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Greenhouse gas emissions from domestic hot water: heat pumps compared to most commonly used systems

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Abstract

We estimate the emissions of the two most important greenhouse gasses (GHG), carbon dioxide (CO_2) and methane (CH_4), from the use of modern high-efficiency heat pump water heaters compared to the most commonly used domestic hot water systems: natural gas storage tanks, tankless natural gas demand heaters, electric resistance storage tanks, and tankless electric resistance heaters. We considered both natural gas-powered electric plants and coal-powered plants as the source of the electricity for the heat pumps, the thermal electric storage tanks, and the tankless electric demand heaters. The time-integrated radiative forcing associated with using a heat pump water heater was always smaller than any other means of heating water considered in this study across all time frames including at 20 and 100 years. The estimated amount of CH_4 lost during its lifecycle was the most critical factor determining the relative magnitude of the climatic impact. The greatest net climatic benefit within the 20-year time frame was predicted to be achieved when a storage natural gas water heater (the most common system for domestic hot water in the United States) fueled by shale gas was replaced with a high efficiency heat pump water heater powered by coal-generated electricity; the heat pump system powered by renewable electricity would have had an even greater climatic benefit, but was not explicitly modeled in this study. Our analysis provides the first assessment of the GHG footprint associated with using a heat pump water heater, which we demonstrate to be an effective and economically viable way of reducing emissions of GHGs.

Introduction

Each of the last three decades has been consecutively the warmest on record since the start of the industrial revolution, and the global temperature will continue to rise to potentially dangerous levels within 10–30 years without an immediate reduction in greenhouse gas (GHG) emissions [1, 2]. The two most important GHGs responsible for accelerating climate change are carbon dioxide (CO_2) and methane (CH_4) that are released when carbon-based fossil fuels are burned for heat and energy. CH_4 has received relatively less attention than CO_2, yet is quite important in climate change. Including indirect effects, the Intergovernmental Panel on Climate Change (IPCC) recognizes in its fifth assessment report (AR5) that CH_4 has 120 times greater radiative forcing than CO_2 on a mass basis during the time both gasses are in the atmosphere [2], updated from its previous fourth assessment report (AR4) of 100 [3] and the third report (AR3) of 85 [4]. The IPCC AR5 concludes that the current radiative forcing by CH_4 is almost 1 W m^{-2}, compared to 1.66 W m^{-2} for CO_2. The model of Shindell et al. [1] indicates it is even more critical to control CH_4 emissions than CO_2 emissions if we are to slow the rate of global warming over the coming few decades: reducing CO_2 emissions has little effect on warming over this time period due to lags in the climate system, whereas reductions in CH_4 emissions have an immediate influence [1, 5].

Heat and energy for human use can be generated from different sources (e.g., electricity from coal or natural gas), and it is useful to have a tool or methodology that allows us to assess potential climate impacts of alternative choices.

Although CH_4 is a more powerful GHG than CO_2, it has a shorter lifetime of about 12 years [6, 7], making it challenging to compare two technologies that result in differing amounts of CO_2 and CH_4 emissions during their lifecycles. The technology warming potential (TWP) approach introduced by Alvarez et al. [8] provides a framework for evaluating a technology for heat and energy generation against a reference technology and has been applied for energy policy assessment and design [9]. The TWP approach can be considered as a two-step process: first, emissions of GHGs, most importantly CO_2 and CH_4, resulting from the application of each technology is estimated. For ease of comparison, the emissions are estimated on a unit energy basis, such as kilograms CO_2 emitted per megawatt-hour (MWh) electricity generated. Next, for each GHG emitted its cumulative radiative forcing over time is computed, and the total radiative forcing over all the GHGs emitted from the alternative technology is compared with that from the reference technology.

Alvarez et al. [8] used the TWP approach and evaluated climatic impacts of generating electricity from a combined cycle natural gas power plant (with an efficiency of 50%) relative to that from a supercritical pulverized coal power plant (39%). They concluded that, at the level of CH_4 emissions they estimated to be associated with the production and use of the natural gas (2.1%) [10] and based on the radiative forcing from the IPCC AR4, generating electricity from natural gas is relatively less damaging to the climate than from coal across all time frames considered. This analysis provides a useful context for discussions and policy development over the future use of natural gas, although there is room for reconsideration. For example, published literature estimating CH_4 emission rates has been rare, but since Howarth et al. [11] reported their first estimates many more measurements and estimates have become available, many of which are higher than the EPA estimate [10] that Alvarez et al. [8] used: an inverse modeling study by Miller et al. (3.6% or above) [12], a satellite data analysis by Schneising et al. (9.5%, shale gas, upstream emission only) [13], a review paper by Brandt et al. (3.6–7.1%) [14], and estimates from aircraft campaigns [15, 16]. Howarth [5] reviewed these studies and suggested the best available data for CH_4 emissions indicates rates of 3.8% for conventional natural gas and 12% for shale gas over the full lifecycle, well to final consumer. In light of the new emission estimates and radiative forcing from the IPCC AR5 (which are higher than those from the IPCC AR4 report) that became available after the analysis by Alvarez et al. [8], we provide a reevaluation of the electricity generation scenario in Data S1, which shows that generating electricity from natural gas can be more damaging to the climate than from coal at the current level of CH_4 emission, especially within the coming few decades.

Electricity generation makes up a large portion of the use of natural gas in the United States (33% in 2009, the year on which the analysis by Alvarez et al. [8] is based), but many other uses are also very important, and the GHG emissions associated with most other uses of natural gas have remained largely unexplored. Alvarez et al. [8] also analyzed the use of natural gas as a long-distance transportation fuel, but that is a very minor use. Residential (23%) and commercial (15%) uses make up other large portions of natural gas use, a substantial portion of which is for space and water heating [17]. According to the U.S. Energy Information Administration (EIA)'s Residential Energy Consumption Survey (RECS) report, in 2009 $\sim 1.9 \times 10^{12}$ MJ of energy was delivered to the U.S. households for water heating (18% of total energy delivered to households) mainly in the form of natural gas (1.3×10^{12} MJ) and electricity (4.5×10^{11} MJ) (http://www.eia.gov/consumption/residential/). Most of the water heaters in the U.S. households have storage tanks (98% in 2009), although tankless water heaters have shown higher energy use efficiencies and may potentially help reduce household energy expenditure as well as GHG emissions associated with water heating.

Another promising new technology for heating water is heat pump water heaters. Powered by electricity, heat pump water heaters operate by transferring heat from the air into the tank [18]. Although currently making up only about 1% of new water heater sales in the U.S., they are becoming more popular (34,000 and 43,000 units sold in 2012 and 2013, respectively; http://www.energystar.gov/) because of their high efficiencies and their potential to improve overall home energy use efficiencies [19]. Their potential for reducing GHG emissions has not been evaluated up to now.

In light of these considerations, here we apply the TWP approach of Alvarez et al. [8], revised with updated CH_4 emissions and radiative forcing values, to evaluate the climatic impacts of using heat pump water heaters relative to other ways of heating water (natural gas and electric resistance water heaters, with and without storage tanks). To test its sensitivity, TWP was calculated under differing assumptions as to the source of electricity and efficiencies of water heaters and power plants. We also introduce a new web-based tool developed for this study, allowing anyone to perform the analysis described in this paper and evaluate his or her own scenarios.

Methods

In section "Emission factors," we describe the estimation of the lifecycle emissions of GHGs (CO_2 and CH_4)

associated with heating water with different water heaters considered in this study: heat pump water heaters as well as storage/tankless natural gas and electric resistance water heaters. Section "Technology warming potential" describes how the time-integrated radiative forcing resulting from these emissions is calculated and compared using the TWP approach. Finally, section "Web-based tool" introduces a web-based tool for making the TWP calculation. This study builds on the previous assessment by Alvarez et al. [8] on the use of natural gas for electricity generation, reconsidered with a number of updates as described in detail in Data S1.

Emission factors

Table 1 summarizes the CH_4 and CO_2 emission factors, expressed in kg emitted per GJ of water heated, resulting from the use of five different types of water heaters: heat pump water heater, storage natural gas water heater, tankless natural gas water heater, storage electric resistance water heater, and tankless electric resistance water heater. Energy factors for these water heaters were obtained from the Air-conditioning, Heating, and Refrigeration Institute (AHRI, http://www.ahrinet.org/) that provided information on 5478 AHRI-certified water heaters as of December 2015. Excluding inactive or discontinued products yielded energy factors for 120 heat pump water heaters (2.21–3.39 with an average of 2.79), 1093 storage natural gas water heaters (0.57–0.82 with an average of 0.64), 378 tankless natural gas water heaters (0.82–0.99 with an average of 0.87), 587 storage electric resistance water heaters (0.9–0.95 with an average of 0.94), and 97 tankless electric resistance water heaters (0.96–1.0 with an average of 0.99).

CH_4 emission factors for the natural gas water heaters are highly sensitive to the estimated emissions of CH_4 during its lifecycle (production, processing, distribution, and use). CH_4 emission factors for the heat pump and electric resistance water heaters are also sensitive to the CH_4 emission rate if the electricity powering these water heaters comes from natural gas power plants instead of coal power plants. In their TWP analysis of electricity generation, Alvarez et al. [8] used emission estimates from U.S. EPA [10] reporting that 2.4% of CH_4 in the natural gas withdrawn in 2009 was lost to the atmosphere (broken down to 1.5%, 0.2%, 0.5%, and 0.3% lost during the field production, processing, transmission/storage, and distribution, respectively). Alvarez et al. [8]

Table 1. CH_4 and CO_2 emission factors used in this study associated with heating water using heat pump, natural gas, and electric resistance water heaters (kg GJ^{-1}).

Efficiency	Source of electricity	CH_4 emission reference	GHG	Heat pump water heater	Natural gas water heater		Electric resistance water heater	
					Storage	Tankless	Storage	Tankless
Base	Coal	Alvarez et al. [8]	CH_4	0.069	0.82	0.60	0.20	0.19
			CO_2	86.2	86.5	63.6	256	243
		Howarth et al. [11], conventional	CH_4	0.069	1.38	1.02	0.20	0.19
			CO_2	86.2	86.5	63.6	256	243
		Howarth [5], shale	CH_4	0.069	4.02	2.96	0.20	0.19
			CO_2	86.2	86.5	63.6	256	243
	Natural gas	Alvarez et al. [8]	CH_4	0.33	0.82	0.60	0.97	0.93
			CO_2	42.0	86.5	63.6	125	119
		Howarth et al. [11], conventional	CH_4	0.44	1.38	1.02	1.30	1.23
			CO_2	42.0	86.5	63.6	125	119
		Howarth [5], shale	CH_4	1.72	4.02	2.96	5.10	4.85
			CO_2	42.0	86.5	63.6	125	119
Best case	Coal	Alvarez et al. [8]	CH_4	0.046	0.64	0.53	0.17	0.16
			CO_2	58.1	67.5	55.9	207	197
		Howarth et al. [11], conventional	CH_4	0.046	1.08	0.89	0.17	0.16
			CO_2	58.1	67.5	55.9	207	197
		Howarth [5], shale	CH_4	0.046	3.14	2.60	0.17	0.16
			CO_2	58.1	67.5	55.9	207	197
	Natural gas	Alvarez et al. [8]	CH_4	0.23	0.64	0.53	0.81	0.77
			CO_2	29.0	67.5	55.9	103	98.2
		Howarth et al. [11], conventional	CH_4	0.30	1.08	0.89	1.08	1.02
			CO_2	29.0	67.5	55.9	103	98.2
		Howarth [5], shale	CH_4	1.18	3.14	2.60	4.23	4.01
			CO_2	29.0	67.5	55.9	103	98.2

assumed that natural gas power plants receive their fuel directly from the transmission system (large, long-distance pipelines) and excluded emissions of CH_4 associated with the distribution loss from smaller, local pipelines (0.3%), resulting in an overall CH_4 emission rate of 2.1% (instead of 2.4%) associated with generating electricity using natural gas. This implies that all the 0.3% distribution loss, which corresponds to 1.4 Tg of CH_4 in 2009 according to the EPA estimates [10], must have occurred while natural gas was used for purposes other than electricity generation. Since electric power plants consumed 33 percent of natural gas produced in 2009 [20], the absence of 0.3% loss in electricity generation translates into additional 0.15% loss in other uses of natural gas (including for water heating), resulting in the overall loss of 2.55%.

After an extensive literature review, Howarth [5] concluded that the best available information suggests the CH_4 emission rate of 3.8% for conventional natural gas (1.3% from upstream emissions and 2.5% from downstream emissions) and 12% for shale gas (9.5% from upstream emissions and 2.5% from downstream emissions). Note that as of 2013, 60% of natural gas in the United States was from conventional sources and 40% from shale gas and other unconventional sources [20]. A new study also reports ~2.5% CH_4 emissions for the distribution system in Boston, MA [21]. Following the distribution loss assumption by Alvarez et al. [8] described above, we excluded emissions of CH_4 associated with the distribution loss (1%, which is 40% of the total downstream loss as assumed by Alvarez et al. [8]) when natural gas is used for electricity generation, resulting in the overall emission rate of 2.8% for conventional gas and 11% for shale gas. The absence of 1% loss in electricity generation translates into additional 0.5% loss in other uses of natural gas, resulting in the overall loss of 4.3% for conventional gas and 12.5% for shale gas.

In consideration of electricity generation scenario, Alvarez et al. [8] assumed an efficiency of 50% for a combined cycle natural gas power plant and 39% for a supercritical pulverized coal power plant, both of which are somewhat higher than the efficiencies reported by the U.S. EIA as the average operating heat rates of natural gas and coal power plants in 2009 (42% and 33%, respectively; http://www.eia.gov/electricity/annual/html/epa_08_01.html). When performing the base efficiency calculation (Table 1), we applied the same power plant efficiencies as used by Alvarez et al. [8] and assumed average efficiency factors obtained from the AHRI (http://www.ahrinet.org/) for the water heaters considered in this study. When performing the "best case" efficiency calculation, natural gas power plants were assumed to be 60% efficient as reported for the GE Flex 60 units (http://www.ge-energy.com/) and coal power plants to be 48% efficient for the ultrasupercritical units [22]. Maximum water heater efficiency factors obtained from the Energy Star (http://www.energystar.gov/) and the AHRI were used under the best case scenario.

The emission factors used by Alvarez et al. [8] for the electricity generation scenario were 3.1 kg-CH_4 MWh^{-1} and 397 kg-CO_2 MWh^{-1} for a combined cycle natural gas power plant, and 0.65 kg-CH_4 MWh^{-1} and 814 kg-CO_2 MWh^{-1} for a supercritical pulverized coal power plant. The following is an example of how the CH_4 emission factor for a heat pump water heater, powered by electricity from shale natural gas, was determined under the best case scenario: 3.1 kg-CH_4 MWh^{-1} (=0.86 kg-CH_4 GJ^{-1}) adjusted for maximum power plant efficiency (60%) and methane emission for shale gas associated with electricity generation (11%) yields 3.77 kg-CH_4 GJ^{-1}. Approximately six percent of electricity production may be lost in transmission and distribution when delivered to homes (EIA; http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3). The emission factor becomes 4.01 kg-CH_4 GJ^{-1} after accounting for this loss, and 1.18 kg-CH_4 GJ^{-1} after applying the efficiency factor of a heat pump water heater (3.39). To estimate how much CH_4 is emitted for a tankless natural gas water heater to heat the same amount of water, we again start with the same emission factor from Alvarez et al. [8] (3.1 kg-CH_4 MWh^{-1}), use the heat rate (efficiency) of a natural gas power plant applied by Alvarez et al. [8] to calculate the emission factor associated with delivering natural gas to power plants (0.432 kg-CH_4 GJ^{-1}), and in turn use it to estimate the emission factor associated with delivering shale natural gas to homes (2.57 kg-CH_4 GJ^{-1}). Finally, by applying the efficiency factor of a tankless natural gas water heater (0.99), we obtain the CH_4 emission factor of 2.60 kg-CH_4 GJ^{-1}. All the emission factors in Table 1 were computed by adjusting these emission rates and efficiencies as they apply to each scenario.

Technology warming potential

In this study, TWP is calculated as the sum of time-integrated radiative forcing from CH_4 and CO_2 emitted by applying one of the four alternative technologies (heating water using a natural gas or electric resistance water heater, with or without a storage tank) divided by that from the reference technology (heating water using a heat pump water heater). TWP can be calculated under three different implementation scenarios: pulse, service life, and fleet conversion [8]. In the case of a permanent fleet conversion, the technology is applied indefinitely by replacing it with an identical unit at the end of its service life. Fleet conversion TWP at year t is calculated as:

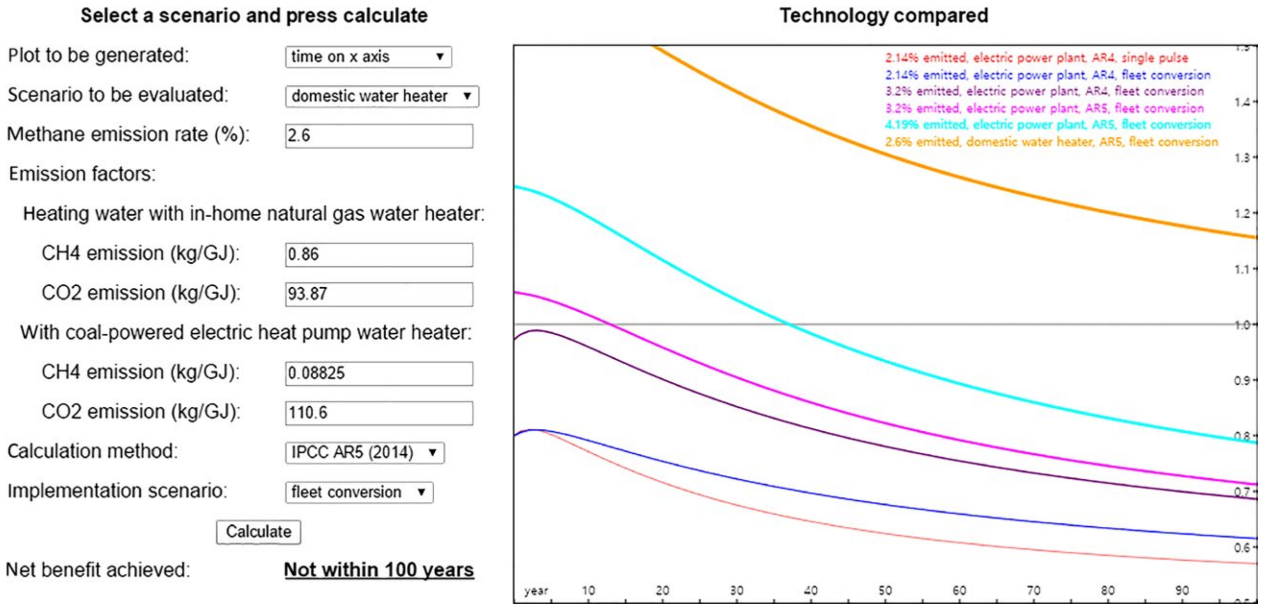
$$\mathrm{TWP}(t)=\frac{E_{\mathrm{a,CH_4}}\times A_{\mathrm{CH_4}}\times\left(\tau_{\mathrm{CH_4}}t-\tau_{\mathrm{CH_4}}^2\left(1-\exp(-\frac{t}{\tau_{\mathrm{CH_4}}})\right)\right)+E_{\mathrm{a,CO_2}}\times A_{\mathrm{CO_2}}\times\left(a_0\frac{t^2}{2}+\sum_{i=1}^{n}a_i\left(\tau_i t-\tau_i^2\left(1-\exp(-\frac{t}{\tau_i})\right)\right)\right)}{E_{\mathrm{r,CH_4}}\times A_{\mathrm{CH_4}}\times\left(\tau_{\mathrm{CH_4}}t-\tau_{\mathrm{CH_4}}^2\left(1-\exp(-\frac{t}{\tau_{\mathrm{CH_4}}})\right)\right)+E_{\mathrm{r,CO_2}}\times A_{\mathrm{CO_2}}\times\left(a_0\frac{t^2}{2}+\sum_{i=1}^{n}a_i\left(\tau_i t-\tau_i^2\left(1-\exp(-\frac{t}{\tau_i})\right)\right)\right)} \quad (1)$$

where: $E_{\mathrm{a,CH_4}}$ = CH_4 emission factor for the alternative technology (kg GJ^{-1}), $E_{\mathrm{a,CO_2}}$ = CO_2 emission factor for the alternative technology (kg GJ^{-1}), $E_{\mathrm{r,CH_4}}$ = CH_4 emission factor for the reference technology (kg GJ^{-1}), $E_{\mathrm{r,CO_2}}$ = CO_2 emission factor for the reference technology (kg GJ^{-1}), $A_{\mathrm{CH_4}}$ = radiative efficiency of CH_4 (W m^{-2} kg^{-1}), $A_{\mathrm{CO_2}}$ = radiative efficiency of CO_2 (W m^{-2} kg^{-1}), $\tau_{\mathrm{CH_4}}$ = lifetime coefficient of CH_4 (years), τ_i = lifetime coefficients of CO_2 (years).

TWP greater than one indicates that the cumulative radiative forcing from choosing the alternative technology at year t is higher than the reference technology. Emission factors ($E_{\mathrm{a,CH_4}}$, $E_{\mathrm{a,CO_2}}$, $E_{\mathrm{r,CH_4}}$ and $E_{\mathrm{r,CO_2}}$) used in this study are given in Table 1 and described in section "Emission factors". Radiative efficiency (radiative forcing per unit mass increase in atmospheric abundance) of CH_4 was updated from 1.82×10^{-13} W m^{-2} kg^{-1} in AR4 [3] to 2.11×10^{-13} W m^{-2} kg^{-1} in AR5 [2], reflecting updated knowledge of the magnitude of the indirect radiative effects of CH_4 on tropospheric ozone and stratospheric water vapor [23]. The remaining part of equation (1) describes the time-integrated change in GHGs after they are released into the atmosphere. This time-integrated portion can be replaced with one that considers single pulse emissions of CH_4 and CO_2 in the same way as done in the global warming potential (GWP) calculation, or that considers service lives of different technologies: CH_4 and CO_2 are emitted continuously throughout the year at a constant rate during the time periods from $t = 0$ to $t = t_{\max}$ over which the technology is applied (for example, a single power plant generating electricity over its full service life of 50 years). Equations for pulse and service life TWP are given in Alvarez et al. [8] and also in Data S1.

Web-based tool

We developed a web-based tool evaluating the GHG footprint of using a heat pump water heater relative to those of alternative technologies (Fig. 1). Written in JavaScript [24], the first version of the tool along with the source code is currently available at http://www.eeb.cornell.edu/howarth/methane/tool.htm and runs on all major web browsers. It allows the user to select the scenario to evaluate (e.g., heating water with a heat pump water heater vs. a storage natural gas water heater), method of radiative



Select a scenario and press calculate

Plot to be generated: time on x axis

Scenario to be evaluated: domestic water heater

Methane emission rate (%): 2.6

Emission factors:

Heating water with in-home natural gas water heater:

CH4 emission (kg/GJ): 0.86

CO2 emission (kg/GJ): 93.87

With coal-powered electric heat pump water heater:

CH4 emission (kg/GJ): 0.08825

CO2 emission (kg/GJ): 110.6

Calculation method: IPCC AR5 (2014)

Implementation scenario: fleet conversion

Net benefit achieved: Not within 100 years

Figure 1. User interface of the web-based tool for evaluating the greenhouse gas footprint from using a heat pump water heater, available at www.eeb.cornell.edu/howarth/methane/tool.htm.

forcing calculation (AR3, AR4, or AR5) and implementation scenario (pulse, service life, or fleet conversion). The user can also choose the type of plot to be generated (time or percent emission on the *x*-axis) and change the CH_4 emission rate or time frame considered. The CH_4 emission factor for the natural gas-based technology is directly proportional to the assumed CH_4 emission rate (section "Emission factors"), and the user can try different emission rates and test their impacts on the TWP calculation. The user can also build his or her own scenarios by directly entering CH_4 and CO_2 emission factors for the reference and alternative technologies (Fig. 1). One way of making use of this tool, although not developed for this purpose, would be to calculate GWP by setting E_{r,CH_4} and E_{a,CO_2} (eq. 1) to zero and E_{a,CH_4} and E_{r,CO_2} to one, and making the "pulse" calculation.

Results and Discussion

Under the base efficiency condition, the time-integrated radiative forcing due to CH_4 and CO_2 emissions associated with heating water with a storage natural gas water heater (which is the most common way of heating water in the U.S.) was greater than that with a heat pump water heater powered by electricity from coal across all time scales considered in this study (up to 100 years), regardless of the method of radiative forcing calculation (AR3, AR4, or AR5) or implementation scenario (pulse, service life, or fleet conversion) (Fig. 2). TWPs were higher when calculated using the AR5 method and under the fleet conversion scenario, although the magnitude of their variation was relatively small compared to the differences due to the emission estimates chosen (from Alvarez et al. [8] for building on the previous TWP analysis, Howarth et al. [11] for conventional gas and Howarth [5] for shale gas). Our analysis indicates that if the natural gas from shale is used for heating water in homes, the accumulated radiative forcing from using a natural gas water heater can be as much as six times higher than from using a heat pump water heater within the first year of their installations, and still more than five times higher after 20 years.

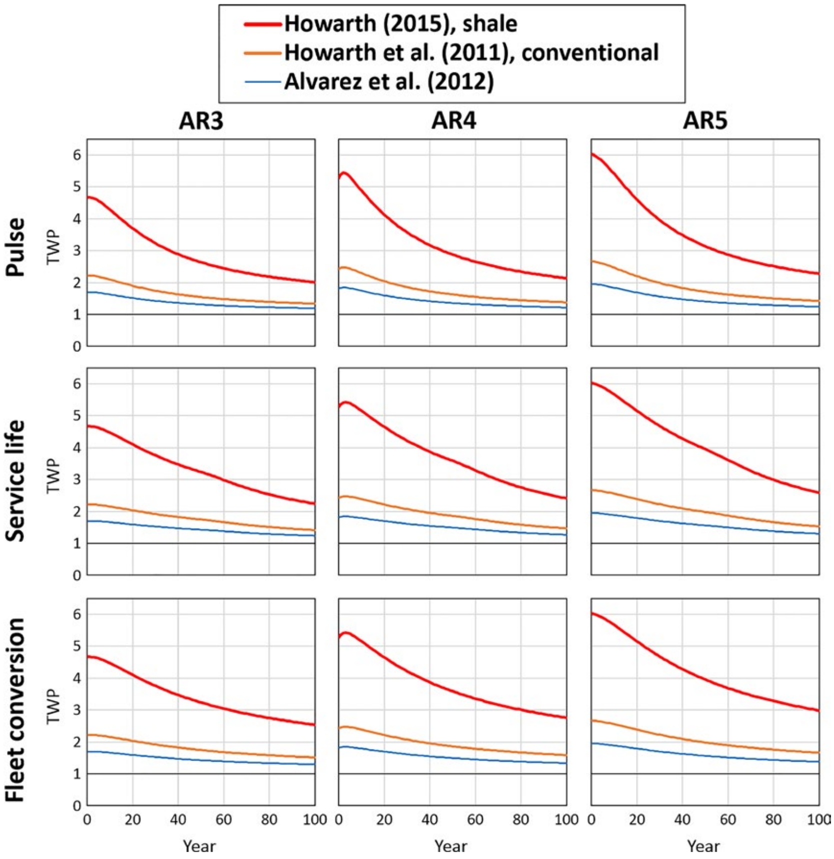


Figure 2. Time-integrated radiative forcing resulting from heating water with a storage natural gas water heater, relative to that from a heat pump water heater powered by electricity from coal. Technology warming potentials are calculated from three emission estimates (Alvarez et al. [8], Howarth et al. [11] for conventional gas and Howarth [5] for shale gas), three calculation methods (AR3, AR4, and AR5), and three implementation scenarios (pulse, service life, and fleet conversion).

The maximum CH_4 emission rate below which the time-integrated radiative forcing associated with using natural gas is smaller than that with an alternative technology for all time horizons considered has been referred to as a “break-even point” [8, 25, 26]. The break-even point for generating electricity from natural gas versus coal was estimated to be 3.2% by Alvarez et al. [8], who based their estimation on the IPCC AR4 parameters [3]. When updated with AR5 parameters that reflect the most recent scientific information on the methane’s indirect effects on tropospheric ozone and stratospheric water vapor [2], this break-even point was revised to be 2.7% (Data S1). The break-even point associated with heating water in homes with a storage natural gas water heater relative to a heat pump water heater was estimated to be a CH_4 emission rate of 0.2%. All published CH_4 emission rates are well above this threshold.

TWPs of using a storage tank natural gas water heater relative to a coal-electric-powered heat pump water heater increased linearly with increasing CH_4 emission rate (Fig. 3). The rate of increase (slope) of the 20-year scale TWP (0.34 per %) was about twice that of the 100-year scale (0.16 per %). The CH_4 emission rate at which both technologies yield the same cumulative forcing (i.e., the storage tank natural gas- and coal-electric-based water heaters have the same climatic impact) was close to 0.2% at both the 20- and 100-year scales. Shale gas was only 15% of the natural gas production in 2009, but had risen to 40% in 2013 [20]. Applying the methane emission estimates from Howarth et al. [11] and Howarth [5] for conventional (3.8%) and shale (12%) gas, the overall emission rate is likely to have increased from ~5% to 7% during this time period, increasing the 20-year TWP for this scenario by about 0.7.

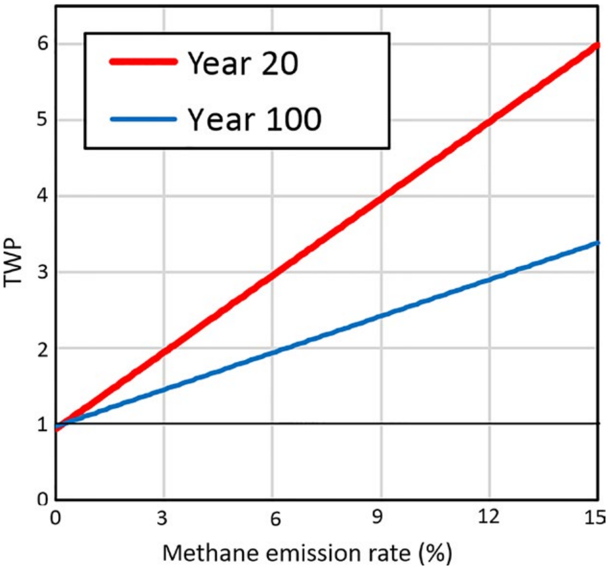


Figure 3. Time-integrated radiative forcing resulting from heating water with a storage natural gas water heater, relative to that from a heat pump water heater powered by electricity from coal. Technology warming potentials are calculated as a function of methane emission rate (%) at two time horizons (20 and 100 years) applying the AR5 calculation method and fleet implementation scenario.

TWPs at 20 and 100 years calculated with the AR5 parameters and under the fleet conversion scenario were always greater than 1, regardless of the type of the water heater compared with the heat pump water heater (natural gas or electric resistance water heater, storage or tankless), efficiencies of power plants and water heaters (base or best case efficiencies) and the source of electricity powering the heat pump and electric resistance water heaters (natural gas or coal) (Table 2). Tankless water heaters yielded lower TWPs than storage water heaters because of their higher efficiencies, and the difference was greater in the natural gas water heaters than in the electric resistance water heaters. TWP values of the electric water heaters were constant over time because the relative magnitude of CO_2 and CH_4 emissions associated with using the electric resistance versus heat pump water heaters stayed the same, only varied by the difference in their efficiencies. The best case scenarios (in which the maximum available efficiencies were assumed for all power plants and all water heaters) always resulted in higher TWPs than those from corresponding base case scenarios, suggesting that the benefit from using heat pump water heaters would be greater when best available technologies are applied. In this study, we have not explicitly modeled the use of heat pump water heaters powered by electricity from renewable sources, but these obviously would have far lower GHG emissions yet.

The highest TWP (5.96) was observed at year 20 in the comparison between the storage natural gas water heater versus heat pump water heater powered by electricity from coal, under the best case efficiency and with emissions from shale gas (Table 2). This TWP was decreased to 2.59 when the electricity powering the heat pump water heater was assumed to come from natural gas, also from shale formations. It appears that, under the low methane emission rate, the net gain of replacing the existing natural gas water heater with a new heat pump water heater would be higher if the electricity powering the heat pump water heater comes from natural gas instead of coal. However, if producing natural gas involves high emissions of CH_4 as is the case for the shale gas, higher net climatic benefits would be gained if electricity comes from coal.

Although it is important to note that replacing any of the water heaters considered in this study with a heat pump water heater will give net climatic benefits over all

Table 2. Time-integrated radiative forcing from heating water with storage/tankless natural gas and electric resistance water heaters relative to that with a heat pump water heater.

Efficiency	Source of electricity	CH_4 emission reference	Time scale (year)	Natural gas water heater		Electric resistance water heater	
				Storage	Tankless	Storage	Tankless
Base	Coal	Alvarez et al. [8]	20	1.79	1.32	2.97	2.82
			100	1.38	1.01	2.97	2.82
		Howarth et al. [11], conventional	20	2.38	1.75	2.97	2.82
			100	1.66	1.22	2.97	2.82
		Howarth [5], shale	20	5.15	3.79	2.97	2.82
			100	2.98	2.19	2.97	2.82
	Natural gas	Alvarez et al. [8]	20	2.25	1.65	2.97	2.82
			100	2.17	1.60	2.97	2.82
		Howarth et al. [11], conventional	20	2.61	1.92	2.97	2.82
			100	2.41	1.77	2.97	2.82
		Howarth [5], shale	20	2.28	1.68	2.97	2.82
			100	2.24	1.65	2.97	2.82
Best case	Coal	Alvarez et al. [8]	20	2.07	1.72	3.57	3.39
			100	1.60	1.32	3.57	3.39
		Howarth et al. [11], conventional	20	2.76	2.28	3.57	3.39
			100	1.92	1.59	3.57	3.39
		Howarth [5], shale	20	5.96	4.94	3.57	3.39
			100	3.46	2.86	3.57	3.39
	Natural gas	Alvarez et al. [8]	20	2.55	2.11	3.57	3.39
			100	2.46	2.04	3.57	3.39
		Howarth et al. [11], conventional	20	2.96	2.45	3.57	3.39
			100	2.73	2.26	3.57	3.39
		Howarth [5], shale	20	2.59	2.14	3.57	3.39
			100	2.54	2.10	3.57	3.39

Technology warming potentials are calculated applying the AR5 calculation method and fleet implementation scenario.

time frames (up to 100 years), it is equally important to recognize that avoiding the use of natural gas-based technology may make it possible to prevent the acute adverse impacts on the climate that may take place in a short foreseeable future (e.g., within the next 20 years), especially when the natural gas is produced from high emission sources [26, 27]. It has been suggested that an increase in global mean temperature by 1.5–2°C above the 1900 baseline, that could happen within the next 15–35 years, may push the earth past a critical threshold into an alternate state for the climate system [1]. Finding currently available alternatives to the use of natural gas-based technologies and thereby reducing the CH_4 emissions immediately would be essential for slowing the climate change over the coming decades.

In 2009, total energy delivered to households for water heating in the U.S. was 1.9×10^{12} MJ (18% of energy delivered to households; http://www.eia.gov/consumption/residential/), 68% of which (1.3×10^{12} MJ) was in the form of natural gas and 24% (4.5×10^{11} MJ) was electricity. Only 2.3% of households had tankless water heaters in 2009. Applying the weighted average efficiency factor for the natural gas water heaters (0.64) and the emission factors derived from Howarth et al. [11] and Howarth [5], we estimate that ~8.3×10^{11} MJ of water was heated by the natural gas water heaters in 2009, and the associated GHGs released into the atmosphere were 1.5×10^{9} kg of CH_4 and 7.2×10^{10} kg of CO_2. Under the best case efficiencies considered in this study, only 2.5×10^{11} MJ of energy would have been needed to heat this much water with the heat pump water heaters, releasing 1.5×10^{8} kg of CH_4 and 4.0×10^{10} kg of CO_2 if we assume that about 66% of the electricity used by the heat pump water heaters comes from the coal and the rest from the natural gas (http://www.eia.gov/electricity/). Likewise, we estimate that ~3.3×10^{8} kg of CH_4 and 8.9×10^{10} kg of CO_2 were released in 2009 while heating 4.3×10^{11} MJ of water in homes with electric resistance water heaters. Again under the best case scenario, 1.3×10^{11} MJ of electricity would have been needed to heat the same amount of water with the heat pump water heaters, releasing 7.7×10^{7} kg of CH_4 and 2.0×10^{10} kg of CO_2. Combining these two sources, the 2009 emissions associated with heating water in homes in the U.S. potentially could have been 2.3×10^{8} kg of CH_4 and 6.0×10^{10} kg of CO_2 (summing up to be a total of

0.08 Pg-CO_2 equivalents) instead of 1.8×10^9 kg of CH_4 and 1.6×10^{11} kg of CO_2 (0.32 Pg-CO_2 equivalents). The net saving would be 0.24 Pg-CO_2 equivalents, which is about 2.8% of the total GHG emissions from fossil fuel use in the U.S. in 2009 (8.4 Pg-CO_2 equivalents [5]) and about 26% of those from the residential and commercial uses, assuming that they comprise ~11% of the total GHG emissions from fossil fuels. In terms of household expenditure, the U.S. households in 2009 spent about 1.1 cents per MJ natural gas delivered and 3.1 cents per MJ electricity delivered. Multiplying these prices to the energy consumption in 2009 results in 29 billion dollars for heating water, consisting of 15 billion dollars for using natural gas and 14 billion dollars for electricity. Replacing the natural gas and electric resistance water heaters with heat pump water heaters and using the electricity generated by high-efficiency power plants could have reduced this spending to 12 billion dollars (7 and 10 billion dollars saved by replacing natural gas and electric resistance water heaters, respectively). Since there were 58 and 47 million households with natural gas and electricity as the main water heater in 2009, the savings in water heating expenses would have been 120 and 214 dollars per household, respectively.

The above consideration provides a strong argument that replacing existing water heaters with high-efficiency heat pumps is an effective and economically viable way of reducing emissions of GHGs. It may be refined further as new relevant information on the water heater efficiencies and CH_4 emission rates become available. For example, typical heat pump water heaters switch to electric resistance mode as ambient temperatures approach freezing point [28]. Thus, the results from the electric resistance water heaters serve as theoretical lower bounds (worst case) of the application of the heat pump water heaters, subject to season and geographic region. Using natural gas water heaters is more damaging to the climate than using electric resistance water heaters powered by electricity from coal, if the natural gas is produced from shale (Table 2).

After Howarth et al. [11, 29, 30], more literature has been published reporting estimates of lifecycle emissions of CH_4 [12–16, 31] that are thoroughly reviewed by Howarth [5, 26]. In our study, we chose to use three estimates: Alvarez et al. [8] for building on the previous TWP analysis, Howarth et al. [11] for conventional gas and Howarth [5] for shale gas. We believe that the CH_4 emission from conventional gas (3.8%), first proposed in Howarth et al. [11] and rigorously reexamined in Howarth [5], is a well-supported, robust estimate that serves as a lower bound of the methane emission associated with the natural gas production in the U.S. today. Several recent studies have estimated upstream methane emissions from shale gas and other unconventional natural gas development using integrated measurement techniques, including airplane flyovers that produced highly variable results [15, 16, 31]. Among the estimation methods available at the moment, the satellite data (on which our shale estimate from Howarth [5] is based) may produce the most robust estimates as they integrate in space and over a longer time period, whereas other methods like the aircraft campaigns are one of several estimates based on relatively short-term observations. This satellite-based estimate is about 20-fold greater than the estimate by Allen et al. [32], a study that worked closely with industry to measure emissions from various component processes of shale gas development. Two papers published in 2015 [33, 34] including one in Energy Science & Engineering cast serious doubts on the Allen et al. [32] estimate that could have been biased downward by the sensor failure of the Bacharach Hi-Flow® Sampler used in their study. It is conceivable that the shale emission estimate that we used in our study (12%) represents the emission levels resulting from the lack of rigorous controls and it may decline with time following improved methane regulations; however, at most, we believe it would come down to the estimate for the conventional natural gas, the current best estimate of which is 3.8% [5].

Concluding Thoughts

Natural gas is often portrayed as a "bridge fuel," with the implication that it is a preferable energy source over other carbon-based fossil fuels resulting in a less adverse impact on the climate, desirable to be used until carbon-free technologies are mature and in place [25, 35]. The analysis presented here provides counterarguments to this idea in two different aspects: that (1) using natural gas-based technologies can result in even higher emissions of GHGs than using coal-based technologies, and that (2) technologies that can support carbon-free sources of energy already exist in an economically viable way. The electricity powering the heat pump water heaters can be generated from carbon-free energy sources such as wind, solar, hydropower, and geothermal sources that have little or no emissions directly related to electricity production; yet, even when powered by electricity from coal and natural gas, total GHG emissions from generating domestic hot water with heat pumps is less than directly using natural gas. Therefore, currently available modern technologies like the heat pump water heater are in fact a true bridge to the clean energy environment.

Our analysis provides the first assessment of the GHG footprint involved with using heat pump water heaters compared to other common ways of heating water at U.S. homes. In the future, we hope to expand this type of analysis to evaluate the use of alternative clean energy sources for energy needs where natural gas currently provides a large amount of the energy. Recent studies [36, 37] show that a transition to a society that is driven only by renewable energy sources can be accomplished in a cost-effective way using the commercially available technologies such as the heat pumps. This transition may also be expedited with the help of web-based tools such as the one introduced here, that allow anyone to incorporate, evaluate, and share new information on the alternative energy sources as it becomes available.

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Conflict of Interest

None declared.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Data S1. Greenhouse gas emissions from domestic hot water: heat pumps compared to most commonly used systems.