5% drop in 2030 emissions relative to 2016. Even with electrification phasing in 2020, as majority of the existing stock in 2030 will still be natural gas based, the emissions in 2030 can only be brought down by 20% below 2016 levels. However, a 25% reduction in hot water demand in the 2020 electrification scenario bring 2030 emissions reduction to over 40%.

Simplified assumptions in this study are the assumptions of the same hot water demand for all household and the limited number of appliance models. A more detailed treatment would consider the range of hot water consumption across household types and the potential market adoption by technology and model types to determine the optimal implementation of energy efficiency standards. For example, a typical federal energy efficiency standard for appliances takes into account the range of LCC impacts across a representative sample of the population but this is beyond the scope of this pathway study.

Not considered here but additional important factors to explore for further work include other market adoption approaches and possible market barriers such as product reliability, maintenance, noise and other technology issues for HPWH that may hinder future customer acceptance. The cooling effect of HP heating is a possible issue in terms of adding incremental heating costs in conditioned spaces and would benefit from further characterization and pilot study.

The impacts of more electrified water heating to electricity load shapes and to the electricity grid has been treated to some extent in Wei et al. (2013a, 2013b), but more study should be done for various technology deployment scenarios. In the Wei study, additional demand from water heating was offset by energy efficiency savings in other sectors, mitigating overall impacts to the grid, although shifting to both electrified water heating and electrified space heating could in some cases shift the electricity system peak in 2050 from a summer peak to a winter peaking system. The costs of electric water heating (ERWH or HPWH) could be lessened with the capability to provide demand response or demand shifting and should take into account typical hot water usage patterns and equipment responsiveness and performance impacts. An aggregated population of electric storage water heaters could provide grid support or greater flexibility for a grid with more intermittent renewables and more studies or testing in this area would be informative for utilities and grid planners.

Finally, identification and evaluation of potentially hidden costs and benefits of wider scale electrification along with additional infrastructure costs due to increased generation should be pursued. Similarly, the impact to natural gas infrastructure and maintenance costs, and, possible avoided costs of lower natural gas transmission and distribution (T & D) infrastructure should be evaluated. In either case, resiliency studies could be undertaken looking at future risks to infrastructure build-outs under more extreme weather and climate conditions.

6. Conclusion and policy implications

We have provided the first detailed stock modeling of water heating decarbonization on a statewide basis for California. We conclude that an 80% or above reduction in 2050 emissions relative to 1990 is technically possible resulting in an annual abatement of over 10 million tons of GHG emissions. We formulate a couple of representative pathways to achieve this deep decabonization. The cost range of the scenarios depends on energy and equipment costs, and hot water consumption. Adhering to a strict pathway to decarbonizing the grid, phasing in electrification of water heating, achieving steady gains in heat pump WH energy efficiency, and transition to lower GWP refrigerants, can result in desired emissions reduction. A 25% reduction in hot water usage can help bring down the energy cost which can help lower the life cycle costs of adopting more efficient and higher priced heat pump technologies. We find that waiting until 2030 for the NG stock to switch to electricity (assuming gradual rates of adoption, i.e. we do not assume a "forced" transition), can at best reduce the 2050 emissions by 50% and that electrification phase-in would need to occur in 2020 to meet the 2050 decarbonization target.

Electrifying the building water heating sector would be a difficult challenge due to the market, policy, and customer adoption challenges described above. However, on a qualitative basis it could be argued that this sector would be less difficult to decarbonize than some other sectors such as heavy duty transport and energy-intensive industrial sectors which require greater technology development and/or greater supplies of low carbon fuels.

There is currently no explicit state policy for fuel substitution in the building sector. California SB 350 statute language calls for doubling of the baseline rate of energy efficiency by 2030. 2017 California Energy Commission staff paper proposes, "establishing sub-targets as internal components of the gas and electric statewide annual targets, using the non-exhaustive list of programs through which the targets may be achieved in Section 25310 (d) of SB 350 as a guide." Further the paper recommends, "including programs that save energy in final end uses by using cleaner fuels to reduce greenhouse gas emissions as measured on a lifecycle basis from the provision of energy services." (California Energy Commission, 2017) However, the California Energy Commission has yet to establish targets for fuel substitution programs. Similarly, for the state to achieve ZNE goals the use of natural gas energy has to be carefully addressed (CA IEPR, 2015). Future GHG policy development can benefit from highlighting the need for decarbonization of the building-heating sector for example through fuel substituting targets and/or more renewable natural gas. Existing methodologies for energy savings through energy efficiency may need to be modified to include and accommodate increased electricity demands from electrification.

For decarbonization of buildings, sustained policies over time could be conducive to provide consistent policy signals to the equipment manufacturing industry to anticipate and plan for potential new demands. This would also provide lead time for grid planners and utilities to plan for additional electricity load. For a large-scale shift to high efficiency electrical heat pumps, one of the main impediments is its high upfront cost. Policies to encourage the adoption of heat pump technologies such as equipment rebates and incentives could result in larger market adoption and increased learning by doing and economies of scale in manufacturing. Finally, hot water conservation can be a potentially large policy lever in reducing decarbonization costs in the residential hot water heating sector, but the costs of reducing hot water consumption should be better quantified.

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Appendix

See Tables 6 and 7.

Table 6
Model Assumptions.

Occupied Households in California 2016 (Millions)	12.87 (assuming 7.4% vacancy)[a]
Annual Population Growth	0.82%
Cost of NG in 2016 ($/therm)[b]	1.138
Cost of Electricity in 2016 ($/kWh)[b]	0.175
Cost Propane in 2026 ($/gallon)	2.05
Carbon Intensity Factor for electricity (kg/kWh)[c]	0.277 (2016), 0.203 (2030), 0.063 (2050)
Carbon intensity of NG (kg/therm)[d]	6.1
Carbon intensity of Propane (kg/gallon)	5.67
Annual increase in fuel price	2%
Discount Rate (social)	4%

[a] State of California, Department of Finance Projections http://www.dof.ca.gov/Forecasting/Demographics/projections/, accessed September 2016.

[b] US Energy Information Administration, average residential retail prices for September 2016.

[c] Author's estimates based on CA IEPR- (2015) electricity demand projections and (CA-RPS, 2016)

[d] PGE (2016). carbon intensity of electricity is estimated using total electricity demand (in-state+ imports) and associated emissions from generation (CA IEPR, 2015, CA-ARB, 2016), natural gas carbon intensity of 13.446 lb./therm; http://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf, accessed September 15, 2016.

Table 7
Water Heater Emissions for 2016 (Estimate).

	Natural Gas		Elec Resistance	Propane	Total
California Stock (%)[a]	90%		6%	4%	
WH Stock size in 1990 (Millions)	*9.3*	*0.6*		*0.4*	
WH Stock Size in 2016(Millions)	11.58	0.77		0.51	
Energy Efficiency (2016)[b]	0.62	0.96		0.62	
Energy use(Units/WH/year)	5390 kWh	3485 kWh		5360 kWh	
Annual Emissions (MMTCO$_2$e)	**13**	**0.75**		**0.59**	**14.3**

[a] RAAS (2009).

[b] For natural gas, this is computed as the weighted average of the energy factors of the fraction of stock alive from varying past vintages.

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