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Nelson Sommerfeldt
The Royal Institute of Technology (KTH)

Joshua M. Pearce
Michigan Technological University, pearce@mtu.edu

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Can grid-tied solar photovoltaics lead to residential heating electrification? A techno-economic case study in the midwestern U.S.

Nelson Sommerfeldt [a,b,*], Joshua M. Pearce [b,c]

[a] Department of Energy Technology, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
[b] Department of Material Science & Engineering, Michigan Technological University, Houghton, MI 49931, USA
[c] Department of Electrical & Computer Engineering, Ivey Business School, Western University, London, ON Canada

HIGHLIGHTS

- Techno-economic potential of photovoltaics (PV) to support heat pumps (HP)
- Compares (1) gas heating + grid electricity, (2) gas + PV, (3) HP + grid, and (4) HP + PV
- Electricity prices have the greatest influence on HP and PV
- High inflation rates strongly favor PV and by extension HP, acting as a cost hedge
- Policies and business models needed to support prosumer technology adoption

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ABSTRACT

This study aims to quantify the techno-economic potential of using solar photovoltaics (PV) to support heat pumps (HP) towards the replacement of natural gas heating in a representative North American residence from a house owner's point of view. For this purpose, simulations are performed on: (1) a residential natural gas-based heating system and grid electricity, (2) a residential natural gas-based heating system with PV to serve the electric load, (3) a residential HP system with grid electricity, and (4) a residential HP+PV system. Detailed descriptions are provided along with a comprehensive sensitivity analysis for identifying specific boundary conditions that enable lower total life cycle cost. The results show that under typical inflation conditions, the lifecycle cost of natural gas and reversable, air-source heat pumps are nearly identical, however the electricity rate structure makes PV costlier. With higher rates of inflation or lower PV capital costs, PV becomes a hedge against rising prices and encourages the adoption of HPs by also locking in both electricity and heating cost growth. The real internal rate of return for such prosumer technologies is 20x greater than a long-term certificate of deposit, which demonstrates the additional value PV and HP technologies offer prosumers over comparably secure investment vehicles while making substantive reductions in carbon emissions. Using the large volume of results generated, impacts on energy policy are discussed, including rebates, net-metering, and utility business models.

1. Introduction

One of the largest contributors to global greenhouse gas emissions after electricity generation, is heating and cooling systems, which account for 38% of the carbon dioxide (CO_2) emission from the residential sector in the U.S. and 30% for the commercial sector [1]. To reduce heating and cooling related emissions it is possible to drive these systems with renewable energy [2–4]. The combination of heat pumps (HP) with solar energy has been studied extensively [5,6]; a range of solar thermal (ST) combinations have been studied with various heat pump types in Europe [7], China [8], and North America [9]; solar photovoltaics (PV) have been studied considering techno-economic factors [10–12] and intelligent controls [13]; solar PV/thermal hybrids (PVT) are investigated for mixed hot water preparation and as a heat pump source [14,15] or as a heat source supplement with borehole seasonal storage [16,17].

* Corresponding author.
E-mail address: nelson.sommerfeldt@energy.kth.se (N. Sommerfeldt).

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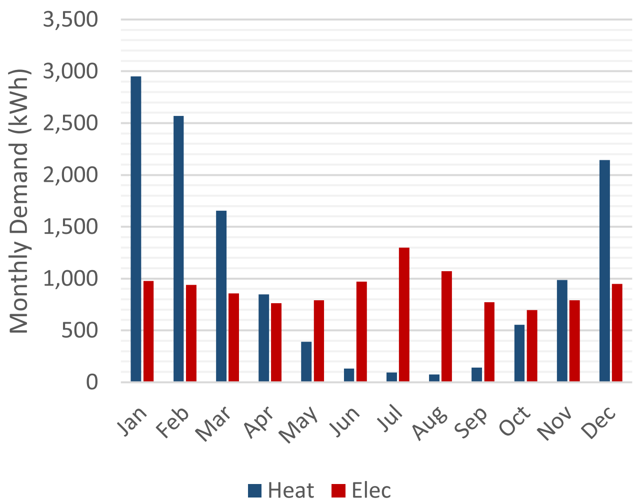

Fig. 1. Thermal (kWh_{th}) and electrical (kWh_{el}) appliance energy demands

While historically HP+ST systems have received the most attention [6], the growth of PV [18] and decline of ST [19] in prosumer systems suggests that HP+PV combinations will be more common in the marketplace. One advantage is that the two systems can be installed independently, providing more flexibility in adoption. PV also enables higher solar fractions due to the ability to freely supply energy to the heat pump, other appliances in the building [20], or electric vehicles [21,22]. Advanced system controllers can also maximize self-consumption for reducing impact on the grid [23–25] and/or economic gains [20,26–28].

A recent study showed electrifying heating systems using HP+PV can be economic at the residential level in the U.S. if replacing propane [12]. These systems, however, are generally only used in low population density rural areas without access to natural gas. In one Midwest region with particularly high electricity prices, HP with PV can be cost effective when replacing natural gas-based heating [10]. Although all the systems had a simple payback time shorter than the lifetime under warranty, which indicated that all cases provide a positive return, this was only possible because of the low levelized cost of electricity (LCOE) [29] of the PV compared to the high cost of grid electricity.

There is a complex relationship between HP, PV, and electricity prices [12,30,31]; homeowners generally wish for lower prices, which is a positive for HP, but a negative for PV. This study aims to quantify the techno-economic potential of using PV to support HP in the replacement of natural gas heating in a representative North American residence from a house owner's point of view. There are complex technical, economic and policy factors that drive the market, and subsequently climate impact, potential for these technologies, and this study aims to provide new insights via comprehensive sensitivity analyses that capture a range of technical and economic scenarios considering technical performance, installation costs, energy prices, and inflation. For this purpose, simulations are performed on: (1) a residential natural gas-based heating system and grid electricity, (2) a residential natural gas-based heating system with PV to serve the electric load, (3) a residential HP system with grid electricity, and (4) a residential HP+PV system. Using the large volume of results generated, impacts on energy policy are discussed, including rebates, net-metering, and utility business models.

2. Objective and methodology

The objective is to define the technical, economic and policy conditions necessary for heat pumps and solar PV to compete economically with natural gas in single family, residential homes in the Midwest region of the United States. The state of Ohio is used as the source for nominal boundary conditions, however, most of the middle to upper Midwest has comparable climatic and economic conditions.

The objective is met through the techno-economic modeling of a single-family home considering four potential energy supply systems, which include combinations of natural gas versus heat pump heating, and grid versus solar PV electricity. In each case with solar PV, the systems are sized to generate 100% of the electricity demand (i.e., net-zero) in year one and are compensated through a net-metering policy.

The study consists of two parts: a detailed breakdown of the economic outcomes, presented using nominal values, and a multi-dimensional sensitivity analysis on critical boundary conditions. The system alternatives are compared economically using total life cycle cost (TLCC) as the main indicator, whereby a lower TLCC is considered preferential. In the nominal analysis, the detailed breakdown of expenses for equipment, gas, electricity, and maintenance are used to extract additional insights through a discussion regarding upfront capital expenses versus lifetime operational expenses. Using the gas furnace and grid electricity as a default/baseline, simple payback time (SPB) and the real internal rate of return (IRR) are also calculated for the nominal boundary conditions.

3. Model description

The building's hourly thermal and appliance demands are taken from the National Renewable Energy Laboratory's (NREL) dataset of EnergyPlus load profiles accessed via OpenEI [32] using the B10 baseline benchmark [33] and typical meteorological year (TMY) climate data for Columbus, Ohio [34]. The B10 benchmark refers to a house built to the 2009 International Energy Conservation Code (IECC) with specific descriptions for construction, space conditioning equipment, and appliance usage. In short, the profile used here represents a typical modern home in the U.S. Midwest (IECC climate zone 5), and full details of the building parameters used in the simulations can be found in [33]. Monthly heat and appliance electricity demands are presented in Fig. 1, with annual totals of 12,539 kWh_{th} for heat and 10,863 kWh_{el} for electricity. It should also be noted that cooling loads are included in the electricity demand.

The TLCC for supplied energy is given in Equation (1), and includes all equipment investments (I_x), operational and maintenance costs (OM_{sys}), and the residual value of the PV system (RV_{pv}). The operational costs (OM_{sys}) are calculated annually (i) and summed over the 20-year system lifetime (L_s), as described by Equation (2). It includes natural gas purchases, grid electricity purchases, annual fees, maintenance costs, and a deduction for net metering credits. The PV system's residual value (RV_{pv}) takes into account the self-consumed generation, the net metering credits, and maintenance costs for the PV's longer lifetime (L_{pv}), given in Equation (3). All costs are discounted to current USD using the nominal discount rate (d_n), which is tested as part of the inflation investigation described later in more detail. Specific symbols are described through the model description.

$$TLCC = I_g + I_{hp} + I_{pv} + OM_{sys} - RV_{pv} \tag{1}$$

$$OM_{sys} = \sum_{i=1}^{L_s} \frac{\left(Q_g P_g + F_g\right)_i + \left(Q_e P_e + F_e\right)_i + \left(OM_{ge} + OM_{pv}\right)_i - \left(Q_{pv} P_{nm}\left[1 - S_{pv}\right]\right)_i}{\left(1 + d_n\right)^i} \tag{2}$$

$$RV_{pv} = \sum_{i=L_s+1}^{L_{pv}} \frac{\left(Q_{pv} P_e S_{pv}\right)_i + \left(Q_{pv} P_{nm}\left[1 - S_{pv}\right]\right)_i - OM_{pv,i}}{\left(1 + d_n\right)^i} \tag{3}$$

Thermal energy supply is determined using an hourly coefficient of performance (COP). For the gas furnace this is a constant value and set nominally to 86%, representing the annual fuel utilization efficiency (AFUE) for the 20-year lifetime of a well-maintained condensing furnace [35]. Final gas consumption in m^3 is found by converting thermal supply (in kWh_{th}) using a lower heating value of 12.8 kWh/kg and a density of 0.79 kg/m^3. For the nominal 86% efficient gas furnace, 1,444 m^3 of natural gas are consumed annually (Q_g).

Natural gas prices (P_g) in Ohio vary considerably during the year, therefore gas prices are determined using a weighted average based on monthly consumption and prices. The inflation adjusted prices between 2010 and 2021 ranges between 0.317 and 0.433 USD/m^3, with average of 0.361 USD/m^3 [36]. The 2021 average was 0.359 USD/m^3, and therefore the nominal price is set here at 0.360 USD/m^3. To match local pricing models, a fixed annual fee (F_g) of 420 USD for gas service is also added to the customer cost [37]. The price of a gas furnace (I_g) can vary based on model, installer, region, and home; therefore a range of capital costs (CAPEX) are tested, from 1800 to 3600 USD, with a nominal price of 2600 USD as a median value [35,38].

The heat pump is modeled as an air-to-air type and is therefore subject to efficiency changes due to outdoor temperature. The TMY3 ambient air temperatures (t_a) used to derive the building loads are also used to calculate an hourly COP using Equation (4) [12]. The annual sum of thermal demand divided by the sum of electrical loads results in a seasonal COP of 2.51. This value is derated by a conservative 25% to account for losses due to defrosting, fans, heat exchanger fouling, and backup heating element use [39], resulting in a nominal seasonal performance factor (SPF) of 1.9 and an annual electricity use of 6,652 kWh_{el} for heating. When combined with appliance loads, the total annual electricity demand of the heat pump house is 17,462 kWh_{el}.

$$COP = 0.0015 \bullet t_a^{\,2} + 0.1 \bullet t_a + 2.7 \tag{4}$$

Like furnaces, installation prices for heat pumps (I_{hp}) will vary along several dimensions. A reasonable range for air-to-air heat pumps is assumed to be 4000 to 8500 USD to supply an entire home, with 6500 USD used as the nominal value [40,41]. The average price for residential electricity (P_e) in Ohio is 0.123 USD/kWh [42], however prices from the largest utility, American Electric Power (AEP), are used where the 2021 prices are 0.11 USD/kWh [43]. Prices have remained stable over recent years [42], however a wide range of prices, from 0.07 to 0.16 USD/kWh, are tested to capture a wide range of possible outcomes. For example, a return to price growth seen during the 2000′s or the introduction of a reduced-price program for homes with electric heating. A fixed annual fee (F_e) of 120 USD is also included as part of the electricity service that is not offset by net metering [43].

The PVWatts model accessed via System Advisor Model [44] is used to derive the first year PV yield. TMY3 climate data [34] from five Ohio cities (Cincinnati, Cleveland, Columbus, Toledo, and Youngstown) are simulated using the premium module type, an 85% performance ratio [45], and no shading losses. At the optimal orientation of 30° tilt and 180° azimuth, the average first year yield is 1,221 kWh/kW_p across all cities, with a maximum of 1,283 kWh/kW_p in Toledo. As an emerging technology, it is assumed that the most productive homes will install solar PV first. A parametric analysis of tilt and azimuth from 0°-90° for tilt and 90°-270° for azimuth show that the upper 1/3 of yields starts at 1,100 kWh/kW_p and is therefore used as the lowest tested value. The maximum value tested is 1,280 kWh/kW_p and the nominal value of 1,200 kWh/kW_p represents the top decile of sunniest orientations in Ohio. Yields are then degraded over time using a 0.25 %/yr rate, commensurate with high quality, monocrystalline silicon PV modules [46], resulting in net-zero PV generation (Q_{pv}) in year one and increasingly more grid electricity (Q_e) purchased over the lifetime.

PV capacities are determined by dividing the expected annual electricity demand by the first-year yield. This means that capacities (and by extension CAPEX) change with varying yields during the sensitivity analysis, but for the nominal cases, with a gas boiler the PV array is 9.05 kW_p and with a heat pump it is 14.60 kW_p. The market CAPEX for PV systems of this size is approximately 3.0 USD/kW_p and has been declining continuously over the recent decade [47]. To account for future price developments and possible rebates, the CAPEX tested here ranges from 2.0 to 2.9 USD/kW_p, with a nominal value of 2.5 USD/kW_p, resulting in a PV CAPEX (I_{pv}) of 22,631 and 36,380 USD for the 9.05 and 14.60 kW_p systems, respectively.

Operational and maintenance (O&M) costs are broken down by component. Regular inspection, cleaning, and tune-ups for both the furnace and heat pump (OM_{ge}) are assumed to be 200 USD/yr [48,49], while PV O&M is estimated at a conservative 20 USD/kW_p [50]. The analysis lifetime (L_s) is 20 years, which is a typical expected lifetime for heating system equipment [35,40]. The PV system is assumed to have a 30-year lifetime (L_{pv}) [51], therefore the residual, discounted value of the PV generation for the final 10 years is removed from the 20-year total lifecycle cost.

Discounting is tested in two dimensions – real discount rate and inflation. The real discount rate is known to be a highly sensitive input for renewable energy investment analysis due to its relatively high CAPEX and low OPEX as compared to combustion fuel sources. For brevity a full sensitivity analysis is not presented, but real rates are bookended at 0% and a modest 3% based on the approximate cost of debt [51]. The U.S. Federal Reserve sets a long-term inflation rate goal of 2% [52], and while the most recent decades have experienced low inflation, the COVID-19 pandemic is causing rates to increase, most of all within energy [53]. The average annual inflation rate in 2021 was 4.7% and the first quarter of 2022 (with the added burden of the Russian invasion of Ukraine) was 8.0% [54]. The nominal discount rate (d_n) is formed with real discount rate (d_r) and inflation (INF) using Equation (5).

Table 1
Nominal input values and sensitivity ranges

Input	Unit	Nominal	Low	High	Step
Furnace CAPEX	USD	2600	1800	3600	200
HP CAPEX	USD	6500	4000	8500	500
Gas Price	USD/m^3	0.36	0.30	0.43	0.02
Electricity Price	USD/kWh	0.07	0.11	0.16	0.01
Furnace Efficiency	–	0.86	0.70	0.88	0.02
HP Efficiency	SPF	1.9	1.5	2.4	0.1
PV Yield	kWh/kW_p	1200	1100	1280	20
PV CAPEX	USD/kW_p	2.5	2.0	2.9	0.1
Real Disc. Rate	–	1 %	0 %	3 %	3 %
Inflation	–	2 %	2 %	6 %	2 %

$$d_n = (1 + d_r)(1 + INF) - 1 \tag{5}$$

Since the purchase of a PV system is tantamount to pre-paying for 30 years of electricity, it can act as a hedge against inflation. In aggregate, consumers can correctly predict inflation at a national level, however individual perceptions vary widely depending on their own local conditions and perceptions of the world [55]. In some cases, consumers have overestimated inflation by as much as 6% [56]. Additionally, real wage growth in lower income classes has stagnated purchasing power [57], further providing an impression of rising prices relative to income. Therefore, in addition to a traditional investment analysis where purchasing power rises with 2% inflation, cases with long-term inflation rates of 2% and 4% above baseline inflation (i.e., 4% and 6% in total) are presented. These cases are presented as scenarios which could be present in consumer's minds when considering energy system purchases and/or represent potential prosumers that do not expect wages to grow at the same rate as inflation, thereby reducing purchasing power.

For homes with a PV system, final electricity purchased from the grid (Q_e) is the net value of annual demand reduced by self-consumed PV generation ($Q_{pv}S_{pv}$) calculated on a monthly basis (i.e. monthly net metering). The two net metering policies tested and discussed vary by rollover credits. The baseline variant used in the nominal and sensitivity analyses, is the current policy at AEP Ohio and provides a credit (P_{nm}) of 0.054 USD/kWh for excess PV generation at the end of each month. The alternative net metering policy values excess PV generation ($Q_{pv}(1\text{-}S_{pv})$) at the full retail price (P_e). The full range of input sensitives and the nominal values are listed in Table 1.

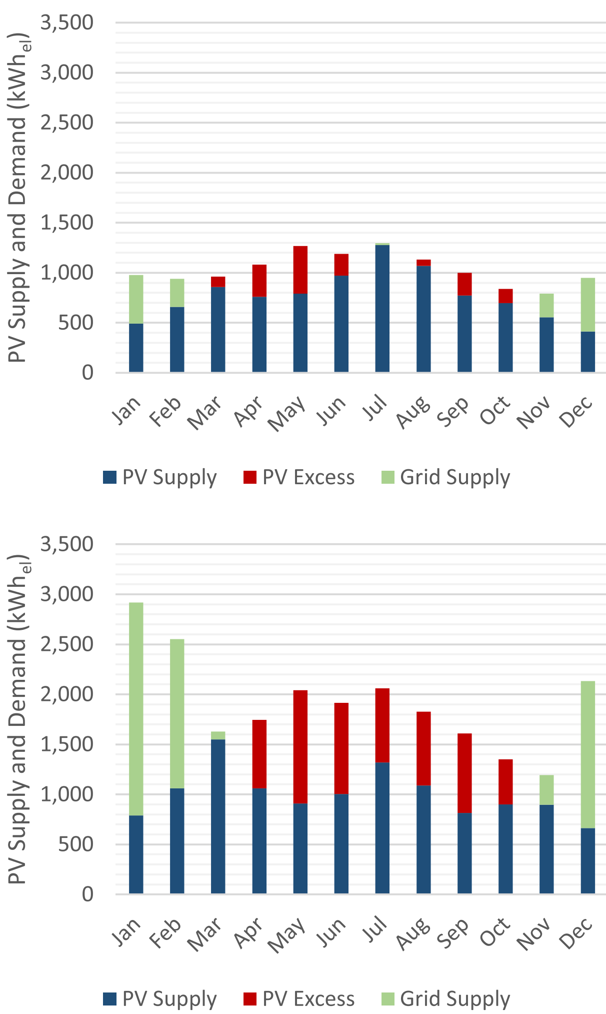

Fig. 2. Monthly net electricity supply for Gas+PV (top) and HP+PV (bottom)

4. Results

The current net metering structure in Ohio is performed monthly, where excess generation at the end of the month is valued at the cost of energy (P_{nm}) only (i.e., excluding distribution), currently 0.054 USD/kWh. The monthly net supply of electricity for the Gas+PV and HP+PV cases are shown in Fig. 2, where the heat pump system results in higher excess PV generation during summer months due to the larger PV capacity and greater seasonal mismatch between supply and demand. Annually, the Gas+PV system has 14% PV excess (86% self-consumption (S_{pv})), whereas the HP+PV system has 31% excess (69% self-consumption). Therefore, the gas heated home has a total energy self-sufficiency of 40%, whereas the HP home is 69% self-sufficient due to the electrified heating being partially supplied by solar.

4.1. Nominal life cycle costs

Using the nominal input values, the life cycle costs are shown by component in Fig. 3, including capital investment (CAPEX), operational expenses for natural gas (Gas OPEX) and electricity (El. OPEX) separately, operations and maintenance (O&M) for all equipment, and the residual value of the PV system (shown as a negative value) at the end of 20 years (PV Res.). The final total life cycle cost (TLCC) is shown with a red bar, which is the sum of all life cycle components. The columns are separated by real discount rate (excluding inflation) while the rows are separated by expected inflation rate. The bottom row with 2% inflation matches the expected inflation rate of 2%, and therefore represents a typical investment analysis.

When comparing the baseline Gas+Grid alternative to the HP+Grid, the heat pump has a comparable cost under all discounting alternatives to within a few percent. The heat pump has a higher up-front cost, but a modestly lower operating cost due in large part to the savings of fixed gas network fees, which largely balance out over time. Discounting has almost no effect on the relative TLCC, but the gap between the furnace and heat pump grows with inflation in favor of the heat pump. The difference, however, remains small enough to be within a reasonable margin of uncertainty. This indicates that HP technology alone already enables an approximately equivalent cost for electrification for heating in the Midwest, but the high upfront cost means some incentive may be needed to increase the diffusion rate of the technology.

When PV is included in the system, the discounting alternatives play a significant role due to the much higher CAPEX and lower OPEX. The most positive outcome is when a prosumer does not discount the future and inflation is higher than historically expected (0% discount, 6% inflation), shown in the upper left corner of Fig. 3. Here PV reduces the TLCC by 49% and 81% for the Gas and HP, respectively, however this is primarily due to the residual value of the PV generation after year 20. The realized cost in year 20 for the PV systems is higher, but still less than the systems with natural gas. Adding a 3% discount rate reduces the PV's residual value, and while the TLCC is still lower for the PV systems it is within a few percentage points. Likewise, when inflation rises at 2% as expected, the PV systems have a higher TLCC than systems without.

The results with 2% inflation in the bottom row of Fig. 3 show that a PV+HP system is the lowest cost alternative when there is no discounting. The PV systems do have higher 20-year realized costs, however, with the lower TLCC values coming from the residual PV value. With a 3% discount rate, the Gas+PV systems have the lowest TLCC, but well within the margin of uncertainty with the HP+Grid alternative.

To provide more context on the investment alternatives relative to the baseline Gas+Grid, Table 2 shows the real IRR and simple payback times under each inflation scenario. The real IRR is approximately double for the systems with PV but is influenced by the longer PV lifetimes over the heating equipment. As expected, the simple payback (SPB) times are shorter with higher inflation rates, highlighting how perceived increases in energy cost can be a motivation for homeowners to invest in PV, who often use simple payback time as their primary

Fig. 3. Deconstructed nominal life cycle costs by system as a function of real rate and inflation. TLCC is shown with a red bar. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

Table 2
IRR and SPB results for each alternative

	Gas+PV	HP+Grid	HP+PV
Real IRR	1.72 %	0.90 %	1.92 %
2% inflation SPB (years)	18.8	15.5	18.6
4% inflation SPB (years)	16.1	13.6	15.8
6% inflation SPB (years)	14.3	12.3	15.0

investment metric [58]. As can be seen in Table 2 the HP+PV provides the highest IRR for consumers that do full life cycle economic analysis, yet for every level of inflation the HP+Grid has the lowest SPB.

4.2. *Sensitivity analysis*

It should be noted that the nominal results in Section 5.1 can vary widely, and that the TLCC values are often within a few percentage points. Since there are many factors that can impact lifecycle costs, the

Gas Furnace Capex (kUSD) \ Heat Pump Capex (kUSD)	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1.8	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
2.0	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
2.2	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
2.4	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
2.6	-4%	-3%	-2%	-2%	-1%	**63.5**	1%	2%	2%	3%
2.8	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
3.0	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
3.2	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
3.4	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%
3.6	-4%	-3%	-2%	-2%	-1%	0%	1%	2%	2%	3%

Gas Price (USD/m3) \ Electricity Price (USD/kWh)	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16
0.30	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.32	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.34	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.36	-15%	-6%	0%	0%	**63.5**	0%	0%	1%	1%	1%
0.38	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.40	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.42	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.44	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.46	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%
0.48	-15%	-6%	0%	0%	0%	0%	0%	1%	1%	1%

Electricity Price (USD/kWh) \ Heat Pump Efficiency (SPF)	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
0.07	-9%	-10%	-12%	-13%	-15%	-16%	-17%	-18%	-18%	-19%
0.08	1%	-1%	-3%	-5%	-6%	-7%	-9%	-10%	-11%	-11%
0.09	7%	5%	3%	1%	0%	-2%	-3%	-4%	-6%	-7%
0.10	8%	6%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.11	9%	7%	4%	2%	**63.5**	-2%	-3%	-5%	-6%	-7%
0.12	11%	7%	5%	2%	0%	-2%	-3%	-5%	-6%	-8%
0.13	12%	8%	5%	3%	0%	-2%	-3%	-5%	-7%	-8%
0.14	12%	9%	6%	3%	1%	-2%	-4%	-5%	-7%	-9%
0.15	12%	10%	7%	4%	1%	-1%	-4%	-6%	-7%	-9%
0.16	12%	11%	7%	4%	1%	-1%	-4%	-6%	-8%	-9%

Gas Price (USD/m3) \ Furnace Efficiency (AFUE)	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84	0.86	0.88
0.30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.32	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.34	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.36	0%	0%	0%	0%	0%	0%	0%	0%	**63.5**	0%
0.38	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.40	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.42	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.44	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.46	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.48	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

PV Yield (kWh/kWp) \ PV Capex (USD/Wp)	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
1100	-4%	-2%	1%	3%	5%	8%	10%	12%	14%	17%
1120	-5%	-3%	-1%	1%	4%	6%	8%	11%	13%	15%
1140	-7%	-5%	-2%	0%	2%	5%	7%	9%	11%	14%
1160	-8%	-6%	-4%	-2%	1%	3%	5%	8%	10%	12%
1180	-10%	-8%	-5%	-3%	-1%	2%	4%	6%	8%	11%
1200	-11%	-9%	-7%	-5%	-2%	**63.5**	2%	5%	7%	9%
1220	-13%	-11%	-8%	-6%	-4%	-2%	1%	3%	5%	8%
1240	-14%	-12%	-10%	-8%	-5%	-3%	-1%	2%	4%	6%
1260	-16%	-14%	-11%	-9%	-7%	-5%	-2%	0%	2%	5%
1280	-18%	-15%	-13%	-11%	-8%	-6%	-4%	-1%	1%	3%

Furnace Efficiency (AFUE) \ Heat Pump Efficiency (SPF)	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
0.70	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.72	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.74	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.76	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.78	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.80	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.82	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.84	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.86	9%	7%	4%	2%	**63.5**	-2%	-3%	-5%	-6%	-7%
0.88	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%

Gas+Grid Gas+PV HP+Grid HP+PV

Fig. 4. Sensitivity results with 0% real discount rate and 6% inflation

sensitivity analysis results are shown using two related parameters at a time across six tables. Each cell in the table is color coded to represent the system configuration with the lowest TLCC. The nominal TLCC is shown in bold with a border outline, and in absolute USD. All other cells are shown with the percentage change relative to the nominal value. This way, all tables are also comparable since the relative percentages are all based on the same nominal value. Each inflation scenario is presented with a separate figure, however only results for 0% real discount are presented to show the trends of inflation with clarity and brevity.

The results for 6% inflation are given in Fig. 4 where PV+HP is the dominant solution under nearly every condition. Once electricity prices fall below 0.09 USD/kWh, then PV is removed. With the combination of a low heat pump efficiency and high electricity price, then gas heating has lower costs, but the high electricity prices mean that a PV system is still recommended.

The 4% inflation rate scenario is shown in Fig. 5, where heat pumps are present in nearly every alternative and there are less instances with PV. The most sensitive variables are again electricity price, heat pump efficiency, and now PV yield and CAPEX. If the electricity price falls below 0.11 USD/kWh, then PV will increase TLCC. If heat pump SPF falls below 1.8, then gas furnaces can become the lowest cost alternative. The line separating HP+Grid and HP+PV as a function of PV yield and CAPEX is notable since these yields represent the top 10% of roofs in Ohio (and the Midwest in general). This underscores the need to drive the PV installed costs down to those observed in other nations, such as Germany, where residential PV CAPEX is on average half of the U.S., leading to generally lower PV-electricity costs than grid electricity, even at the residential level [47,59]. This can be done through the following mechanisms including: (1) larger penetration rates and increased competition among PV system installers (e.g. encouraging multiple quotes and quote platforms), (2) reducing or eliminating arbitrary soft costs (e.g. connection fees and application fees, permitting costs, standardizing structural analysis, etc. [60]), (3) eliminating redundant system component mandates (e.g. multiple disconnect switches [61]), (4) using open source racking designs made from commonly available building materials (e.g. lumber for ground mounted residential systems [62,63], pipes and cables [64] and roofing materials [65]), 5) enabling using partial DIY installations [66] or plug-and-play installation [61,67,68], and 6) encourage or require that PV system installation be integrated into the new construction and roof replacement process [60].

Under 2% inflation, shown in Fig. 6, the dominant system throughout the sensitivities is the HP+Grid, however there is a greater mix of alternatives and more instances of gas furnaces. The cost of gas versus heat pump is very similar, and any increase in CAPEX or electric prices, or reduction of SPF, tips the costs in favor of gas. In most sensitivities, the differences are only a few percent, except for electricity price which has the greatest influence on lifecycle cost. For PV systems to

Gas Furnace Capex (kUSD) \ Heat Pump Capex (kUSD)	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1.8	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
2.0	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
2.2	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
2.4	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
2.6	-4%	-3%	-3%	-2%	-1%	59.3	1%	2%	3%	3%
2.8	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
3.0	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
3.2	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
3.4	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%
3.6	-4%	-3%	-3%	-2%	-1%	0%	1%	2%	3%	3%

Gas Price (USD/m3) \ Electricity Price (USD/kWh)	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16
0.30	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.32	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.34	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.36	-25%	-17%	-10%	-3%	59.3	0%	0%	1%	1%	1%
0.38	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.40	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.42	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.44	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.46	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%
0.48	-25%	-17%	-10%	-3%	0%	0%	0%	1%	1%	1%

Electricity Price (USD/kWh) \ Heat Pump Efficiency (SPF)	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
0.07	-19%	-21%	-22%	-24%	-25%	-26%	-26%	-27%	-28%	-29%
0.08	-11%	-13%	-15%	-16%	-17%	-18%	-19%	-20%	-21%	-22%
0.09	-3%	-5%	-7%	-9%	-10%	-11%	-12%	-13%	-14%	-15%
0.10	2%	2%	1%	-1%	-3%	-4%	-5%	-6%	-8%	-8%
0.11	4%	4%	4%	2%	59.3	-2%	-3%	-4%	-5%	-6%
0.12	4%	4%	4%	2%	0%	-1%	-3%	-4%	-6%	-7%
0.13	4%	4%	4%	2%	0%	-1%	-3%	-4%	-6%	-7%
0.14	4%	4%	4%	3%	1%	-1%	-3%	-5%	-6%	-7%
0.15	5%	5%	5%	3%	1%	-1%	-3%	-5%	-6%	-8%
0.16	5%	5%	5%	3%	1%	-1%	-3%	-5%	-7%	-8%

Gas Price (USD/m3) \ Furnace Efficiency (AFUE)	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84	0.86	0.88
0.30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.32	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.34	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.36	0%	0%	0%	0%	0%	0%	0%	0%	59.3	0%
0.38	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.40	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.42	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.44	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.46	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.48	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

PV Yield (kWh/kWp) \ PV Capex (USD/Wp)	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
1100	-6%	-3%	-1%	2%	4%	5%	5%	5%	5%	5%
1120	-7%	-5%	-2%	0%	3%	5%	5%	5%	5%	5%
1140	-8%	-6%	-3%	-1%	1%	4%	5%	5%	5%	5%
1160	-10%	-7%	-5%	-2%	0%	3%	5%	5%	5%	5%
1180	-11%	-9%	-6%	-4%	-1%	1%	4%	5%	5%	5%
1200	-12%	-10%	-7%	-5%	-2%	59.3	2%	5%	5%	5%
1220	-14%	-11%	-9%	-6%	-4%	-1%	1%	4%	5%	5%
1240	-15%	-12%	-10%	-8%	-5%	-3%	0%	2%	5%	5%
1260	-16%	-14%	-11%	-9%	-6%	-4%	-1%	1%	3%	5%
1280	-17%	-15%	-13%	-10%	-8%	-5%	-3%	0%	2%	5%

Furnace Efficiency (AFUE) \ Heat Pump Efficiency (SPF)	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
0.70	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.72	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.74	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.76	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.78	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.80	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.82	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.84	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%
0.86	9%	7%	4%	2%	63.5	-2%	-3%	-5%	-6%	-7%
0.88	9%	7%	4%	2%	0%	-2%	-3%	-5%	-6%	-7%

Gas+Grid Gas+PV HP+Grid HP+PV

Fig. 5. Sensitivity results with 0% real discount rate and 4% inflation

become the low-cost leader, the electricity price needs to reach 0.13 USD/kWh for both gas and HP systems.

5. Discussion

The adoption of solar PV is growing rapidly but given that space conditioning and hot water (i.e., heat) make up most of the energy demand in residential buildings, there is a need to replace natural gas to meet international climate goals [69]. Heat pumps are a mature product, already commonplace in several European countries (e.g., Sweden and Switzerland), and are the cornerstone for Europe's plan to remove Russian gas from its building energy supply [70]. HP are also promoted in the United States for building decarbonization [71,72]. The results here show that heat pumps are an economically viable alternative to natural gas in Ohio, particularly when paired with PV.

These results are in line with the authors' previous work with higher electricity prices [10] and others who have shown potential cost savings associated with heat pumps in temperate climates [73,74] and solar PV [47,75,76] in the North America. To place the results in perspective, the interest rates on offer for certificates of deposit (CD) in Ohio banks during 2022 are 0.03–0.05% [77,78]. The IRR results in Table 2 show a heat pump producing 0.9%, and 1.9% with PV added, which are real rates of return versus the nominal returns from CDs. Given that the inflation rate target is 2% and are much higher in 2022, this demonstrates the additional value PV and heat pumps offer over comparably secure investment vehicles. Also, not included in the results are the potential increase in home value due to heat pumps [79] and PV [80], which strengthen the economic results further.

The certainty, or risk, of the returns with PV and heat pumps are down to a few key factors. As the study shows, inflation in energy prices does increase energy costs, but does not significantly affect the relative costs of owning a heat pump. While the relative prices between natural gas and electricity can affect the value of heat pumps, given that most of the Midwest's electricity supply is natural gas [81], the two are somewhat interlinked. Meanwhile, the cost of electricity from PV will be effectively constant over its lifetime, meaning it is isolated from the effects of inflation and becomes a valuable hedge [82]. A PV+HP system would largely fix the homeowner's energy costs, which could be particularly valuable to low- or fixed-income households and help avoid energy poverty as consumer prices increase.

The pre-requisite for securing fixed heating and electricity costs is the use of a net metering policy with PV systems. Annual net metering is in the process of being phased out in many states due to pressure from electric utilities, who tend to lose revenues since customers are now supplying much of their electricity from their own investment in PV. Changing from a net metering scheme at the monthly level to the annual level, despite the divergence in excess solar electricity observed in Fig. 2 (annually, the Gas+PV system has 14% PV excess, whereas the HP+PV

Gas Furnace Capex (kUSD) \ Heat Pump Capex (kUSD)	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1.8	-5%	-4%	-3%	-2%	-1%	-1%	-1%	-1%	-1%	-1%
2.0	-5%	-4%	-3%	-2%	-1%	0%	0%	0%	0%	0%
2.2	-5%	-4%	-3%	-2%	-1%	0%	0%	0%	0%	0%
2.4	-5%	-4%	-3%	-2%	-1%	0%	0%	0%	0%	0%
2.6	-5%	-4%	-3%	-2%	-1%	51.3	1%	1%	1%	1%
2.8	-5%	-4%	-3%	-2%	-1%	0%	1%	1%	1%	1%
3.0	-5%	-4%	-3%	-2%	-1%	0%	1%	2%	2%	2%
3.2	-5%	-4%	-3%	-2%	-1%	0%	1%	2%	2%	2%
3.4	-5%	-4%	-3%	-2%	-1%	0%	1%	2%	2%	2%
3.6	-5%	-4%	-3%	-2%	-1%	0%	1%	2%	3%	3%

Gas Price (USD/m3) \ Electricity Price (USD/kWh)	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16
0.30	-27%	-20%	-14%	-7%	-3%	2%	3%	3%	4%	4%
0.32	-27%	-20%	-14%	-7%	-2%	3%	4%	5%	5%	5%
0.34	-27%	-20%	-14%	-7%	0%	4%	6%	6%	6%	6%
0.36	-27%	-20%	-14%	-7%	51.3	5%	7%	7%	7%	7%
0.38	-27%	-20%	-14%	-7%	0%	6%	8%	8%	8%	8%
0.40	-27%	-20%	-14%	-7%	0%	7%	9%	9%	9%	9%
0.42	-27%	-20%	-14%	-7%	0%	7%	10%	10%	10%	10%
0.44	-27%	-20%	-14%	-7%	0%	7%	10%	10%	10%	10%
0.46	-27%	-20%	-14%	-7%	0%	7%	10%	10%	10%	10%
0.48	-27%	-20%	-14%	-7%	0%	7%	10%	10%	10%	10%

Electricity Price (USD/kWh) \ Heat Pump Efficiency (SPF)	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
0.07	-22%	-24%	-25%	-26%	-27%	-28%	-29%	-30%	-30%	-31%
0.08	-15%	-17%	-18%	-19%	-20%	-21%	-22%	-23%	-24%	-25%
0.09	-8%	-9%	-11%	-12%	-14%	-15%	-16%	-17%	-18%	-18%
0.10	-3%	-3%	-4%	-5%	-7%	-8%	-9%	-10%	-11%	-12%
0.11	1%	1%	1%	1%	51.3	-1%	-3%	-4%	-5%	-6%
0.12	5%	5%	5%	5%	5%	5%	4%	3%	1%	0%
0.13	7%	7%	7%	7%	7%	7%	6%	5%	4%	3%
0.14	7%	7%	7%	7%	7%	7%	6%	5%	4%	2%
0.15	7%	7%	7%	7%	7%	7%	6%	5%	3%	2%
0.16	7%	7%	7%	7%	7%	7%	6%	5%	3%	2%

Gas Price (USD/m3) \ Furnace Efficiency (AFUE)	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84	0.86	0.88
0.30	0%	0%	0%	0%	-1%	-1%	-2%	-2%	-3%	-3%
0.32	0%	0%	0%	0%	0%	0%	-1%	-1%	-2%	-2%
0.34	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%
0.36	0%	0%	0%	0%	0%	0%	0%	0%	51.3	0%
0.38	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.40	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.42	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.44	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.46	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.48	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

PV Yield (kWh/kWp) \ PV Capex (USD/Wp)	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
1100	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1120	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1140	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1160	-2%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1180	-4%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
1200	-5%	-2%	0%	0%	0%	51.3	0%	0%	0%	0%
1220	-6%	-3%	0%	0%	0%	0%	0%	0%	0%	0%
1240	-7%	-4%	-2%	0%	0%	0%	0%	0%	0%	0%
1260	-9%	-6%	-3%	0%	0%	0%	0%	0%	0%	0%
1280	-10%	-7%	-4%	-1%	0%	0%	0%	0%	0%	0%

Furnace Efficiency (AFUE) \ Heat Pump Efficiency (SPF)	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
0.70	5%	5%	3%	2%	0%	-1%	-3%	-4%	-5%	-6%
0.72	5%	5%	3%	2%	0%	-1%	-3%	-4%	-5%	-6%
0.74	4%	4%	3%	2%	0%	-1%	-3%	-4%	-5%	-6%
0.76	3%	3%	3%	2%	0%	-1%	-3%	-4%	-5%	-6%
0.78	3%	3%	3%	2%	0%	-1%	-3%	-4%	-5%	-6%
0.80	2%	2%	2%	2%	0%	-1%	-3%	-4%	-5%	-6%
0.82	2%	2%	2%	2%	0%	-1%	-3%	-4%	-5%	-6%
0.84	1%	1%	1%	1%	0%	-1%	-3%	-4%	-5%	-6%
0.86	1%	1%	1%	1%	51.3	-1%	-3%	-4%	-5%	-6%
0.88	0%	0%	0%	0%	0%	-1%	-3%	-4%	-5%	-6%

Gas+Grid Gas+PV HP+Grid HP+PV

Fig. 6. Sensitivity results with 0% real discount rate and 2% inflation

system has 31% excess) does not impact the choice of technology on a TLCC basis regardless of discount and inflation rate pairing. Moving to a monthly net-metering program discourages prosumer investment but can replace annual net metering without resorting to an hourly self-consumption or net-billing policy that would have a greater negative impact on the economics [12,76].

These results also present a warning to those working on utility rate design of the unintended consequences of trying to match utility rate design to how utilities are funded. High monthly fixed fees are largely responsible for making PV+HP more economic than gas. This can thus also be seen as a warning to the electricity industry – as the same can happen with grid electricity when compared to PV combined with a battery and some form of back up generation. The greater the discrepancy between what PV owners pay for electricity and what they are compensated for it by the utility, the greater the risk of grid defection as that is already economic under some utility rates in the Midwest U.S. for both residential [83] and small business customers [84]. From both greenhouse gas mitigation and avoiding utility death spiral [85] perspectives, it is better to encourage electrification in colder climates with grid connections maintained, as such off-grid systems use generators or gas-fired combined heat and power systems to minimize battery size.

A potential barrier to adoption for both heat pumps and PV are the higher capital costs [86–88], placing emphasis on the continued need for support programs [89], access to capital [83], and/or third-party business models [90,91]. Here heat pumps are 2.5 times more expensive than the gas furnace, assuming they can share the same distribution infrastructure (e.g., ducting, electric panel). A survey of U.S. heat pump adopters, however, suggests that retrofit heat pumps cost, on average, double what a new home installation costs [92]. A 2021 proposal in the U.S. Senate would support qualified electrification investments up to 10,000 USD, which would help reduce the economic barriers to heat pump retrofits [93]. PV systems make the barrier significantly higher, where a PV+HP system costs 40,000 USD more than a gas furnace. If this study's PV system CAPEX were the same as Germany's (2 USD/Wp) [59], the difference falls to 35,000 USD. This is still a large sum, and the difference would be greater if using current market prices, but the German PV price would make the lifecycle economics favor the PV+HP even in low inflation scenarios and boost the real IRR to 3.4%.

There exists an economic opportunity for north American electric utility companies to capture additional market share from natural gas by encouraging the use of HPs. Some utilities are already aware of this and provide rebates on heat pumps to attract potential customers [94,95]. This makes sense given that they can increase their load base significantly. In this study's case, the electricity demand rises by 60% (nearly 7000 kWh/year). Most rebates are between 300 and 1200 USD, with the higher rebates going towards more expensive ground source (geothermal) heat pumps [96].

In general, most utilities offer a rebate of approximately 300 USD on air-source heat pumps [97], which has minimal impact on the total lifecycle cost for customers but earns the utility up to 20x in lifetime revenues. This is due to OPEX making up most of the lifecycle costs, meaning electricity prices and net metering are more critical factors in the economic success of heat pumps and PV. It has been previously shown that rebates have limited effectiveness as a policy tool for energy efficient technologies, with more focus suggested on operational expenses [98], which the results here confirm. However, as more and more homes install or replace air conditioning due to increased frequency of heat waves, rebates can cover the modest cost increase for a reversable model meaning that heat pumps can be installed for no marginal cost [99].

Another barrier to adoption is the lack of availability. Residential PV has higher prices in smaller less competitive markets [60] and is virtually nonexistent in some areas (e.g. West Virginia and Wyoming only have 152 and 311 solar jobs in the whole state, respectively; while Ohio by comparison has over 6,500) [100]. This means that in practical terms a West Virginian interested in installing PV may simply not have any installers in their region. Similarly, heat pump technology although mature on a global scale, is just beginning to take hold in the U.S. [101,102]. Heating electrification is growing in regions already using cooling, however more effort is needed in more temperate or colder regions [103]. In particular, heating contractors/installers need to become more familiar with the technology [103], as previous experience has shown is a key barrier to uptake in the market [104].

What is abundantly clear from the results is that the homeowner's perception of energy price inflation has the greatest influence on economic feasibility. In times of inflationary uncertainty, PV's ability to hedge against inflation is a unique attribute that can, and should, be used as an asset [105]. The ability to lock in electricity, and when combined with a heat pump, heating and cooling costs for 20–30 years is likely to be front-of-mind for many homeowners experiencing energy price inflation, now and in the coming years. Additionally, payback times for PV+HP systems is around 15–18 years, which is long, but acceptable for early adopters [58].

Rather than work against distributed generation and PV from their own customers [106], the results of this study show that distributed PV can be encouraged along with increased electricity demand with the use of solar-assisted HPs. This transition is already underway in Europe [107,108], where prosumer rights are established by EU law, causing a wide range of policies and business models to facilitate the transition. One adaptation incumbent electricity providers have made is to sell prosumer technologies (PV, batteries, energy management, etc.) so as to enhance their connection with customers and not lose revenues to third parties [109]. Following the European example, this study has shown that U.S. utilities may want to explore entering the PV and HP business but that prosumer specific policies are needed to guide the energy transition [110,111].

Future work on this topic should incorporate additional electrification technologies, in particular electric vehicles and stationary batteries, which add further complexity to the techno-economic relationship in prosumer systems. More detailed analysis into the hedging against energy prices, in particular natural gas, is also needed given the criticality shown here. Rising prices are also closely linked to energy justice issues [112,113], and the results here show that both electricity and heating costs can become fixed at less cost for homeowners, and policies should be developed around this concept. Conversely, the relationship of net-metering policies to electricity grid costs must also be incorporated [114], and more work into utility regulation and business models to align the interests of homeowners and utilities [106,115].

6. Conclusions

This paper sought to define the technical, economic and policy conditions necessary for heat pumps and solar PV to compete economically with natural gas in single family, residential homes in the Midwest region of the United States. The results show that under typical inflation conditions, the lifecycle cost of natural gas and reversable, air-source heat pumps are nearly identical, however the electricity prices are too low for PV. With higher rates of inflation, as are being experienced in 2021–2022, PV becomes a hedge against rising prices and encourages the adoption of heat pumps by also locking in heating cost growth. The real internal rate of return is 20x greater than a long-term certificate of deposit, further demonstrating the economic potential.

The capital costs of heat pumps are higher than a gas furnace, leading utilities and governments to offer rebates on the investment cost. The sensitivity analysis here shows that the lifecycle costs are relatively insensitive to CAPEX and a greater focus should be placed on operational cost. Of particular importance are electricity and gas prices and to a lesser extent heat pump efficiency. Due to the much higher CAPEX and lower OPEX, solar PV investment costs are more critical to the deployment of HP+PV systems, and more efforts are needed to bring U.S. costs closer to those for prosumer systems in Europe, particularly for expanding past the most productive rooftops. Monthly net-metering and higher electricity prices also support the economics of PV, where approximately 0.13 USD/kWh is found as a tipping point under normal inflation levels.

This paper has provided a valuable and detailed description of the techno-economic conditions needed for heat pumps and solar PV to replace natural gas heating in the temperate climates within the central U.S. The comprehensive sensitivity analysis is unique in its ability to capture six dimensions at once and is useful for identifying specific boundary conditions outside of the nominal values applied here. The results are therefore applicable to a wide number of potential residential prosumers in the U.S. with a comparable climate and can be used as a reference for engineers, researchers, and policy makers.

CRediT authorship contribution statement

Nelson Sommerfeldt: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Joshua M. Pearce:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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