HOW DO DISTRIBUTED ENERGY RESOURCES CHANGE THE ECONOMICS OF DECARBONIZATION IN MICHIGAN

by

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Table of content

Abstract

Residential space heating is responsible for about 7% of U.S. greenhouse gas emissions. Many analysts believe that electrification with electric heat pumps, energized by clean energy, is a straightforward way of decarbonizing this sector. However, electrification is expected to raise heating bills in cold climates (e.g., in Michigan), making adoption difficult. Here, we use actual electricity and gas prices and rate structures in Michigan, combined with simulated hourly energy use data from nearly 3000 single-family homes, to investigate whether coupling heat pumps with rooftop solar photovoltaic generation (solar PV) might ameliorate the increase in bills from heating electrification. Using projected short run marginal emissions factors from the National Renewable Energy Laboratory's Cambium database, we investigate to what extent combining rooftop solar PV with heat pumps might affect the reduction in greenhouse gas emissions. We find that, for most Michigan homes, the reduction in bills brought by the combination of heat pumps and solar PV is more than the sum of savings from each strategy individually; that is, the strategies are synergistic in terms of bill reductions. The installation of electric heat pumps will reduce greenhouse gas emissions more than solar PV if the electricity grid is decarbonized by 2035. However, if the grid is only decarbonized by 2050 solar PV would be more effective at reducing emissions. We find that heat pumps and solar PV are not always synergistic in terms of greenhouse gas emissions reductions.

Acronyms

EIA	Energy Information Administration
DER	Distributed energy resource
HP	Heat pump
PV	Photovoltaic system
COP	Coefficient of performance
GHG	Greenhouse gas
NREL	National Renewable Energy Laboratory
NoSolarNoHP	Households without solar panels or heat pumps (baseline scenario)
SolarNoHP	Households with solar panels but without heat pumps
HPNoSolar	Households with heat pumps but no solar panels
HP+Solar	Households with both heat pumps and solar panels
IRA	Inflation Reduction Act
SRMER	Short-range marginal emissions rate
DTE	Detroit Edison
Consumers	Consumers Energy
MGU	Michigan Gas Utilities
GLE	Great Lakes Energy
SEMCO	Semco Energy Gas
IOU	Investor-owned utility
COOP	Utility cooperative
TOU	Time of use rate
IQR	Interquartile range

Introduction

In 2022, the residential sector accounted for 16% of the end-sector energy consumption ("U.S. energy facts explained - consumption and production - U.S. Energy Information Administration (EIA)," 2023) and approximately 10% of the total greenhouse gas emissions ("Carbon Flow Charts | Flowcharts," 2022) in the US. Natural gas is one of the main energy sources in the residential sector and, supplying 64% of households with heating, cooking, and drying ("Energy Information Administration (EIA)- About the Residential Energy Consumption Survey (RECS)Table HC1.1 Fuels used and end uses in U.S. homes by housing unit type, " 2015), thereby contributing significantly carbon emissions. Consequently, building electrification could be a cost-effective pathway to decarbonize. Researchers have explored various strategies, including the substitution of traditional heating methods with electric heat pumps (HPs), evaluating their economic and environmental benefits.

Heat pumps are recognized for their role in decarbonization efforts. Gaur et al highlighted in their comprehensive review that HPs have demonstrated efficacy in reducing energy consumption and carbon emissions internationally ("Heat pumps and our low-carbon future: A comprehensive review - ScienceDirect," 2021): For instance, studies from Italy have confirmed HPs' effectiveness in reducing carbon emissions(Alla et al., 2018); in Sweden, a modeling analysis identified HPs as the optimal heating choice for minimizing CO2 emissions and energy system impacts(Sandvall et al., 2017); and research in China has pointed to economic and energy savings linked with HP development projects(Yunna and Ruhang, 2013).

In the United States, the adoption of HPs also shows promise for decarbonization. Deetjen et al suggested that HP (Deetjen et al., 2021) would reduce greenhouse gas associated with heating and cooling in single family homes everywhere in the U.S., given grid decarbonization at a modest pace. The same analysis also showed that only 32% of US single-family homes would benefit economically from installing a HP.

Researchers have found that HPs will bring economic savings in general, as Vaishnav et al (Vaishnav and Fatimah, 2020) concluded from their study that switching from natural gas to heat pumps will reduce most of the heating bills in the Pacific Northwest and the South. However, there might be an increase in bills for cold weather areas such as the upper Midwest where the efficiency of heat pumps will be lowered due to coldness and natural gas prices are lower. A study by Walker et al (Walker et al., 2022) also recommended that high-performance HPs with a coefficient of performance (COP) greater than three are necessary in states with lower natural gas costs, such as in the upper Midwest, to achieve energy cost parity, while a COP of around two suffices in states like Texas and Florida.

The U.S. Inflation Reduction Act (IRA), enacted in August 2022, has catalyzed a market shift towards HPs and photovoltaics (PVs). HPs have experienced the highest growth rate at more affordable prices with various subsidies. The ambitious commitment to reach 20 million residential electric heat pump installations by 2030 further underscores HPs' core role in the decarbonization strategy (Solomon, 2023). Concurrently, the residential PV market has grown by 40% over 2021, influenced by the IRA ("Global Market Outlook For Solar Power 2023 - 2027 - SolarPower Europe," 2023), which has also stimulated interest in the economic impacts of transitioning from conventional fuels to HPs.

Given these insights, the upper Midwest, and Michigan in particular, should closely examine HP and PV performance. Michigan ranks as one of the top five states in natural gas consumption and the first in propane consumption for the residential sector ("Michigan Profile," 2023) as more than three-fourths of households use natural gas as their primary source for heating, according to EIA. Moreover, natural gas is largely used for electricity generation in this state ("Michigan Profile," 2023), thus further emphasizes the importance of decarbonization here to reach carbon neutrality. It is thus beneficial to assess both the environmental and economic impacts of integrating PVs with HPs. A case study by Padovani et al (Padovani et al., 2021) has concluded that with the total life cycle cost taken into consideration, a combination of PV with HP electrification strategy replacing propane can reduce residential building greenhouse gas (GHG) emissions by up to 50% immediately in the upper Midwest area.

Shifting the focus from propane, this study aims to explore a broader range of fuels, including natural gas and propane, and their replacement with HPs and rooftop solar PV systems. It evaluates the immediate effect on utility bills in Michigan with local utility gas and electricity rates and examines the CO_2 lifetime emissions under two decarbonization scenarios from 2025 to 2050, assuming residents maintain their 2018 energy consumption patterns. This paper investigates the synergies between rooftop solar PV and HP adoption in Michigan. Installation costs, tax credits, and carbon tax are not included in this analysis.

Methods

Resstock, a highly granular model of the U.S. residential housing stock developed by the National Renewable Energy Laboratory (NREL) based on a large number of statistically sampled methods with a realistic diversity of building characteristics(Wilson et al., 2022), is being employed to analyze the potential environmental and economic benefits of combining solar panels and heat pumps in this study.

Our analysis focuses on the projected reductions in lifetime emissions and the annual utility bills of sampled households from 2025 to 2050 across four scenarios: households without solar panels or heat pumps (NoSolarNoHP), households with solar panels but without heat pumps (SolarNoHP), those with heat pumps but no solar panels (HPNoSolar), and households with both heat pumps and solar panels (HP+Solar). To represent these scenarios accurately, this study employs the basic enclosure simulation package (-0) that reflects the residential building stock as it existed in 2018 and the high-efficiency heat pumps with electric backup simulation packages (-4) from AMY 2018, which were released in 2022.

After calculating the utility bill and life time emission changes in these four scenarios, the synergy of each household are assigned to be positive if the reduction in bills or emission from the HPNoSolar and SolarNoHP is smaller than the reduction in bills or emission from HP+Solar; the synergy would be negative if the reduction in bills or emission from the HPNoSolar and SolarNoHP is larger than the reduction in bills or emission from HP+Solar; there would be no synergy if the reduction in bills or emission from the HPNoSolar and SolarNoHP is equal to the reduction in bills or emission from HP+Solar.

The method section expands on the sampling process from Resstock's metadata, including the identification of utility providers for the households studied, the estimation of utility bills based on hourly energy consumption under the respective rate structures and tariffs, and the calculation of life time emissions using the hourly energy consumption coupled with the short-range marginal emissions rate (SRMER) from two decarbonization scenarios provided by Cambium—datasets that contain modeled hourly emissions, costs, and operation data for a variety of potential futures for the U.S. electricity sector through 2050 (Gagnon et al., 2024). The reduction in utility bills and emissions under two decarbonization scenarios are calculated. A schematic diagram of the method is shown in Figure.1.

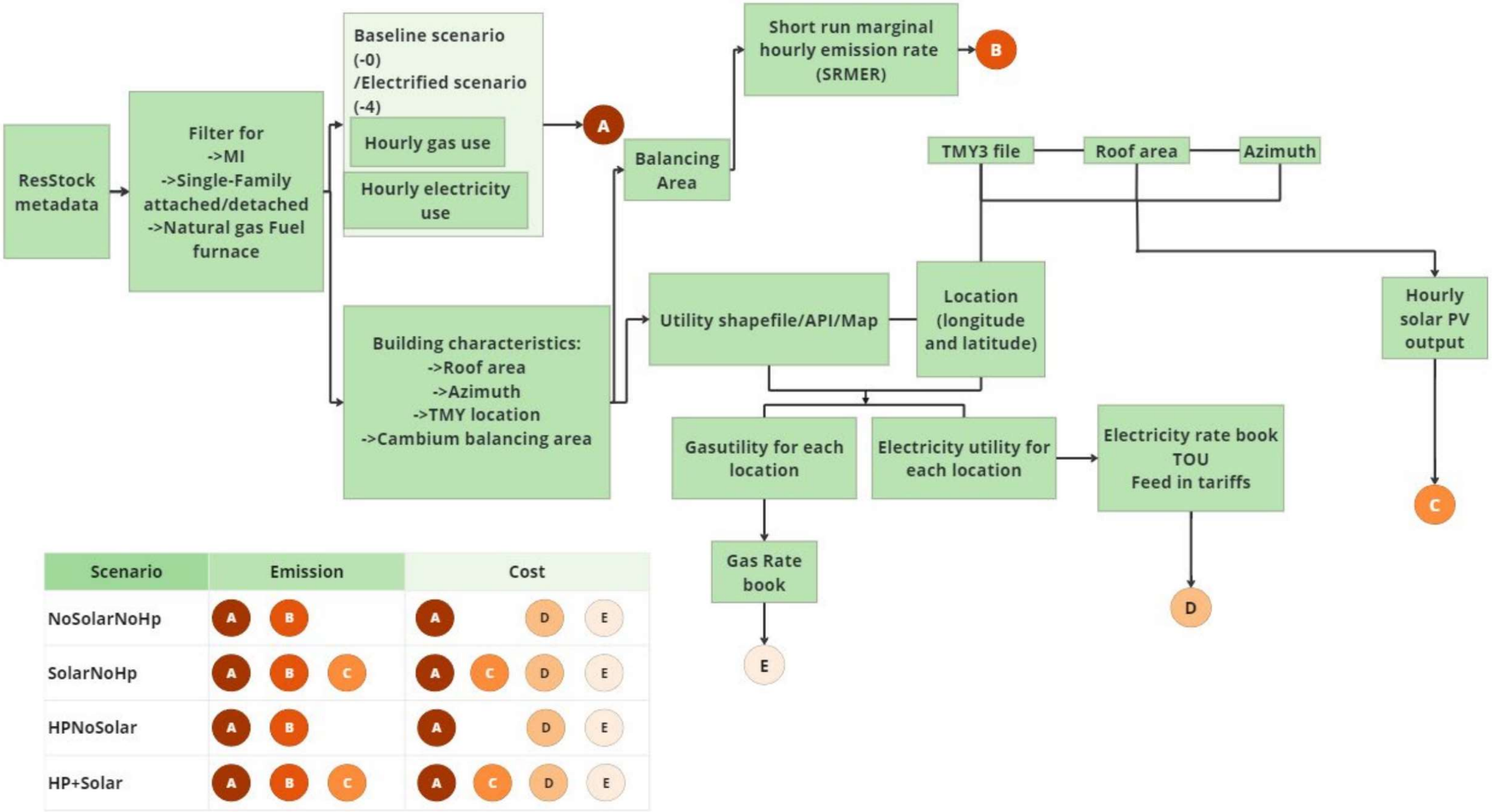

Fig.1 Schematic diagram of the study’s method

Data source and sampling

Resstock has a metadata containing information on 18,744 simulated households from 34 areas (32 cities, not in the census area, and in another census area) in Michigan. To enhance efficiency and optimize computation resources, a smaller representative sample is selected from the substantial metadata of ResStock. The meta-dataset is refined down to 3,022 households by focusing on housing types (‘in.geometry_building_type_recs’ in Resstock metadata and annual result) of ‘Single-family detached’ (standalone residential structure) or ‘Single-family attached’ (townhouses, duplexes, etc.) and the heating fuel (‘in.hvac_heating_type_and_fuel’ in Resstock metadata and annual result) of ‘Natural gas furnace fuel’.

Guided by the method from Deetjen et al (Deetjen et al., 2021), which recommends that a sample size of 400 from each location would be representative of 88%–96% of the variation in annual heating demand that would be captured by a model that uses 4500 houses. Therefore, the study samples 400 random households from each city for inclusion. For cities with fewer than 400 households in Resstock’s metadata, all existing samples from those municipalities are incorporated into the analysis.

Hourly end use profile

Resstock provides the hourly end use profiles of each household using ‘Natural gas furnace fuel’ heating system with the current gas heating system (Fig.1 output A) for NoSolarNoHP scenario and with an electric heat pump for heating and cooling for HPNoSolar (Fig.1 output A). The hourly solar PV output (Fig.1 output C) in SolarNoHP and HP+Solar scenarios are analyzed by calculating the potential solar energy generation based on the azimuth and roof areas of households from the associated XML files and TMY3 weather files.

In this study, it is assumed that each household with a roof azimuth that is in the range of 135 and 315 is economically viable for installing solar panels with a 70% roof coverage rate. The conversion efficiency of panels is set to be 20% based on the current market(“Photovoltaic Energy Factsheet,” 2023). Comprehensive calculations of each household’s potential solar generation are provided in Appendix D.

Bill calculation

The electricity and natural gas bills for each household are calculated under all four scenarios. In scenarios involving the installation of PV systems, households are credited for the excess electricity they contribute to the grid. The study further evaluates the variations in utility bills from each scenario, offering insights into the economic implications of adopting PV systems and HPs in residential settings.

Natural gas and Electricity service identification

The service providers for natural gas and electricity for the 3,022 households are identified using geographic data tools. The shapefile for natural gas providers from the Homeland Infrastructure Foundation-Level Data (HIFLD) repository (“Natural Gas Service Territories | Natural Gas Service Territories | HIFLD Open Data,” 2017) and the Utility Rate Database's API designed by the National Renewable Energy Laboratory (NREL) (“Utility Rate Database | Open Energy Information,” 2017) are employed in the identification process. By inputting each household’s longitude and latitude into these resources, the respective service providers are returned. To further streamline the analysis and save computing time, the research focuses on households within the service areas of the three largest natural gas and electricity providers in Michigan, based on customer numbers. The top three natural gas service providers(“Natural Gas Utility Annual Reports,” 2022) are Detroit Edison Company (DTE, IOU), Consumers Energy Company (Consumers, IOU), and Michigan Gas Utilities Corporation (MGU, COOP). The top three electricity service providers(“Electricity Data - U.S. Energy Information Administration (EIA),” 2023) are DTE, Consumers, and Great Lakes Energy Cooperative (GLE, COOP). The selected sample is further narrowed down to 2681 households (Table.1). The selected utility providers’ rate structures for gas, Time of Use (TOU) structure for electricity, and net metering policy are used to calculate how electricity tariffs change if excess solar energy generation can be fed into the grid.

Table.1 number of random samples from each area

City	Initial size of random sample	Final size of random sample (narrowing down to largest three natural gas and electricity utilities)
Ann Arbor	70	70
Dearborn	90	90
Detroit	400	400
Farmington Hills	60	60

Flint	117	117
Grand Rapids	144	144
Jackson	26	26
Kalamazoo	53	0
Kentwood	42	42
Lansing	95	3
Lincoln Park	30	30
Livonia	98	98
Midland	34	34
Muskegon	32	32
Novi	57	57
Pontiac	53	53
Portage	31	0
Rochester Hills	62	62
Roseville	44	44
Royal Oak	65	65
Saginaw	40	40
Southfield	59	59
Sterling Heights	109	109
Taylor	62	62
Troy	70	70
Warren	134	134
Westland	81	81
Wyoming	64	64
In another census place	400	313
Not in a census place	400	322

Natural gas bill

DTE("Natural Gas Rates & Suppliers | DTE Energy," 2022), Consumers("How Natural Gas Rates Are Set | Consumers Energy," 2024), and MGU("MGU Rate Book | Michigan Gas Utilities," 2023) have similar residential rate structures. Each rate structure consists of a monthly customer charge, a commodity charge that includes the distribution charge, cost recovery charge, reservation charge, and a monthly IRM surcharge depending on the utilities. A detailed breakdown of each utility's rate can be found in Appendix A. The general equation used to calculate the monthly natural gas bill is in equation 1:

$$\text{Monthly customer surcharge} + \text{hourly natural gas consumption} * \text{Commodity charge} \quad (\text{eq.}1)$$

By aggregating twelve monthly natural gas bills, the annual natural gas utility bill for each household is obtained. To account for global market influences, specifically the impact from the relationship between Russia and Ukraine, the commodity charge set in February 2023 is used as a representative rate to estimate the general commodity charges for the year 2023.

Electricity bill

DTE("MPSC-Approved DTE Electric Rate Books and Cancelled Sheets," 2018) and Consumers("MPSC-Approved Consumers Energy Electric Rate Books and Cancelled Sheets," 2020) adopt similar residential TOU rate structures. These TOU structures include a constant service charge, a distribution charge per kilowatt-hour (kwh), summer on-peak and off-peak charges per kWh, which are further divided into capacity and non-capacity charges, winter on-peak and off-peak charges per kWh, residential tax, and other factors. In addition to these components, there is also a low-income energy assistance fund surcharge (LIEAF). GLE("Great Lakes Energy Cooperative Rate Books and Cancelled Sheets," 2015) has not yet implemented a TOU schedule, therefore the cost per kWh remains constant. The general equation used to calculate the monthly electricity bill is in equation (2):

$$\begin{aligned}&\text{Monthly service charge} + \text{On-Peak electricity consumption} * (\text{Capacity charge} + \text{Non-Capacity charge})\\&+\text{Off-Peak electricity consumption} * (\text{Capacity charge} + \text{Non-Capacity charge}) \qquad (eq.2)\end{aligned}$$

Upon summing up the electricity bills for each month and adding other factors in, the annual electricity utility bill of that household is obtained. The detailed composition of each utility's TOU structure is presented in Appendix B.

Net metering bill

Residents who install solar panels and generate excess electricity may feed the surplus back into the grid for credits under net metering policy. These credits are bankable for future electricity use and do not expire. Utility providers might have various names for their net metering policy. For simplicity, it is all referred as net metering policy here. DTE (“MPSC-Approved DTE Electric Rate Books and Cancelled Sheets,” 2018)and Consumers(“MPSC-Approved Consumers Energy Electric Rate Books and Cancelled Sheets,” 2020) adopt the TOU structure for their net metering policy and the value of the credits changes based on whether the excess electricity is fed into the grid during On-Peak or Off-Peak times. GLE (“Great Lakes Energy Cooperative Rate Books and Cancelled Sheets,” 2015) doesn’t adopt TOU structure and hence users receive constant credits throughout the year.

The specific definitions of On-Peak and Off-Peak slightly varies across utilities, with some additional incorporation of ‘critical peak’ that will be announced in the year. To simplifying this study, it is presumed that all other utilities conform to the On-Peak and Off-Peak definitions provided by DTE. Furthermore, it is assumed that the solar panels are of a typical residential scale and that critical peak periods will not be factored into the analysis. Full details of each utility’s net metering structure can be found in Appendix C.

Emission calculation

To reflect the ongoing decarbonization of the grid, this study incorporates two projected short-run hourly marginal emission (SRMER) rates: ‘Mid-case with 95% Decarbonization by 2050’ and ‘Mid-case with 100% Decarbonization by 2035’ modeled by NREL’s cambium 2023(Gagnon et al., 2024). Assuming the energy consumption pattern in 2025 to 2050 remains the same as the energy consumption pattern in 2018, the CO2 lifetime emissions are calculated with hourly energy profile. The emissions from natural gas and propane are calculated using the corresponding emission factors (Appendix E), multiplied by a factor of 26 for lifetime emission. By tallying the emissions from natural gas usage with those from electricity consumption, the study estimates the changes in emissions across different scenarios in comparison to the baseline scenario (NoSolarNoHP).

Sensitivity analysis

During the identification of natural gas service providers, 669 households are returned with null results. This issue arises because the shapefile was published in 2017 and hasn’t been updated recently. For these households, it is presumed that their natural gas service providers coincide with their electricity service providers, as determined by the Utility Rate Database API employed in the preliminary analysis. More specifically, for those within GLE's realm, it is assumed they receive natural gas services from MGU, because GLE does not offer natural gas services (labeled as 'Assuming natural gas utility to be the same as the electricity utility').

If the shapefiles are indeed accurate, it is possible that those households are not served by any natural gas utility. To address this possibility, we conduct a sensitivity analysis in which we assume that such households use propane. For this analysis, an assumption is made that a comparable amount of propane is used in place of the modeled natural gas consumption. The analysis uses the state average propane price ($2.30 per gallon) and the emission factor for propane, with further details presented in Appendix F (labeled as ‘Assuming some household use propane instead of natural gas’).

Additionally, a manual approach to pinpoint the service providers for households with null results could be implemented by cross-referencing their geographical coordinates with the natural gas provider regions published by the state government(“Utility Provider Search,” 2024). Therefore, a separate suite of analyses (labeled as 'Identifying electricity utility manually') is carried out to provide a more accurate assessment.

Results and Discussion

Utility bills

In cases where the identification of natural gas providers resulted in 'null' results, the study proceeds under the assumption that these households have the same provider for their natural gas services as they have for their electricity. Additionally, households within the jurisdiction of GLE are assumed to have MGU as their natural gas provider.

This assumption allows for the estimation of the total utility bill, which includes both natural gas and electricity bills. Furthermore, the study calculates the potential reduction in utility bills that could result from interventions such as the adoption of PVs and HPs. These estimations are illustrated in Figure 2.

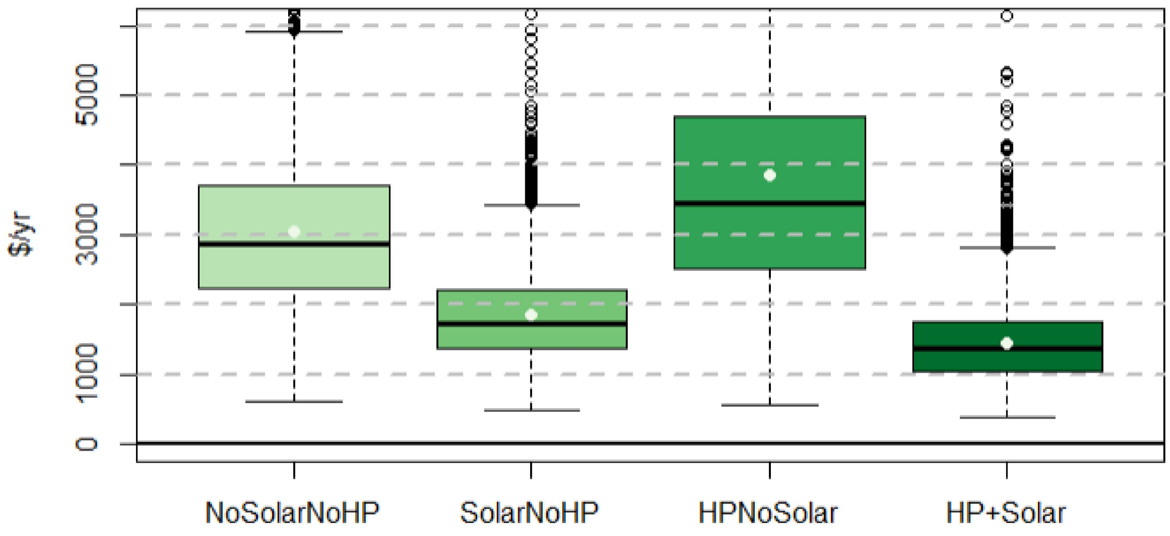

Fig. 2 Single-year utility bill per household with a focus on the IQR, n=2681

Households with HPs but no PVs (HpnoSolar) have the highest average annual bill, with a mean of $3,852 per household, and also the widest interquartile range (IQR of $2,177). This is followed by the baseline scenario (NoSolarNoHP), with an average annual bill of $3,053 per household (IQR=$1,485). Households with PVs but no HPs (SolarNoHP) have a lower average bill of $1,866 per year (IQR=$825), and the scenario combining both PVs and HPs (HP+Solar) has the lowest average annual bill of $1,458 per household (IQR=$711).

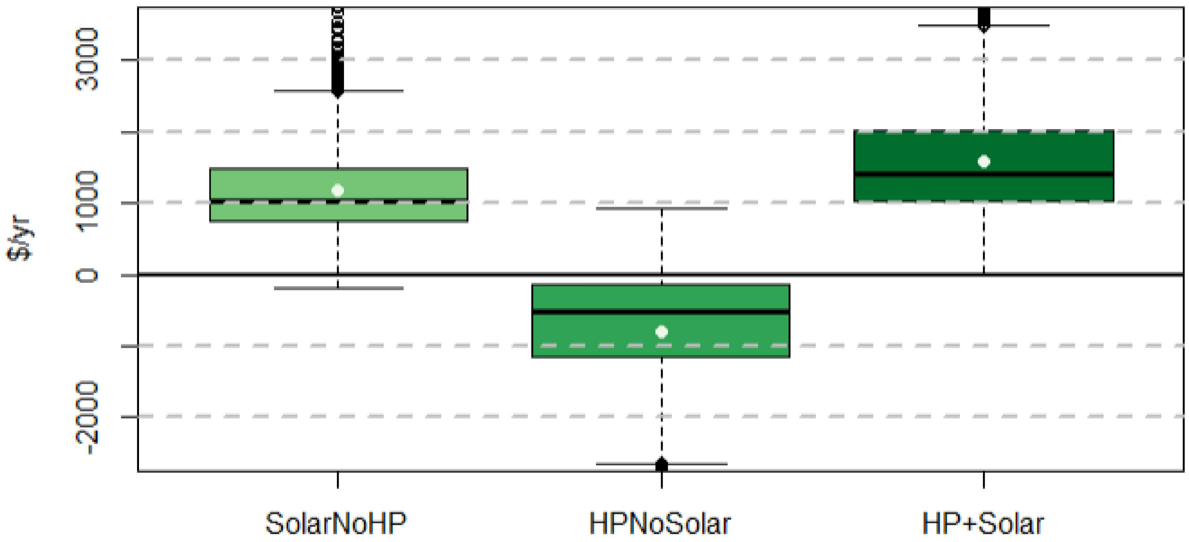

Fig. 3 Single-year reduction in utility bill per household with a focus on the IQR, n=2681

Compared to the baseline (NoSolarNoHP), the installation of PVs could lower the energy bill due to net metering policies, which allow for the compensation of excess generated electricity, as demonstrated by an average annual savings of $1,187 per household. This is shown in Figure 3 with an average decrease of $1,187 per household per year. Although the use of HP is associated with increased electricity usage as natural gas consumption is replaced, and hence higher bills, the addition of PV systems can counterbalance this increase due to the financial benefits from net metering. This ultimately leads to an overall potential average decrease in utility bills of $1,594 per household per year.

The average financial savings from the combined installation of HPs and PVs (HP+Solar) is $989 per household annually. It is greater than the savings from installing only PVs (SolarnoHP), which has an average of $735 savings per household per year. This suggests that the combination of HP and PV technologies can provide slightly more economic benefits over adopting PV alone.

In addition to that, it is found that from these 2681 households that 2660 of them have shown positive synergies, none of them has no synergies, and 21 of them have negative synergies. Hence the adoption of HP and rooftop solar PV will make each other more attractive and is beneficial in Michigan for economic savings. Furthermore, a discussion on the utility bill with the vintage year and floor area of the household can be found in Appendix G.

Emissions

The lifetime emissions across the four scenarios vary according to the specific decarbonization approach employed. Under the scenario of achieving 100% decarbonization by 2035, the baseline emission level remains the highest, with a mean of 219.3 metric tons and an interquartile range (IQR) of 110 metric tons. In the scenario that considers the installation of solar PV, there could be negative emissions since the excess generation that has been fed into the grid helps it to avoid emissions. The installation of PV alone would lead to an average emission of 169 metric tons (IQR =117 metric tons) that is slightly higher than the average emission level of installing HP only (115.7 metric tons with an IQR of 61 metric tons). The combination of HP and PV is the lowest (with a mean of 65.4 metric tons and an IQR of 65 metric tons) and hence the most effective in terms of emission reduction.

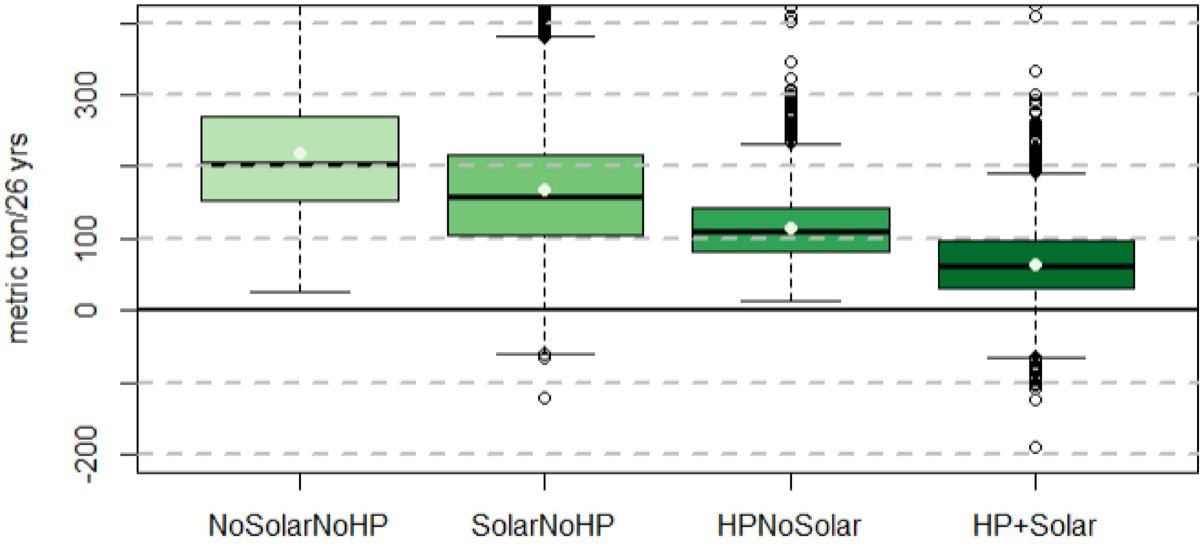

Fig.6 Life time emission in Mid-case with 100% decarbonization by 2035, n=2681; the y-axis is truncated at 350 metric tons per 26 years.

This effectiveness can be further supported in Figure 7. A combination of HP and PV could reduce the most emission, with a mean of 153.9 metric tons for the lifetime and an IQR of 90 metric tons. The installation of HP alone would reduce 104 metric tons for the lifetime on average with an IQR of 64 metric tons and the installation of PV only would reduce 50.3 metric tons for the life time with an IQR of 43 metric tons.

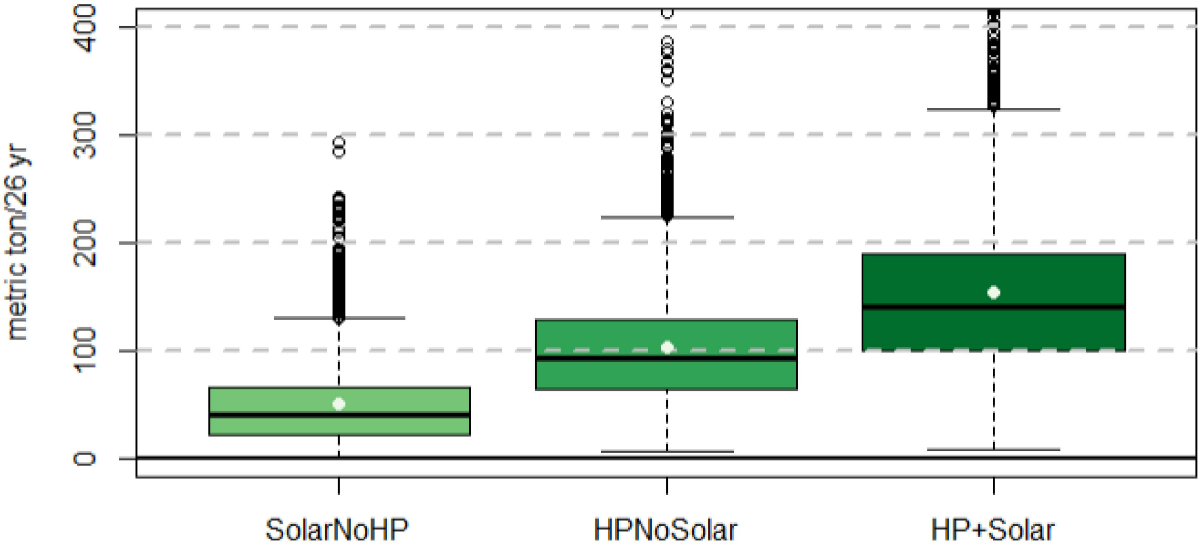

Fig.7 Reduction in lifetime emissions in Mid-case with 100% decarbonization by 2035, n=2681; the y-axis is truncated at 400 metric tons per 26 years.

In the scenario of 95% decarbonization by 2050, the combination of HP and Solar PV emerges as the most effective approach, resulting in the lowest emissions among the four scenarios with a mean of 105 metric tons (IQR=108 metric tons). However, the emission brought by the installation of PV is slightly lower with a mean of 171 metric ton (IQR=130 metric tons) than the emission brought by the installation of HP with a mean of 195 metric ton (IQR= 105 metric tons), which contrasts with the outcomes seen in the 100% decarbonization by 2035 case. The baseline scenario is still the highest, with a mean of 261 metric tons (IQR=130 metric tons).

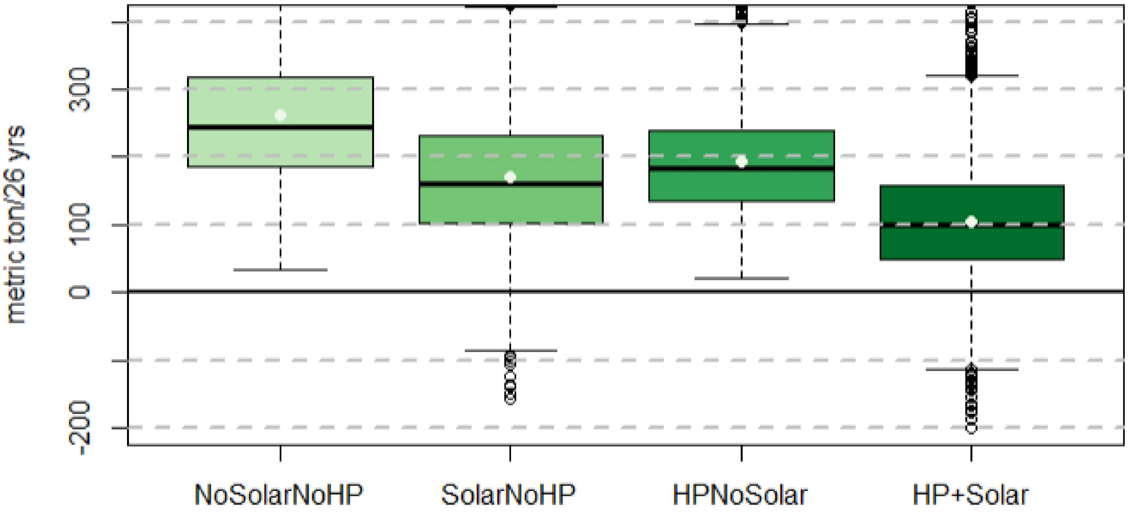

Fig.8 Lifetime emission in Mid-case with 95% decarbonization by 2050, n=2681; the y-axis is truncated at 350 metric tons per 26 years.

The emission reduction achieved solely through PV installation is slightly greater than that achieved by just installing HP in this decarbonization scenario, with a mean reduction of 89.6 metric tons (IQR = 77 metric tons) compared to 66.4 metric tons (IQR = 50.23 metric tons) for HP. The range of reduction in lifecycle emissions in the 2050 scenario is also broader than the lifecycle emission in the 2035 scenario, with more outliers in the 2050 scenario as well. This is unsurprising since the former scenario represents much faster decarbonization of the electricity grid that the latter one.

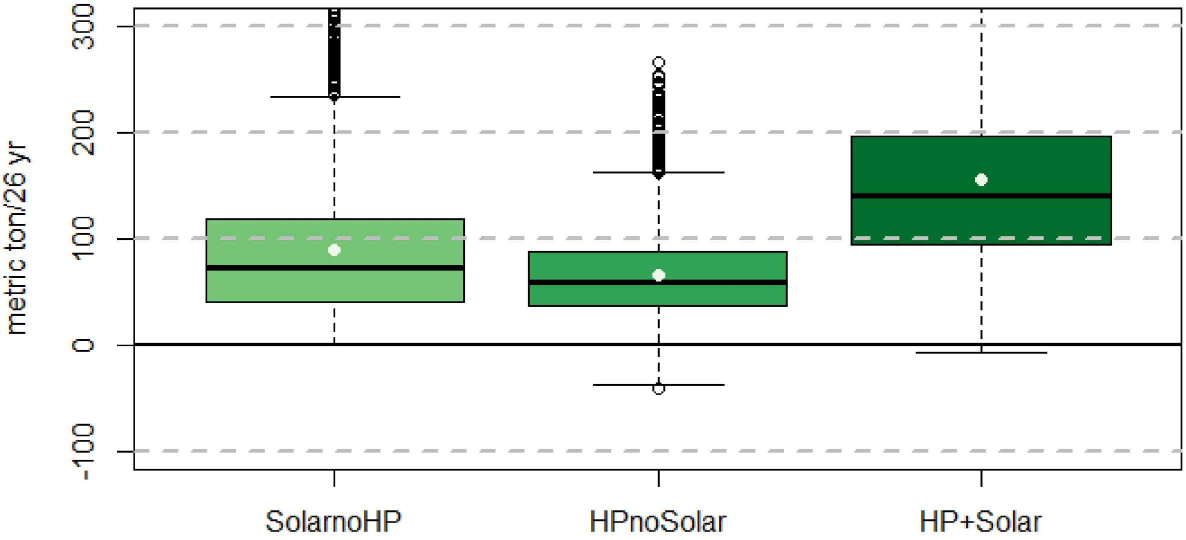

Fig.9 Reduction in lifetime emission in Mid-case with 95% decarbonization by 2050, n=2681; the y-axis is truncated at 300 metric tons per 26 years.

Additionally, it is observed that the relative impact of HP and PV installations differs between the two decarbonization timelines, mirroring trends described earlier. In the context of achieving 100% decarbonization by 2035, HP installations are found to outperform PV installations. In the 95% decarbonization by 2050 scenario, PV installations exhibit a greater impact relative to HP. However, the positive, no, and negative synergies in the Mid-case with 100% decarbonization by 2035 are found to be 1084, 554, and 1043 respectively. This is also similar in the Mid-case with 95% decarbonization by 2050 which has 1136, 411, and 1134 counts of positive, no, and negative synergies. Unlike the synergies shown in the reduction in utility bills, there is no concrete conclusion on the synergies in emission reduction in Michigan. The variance in the energy consumption pattern and housing characteristics might lead to this difference in synergies. More in-depth studies need to be taken to investigate further.

Sensitivity analysis

The economic savings and emission reduction in the scenario assuming natural gas utility to be the same as the electricity utility is similar in the scenario that identifying electricity utility manually. Hence it is not discussed in the main body and the detail can be found in Appendix F.

However, the economic saving and emission reduction in the scenario assuming some households use propane instead of natural gas slightly differ from the two scenarios mentioned above. Hence it is discussed in the following section, with a focus on the 669 households that are assumed to use propane.

Sensitivity analysis assuming household use propane instead of natural gas

For the 669 households that are assumed to use propane instead of natural gas, the installation of PV solely, HP solely, and a combination of HP and PV would all lower the utility bill and emission which is consistent as discussed above.

The baseline scenario in this analysis has the highest utility bill, with a mean of $5073 per year and an IQR of $1855. Unlike the situation that HP would raise bill in the case that assuming households' natural gas utility provider are the same as the electricity provider, the installation of HP has a lower bill, with a mean of $3850 (IQR=$2073).

The extent of reduction in emission and utility bill is the largest brought by the combination of HP and PV, followed by HP solely, and then Solar solely in terms of the IQR, though the outliers from the PV have a broader range than HP. This performance of HP is slightly different in this analysis is slightly different than the performance of HP in other two analyses, where HP would raise the bills. This is largely due to the price and emission factor of propane.

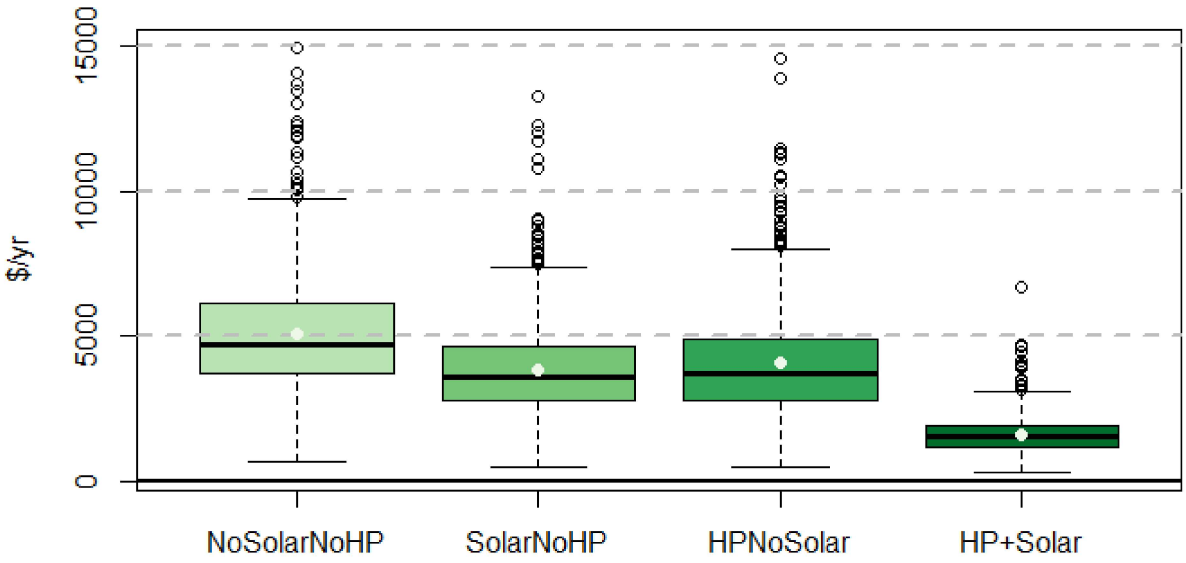

Fig.14 Single-year utility bill per household, n=669

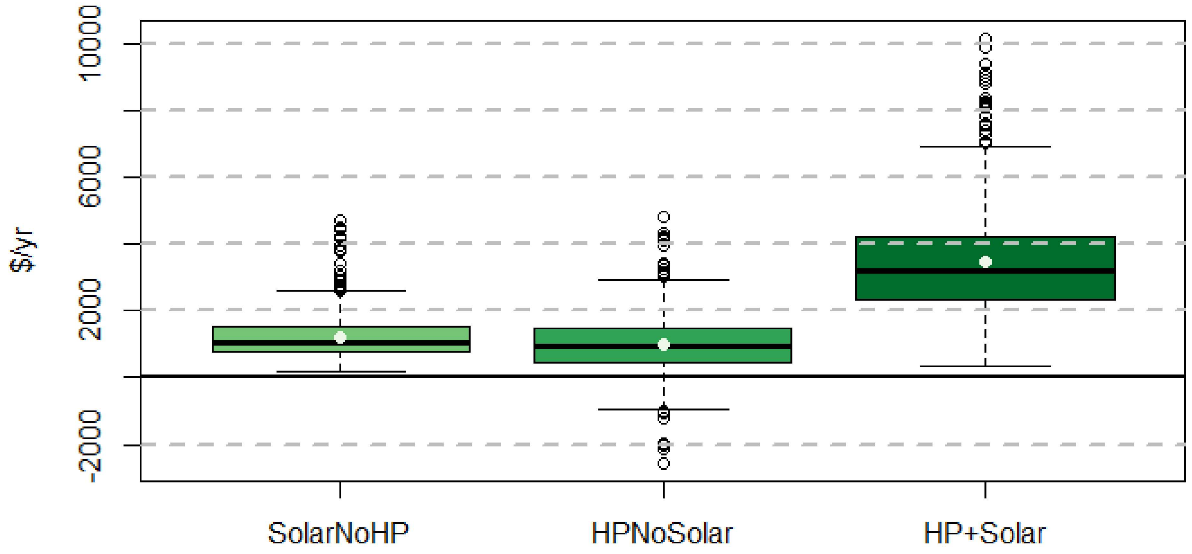

Fig.15 Reduction in single-year utility bill per household, n=669

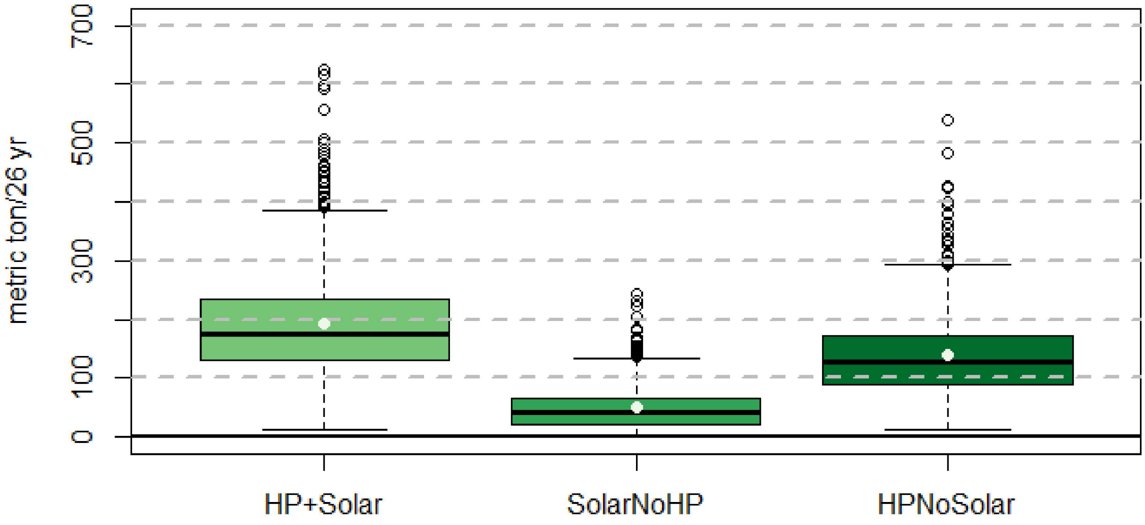

Fig.16 Reduction in lifetime emission in Mid-case with 100% decarbonization by 2035, n=669

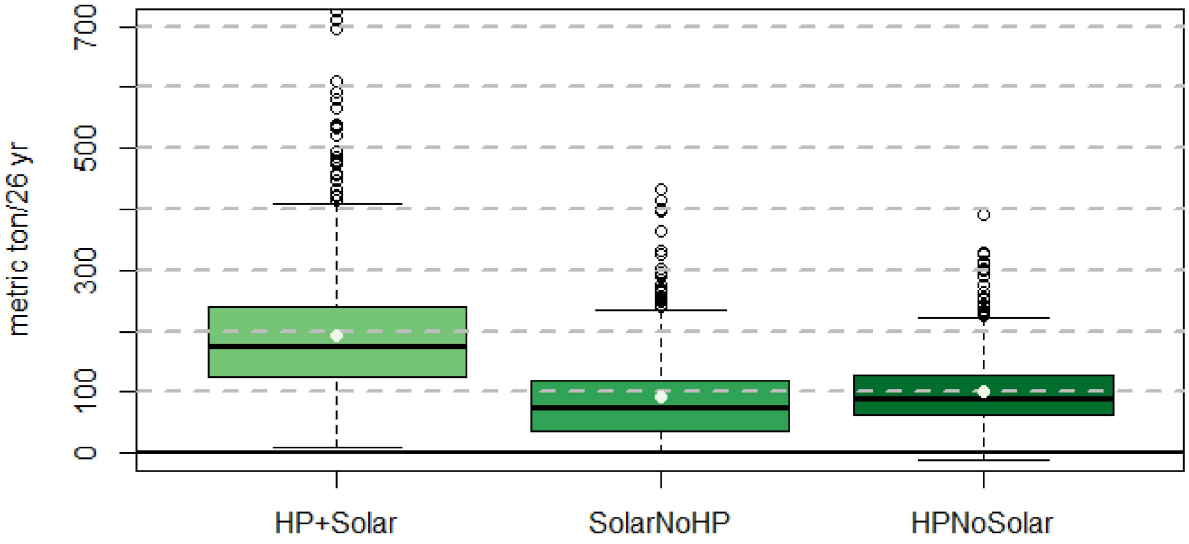

Fig.17 Reduction in lifetime emission in Mid-case with 95% decarbonization by 2050, n=669

Conclusions

In Michigan, while the installation of HP tends to increase the utility bill, the installation of PV systems or a combination of PV and HP systems results in a reduction in the utility bill. The reduction in utility bill brought by the combination is the greatest among all the three choices, followed by the installation of PV solely under the current net metering policy and rate structures, without considering upfront and other maintenance costs. The performance of rooftop solar PV and heat pump adoption has also shown positive synergies in Michigan based on the calculations.

From the environmental perspective, HP, PV, and a combination of HP and PV would all reduce emission compared to the baseline scenario in 2018. However, the extent of emission reductions varies with the decarbonization timeline. If 100% decarbonization is achieved by 2035, HP installations are more effective at cutting emissions than standalone PV installations. Alternatively, with a decarbonization target of 95% by 2050, the performance of HP and PV in isolation is comparatively similar. This pattern remains consistent across sensitivity analyses. There are about 50% of the households that have shown positive synergies. Synergies could depend on the specific household characteristics that need to be investigated further.

For the subset of 669 households assumed to use propane as opposed to natural gas, both utility bills and emissions are slightly higher than those observed in the other two sensitivity analyses. This may be attributed to the higher heat content and cost associated with propane. Consequently, the potential for bill and emission reductions is also greater for these households when switching to HP, PV, or a combination of both technologies.

Moreover, when considering the age and size of the homes, it is evident that larger homes receive greater benefits from incorporating PV or a combination of PV and HP, likely due to more efficient energy consumption at scale. Older homes also tend to benefit more from these installations compared to newer homes, possibly because newer constructions have integrated energy efficiency into their design.

Future work

This study focuses on analyzing utility bills and the annual reduction of these bills, particularly considering systems like HP and PV. There are factors not included in this study's scope such as the lifecycle bills of switching to HP and PV, upfront installation costs, additional soft costs, or the implications of a carbon tax. To fully assess the economic savings and emission reductions that can be brought by HP and PV, it is essential to broaden the scope of the research to incorporate these elements into future analysis. This also applies to the emissions side as the study operates under the assumption that energy consumption patterns remain consistent throughout the HP and PV systems' lifetimes from the use phase. It would also be worthy to convert the study into a life cycle research.

Furthermore, statistical analyses such as regression and ANOVA (Analysis of Variance) could elucidate the impact of specific household features on utility costs and emissions. These analytic methods would be beneficial in forecasting utility and emission outcomes for a given set of household characteristics and in identifying the factors that most significantly influence cost and environmental performance improvements.

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Appendix

Appendix A.

Natural gas utility rate structure
DTE ("Natural Gas Rates & Suppliers | DTE Energy," 2022) has a constant monthly customer surcharge of $13.50 per month, a $2.19 IRM surcharge that is used to fund replacement of cast iron service line with newer and safer material, and a commodity charge that sums up to be $0.91 per 100 CCF that includes distribution charge, GCR factor, energy waste reduction surcharge, reservation charge.

Consumers ("How Natural Gas Rates Are Set | Consumers Energy," 2024) has a constant monthly customer surcharge of $12.60 per month, a $0 IRM surcharge, and a commodity charge that sums up to be $1.09 per 100 CCF that includes distribution charge, GCR factor, energy waste reduction surcharge, reservation charge.

MGU ("MGU Rate Book | Michigan Gas Utilities," 2023) has a constant monthly customer surcharge of $13.00 per month, a $0 IRM surcharge, and a commodity charge that sums up and is converted to be $0.71 per 100 CCF that includes distribution charge, GCR factor, energy waste reduction surcharge, reservation charge.

In the sensitivity analysis that missing natural gas providers are manually identified, the households are identified to be served by DTE or SEMCO. SEMCO ("SEMCO Energy Gas Company MPSC Approved Rate Books," 2020) has a constant monthly customer surcharge of $12.25 per month, a $0 IRM surcharge, and a commodity charge that sums up to be $0.89 per 100 CCF that includes distribution charge, GCR factor, energy waste reduction surcharge, reservation charge.

Appendix B.

Electricity utility rate structure
For the three electricity utilities selected in this study, it is assumed that all of them impose a LIEAF (Low Income Energy Assistance Fund) of $0.88 per billing meter and a residential use tax of 3.9%. Other available credits or surcharges are not considered in this study.

DTE ("MPSC-Approved DTE Electric Rate Books and Cancelled Sheets," 2018) adopts a TOU structure (D1.11), which means that they will charge different prices in different periods. On-Peak Hours are from 3:00 PM to 7:00 PM Monday through Friday and Off-Peak Hours are the other period. For June through September, the capacity energy charge is $0.07941 per kWh and non-capacity energy charge is $0.0616 per kWh for On-Peak Hours, and a $0.04828 of capacity charge, a $0.03746 per kWh of non-capacity charge for Off-Peak Hours. For October through May, the capacity energy charge is $0.5560 per kWh and non-capacity energy charge is $0.04313 per kWh for On-Peak Hours, and a $0.04828 per kWh of capacity charge, a $0.03746 per kWh of non-capacity charge for Off-Peak Hours. Besides these charges, the structure also consists of a constant service charge of $8.5 per month and a distribution charge of $0.006879 per kWh for all kWh charge.

Consumers("MPSC-Approved Consumers Energy Electric Rate Books and Cancelled Sheets," 2020) also adopts a TOU structure, although with a slight modification on the definition of On-Peak (2:00 PM to 7:00 PM Monday through Friday) and Off-Peak Hour (7:00 PM to 2:00 PM Monday through Friday, all Saturday and Sunday). However, to simplify the calculation process, Consumer's definition of On-Peak and Off-Peak hour is assumed to align with the definition from DTE. For June through September, the capacity energy charge is $0.04838 per kWh and non-capacity energy charge is $0.109931 per kWh for On-Peak Hours, and a $0.04828 of capacity charge, a $0.079331 per kWh of non-capacity charge for Off-Peak Hours. For October through May, the capacity energy charge is $0.02794 per kWh and non-capacity energy charge is $0.77952 per kWh for On-Peak Hours, and a $0.03674 per kWh of capacity charge, a $0.079331 per kWh of non-capacity charge for Off-Peak Hours. Besides these charges, the structure also consists of a constant service charge of $8 per month and a distribution charge of $0.06415 per kWh for all kWh charge.

GLE("Great Lakes Energy Cooperative Rate Books and Cancelled Sheets," 2015) hasn't adopted the TOU structure for its electricity rate yet, therefore its charges are all constant. Its structure consists of a service charge of $34.21 per month and a charge of $0.11698 per kWh of electricity throughout the year.

Appendix C.

Net metering structure

All of the three selected utilities have a net metering policy. For DTE ("MPSC-Approved DTE Electric Rate Books and Cancelled Sheets," 2018), the current policy is called Rider NO.18 and follows the TOU structure. The On-Peak hours from June through September credit is $0.14101 per kWh, Off-Peak hours from June through September is $ 0.08574 per kWh, On-Peak hours from October through May credit is $0.09873 per kWh, Off-Peak hours from October through May credit is $0.8574 per kWh.

Consumers ("MPSC-Approved Consumers Energy Electric Rate Books and Cancelled Sheets," 2020) has another definition of a critical peak, which will be announced depending on the time of the year. Therefore its related credits are not considered in this study. The residential TOU On-Peak hours from June through September credit is $0.158384 per kWh, Off-Peak hours from

June through September is \$0.103280 per kWh. For the rest of the time, the credit is \$0.095195 per kWh.

Unlike DTE and Consumers, GLE's net metering policy("Great Lakes Energy Cooperative Rate Books and Cancelled Sheets," 2015) allows residents to receive a constant credit of \$0.056 per kWh throughout the year.

Appendix D.

Solar energy generation algorithm

To calculate the solar energy potential, the algorithm is referred from Vaishnav et al(Vaishnav et al., 2017). The azimuths of the roof and weather file information are provided by Resstock (Walker et al., 2022). The azimuth of roof needs to be larger than 135 and smaller than 315. If the roof's azimuth does not meet the requirement, then it is assumed the household will not install panels and therefore has no solar generation. Each selected household's TMY3 2018 weather file that has information on the global horizontal radiation, direct normal radiation, and diffuse horizontal radiation in that region are also used in the calculation.

For households with roofs that meet the above requirement, each of their roof area that can be used to generate 1kw solar energy is calculated first. This is done by dividing the solar insolation (1kw/m^2) to the roof's area to get the size of panel that can be installed, assuming a 70% coverage ratio.

To calculate the solar energy generation, which is a sum of direct beam radiation and diffuse radiation (eq.1), solar declination (δ) and other factors needed to be calculated first.

$$solar\ energy\ generation = direct\ beam\ radiation\ +\ diffuse\ radiation \quad (eq.1)$$

$$Direct\ beam\ radiation = DNI * \ (sin(\delta) * sin(\varphi) * cos(\beta) - sin(\delta) * cos(\varphi) * sin(\beta) * \boldsymbol{cos(\psi) + cos(\delta) * cos(\varphi) * cos(\beta) * cos(hours) + cos(\delta) * sin(\varphi) * sin(\beta) * cos(\psi) * cos(hours) + cos(\delta) * sin(\psi) * sin(hours) * sin(\beta)} \quad \boldsymbol{(eq.2)}$$

$$\text{Diffuse}\ radiation = DHI * \ (180 - \beta) \quad (eq.3)$$

Where solar declination is calculated using the equation (1) below, where N=day of the year:

$$\delta\ =\ 23.45\, sin\, [\, 360\ 365\ (\, 284\ +\ N\,)\,]\ \ (eq.4)$$

The angle of elevation (α) is also calculated using equation (4), where φ is the latitude in radian:

$$\alpha = \delta + \frac{\pi}{2} - \varphi \; (eq.5)$$

ψ=180-azimuth/Π (eq.6)

Appendix E.

Emission calculation in analysis

Table.1 Emission factors and fuels

Fuels	Emission factor
Natural Gas	54.87 kg/thousand cubic feet
Propane	5.75 kg/gallon

Appendix F.

Sensitivity analysis

Bill

Across the three sensitivity analyses, the utility bill assuming some households use propane has a broader IQR than the rest. The utility bill assuming natural gas utility to be the same as the electricity utility has a similar IQR to the utility bill identifying natural gas utility manually. All of them also follow a trend of having the highest utility bill in terms of the mean, median, IQR range, and the number of outliers in the HPNoSolar scenario, followed by the baseline NoSolarNoHP scenario, SolarNoHP, and Solar+HP scenario. It suggests that the installation of HP would raise the utility bill in Michigan as a cold weather area, the installation of PV will bring economic savings, and a combination of both makes PV's economic benefits outweigh the HP's raise in the bill, resulting in a lowest utility bill.

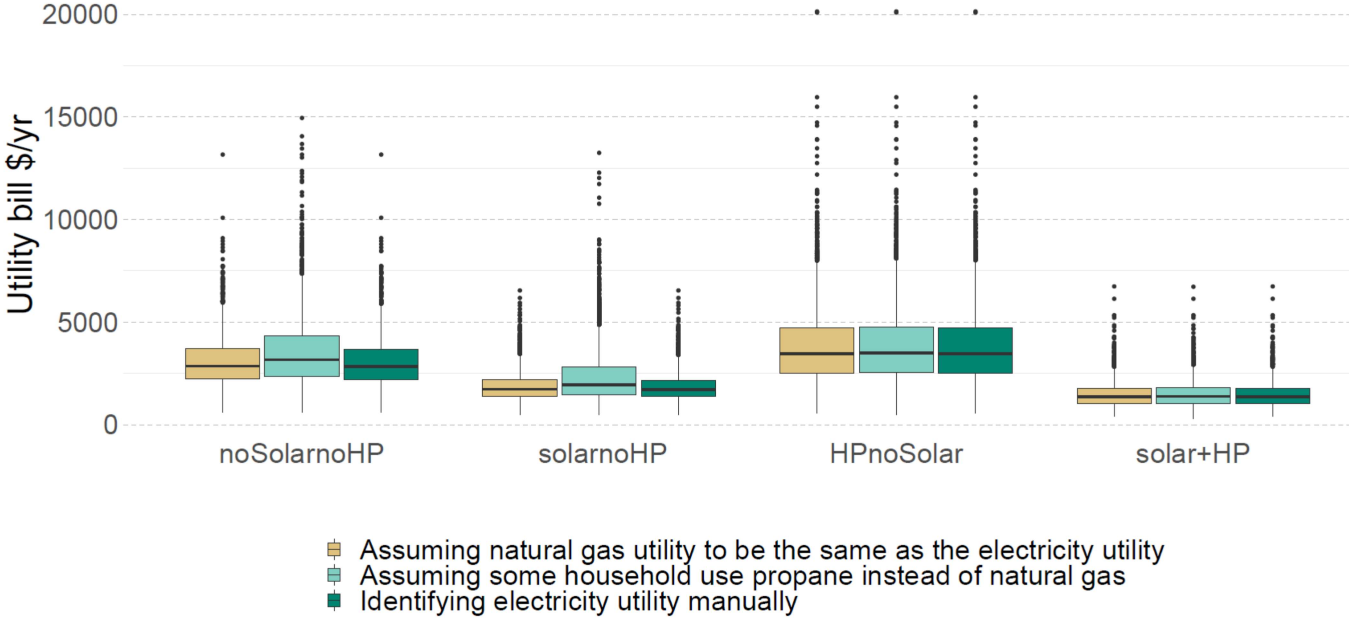

Fig.1 Sensitivity analysis of utility bill

This can be further supported from the Fig.2 on the reduction in utility bills compared to the baseline scenario, which also follows a similar trend as in the total utility bill situation, with visible savings in the bill from either installing PV or a combination of PV and HP, while the sole installation of HP would increase the bill, though in the analysis that assuming some huoseholds use propane the installation of HP might reduce some households' bill. It can also be seen that the installation of PV can bring the maximum economic benefits across the three scenarios, with a slightly higher saving from the propane case. The second highest saving is from installing PV and HP, with a similar range of savings across the three different analyses. Installing HP solely would probably raise the bill in most of cases.

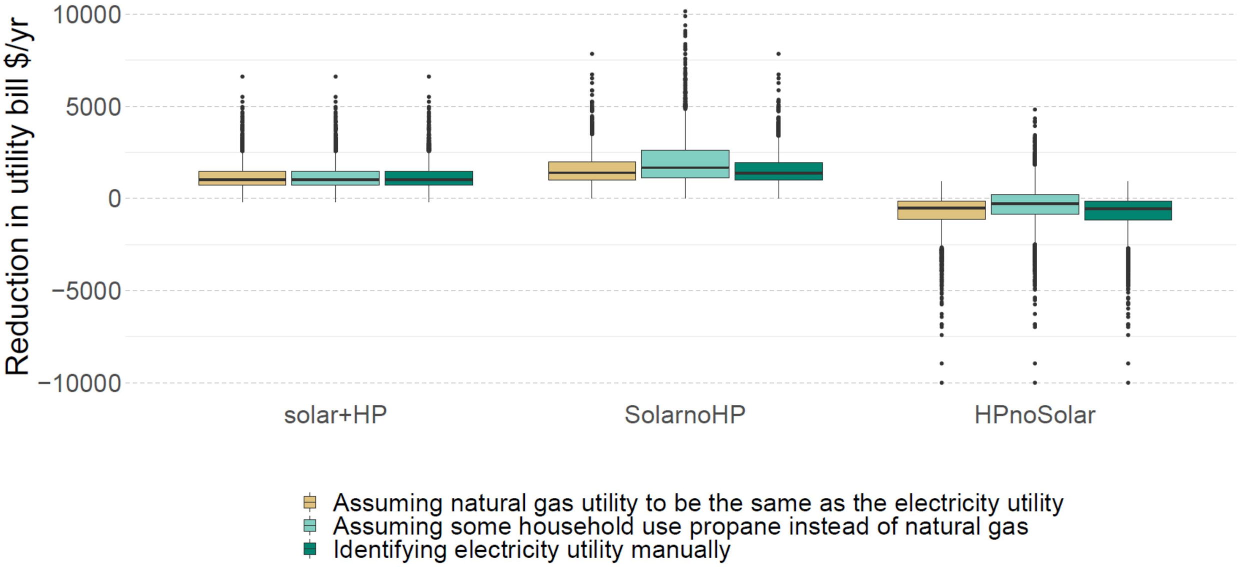

Fig.2 Sensitivity analysis of reduction in utility bill

Emission

Depending on the decarbonization process, the performance of HP and PV differ slightly in the two chosen decarbonization scenarios. In the Mid-case 100% decarbonization by 2035 scenario, HP solely outperforms the PV in terms of emission reduction. While in the Mid-case 95% decarbonization by 2050, PV solely outperforms the HP in terms of emission reduction.

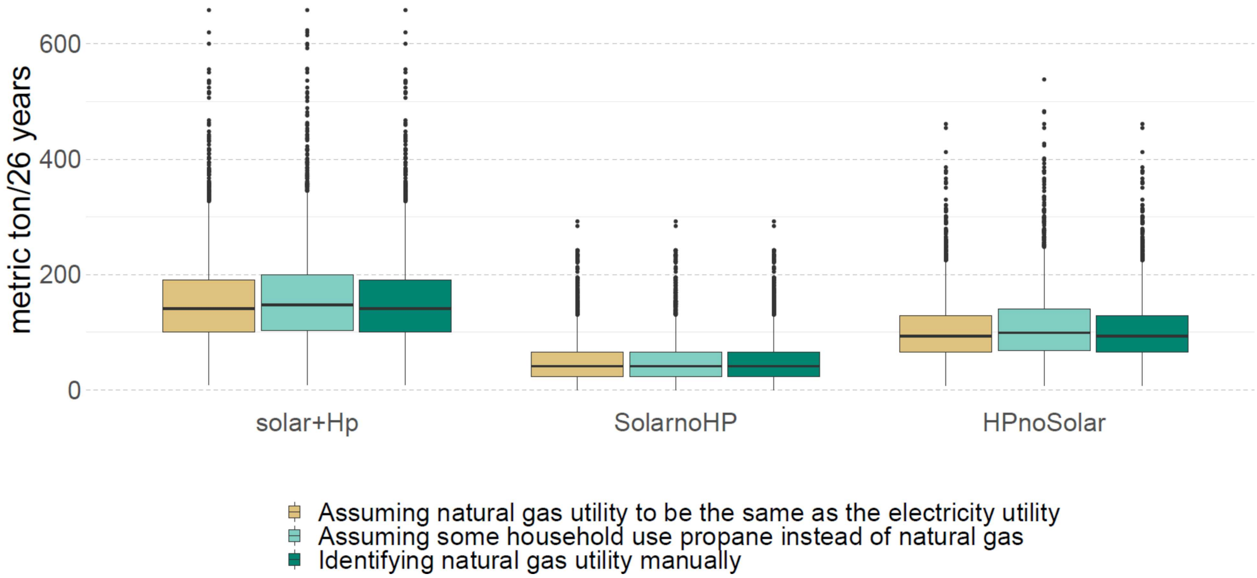

Fig.3 Sensitivity analysis of reduction in lifetime emission in the Mid-case 100% decarbonization by 2035 scenario

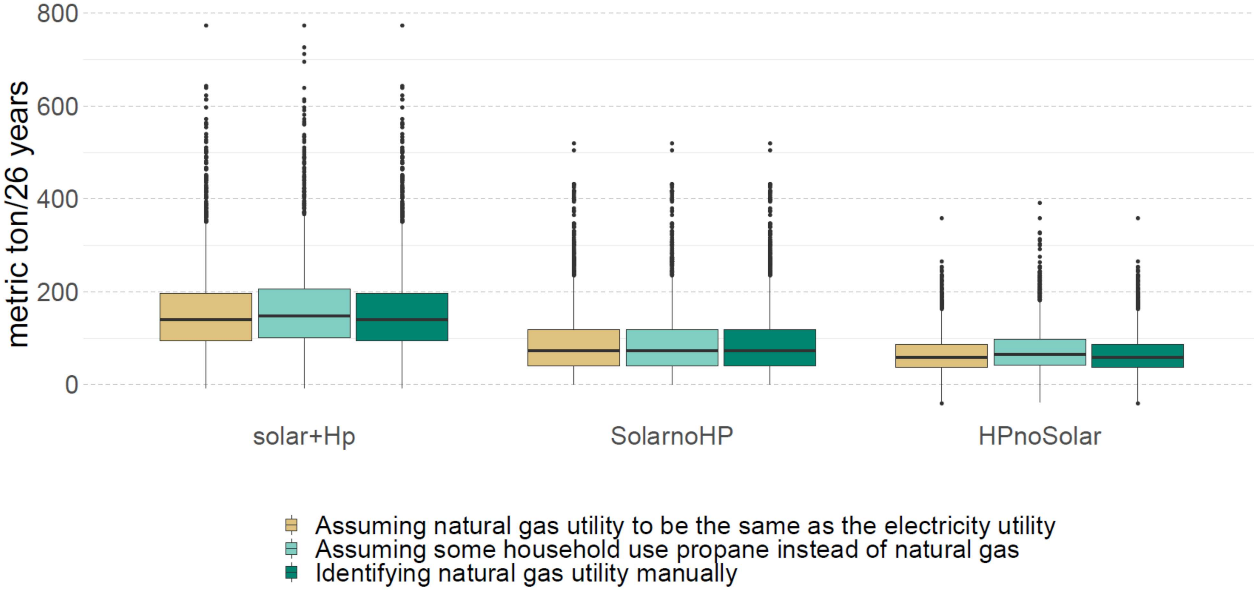

Fig.4 Sensitivity analysis of reduction in lifetime emission in the Mid-case 95% decarbonization by 2050 scenario

Appendix G

Generally, the installation of HP tends to increase utility costs, whereas adopting PV alone, or in combination with HP (HP+Solar), leads to reduced utility bills. Deetjen.et al(Deetjen et al., 2021) in their paper looked at the vintage year and size of the house associated with the NPV. Therefore it would also be interesting to look at the relationship between the utility bill or reduction in utility bill related to the vintage year and the size of the household, which is included in the original metadata. From Figure 4, the general trend mentioned above is followed no matter in which year the building is built or the size of the house. The larger homes also have a higher and broader range of utility bills, likely due to the greater volume of space that requires heating and cooling. Older houses generally have a higher and broader range of utility costs, which may be owing to less efficient thermal insulation, outdated HVAC systems, or other legacy construction features that negatively affect energy efficiency.

Figure 5 illustrates that as the size of a house increases, the potential for bill reduction through the installation of PV systems or a combination of PV and HP (HP+Solar) also grows. This trend may be attributable to the fact that larger homes have more roof areas, which can accommodate more solar panels, thus increasing the potential for energy generation and resulting in greater savings. In addition to that, the same figure shows that larger houses experience a greater increase in utility bills when only heat pumps are installed. This is potentially because larger spaces require more energy for heating and cooling. HP can be more expensive than the current fuel sources they replace, such as natural gas or propane, especially in regions where electricity prices are higher.

Overall, Figure 5 emphasizes the scale of impact that renewable energy technologies of PV and HP can have on utility bills. Size of the household and vintage year could be significant factors in the extent of financial benefits or costs incurred. The economic saving analysis underscores the importance of considering the dimensions of a home when evaluating the economic implications of energy upgrades. These can be further verified with regression or ANOVA techniques to conclude which factor has a higher influence.

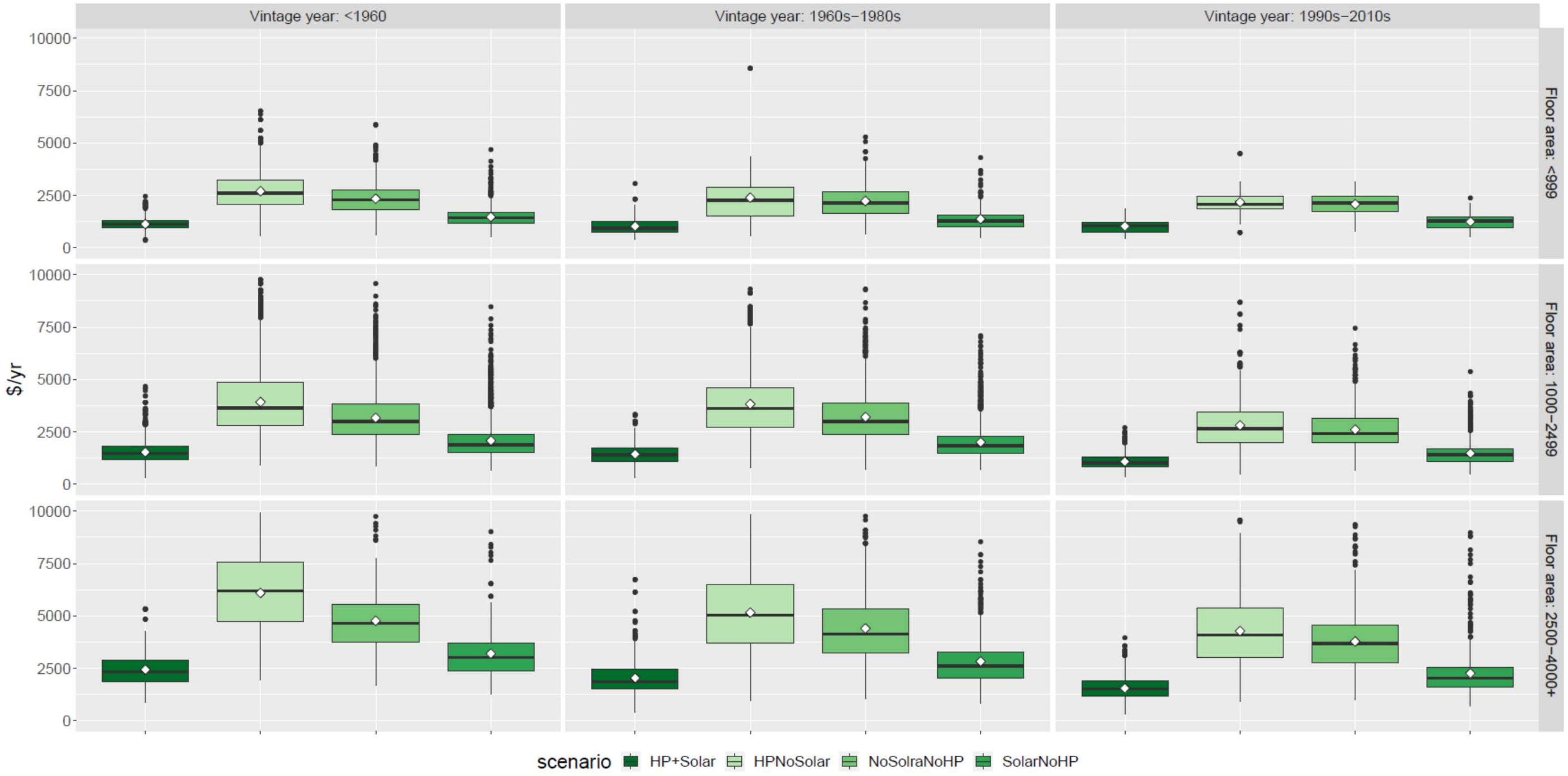

Fig. 5 Utility bill across vintage year and floor area

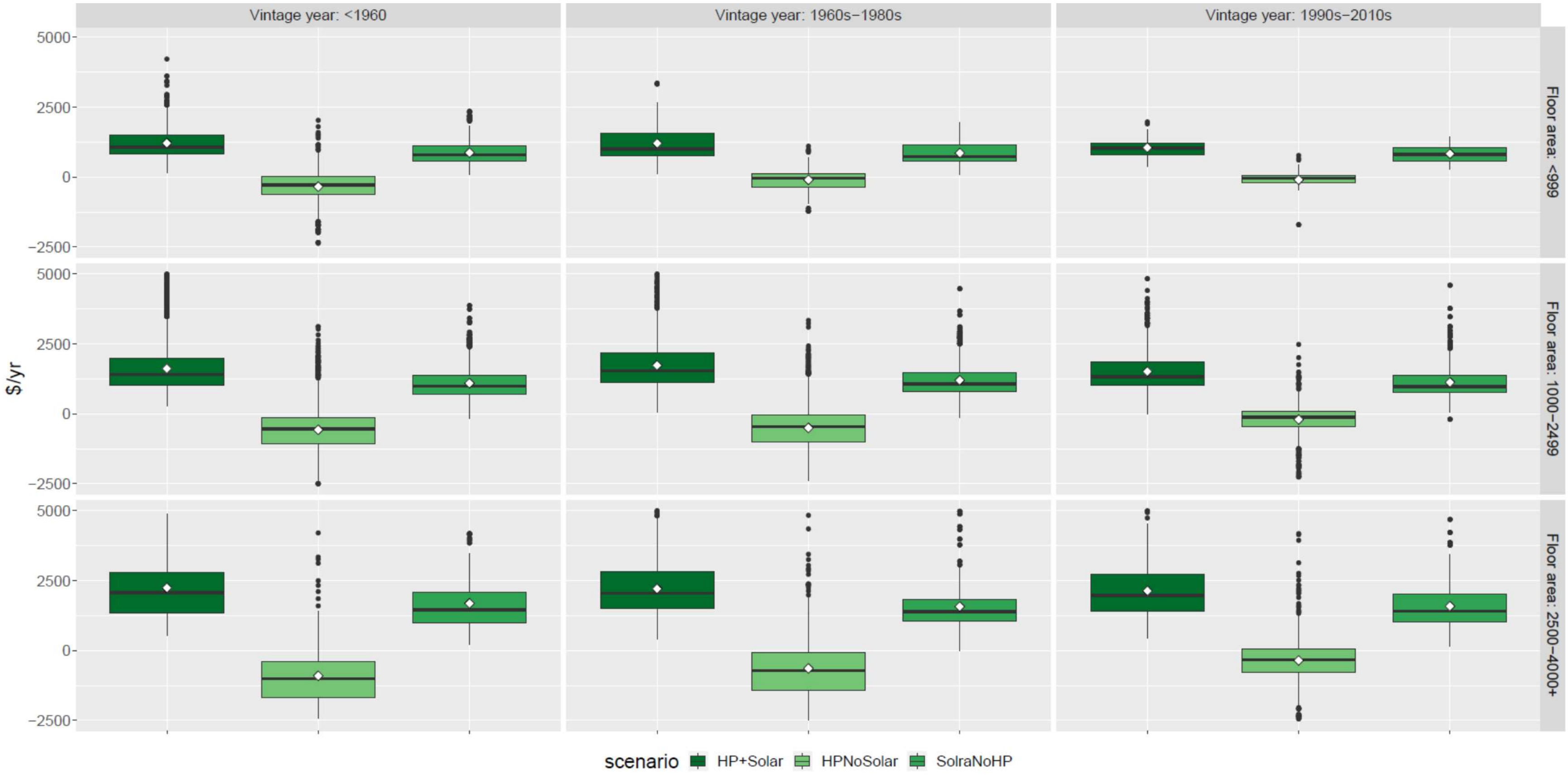

Fig. 6 Reduction in utility bill across vintage year and floor area

Appendix F

Linking the data on emission and emission reduction with the original metadata that has detailed information on the size and the vintage year of the building which can be associated with the: In general, the larger the house size and the older the house the more it will reduce its emission and the more it will benefit from upgrading with HP, PV or a combination of HP and PV.

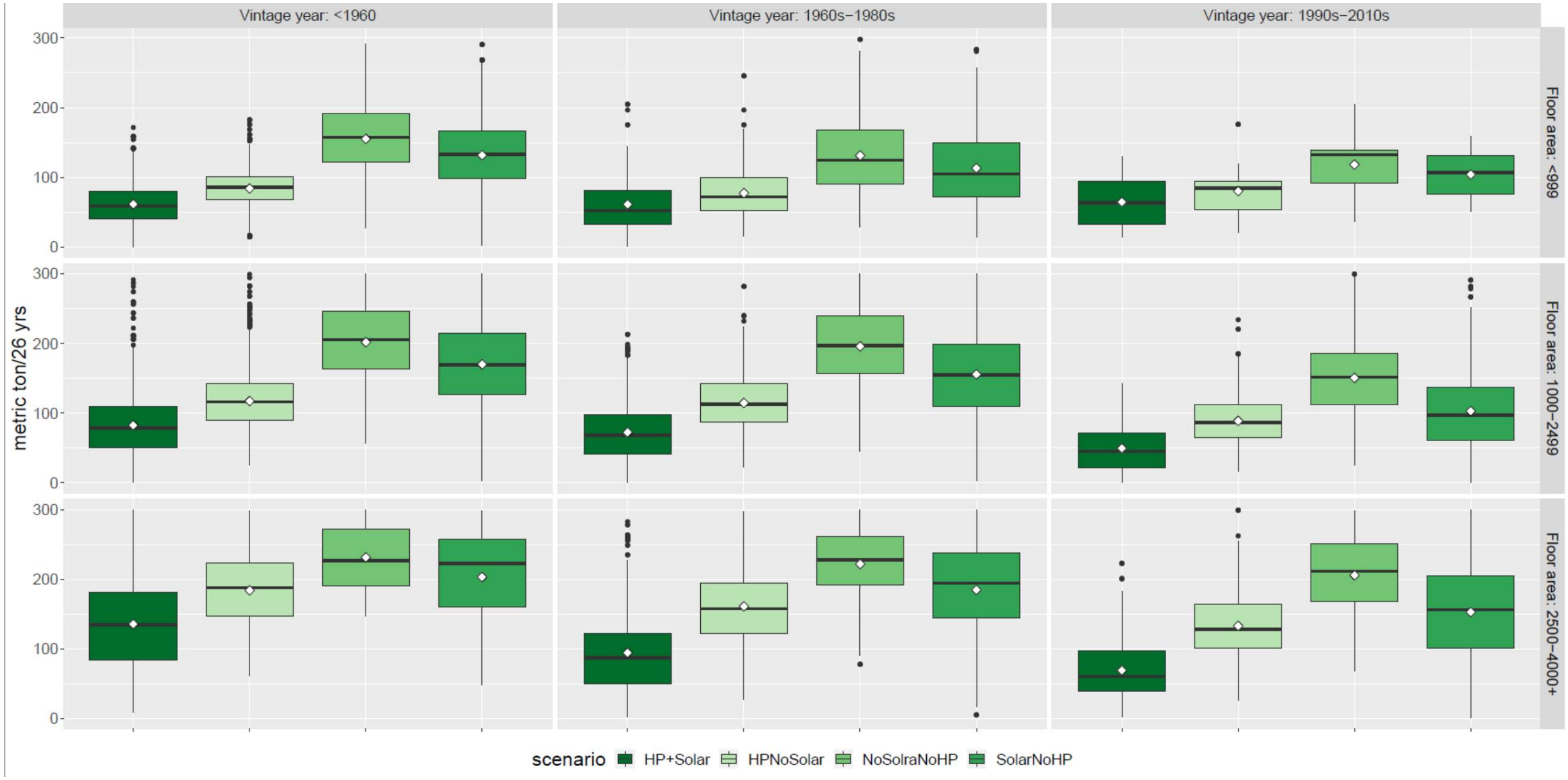

Fig.7 Life time emission across vintage year and floor area in Mid-case with 100% decarbonization by 2035

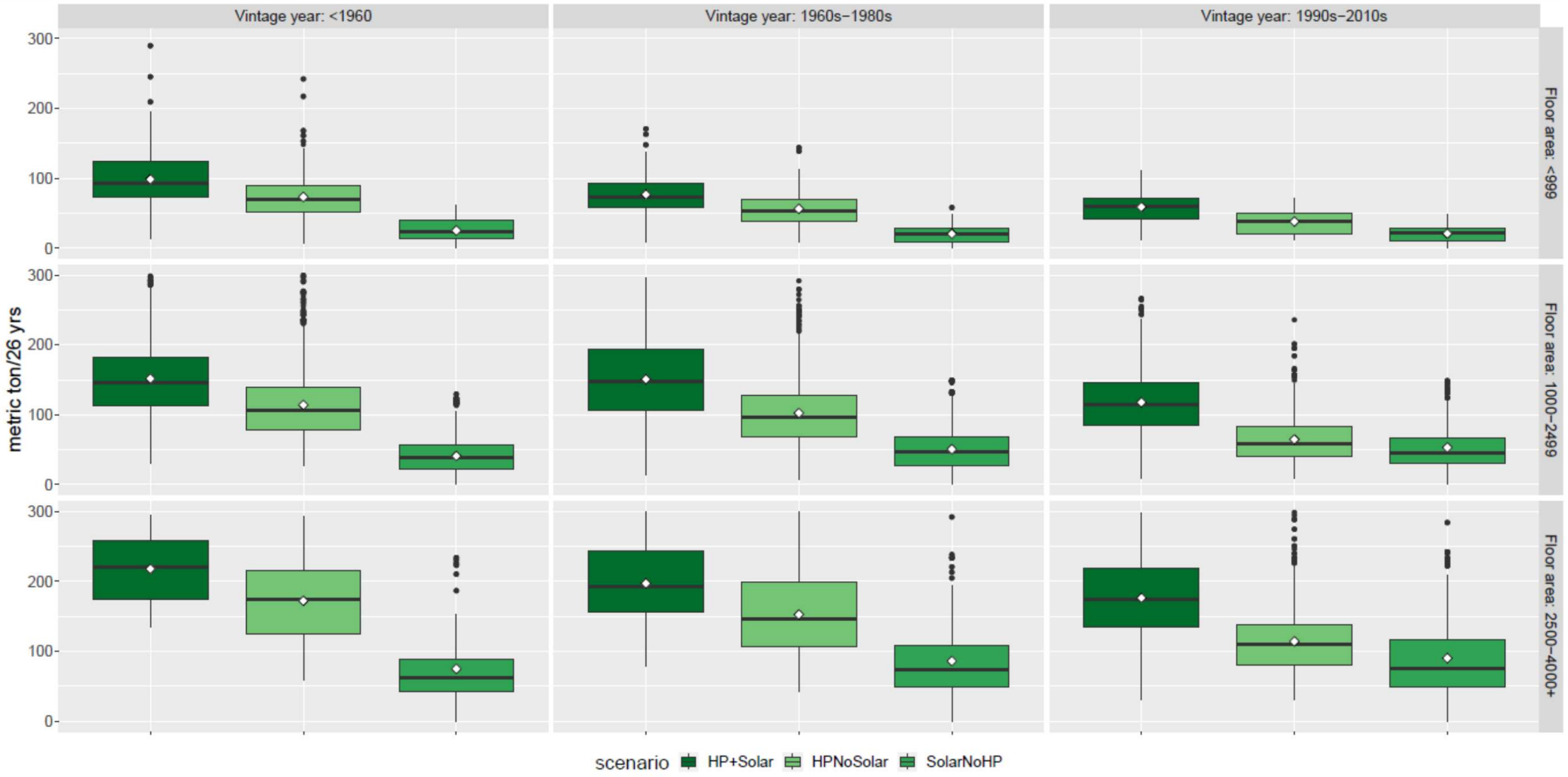

Fig.8 Reduction in life time emission across vintage year and floor area in Mid-case with 100% decarbonization by 2035

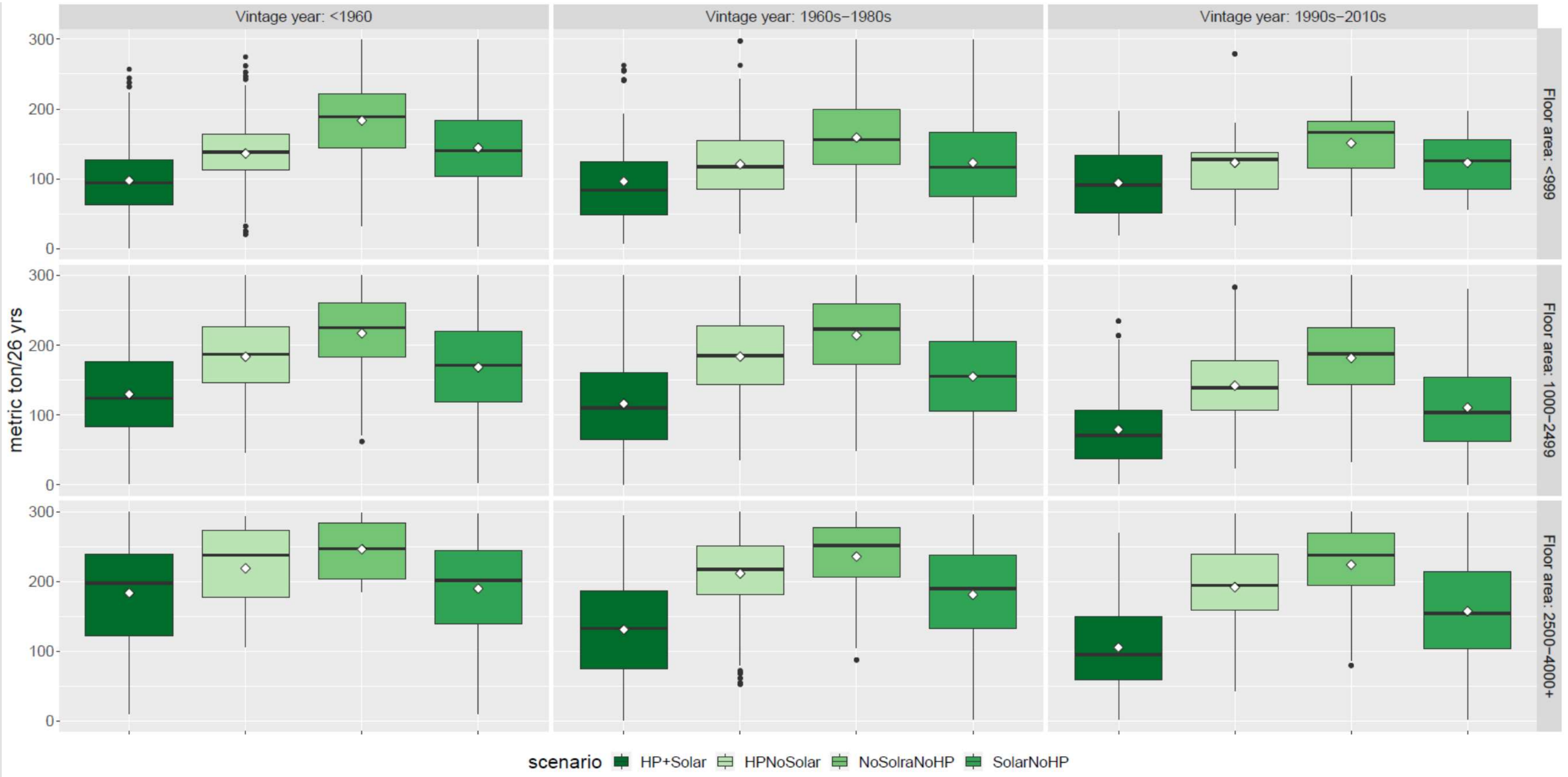

Fig.9 Lifetime emission across vintage year and floor area in Mid-case with 95% decarbonization by 2050

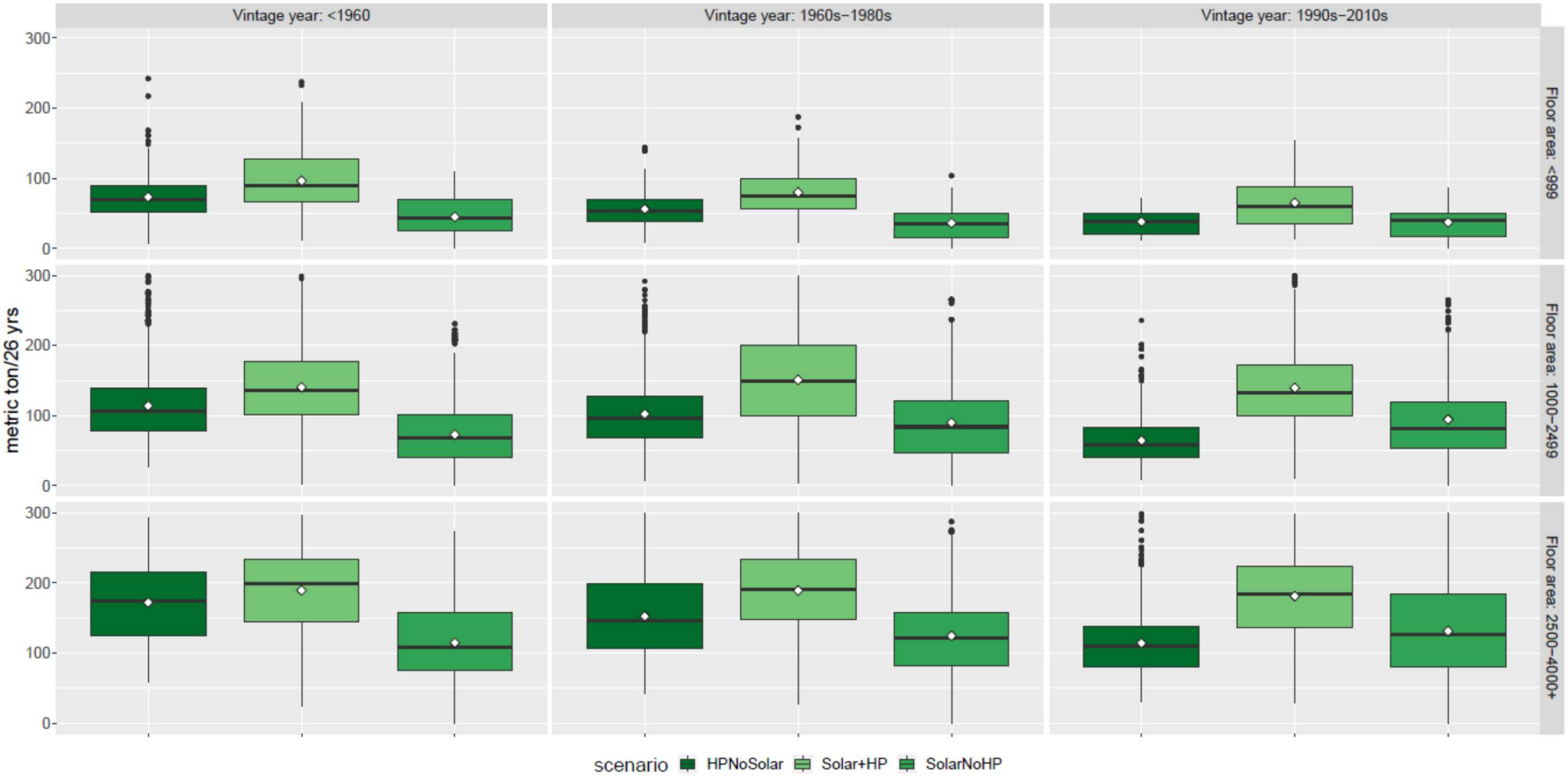

Fig.10 Reduction in lifetime emission in Mid-case with 95% decarbonization by 2050

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