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Quantifying the Financial and Climate Impacts of Greenhouse Gas Abatement Pathways in Residential Space Heating

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Abstract: New York State (NYS) has set strict greenhouse gas (GHG) emission reduction targets across all sectors of its economy, including the heating sector. This study examines the financial value and environmental impacts of the residential space heating sector in NYS under different GHG abatement options by comparing the existing natural gas heating pathway with three potential GHG abatement pathways: renewable natural gas (RNG), hydrogen blended into RNG, and air-source heat pumps (ASHPs). These pathways are analyzed via a comparative net present value (NPV) framework from 2022 to 2042 with the emission reduction represented as a revenue stream that serves as a function of the social cost of GHGs. The investment timing of each of these pathways is also accounted for to reflect the pathways' varying deployment timelines. The ASHP pathway with a 10% financial discount rate and a 2% social cost of the GHG discount rate achieves the lowest NPV. The RNG pathway achieves the highest NPV. A sensitivity analysis determines the impact of key factors on the NPV results. This study aims to inform policymakers, homeowners, and stakeholders of the potential benefits and costs of each of the four pathways to aid them in their decision-making process.

Keywords: natural gas; renewable natural gas; hydrogen; air-source heat pump; social cost; net present value



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1. Introduction

The United Nations Intergovernmental Panel on Climate Change recently determined that cumulative net carbon dioxide (CO₂) emissions between 2010 and 2019 were equal to about one-third of the remaining carbon budget from 2020 onwards for a 67% probability to limit global warming to 2 °C [1]. A rapid reduction in economywide greenhouse gas (GHG) emissions is needed to prevent a global temperature increase of 2 °C and catastrophic climate change. In New York State (NYS) in 2019, the building sector was responsible for the largest share of emissions (32% of the total), of which 34% was from the combustion of fossil fuels in residential buildings [2]. Thus, the widespread and rapid displacement of fossil fuel combustion in the residential building sector is a necessary component of the state's deep decarbonization efforts. This transition must happen with sustainable renewable resource utilization as a guiding principle in order to achieve such displacement.

Enacted in 2019, the NYS Climate Leadership and Community Protection Act (CLCPA) has among the most aggressive climate and clean energy targets in the United States, including (1) a mandated reduction in economywide GHG emissions by at least 85% (from 1990 levels to 2050 levels) and (2) a goal of economywide net zero emissions by 2050 [2]. Currently, in NYS, three out of five homes are heated with natural gas (NG), and one out of five are heated with petroleum products [3], contributing to the NYS building sector's large

contribution to the state's overall GHG emissions. NYS provides incentives and rebates for residents to switch from combustion heating systems that are fueled by natural gas to heat pumps that are powered by electricity, and the state's long-term objective is for electric heat to contribute to the strategic downsizing of its natural gas distribution system [2]. However, the electricity grid in NYS is not 100% zero-emission yet and is not required by the CLCPA to be so until 2040. Any reductions to the building sector's GHG emissions attained via heating electrification will therefore be gradual, and their magnitude and timing will be determined by the pace of both the market penetration of heat pumps and the deployment of zero-emission electricity generation capacity.

The CLCPA's implementation is unique among existing climate policies in that it explicitly requires the deep decarbonization of the residential heating sector. While relatively novel among developed economies at the time that it became law, similar policies are being adopted by other large state and national economies, and an analysis of the residential heating sector's decarbonization pathways under the CLCPA provides important information for those other economies as well. This analysis fills a critical gap in the literature by analyzing the climate impacts of NYS's residential heat decarbonization systems from the perspective of both magnitude and time. This analysis is necessary in order to inform how scarce renewable electricity resources should be used most effectively and efficiently. The CLCPA implements a cost-benefit analysis framework that utilizes net present value (NPV) modeling in which GHG emission reductions are treated as a time-discounted revenue stream under a social cost framework [4]. This policy choice has important implications for the analysis of decarbonization options of the NYS residential heating sector. The discounting of benefits (and costs) according to time gives greater weight to near-term decarbonization options than those that occur further in the future, with other factors being equal.

The use of an NPV approach in which the social cost of GHG values the benefits of residential heat decarbonization options under different deployment timelines has not been covered extensively in the scientific literature despite its use to implement climate policy in a major economy such as that of NYS [5]. Fridlyand and Glanville [6] compared emissions while also analyzing the economic savings of different residential heating decarbonization pathways. They analyzed four pathways, namely (1) gas absorption heat pumps (GAHPs), (2) boilers, (3) furnaces, and (4) electric heat pumps, with the objective of estimating the cost and energy savings of the GAHP combined space and water heating system. To determine the economic and environmental impacts, they used three building models along with carbon intensity equivalents and energy prices. Across all locations, they found the GAHP pathway to have the lowest operating cost and the largest emission reduction. However, their study did not value the emission reduction under a social cost framework, nor did it account for differences in deployment timelines between the options. It also utilized carbon equivalent values rather than the intensities of the individual gases, which can under- or overestimate the effects of certain gases based on the lifespan of the gas.

Padovani et al. [7] conducted a techno-economic analysis of decarbonization in rural residential buildings. This study analyzed isolated residential buildings in the Midwest U.S. that did not have a natural gas connection. Four levels of electrification were modeled with different solar PV sizes based on the energy used to heat and cool the space and heat the water. The base case utilized propane for all of the heating needs. Their results showed that emissions were reduced by 50% when heat pumps were combined with PV. This study did not account for the emissions from the current electric grid; rather it studied the combination of heat pumps with solar PV. Along with the past study, the study by Padovani et al. [7] did not value the emission reduction under a social cost framework and did not account for differences in the deployment timeline. This study also analyzed carbon equivalent emissions rather than individual gases, which, again, can under- or overestimate the effects of certain gases based on the lifespans of those gases.

Frank et al. [8] quantified the climate and financial impacts of residential heating pathways in NYS. They analyzed four pathways: an ultra-low sulfur diesel (heating oil)

baseline scenario, a ‘bioheat’ scenario where biomass-based diesel was blended with heating oil, a natural gas scenario where a new natural gas heating system was deployed, and an ASHP. The study found that, for the baseline scenario, the ‘bioheat’ pathway yielded the highest NPV under a framework incorporating the climate benefit via the social cost of carbon dioxide while also yielding the second lowest emissions. The study was notable for its use of different deployment timelines for the decarbonization options. Unlike the present study, however, it did not analyze RNG as a decarbonization option, nor did it utilize an existing NG system as the baseline scenario. Frank et al.’s [8] study focused on liquid rather than gaseous renewable fuels as decarbonization options.

The current study is novel due to its utilization of varying deployment timelines for heat decarbonization, and it fills an important gap in the literature by quantifying the NPV under a social cost framework of a baseline pathway and three different GHG abatement pathways:

- (1) An existing natural gas (NG) system (baseline);
- (2) Renewable natural gas (RNG) derived via anaerobic digestion;
- (3) RNG blended with hydrogen (Hydrogen);
- (4) Air source heat pumps (ASHPs) with supplemental RNG.

The present study also accounts for differences in deployment timelines between the pathways and examines the impact of GHG abatement pathways in the residential space heating sector along different investment timing scenarios within NYS between 2022 and 2042. Both the economic and environmental impacts of transitioning from the existing NG pathway to GHG abatement pathways are analyzed. The NPV is based on a techno-economic analysis where the value of GHG abatement is a function of the social cost of GHG and is shown as a form of revenue. This study can help policymakers understand both the environmental and economic benefits of different GHG abatement heating pathways so that they can be more informed when making decisions and considering regulations about residential space heating.

2. Materials and Methods

This techno-economic analysis quantifies the financial and climate impacts of three different GHG abatement pathways with varying deployment timelines relative to the baseline fossil fuel pathway in the residential heating sector in NYS. This study calculates the NPVs of each pathway from 2022 until 2042 where GHG emission reductions are accounted for as a revenue stream via the application of a social cost to pathway-specific GHG intensity values. The existing residential heating pathway in NYS, NG, is the baseline pathway and is compared with three GHG abatement pathways: RNG, Hydrogen, and ASHP.

Three geographic locations within NYS are modeled to reflect the diversity of climate, RNG feedstock mixes, GHG intensity values, and energy and equipment costs within the state. The ‘Upstate’ location broadly reflects the region north of New York City (NYC), which is characterized by colder winter temperatures, low energy costs, the presence of a substantial dairy industry, and a more renewable energy electric grid. The ‘NYC’ location reflects the city’s dense urban population, warmer winter temperatures, high energy costs, and the presence of large wastewater treatment plants. The Long Island (‘LI’) location is characterized by warmer winter temperatures (similar to the NYC location), energy costs that fall between those of the Upstate and NYC locations, and a mix of RNG feedstock sources. All pathways are calculated per average single-family residence with a site reference size set at 4 tons or 50.64 MJ/h of thermal capacity [9]. The energy demand for the average single-family residence for all of the gaseous pathways in Upstate is 91,790 MJ/year and 25,505 kWh/year for the ASHP. In NYC and LI, the energy demand for the average single-family residence for all of the gaseous pathways is 71,744 MJ/year and 20,058 kWh/year for the ASHP.

2.1. Inputs in Residential Space Heating Pathways

The existing heating pathway for residents in NYS is NG, so it is assumed to already be in place at the start of the time period covered by the analysis. The GHG intensity values

remain constant for all GHGs from 2022 to 2042 as the intensity for natural gas is already determined and does not change over time. These intensity values are a combination of estimates from the GREET 2022 model with the addition of the Environmental Protection Agency's (EPA) GHG intensity values for the combustion of NG [10].

The RNG pathways assume that the RNG is derived from biogas via the anaerobic digestion of (1) food waste, (2) dairy manure, (3) fats, oils, and greases (FOGs), (4) wastewater, or (5) a combination of feedstocks (Table 1). Feedstock combinations are a function of the three different locations modeled. The Upstate location assumes a mix of dairy manure and food waste. The NYC location assumes primarily wastewater feedstock due to the presence of large wastewater treatment plants in the area. The LI location assumes a feedstock of mostly food waste with some wastewater and fats, oils, and greases (FOGs). While landfills have historically been sources of methane emissions in NYS, in 2022, the state enacted a landfill diversion mandate that requires large generators of food waste to redirect their food scraps to organic recycling facilities, such as anaerobic digestion systems [11]. RNG production via anaerobic digestion is widely deployed in the U.S.; it is therefore assumed to have a Year 0 start date in the NPV analysis because it is used with the existing natural gas heating infrastructure [12]. The GHG intensity values of each location of the RNG and, by extension, the Hydrogen and ASHP pathways' locations operate as a function of the RNG feedstock mix [13] (Tables 2–4). The GHG intensities for the RNG pathway remain constant from 2022 to 2042 as the intensity for the RNG derived from each type of feedstock is already determined and does not change over time.

Table 1. Anaerobic digestion feedstock mix based on region.

	Upstate	NYC	LI
Dairy Manure	48.4%	0%	0%
Food Waste	51.6%	5%	85%
FOGs	0%	0%	5%
Wastewater	0%	95%	10%

The Hydrogen pathway assumes a blend of 90% RNG and 10% hydrogen by volume, with the latter being produced via water electrolysis using the NYS electric power grid. In the first four years, this pathway uses 100% RNG, and then hydrogen is assumed to be blended with the RNG in Year 5 (since this technology is not readily available in NYS today). The GHG intensities of this pathway are a function of the (1) RNG feedstock mix per location and (2) GHG intensities of the NYS power sector. The GHG intensities are assumed to decrease over time as the state complies with the CLCPA's requirement of 100% zero-emission power by 2040. Tables 2–4 present the GHG intensities for the Hydrogen pathway at all three locations from 2022 to 2042.

The ASHP pathway assumes the use of ASHPs powered by the NYS electric grid with supplemental heat provided by RNG when temperatures are $<-9^{\circ}\text{C}$ [14]. Electric resistance heat is another possible option to add to an ASHP and provide supplemental heat, but this source is not as efficient and has the potential to increase GHG emissions in comparison to RNG. The amount of supplemental heat needed for each scenario was determined by the average number of days in each location over the past 5 years in which temperatures reached $<-9^{\circ}\text{C}$ [15]. While ASHP technology is available in NYS, it currently has low market penetration. Furthermore, ASHPs represent a new source of electricity demand and require new power generation capacity to come online before widespread market penetration can be achieved. This pathway accounts for this by assuming that RNG is used in Years 0 to 4, and then ASHPs are installed in Year 5, after which point RNG is only used to provide supplemental heat. Since this pathway scenario is also assumed to be powered by the NYS electric grid, its GHG intensity values decline between 2022 and 2042 based on the goals of increasing renewable energy in NYS (Tables 2–4).

Table 2. Carbon intensity (g CO₂/MJ) from 2022 to 2042.

	Upstate	NYC	LI	Source
NG	56.56	56.56	56.56	[10,13]
RNG	16.63	−62.81	2.75	[13,16]
Hydrogen	16.09–14.97	−45.91–−56.53	13.09–2.47	[13,16,17]
ASHP	11.61–1.31	104.52–0.62	104.09–0.06	[13,16,17]

Table 3. Methane intensity (g CH₄/MJ) from 2022 to 2042.

	Upstate	NYC	LI	Source
NG	0.21	0.21	0.21	[10,13]
RNG	−3.86	−1.13	−3.37	[13,16]
Hydrogen	−3.47–−3.47	−0.96–−1.02	−2.97–−3.03	[13,16,17]
ASHP	−0.25–0.30	0.57–0.01	0.51–0.07	[13,16,17]

Table 4. Nitrous oxide intensity (g N₂O/MJ) from 2022 to 2042.

	Upstate	NYC	LI	Source
NG	0.00	0.00	0.00	[10,13]
RNG	0.00	−0.02	0.00	[13,16]
Hydrogen	0.00–0.00	−0.02–0.02	0.00–0.00	[13,16,17]
ASHP	0.00–0.00	0.00–0.00	0.00–0.00	[13,16,17]

2.2. Inputs in Sensitivity Analysis

Four sensitivity analyses are conducted on each pathway in the Upstate NY zone. The fuel cost, NPV discount rate, social cost of the GHG discount rate, and home equipment expenses are varied according to the minimum, maximum, and baseline values. Using NYSERDA's [9] New Efficiency report and the U.S. EIA [18] natural gas prices, the fuel cost for the NG pathway uses a minimum value of 11.37 USD/GJ, a baseline value of 16.36 USD/GJ, and a maximum value of 19.82 USD/GJ. The RNG pathway also utilizes the New Efficiency [9] report along with the Potential of RNG in the NYS report [16] to assume a minimum, baseline, and maximum of 21.84 USD/GJ, 27.52 USD/GJ, and 37.73 USD/GJ. The Hydrogen pathway uses the New Efficiency report and NREL's H2A model to analyze a minimum fuel cost of 21.32 USD/GJ, a baseline of 26.60 USD/GJ, and a maximum of USD 35.62 [9,19]. The ASHP pathway utilizes the New Efficiency report, NYSERDA monthly average retail price of electricity, and energy estimates from U.S. EIA to determine the minimum, baseline, and maximum value of 0.08 USD/kWh, 0.09 USD/kWh, and 0.25 USD/kWh [3,9,20].

NPV discount rates of 5%, 10%, and 15% are examined. The discount rate of the social cost of GHG is based on the NYS Department of Environmental Conservation's (DEC) [5] Establishing a Value of Carbon report. The sensitivity analysis used a maximum of 3% social cost of the GHG discount rate, a baseline of 2% social cost of the GHG discount rate, and a 1% minimum social cost of the GHG discount rate. The final sensitivity analysis examined the impact of the home equipment expense on the NPV. The minimum and maximum values calculated are 30% (+/-) of the baseline value of each pathway's home equipment costs.

3. Results

3.1. Calculations

The environmental and economic impacts of each pathway are calculated with the NPV formula. The social cost of GHG determines the environmental impact as it represents the benefits of reducing emissions. The NPV is calculated for each pathway using the following formula:

$$NPV = \sum_{t=20} \frac{SC - \text{Annual Fuel Cost} - \text{Annual Maintenance}}{(1 + 0.10)^{20}} - \text{Initial Investment}$$

In Tables 2–4, there are negative GHG intensities because of the RNG that is produced from uncapped sources of emissions that would otherwise be released into the atmosphere. The GHG intensities for each pathway are applied to the energy demand for a single-family residence to determine the annual emissions. The annual emission difference is then calculated by subtracting the annual emissions of the GHG abatement pathway from the existing NG pathway. The NYS DEC’s social cost is applied to the annual emissions difference, with the social cost being defined as “an estimate, in dollars, of the present discounted value of the future damage caused by a metric ton increase in emissions of a specific GHG into the atmosphere in that year or, equivalently, the benefits of reducing emissions of that gas by the same amount in that year. It is intended to provide a comprehensive measure of the net damages—that is, the monetized value of the net impacts—from global climate change that result from an additional ton of emissions” [21].

Using an average discount rate of 2%, the social cost of carbon dioxide ranges from USD 124 per metric ton in 2022 to USD 156 per metric ton in 2041; the social cost of methane ranges from USD 2800 per metric ton in 2022 to USD 4200 per metric ton in 2041; and the social cost of nitrous oxide ranges from USD 44,000 per metric ton in 2022 to USD 58,000 per metric ton in 2041. It is important to note that the value of heat is not categorized as a revenue source in this analysis since there is no set market price for residential heat in NYS. For this reason, the comparative NPV results are more important than the individual results of each pathway. The comparative NPV is calculated by taking the GHG abatement pathway’s NPV and subtracting it from the existing NG pathway’s NPV. Both capital and operating expenses are included in the NPV calculations. The capital cost is the home equipment costs incurred when the system is installed based on the investment timing. These costs were adjusted according to NYSERDA’s ‘Assumed Nominal Cumulative Change in CAPEX by Year’ [9]. The operating expenses include the annual fuel cost and the annual maintenance cost for single-family houses. The annual fuel cost is calculated based on the unit fuel cost of each pathway multiplied by the amount of energy a single-family household uses per year. The cost assumptions can be seen in Table 5 below.

Table 5. Cost assumptions for residential heating pathways.

	Upstate	NYC	LI	Unit	Source
Annual Fuel Cost: NG	USD 1417	USD 1107	USD 1107	USD/year	[18]
Annual Fuel Cost: RNG	USD 2526	USD 1869	USD 1648	USD/year	[16]
Annual Fuel Cost: Hydrogen	USD 2442	USD 2156	USD 1710	USD/year	[9,16,19]
Annual Fuel Cost: ASHP	USD 2048	USD 4686	USD 3360	USD/year	[9]
Annual Maintenance: NG, RNG, Hydrogen	USD 143	USD 143	USD 143	USD/year	[9]
Annual Maintenance: ASHP	USD 243	USD 243	USD 243	USD/year	[9]
Home Equipment Cost: NG, RNG, Hydrogen	USD 4905	USD 5449	USD 5070	USD	[9]
Home Equipment Cost: ASHP	USD 21,200	USD 23,551	USD 21,913	USD	[9]

3.2. Residential Space Heating Pathways Results

Across all emissions and regions, RNG achieves the lowest emissions, except for the Upstate CO₂ emissions (Tables 6–8). This is because the Upstate region's feedstock is a mix of dairy manure and food waste, which is where the RNG is derived from. The GREET model estimates dairy manure and food waste having a positive carbon intensity, while methane and nitrous oxide have negative intensities. The NYC feedstock mix includes wastewater, which has a negative GHG intensity. The negative GHG intensities of the RNG pathway cause the hydrogen and ASHP pathways to achieve a comparatively greater cumulative emission reduction even after their electricity emissions reach zero in 2040.

Table 6. Cumulative CO₂ emissions generated in the 2022–2042 period (g CO₂).

	Upstate	NYC	LI
NG	103,831,020	81,155,280	81,155,280
RNG	30,533,789	−90,126,348	3944,490
Hydrogen	128,278,103	−74,664,359	9999,395
ASHP	2711,032	17,604,555	17,687,715

Table 7. Cumulative CH₄ emissions generated in the 2022–2042 period (g CH₄).

	Upstate	NYC	LI
NG	390,089	304,897	304,897
RNG	−7083,642	−1626,438	−4830,529
Hydrogen	−6370,868	−1428,136	−4311,818
ASHP	−144,017	94,224	70,291

Table 8. Cumulative N₂O emissions generated in the 2022–2042 period (g N₂O).

	Upstate	NYC	LI
NG	2641	2064	2064
RNG	−8878	−27,263	−2870
Hydrogen	−7985	−24,491	−2537
ASHP	−243	139	219

Despite the cumulative CO₂ emissions being greater for the RNG pathway than the Hydrogen and ASHP pathways in the Upstate location, the comparative NPVs show that the RNG pathway achieves the highest NPV across all three regions compared to the baseline NG pathway (Table 9). This is primarily because of the large negative emissions achieved through the anaerobic digestion of waste and the consequent avoidance of biogenic methane emissions. The Hydrogen pathway achieves the second highest NPV across all locations due to its high RNG blending percentage, which again is derived via waste streams. The ASHP pathway achieves the lowest NPV across all locations and appears negative as it is smaller than the NG pathway. The ASHP's low result is caused by two factors: its comparatively slow deployment and the lack of a zero-emissions electricity grid in NYS. Although the deployment of ASHP is slow, the NYS electric grid still relies on nonrenewable energy in Years 1–5, which is assumed to have the greatest GHG intensities compared to future years as the increase in the electricity grid becomes closer to zero emissions.

Table 9. Comparative net present values (NPVs) relative to NG pathway.

	Upstate	NYC	LI
RNG	USD 11,922	USD 11,765	USD 12,174
Hydrogen	USD 11,777	USD 9144	USD 11,012
ASHP	USD −10,378	USD −30,601	USD −22,876

Table 9 shows the NPV results relative to the existing NG pathway. In all three locations, the ASHP pathway is the only pathway that is more expensive than the existing NG. Immediately replacing natural gas with RNG (before eventually transitioning to renewable electric heat) provides greater climate benefits than an immediate transition to renewable electric heat. Given that there is not enough renewable electricity to go around, policymakers may achieve the greatest climate benefits by initially utilizing renewable electricity in sectors such as light-duty transportation and other existing power demands that do not have better decarbonization options available at present.

3.3. Sensitivity Analysis Results

The social cost of the GHG discount rate is the most sensitive input in all pathways across all locations. All of the energy pathways achieve the highest NPVs under the 1% social cost of GHG discount rate, except for the NG pathway, where the social cost of GHG is not a benefit to the NPV calculations; rather, it is a cost as the emissions are greater. The two lowest NPVs under the 1% social cost of the GHG discount rate are the NG pathway at USD −38,399 and the ASHP pathway at USD −23,840. The highest two NPVs under the 1% social cost of GHG discount rate and overall are the Hydrogen pathway at USD 7825 and the RNG pathway at USD 9276.

The baseline NPV for the NG pathway is USD −24,744. Since this model does not use the value of heat as a part of the revenue calculations, all of the NPV calculations for the NG pathway are negative (Figure 1a). As noted earlier, the 1% social cost discount rate shows the lowest NPV for this pathway. The second lowest NPV (USD −34,120) in this pathway is under the 5% discount rate, followed by the maximum fuel cost at USD −27,294. The highest NPV in this pathway is yielded by the 15% discount rate at USD −19,419. Following that is the minimum fuel cost at USD −21,065, and the third highest NPV in the NG pathway is under the minimum social cost discount rate of USD −21,185. The largest change in the NPV is in the maximum social cost discount rate. The smallest change from the baseline NPV is the home equipment costs.

The baseline value for the RNG pathway is USD −12,822 (Figure 1b). Despite the lack of a value of heat, the maximum social cost discount rate showed a positive NPV. The next highest NPV is achieved by the minimum fuel cost at, USD −8386, followed by the minimum discount rate of USD −10,962. The lowest NPVs under the RNG pathway are yielded by the maximum fuel cost (USD −20,800) and the minimum social cost discount rate (USD −19,579). The greatest change to the baseline NPV is seen in the maximum social cost discount rate, followed by the maximum fuel cost. The smallest change from the baseline NPV is in the home equipment expenses, with the cost showing very little effect on the overall NPV.

Figure 1c contains the tornado plot for the Hydrogen pathway in which the baseline value is USD −12,966. This pathway also shows all sensitivity analyses in this pathway to be negative except for the 1% maximum social cost discount rate NPV (USD 7825). The second highest NPV for the Hydrogen pathway is yielded by the minimum fuel cost at USD −8131, followed by the minimum discount rate at USD −11,053. The lowest NPV under the Hydrogen pathway is the maximum fuel cost (USD −19,766), and it is closely followed by the minimum social cost discount rate (USD −19,666). Figure 1c follows the same pattern as the RNG tornado diagram (Figure 1b) since the hydrogen is blended in with the majority of RNG.

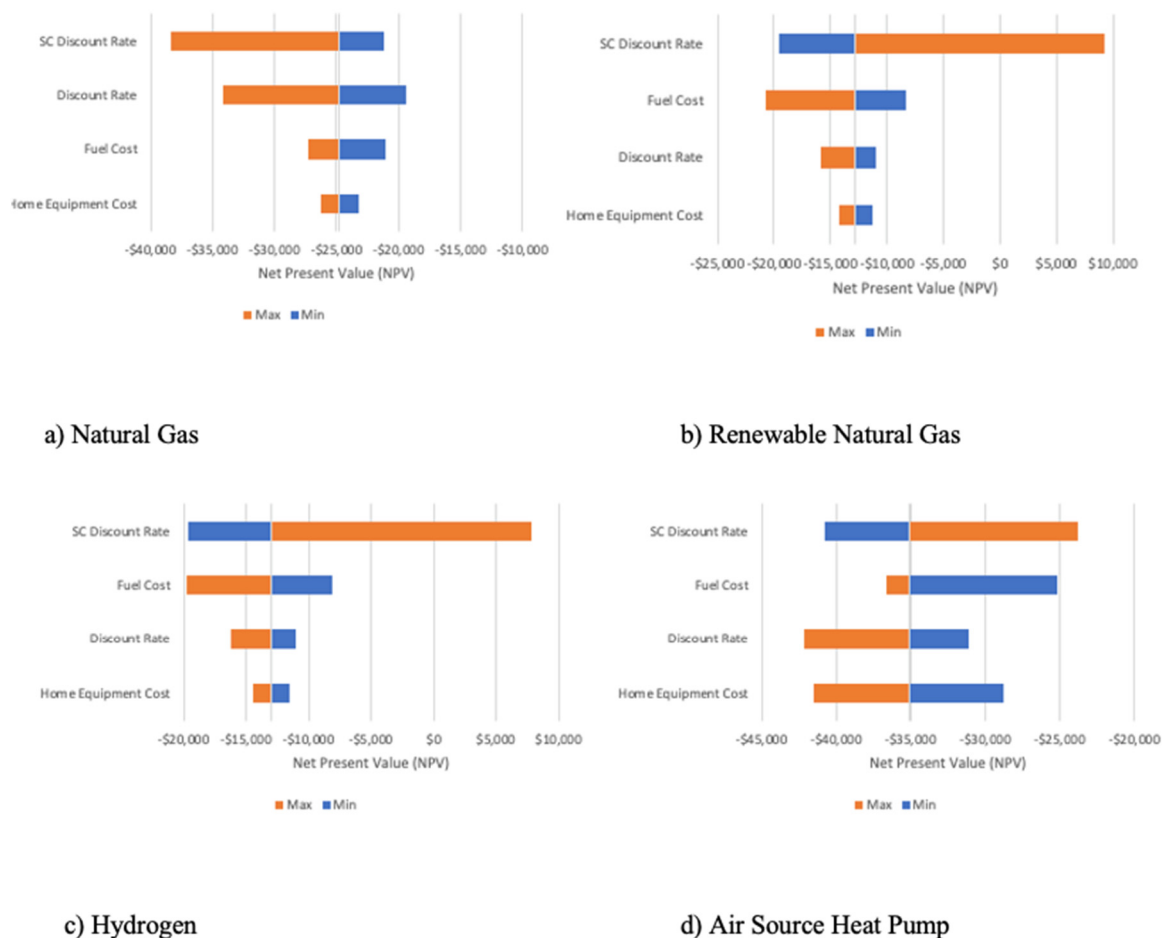


Figure 1. Tornado plot of each NPV pathway.

The baseline NPV for the ASHP pathway is USD −35,122. All the sensitivity analysis NPVs are negative for this pathway (Figure 1d). The highest NPV in this pathway is also under the maximum social cost discount rate at USD −23,840. The second greatest NPV in this pathway is the minimum fuel cost (USD −25,139), followed by the minimum home equipment cost (USD −28,762). Unlike the other pathways, the lowest NPV in this pathway is the maximum discount rate at USD −42,123, followed by the maximum home equipment cost at USD −41,482. The third to lowest NPV in the ASHP pathway is under the minimum social cost discount rate at USD −40,799. The maximum social cost discount rate shows the greatest change to the baseline NPV.

4. Conclusions

Three GHG abatement pathways in residential heating are compared with the existing natural gas pathway in three different New York State (NYS) locations, namely Upstate, New York City, and Long Island, to quantify their environmental and financial performance under a Net Present Value (NPV) framework. This study is novel in the fact that it quantifies the NPV under a social cost framework. The present study also accounts for differences in deployment timelines between the pathways and examines the impact of GHG abatement pathways in the residential space heating sector along different investment timing scenarios within NYS between 2022 and 2042. The lowest baseline comparative NPV pathway (which uses a 10% financial discount rate and a 2% social cost of GHG discount rate) is the Air Source Heat Pump (ASHP) pathway for every location. This is due to the slow deployment of ASHPs and the lack of a zero-emissions electricity grid in NYS during this transition period. The highest baseline comparative NPV pathway is the renewable natural gas (RNG) pathway in all locations. This is due to the large negative emissions achieved through

the anaerobic digestion of the different waste streams and the consequent avoidance of biogenic methane emissions. A sensitivity analysis determines that the social cost of GHG discount rate has the greatest impact on the NPV for all of the pathways, while the home equipment cost has the least impact.

This analysis demonstrates the importance of using a decarbonization pathway with negative GHG intensities, such as renewable natural gas, and how that results in negative cumulative GHG emissions (including when paired with a non-negative decarbonization pathway, such as zero-emission electricity). It also shows that the speed with which deep decarbonization is achieved has a significant impact on each GHG abatement pathway's NPV relative to that of natural gas, inclusive of the social cost of GHG. This study finds that the ASHP pathway has a lower NPV (inclusive of social cost of GHG) than the baseline natural gas pathway due to the positive GHG intensity of the electric grid prior to 2040. This study was limited by not quantifying the value of heat. Future research is needed to quantify other non-financial impacts of the residential heating pathways analyzed here (such as human health) under an NPV framework.

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