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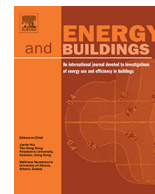
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Decarbonizing rural residential buildings in cold climates: A techno-economic analysis of heating electrification

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ABSTRACT

Given the need for decarbonization of the heating sector and the acute need of a propane replacement in the U.S. Upper Midwest, this study quantifies the techno-economic characteristics of sustainable heating electrification in isolated rural, residential buildings in cold climates without natural gas supply. Archetypal buildings are modeled under four levels of electrification. At each electrification level, a parametric solar photovoltaic (PV) sizing analysis is performed and the total life cycle cost, renewable fraction and greenhouse gas (GHG) emissions are calculated based on the primary energy supply for each building type. Cost optimal solutions are stress-tested with multi-dimensional sensitivity analyses. The results show that the total life cycle cost favors heating electrification in all cases and combining PV with heat pumps can reduce residential building GHG emissions by up to 50% immediately. This effect will grow over time, with over 90% reduction of building emissions if renewable energy targets are met. In using primary energy and emissions along with the multi-dimensional sensitivities, this study unique demonstrates the complex techno-economic interactions of PV and heat pumps. It is concluded that electrification is an economically viable decarbonization method for cold climates both now and in the future.

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1. Introduction

Natural gas is the most common residential heating fuel in the United States (U.S.), accounting for about 2/3 of space heating and hot water supply [1]. In the heating dominated cold or very-cold climates, this proportion rises to 72.8%. In total, 88.4% of all heating supply in U.S. cold climates comes from direct combustion of fossil fuels.

Electrification is an oft-cited approach to decarbonizing sectors currently relying on combustion fuels, such as heating and transport [2–6]. Low-cost electric heating devices are already commonly available and represent the second largest share of heat supply [1]. This electrification, however, is generally supplied by resistive elements, and would be far more efficient with heat pumps.

Heat pump penetration is growing in the U.S. with 3.1 million units sold in 2019 [7]. This is largely dominated by southern climates, where space cooling is the priority and units are reversed to provide heating [8]. While at much lower penetrations, cold climates are also seeing an increase in heat pumps in homes replacing

an air conditioning unit, or in rural properties relying on relatively expensive fuels [9].

Although it makes up a relatively small 8% of total heating supply, the Midwestern region of the U.S. has five of the ten largest propane consuming states [10,11]. Michigan is the largest, with 12.5 GWh consumed in 2018 and 75% being used in the residential sector [10]. Additionally, a pipeline crossing the Great Lakes between Upper and Lower Michigan is under consideration for closure due to the risk of failure, making propane supply for the state an acute environmental and political concern [12].

For rural Midwesterners, heat pumps could provide an alternative to propane and be the start of heating decarbonization. Decarbonization, however, requires replacing fossil fuels in the electricity supply with low-carbon alternatives. For example, in China it has been shown that coal based district heating can emit less CO₂ than low-efficiency heat pumps relying on low-efficiency coal power plants [13]. Similar analyses have been performed with electric vehicles, where coal-heavy electricity portfolios dramatically reduce the environmental benefits of electrification [14–16].

In conjunction with grid electricity, distributed solar photovoltaics (PV) can also decarbonize residential electricity supply. PV is already known to reduce electricity costs in the region [17–

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Nomenclature

Symbols

C	Capital Expenditure (USD)
L	Lifetime (Years)
O	Operational Expenditure (USD)
R	Revenues (USD)
S	Salvage Value (USD)
T	Temperature (°C)
d	Discount Rate
η	Loss Factor
ϕ	Share of generation portfolio

Subscripts

a	Ambient Air
c	Conversion
$CO_2 - eq$	Carbon dioxide equivalent
el	Electricity
g	Grid
s	Site-to-source
th	Thermal
y	Year of occurrence

Abbreviations

ASHP	Air source heat pump
ASHP-R	Reversible air source heat pump
CAPEX	Capital expenditure
COP	Coefficient of performance
DHW	Domestic hot water
EF	Emissions factor
FES	Final energy supply
GHG	Greenhouse Gas Emissions
GHE	Ground heat exchanger
GSHP	Ground source heat pump
HP	Heat pump
OPEX	Operational expenditure
PEF	Primary energy factor
PES	Primary energy supply
PREF	Primary renewable energy fraction
PV	Photovoltaic
RPS	Renewable portfolio standard
SPF	Seasonal performance factor
TLCC	Total life cycle cost
U.S.	United States

19], and the larger electricity loads from heat pumps have the potential to increase the economically viable PV capacities [20,21].

This study quantifies the techno-economic characteristics of sustainable heating electrification in rural, residential buildings in cold climates (represented by the U.S. Upper Midwest and Northeast) without natural gas supply. Following a brief literature review to define the knowledge gap, a more succinct problem definition, objective, and methodology are given. Specifically, archetypal buildings are modeled under four levels of electrification. At each electrification level, a parametric PV sizing analysis is performed and then the total life cycle cost, renewable fraction and greenhouse gas (GHG) emissions are calculated based on the primary energy supply for each building type. A sensitivity analysis is run on all major variables. The results are discussed and conclusions drawn within the context of electrification as a viable decarbonization method for cold climates.

2. Background

There are many heat pump designs considering the available heat source (e.g. air, ground, water) and the method of delivering heat to the building (e.g. ducted air, ductless air, hydronic) [22]. In the broadest sense, they can be divided into two main categories – ground source heat pumps (GSHP) (i.e. geothermal heat pumps) and air source heat pumps (ASHP).

In GSHP, the design of the ground heat exchanger (GHE) is often the most critical component in determining performance and economics [23–25]. Hakkaki-Fard et al. [25] specifically noted high drilling prices as a barrier for GSHP versus ASHP, and Blum et al. [26] notes that GHEs typically account for 50% of the installation cost in Germany, but vary considerably from 10 to 141 €/m. One option to reduce GSHP cost is a horizontal GHE [27], however this approach requires substantially more land area. Lim et al. [28] find that 8% of U.S. homes cannot install any GSHP due to space limitations, and of those that can 61% must use the more expensive vertical GHE. Beyond installation cost, there is a critical relationship between climate, geology, electricity price, fuel prices, and inflation rates on economic outcomes [29] making a single design recommendation difficult for whole regions [30].

ASHP offer a better economic proposition to GSHP by removing the need for GHE entirely, and in recent years the technology has improved to be a viable alternative in cold climates [31]. New refrigerants, ejectors, and dual-stage compression have all worked to lower the minimum operating temperatures and reduce auxiliary heat [32]. At -21 °C, the coefficient of performance (COP) of air-to-air heat pumps can drop down to 1.04 [33], but has also been demonstrated up to 1.5 in commercial model testing [34]. Pre-heating air via buried ducts can improve cold-climate performance [35], but will suffer from the same land and cost barriers as traditional GHE. Partial load control has also translated into improved seasonal performance, with validated simulations from various locations in North America showing heating season COPs from 2.5 to 3.67 [36–38]. Real installation performance can be quite varied, however, highlighting the need for best-practices in design to achieve the expected technical and economic outcomes [39,40].

As with GSHP, the economic competitiveness of ASHP varies by location and application. Asaee et al. [41] and Udovichenka and Zhong [42] have studied Canadian buildings, finding that in most cities ASHP are more expensive than natural gas, with milder climates being the most promising. The majority of the Canadian population lives in such milder climates as does nearly all of the U.S. Mexican populations, making ASHP a potentially economical method of electrification of the heat supply for North America.

Solar heat pumps can have many configurations using thermal and/or photovoltaic collectors, and have been applied in numerous cold-climate techno-economic studies [43]. At an individual building level, PV+HP studies have focused on altering the heat pump controls in order to increase PV self-consumption, relying on weather forecasts [44,45] or real time data [46]. Self-consumption strategies have been compared with alternatives, such as hourly price signals [47,48] or thermal load management [49] which lead to better economic outcomes than PV self-consumption. This is large part due to the limited overlap of heat pump operation and PV generation [50]. A parallel configuration with solar thermal collectors is considered the most effective method of increasing heat pump efficiency [51], however PV electricity can also be used in the house and sold to the grid, giving it more utility. In addition, the exergy for a given roof area is higher

for PV than solar thermal although it can be maximized with solar thermal PV hybrid technology [52].

3. Knowledge gap and objective

The technical performance of heat pumps in cold climates is well described in the literature, but economic performance is highly variable. The majority of studies in North America compare heat pumps to natural gas, which is logical given its dominance as a heating fuel. Rural customers relying on more expensive fuel oil or propane, however, represent a better opportunity for heat pumps, and no studies were found using these fuels as a baseline comparison. This study also provides a comprehensive techno-economic analysis of solar PV heat pumps, which is lacking for cold North American climates.

Given the need for decarbonization of the heating sector and the acute need of a replacement for propane in the U.S. Upper Midwest, this study aims to fill this knowledge gap by describing technical and economic performance of residential building electrification in cold climates as part of the pathway to decarbonization. Heat pumps will be benchmarked against the prevailing energy source, propane, in conjunction with rooftop PV systems. Cost optimal solutions will be stress-tested with sensitivity analyses to gain a broader understanding of the uncertainties and potential for future development. Within this framework, four research questions will be answered:

- What is the economic cost of switching from propane to heat pumps for homeowners?
- What are optimal PV system sizes under electrification?
- What are the CO₂ and primary renewable energy supply for such systems?
- Which policies can be used to realize heating decarbonization?

4. Methodology

A bottom-up residential energy demand model is used to create disparate hourly load profiles for appliances (plug-loads), hot water, and space heating demand, as described by Fig. 1. The model details are given in Appendix A, with comprehensive descriptions and motivations provided in the linked [MethodsX article](#).

Several levels of electrification are considered, defined in Table 1, starting from a baseline (Base) case where propane serves all heating needs, to first electrifying hot water (Level 1) up to full electrification (Level 2). Given the ability for heat pumps to easily reverse (ASHP-R) and provide space cooling in summer, a second fully electrified level (Level 3) is included to describe this additional service. At each electrification level, a parametric PV sizing

Table 1
Description of electrification levels.

Level	Hot Water	Space Heating	Space Cooling
Base	Propane	Propane	None
Level 1	ASHP	Propane	None
Level 2	ASHP	ASHP	None
Level 3	ASHP	ASHP	ASHP-R

analysis is performed. Details on the energy supply equipment are provided in Appendix A.3.

Technical performance is described using primary energy renewable fraction (PREF), which takes into account all source energy used in the final supply of electricity and heat to the building. Primary energy supply (PES) is found by taking the final energy calculated in the models and applying a primary energy multiplier, as described in Appendix A.4. GHG emissions are also calculated using PES.

Economic performance is measured using total life cycle cost (TLCC) using a self-consumption pricing model described in Appendix A.4, and supported in the discussion with investment and operational costs given their salience for the homeowner. Most household equipment is replaced at end of life; therefore, all comparisons are made with the perspective that a choice must be made between propane and electric equipment.

There is a broad range of technical and economic conditions to consider, therefore multiple variables are treated with a sensitivity analysis. From the technical perspective, three envelope efficiencies that encompass the range of ages and conditions of residential buildings are tested. The grid electricity portfolio is also tested considering the Midwestern generation mix available today up to 100% renewable electricity generation. Economic sensitivities are analyzed on capital costs, electricity and propane prices, and discount rates.

Climatic, construction, occupancy behavior and economic boundary conditions are taken from Michigan, but are considered representative of most buildings in North America's cold climate zones. Three building envelope efficiencies are considered and are intended to be archetypal, meaning that they represent the broad class of residential building types and not any specific building. Verification of the models is done qualitatively against published statistics, limiting the scope to a feasibility study on the potential for heat pumps in the market. The building's energy demands are summarized in Table 2 and described with more detail in Appendix A.2.

5. results

The results are broken into two categories – a parametric optimization of the PV and HP systems for each home efficiency and HP

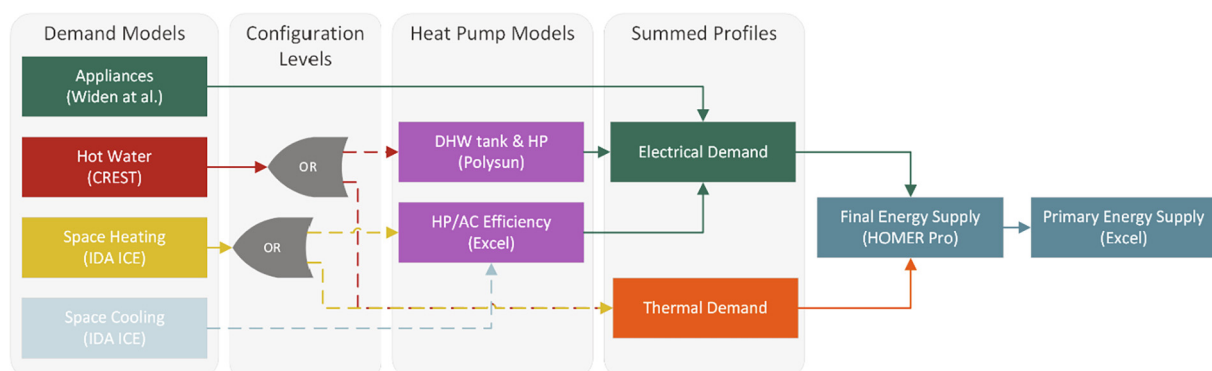


Fig. 1. Bottom-up modeling structure and corresponding loads.

Table 2
Energy demand characteristics of the archetypal buildings.

Application	Demand (MWh/yr)	Peak Load (kW)
Space Heat - High	7.6	13.1
Space Heat - Mid	12.8	17.6
Space Heat - Low	27.5	25.8
Domestic hot water	2.1	10.5
Appliances	3.9	2.0

renovation level, and a sensitivity analysis on the most critical boundary conditions. The maximum PV system capacity is limited to a 100% solar fraction (i.e. net-zero electricity) where generation is equal to electricity load over the year.

5.1. Default boundary conditions

With the current grid portfolios and economic boundary conditions, the results in Fig. 2 show the relationship between primary renewable energy fraction (PREF), GHG emissions and total life cycle cost (TLCC) for each building efficiency considering the range of PV capacities. For each renovation level there is a single point without PV and a range of PV sizes that form a continuous curve in 0.5 kW increments. Maximum PV capacities are indicated on the figures.

The baseline PREF for houses without PV is between 1.8% (a) and 3.6% (c), with higher efficiencies leading to higher PREF due to the higher fraction of electricity in the energy supply. These low values highlight the high fraction of energy used for heating as well as the large losses incurred in thermal power plants and grid transmission.

Adding a heat pump for domestic hot water (DHW) (Level 1) marginally increases PREF by approximately 0.5 percentage points and reaches 7.0% when all heating is electrified (Level 2). This increase of renewable energy supply is due exclusively to the replacement of 100% fossil fuel heating with propane to partially renewable grid electricity. In absolute terms, primary energy supply is nearly identical for all renovation levels without PV due to the similarity of heat pump SPF (2.3) with the grid's primary energy factor (2.57).

The addition of PV to each system increases PREF by up to 300% for each house when the PV is sized for net-zero energy. The Baseline systems have the lowest electric load (3937 kWh/yr) and therefore lead to cost-optimal PV systems of a relatively small 2.5 kW. Moving to Level 1 increases PV capacity to 3 kW, however at Baseline and Level 1 the PV systems increase TLCC by 3% due to the relatively high capital expenditure. At Level 2 the cost-optimal capacities increase up to 10 kW, leading to the PV+HP solution being the most cost-effective for the low-efficiency house, but in the mid- (b) and high-efficiency (c) houses the costs increase by 1%, effectively identical given the uncertainties surrounding economic parameters.

Level 3 renovations are identical to Level 2 in that it is assumed no additional capital investment in cooling equipment is needed, a major benefit of heat pumps. There is an additional operational cost, however this is only 1–3% depending on the efficiency. Given the increased demand of cooling in recent years in historically temperate climates, this can be a notable value stream for heat pumps in addition to the cost savings.

GHG emissions are reduced with heating electrification, by 25% in the High and up to 32% in the Low Efficiency houses. The addition of PV to the heat pumps can further reduce emissions up to 50% from the baseline. It is particularly noteworthy that these reductions are possible while also saving up to 20% on lifecycle energy supply costs, even without subsidies.

Table 3 lists the detailed on-site performance results for the PV systems, including maximum and cost-optimum capacities, solar fraction, self-consumption, and self-sufficiency. In nearly all cases, the optimal PV systems have a solar fraction of 70–80%. Levels 2/3 have the lowest solar fraction due to lower self-consumption caused by the seasonal mismatch of PV and space heating. The lower specific price due to the larger systems, however, allows for a lower self-consumption at the cost-optimal capacity. Self-sufficiency is between 27% and 35%, being the lowest at Level 2 due again to seasonal mismatch. The improved match between generation and cooling increases the optimal PV sizes for the mid- and high-efficiency buildings at Level 3, but self-sufficiency differences are relatively minor due to the low cooling loads.

While the trends in all buildings are the similar, the mid-efficiency house is an interesting economic example due to non-PV systems being the lowest cost alternative except at Level 3 where a 6.5 kW PV system is recommended. Given the low differences in energy demands between Levels 2 and 3, this makes visualizing the cost structures between PV and non-PV alternatives easier, as shown in Fig. 3, where the cost-optimal solution for each renovation level are shown.

From Baseline to Level 1, there is a small capital expenditure (CAPEX) increase of \$200 (4%), from \$5600 to \$5800, but the reduced operational expenses (OPEX) switching from propane to electricity result in a \$1800 (5%) decrease in TLCC. At Level 2 this relationship is taken further with a CAPEX increase of \$2800 (50%) and a \$5700 reduction (15%) in TLCC from baseline. At Level 3 the TLCC is similar to Level 2, but a dramatic shift in cost structure forms with the addition of PV. CAPEX increases considerably, up to \$27,500 (390%) while OPEX is reduced by \$7375 (45%). Additional economic benefits are gained by selling excess PV, earning \$7510, and the residual value in the PV system at the end of 20 years (\$4285) given it is expected to continue operating another 10 years after the heat pump.

The high share of OPEX costs in systems without PV explains why the cost savings decrease when comparing the Low-Efficiency to the High-Efficiency houses in Fig. 2. Even without PV, the TLCC from Baseline to Level 2 in the Low-Efficiency house is reduced by \$11,500, or 18%, whereas in the High-Efficiency this is only 13%, equivalent to \$3900. These results also highlight the savings achieved with energy efficient construction, however a direct cost/benefit analysis is outside the scope of this study.

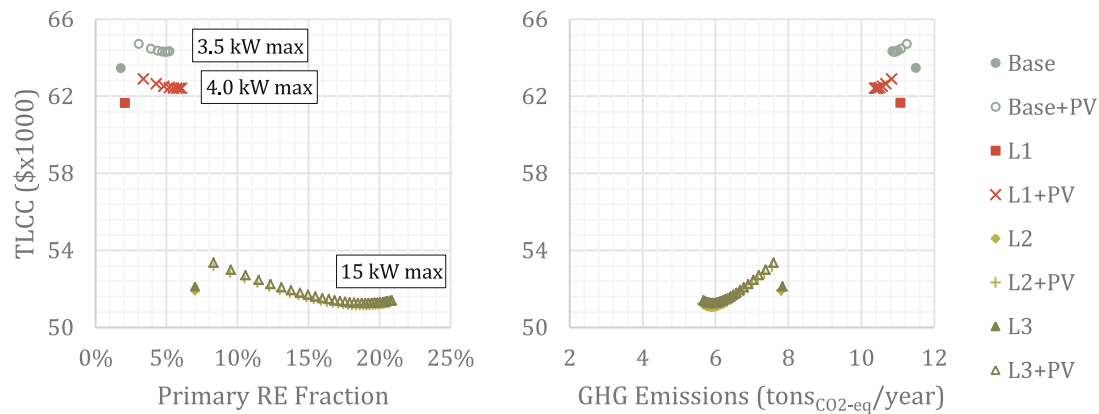
5.2. Sensitivity analyses

The default results show that heat pumps can reduce GHG emissions and costs relative to new propane equipment, with or without PV systems. Many of these results are within a few percent, however, suggesting that regional, local, or specific case difference could tip the conclusions differently. This section is dedicated to a comprehensive sensitivity analysis covering propane prices, the buy and sell prices for electricity, capital costs for PV and HP, and the discount rate. Looking forward towards renewable energy policies across the United States, the fraction of renewable electricity in the grid is also tested. Due to small differences in results for each home, the results from the Mid-Efficiency home are presented in figures while the Low/High Efficiency results are only discussed.

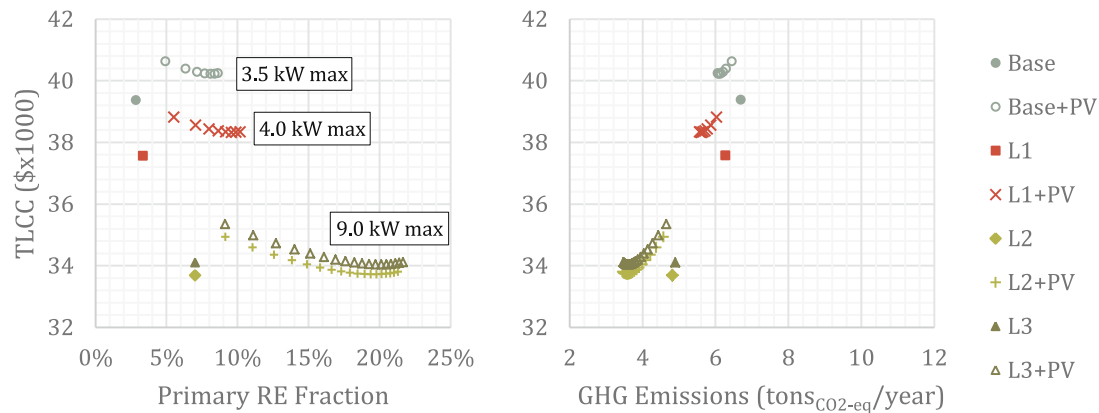
5.2.1. Energy prices

One of the most critical factors driving the adoption of gas vs. electric heaters is the relative price of fuels to run them. This is exemplified in Fig. 4, where separate color regions are used to identify the system configuration with the lowest total lifecycle cost considering variations in electricity and propane prices. The

(a) Low Efficiency



(b) Mid Efficiency



(c) High Efficiency

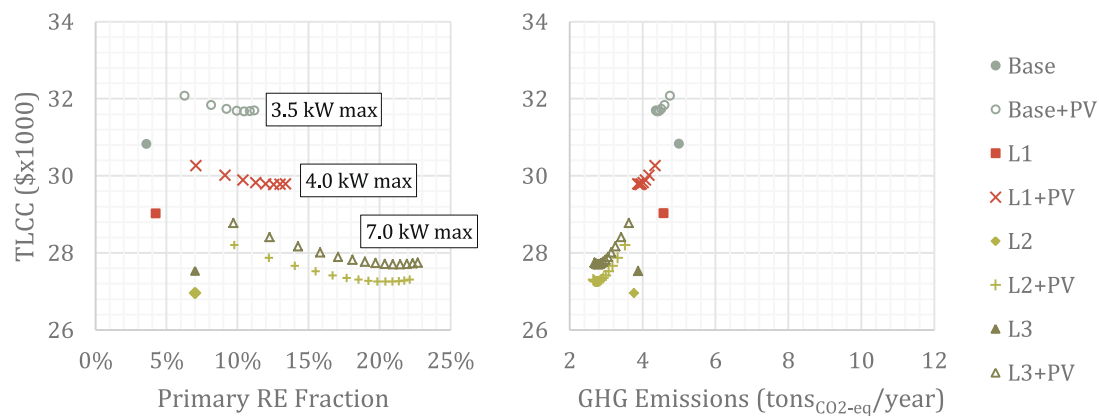


Fig. 2. PREF, CO₂ and TLCC for all three building efficiencies.

relationship is further complicated by the presence of PV given that higher electricity prices favor both PV and propane.

From the default values applied in Section 5.1, marked with the black X, essentially any increase in electricity will make full electrification with PV the most cost-effective alternative. The most

recent prices from the Midwest and Northeast regions are marked with purple and blue X's, respectively. Both fall within the Level 2 regions, where the Northeast's higher electricity prices promote PV adoption whereas the Midwest prices promote heat pumps only. The general trend is the same for Low/High Efficiency houses, the

Table 3
On-site performance indicators for solar PV.

	Peak Cap (kW)	Opt Cap (kW)	Self Con (%)	Sol Frac (%)	Self Suff (%)
Baseline	3.5	2.5	47	74	35
Level 1	4.0	3.0	44	80	35
Level 2	Low-Efficiency				
Level 3	15.0	10.0	38	71	27
Level 3	15.0	10.0	39	72	28
Level 2	Mid-Efficiency				
Level 3	9.0	6.0	41	68	28
Level 3	9.0	6.5	40	75	30
Level 2	High-Efficiency				
Level 3	7.0	5.0	41	74	30
Level 3	7.0	5.5	41	79	32

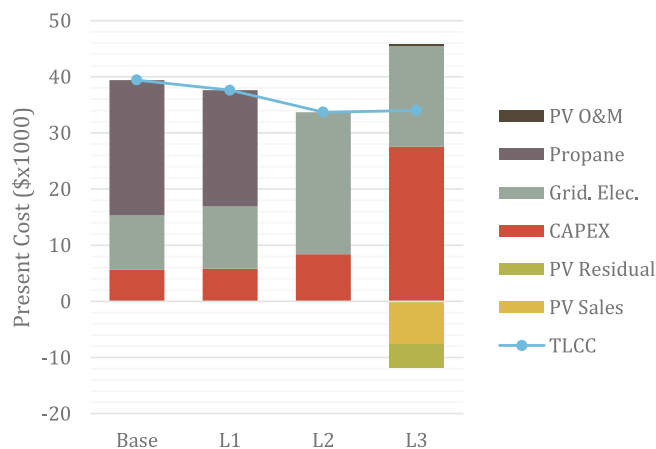


Fig. 3. Cost-optimal TLCC details of the Mid-Efficiency house.

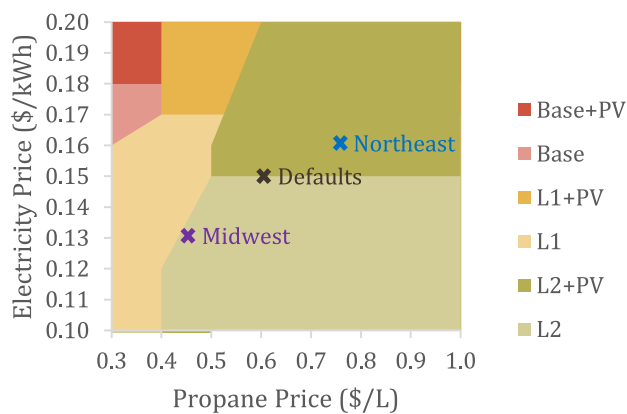


Fig. 4. Lowest cost solution for Mid-Efficiency considering electricity and propane price.

only notable difference being that Low Efficiency homes can benefit from PV at Level 2 until the electricity price is \$0.13/kWh, which then places the current Midwest prices right on the edge of the L2 +PV zone.

5.2.2. Capital costs

Much like the electricity prices, the sensitivity analysis of heat pump and PV capital costs in Fig. 5 show that any decrease in PV cost from the default \$3.1/W will make it cost effective with full electrification. Since life cycle costs are dominated by propane/electricity prices, even a 50% increase in HP prices, equivalent to a \$10k system, does not lead to propane heating becoming the preferred option. Only in the High Efficiency home with a 30% price increase does a Level 1 renovation become cost optimal.

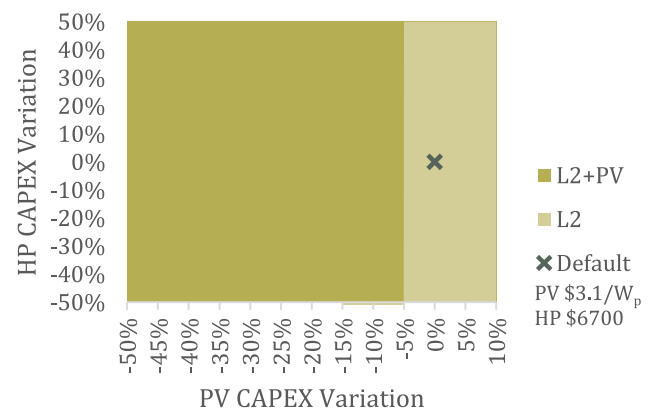


Fig. 5. Lowest cost solution for Mid-Efficiency considering PV and HP CAPEX variations.

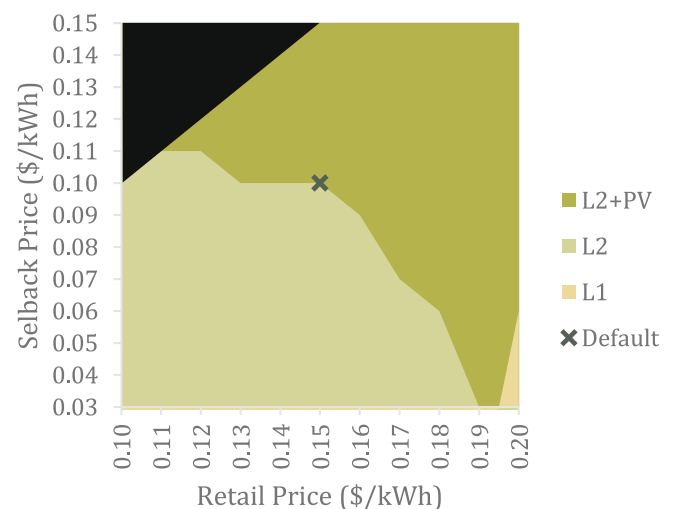


Fig. 6. Lowest cost solution for Mid-Efficiency considering the purchase and sellback prices of electricity.

5.2.3. Overproduction price

With many utilities already eliminating net metering [53] the selection of a sellback price for PV overproduction can be a critical economic factor. Fig. 6 shows the lowest cost solutions considering both the retail purchase price and the sellback price. The sellback price varies from full net metering (up to \$0.15/kWh) down to \$0.03/kWh, the average summer day-ahead price in the Midcontinental Independent System Operator's region during 2017–2019 [54]. Alternatives where the sellback price is higher than the retail prices are omitted.

As noted in Table 3, at the default rates the cost-optimal PV system at Level 2 is 6 kW and has a 41% self-consumption rate. Since most electricity is sold back to the grid, the PV system capacity is more sensitive to the sellback price than the retail purchase price. For example, at a \$0.19/kWh retail price, inclusion of PV in the system is always cost-optimal, however as the sellback price falls the PV capacity also falls until it is 2 kW at the wholesale \$0.03/kWh price. Conversely, if the sellback price rises above \$0.10/kWh, then the maximum capacity (i.e. 100% solar fraction) is recommended.

The relationship with the Low and High Efficiency homes is similar. One primary difference in the High Efficiency house is at high retail prices above \$0.18/kWh and sellback below \$0.07/kWh, a Level 1 renovation without PV is recommended. In this region, Level 2 with PV is still recommended in the Low Efficiency house, however the capacities are reduced as low as 3 kW.

5.2.4. Discount rate

Discount rates can strongly influence the design of renewable energy systems, however in this case building electrification with heat pumps is always cost optimal. Fig. 7 shows the TLCC for the Mid-Efficiency house for the Baseline, Level 1 and Level 2 with real discount rates from 0% to 8% (2% is the default). As expected, TLCC declines with discount rate, however in none of the cases is it cost effective to use propane. Even in the High-Efficiency building, where the costs have the least gap, the difference in TLCC from 0% to 8% is over \$1500.

The main difference comes in the presence of PV, which in Fig. 7 is denoted by the hashed columns. Here the long-term savings from PV are valued enough such that the increased capital cost is recovered. The result is the same for the Low/High-Efficiency buildings, with the only difference being that PV provides the lowest TLCC at Level 3 (L3) in the Low-Efficiency house at a 2% discount rate as well.

5.2.5. Renewable portfolio standards

Several states have set renewable portfolio standards (RPS) much higher than the current Midwest baseline of 18%. For example New York has a 70% RPS for 2030 and a zero-emissions requirement by 2040 [55], and analysis of the Midwest region suggests wind and solar could cover nearly 100% of the load at comparable costs to today [56]. Table 4 shows the emission factors assumed at each RPS level, which are calculated assuming the most carbon intensive fuel sources are phased out first and replaced with a mix of wind and solar up to 100%.

The GHG emissions of the Mid-Efficiency house's cost-optimal systems are given in Fig. 8, demonstrating the importance of electrifying space heating (L2/L3), where already today (18%) a PV+HP system reduces emissions beyond the baseline or L1 systems with

Table 4

Calculated emission factors (EF) for renewable portfolio standard (RPS) levels.

RPS Level	EF (gCO ₂ -eq/kWh)
18%	0.468
30%	0.353
50%	0.152
80%	0.066
100%	0.031

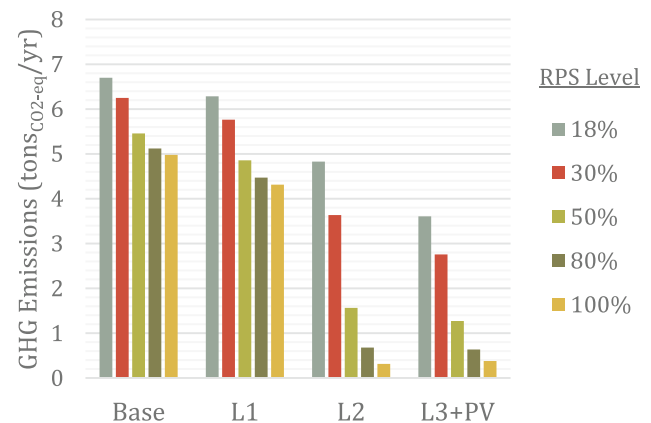


Fig. 8. GHG emissions for Mid-Efficiency house considering RPS portfolios.

a 100% RPS. Comparing L3+PV with L2, the emissions from adding PV are nearly equivalent with a 30% RPS without, which are 25% below the default 18% and 46% below the baseline. There is a large decrease in emissions from a 30% to 50% RPS due to the near phase out of coal, which decreases as less carbon intensive sources are phased out in the 80% and 100% RPS. The differences between L2 and L3+PV are also reduced as RPS increase, meaning the addition of PV is a high-impact action that home owners can take today while the larger, more complex grid transition takes place over subsequent decades. With PV+HP and an 80% RPS, total GHG emissions from home energy supply can be reduced by over 90%.

6. Discussion

It is clear from the results that HP technology has already matured such that the total life cycle cost favors heating electrification in all cases. Stated simply: no one in the region should be continuing to use propane for heating based on economics alone. The economic case can be made even stronger as homes with heat pumps tend to increase in market value by 4.3 to 7.1% [57], which is omitted in these results. Additionally, climbing to a Level 3 renovation, where an ASHP and PV provide hot water, space heating and space cooling, would help prepare for a warmer world from climate change with nearly zero marginal cost.

The approach of this study is similar to those used by Caskey et al. [37], Asaee et al. [41], and Udovichenko & Zhong [42], however, only Caskey et al. found ASHP to be economically competitive to natural gas. Pearce & Sommerfeldt [21] found ASHP with PV in Michigan to compete with natural gas when the systems were net metered (although it should be pointed out the economics would improve if the value of solar (VOS) is used [58] and would decline if lower than market rate is paid for distributed generation). To set the economic scope of this study, the literature search is limited to North America, however similar solar heat pump stud-

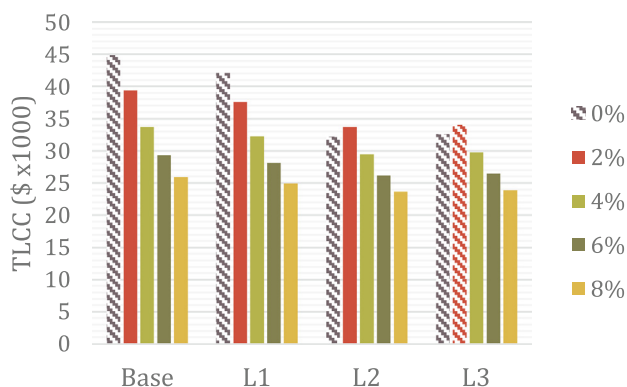


Fig. 7. TLCC sensitivity to discount rate for the Mid-Efficiency house.

ies are performed globally [43,59]. For example, Schreurs et. al [60] found unsubsidized ASHP with PV to be competitive with natural gas in Austria when a carbon tax was applied.

This study is novel in that it applies to propane, which is a more expensive heating gas, includes no explicit subsidies, and finds heat pumps to be economically competitive with or without PV. This study also uses a more comprehensive methodology than previous work, namely the primary energy and emissions are built from the complete electricity generation portfolio that evolves over time and the economic sensitivity analysis is multi-dimensional. This latter aspect is particularly beneficial with PV heat pumps given the conflicting benefits of electricity price on each technology.

It should also be highlighted how the combination of PV with HP has the potential to reduce residential building GHG emissions by up to 50% immediately. This is a conservative value given that only self-consumed PV is considered. If grid sales are included, the total GHG reductions would be over 60% at Level 2 with a cost-optimal PV system – double the impact of heat pumps alone with today's Midwestern electricity portfolio. While GSHP with PV has been shown to reduce emission up to 80% [61], these savings can be achieved with simple equipment switching and low marginal cost differences, meaning adoption should not be an economic barrier. Installer training and customer familiarity are likely more important [62].

The sensitivity analysis shows that any reduction in PV prices makes a Level 2 renovation with PV the cost-optimal system. Therefore, current investment subsidies should be able to encourage adoption regardless of the building's thermal efficiency. The high capital cost of PV remains a barrier [63–65], however past work has shown for the majority can still gain access to capital [18], take advantage of existing support programs [66], and/or third-party business models [67,68].

From a policy perspective, these results are highly relevant towards the transition to a low-carbon energy system. For example, Michigan, the largest consumer of propane in the U.S., is debating the replacement of a key pipeline [69], and the Governor's current plan focuses on investments in legacy systems, such as railroads and increased propane storage [70]. A strategy for switching to heat pumps is notably missing. If the proposed budget for rail renovation were applied to heat pumps, each home with a propane boiler would have \$1000 available, making the fuel switch an even more obvious choice economically and avoids decades of GHG emissions lock-in.

Given the typical 20-year lifetime of a gas furnace [71] and the current low market share of heat pumps [8], it is unlikely that the transition would be made prior to 2050 considering only naturally occurring replacements. There are several policies that can accelerate the adoption of HP and PV, including; incentives to retire propane equipment prior to failure, laws for new construction banning use of propane as a fuel, and enabling a greater percentage of distributed generation on the grid (some Michigan utilities interpret the current 2% minimum as caps [17]) to allow for greater capacities enabled by heat pumps.

A consorted policy effort is needed for the transition to electrification to be completed in good time [4]. As an example, Sweden, with the highest penetration of heat pumps in the world, made a holistic strategy to replace oil and resistance electric heating with heat pumps starting in the early 1970's, but did not get a strong market response until the late 1990's [62]. Much of this time was spent developing the technology, which is no longer critical today, however it was also spent developing a market with informed and experienced installers who are critical to success. High taxes on fossil fuels, including the introduction of a €24/ton CO₂ tax in 1991, are believed to be the strongest economic motivators for switching from oil boilers to heat pumps [62,72].

7. Conclusions

There is a growing attention being paid towards heat pumps as part of a larger strategy to decarbonize buildings via electrification. This study provides new techno-economic results showing the benefits of heat pumps, especially when paired with photovoltaics, and the complex relationships between each technology and energy prices. Qualitatively the electrification strategy is simple to understand, and this study provides a suite of novel quantitative results for what is arguably the most difficult region to convert from gas heating – cold climates.

There is no lifecycle economic cost to homeowners when heat pumps are a drop-in replacement. Even with 50% higher capital costs than average market prices, the lower operational costs of heat pumps compensate. This holds true for the full range of building efficiencies, meaning that envelope upgrades, while beneficial, are not a prerequisite for heat pump adoption.

Heat pumps also enable a much larger penetration of PV systems, up to 4x greater capacities for a cost-optimal solution. This is critical given that a PV+HP system can reduce GHG emissions by at least 60% more than a heat pump alone. Even without subsidies, PV+HP is very close to being the lowest cost energy solution for single-family homes. Assuming the trend in PV cost declines continue, PV+HP will become the clear choice even post investment subsidies within a few years.

This conclusion is highly dependent on electricity prices, both retail and sellback. Lower retail prices benefit heat pumps, but harm PV while higher sellback prices help support PV even when electricity prices are lower, suggesting that a tradeoff can be made with utilities where lost revenues from distributed PV can be more than compensated by the increased demand from heat pumps. This complex interaction between PV, HP, and electricity prices should be considered by regulators and utilities when setting rates, particularly sellback prices.

While the long-term strategy of electrification includes the phase out of fossil fuels, solar heat pumps already today reduce GHG emissions by up to 50%. This effect will grow over time, with over 90% reduction of building emissions if renewable energy targets are met. Therefore, investment in legacy infrastructure for propane should instead be aimed towards electricity network and building upgrades in the effort to transition away from fossil fuel heating. Even in cold-climates, heat pumps are poised to be the heat source of a decarbonized building stock.

8. Future work

This study investigated low hanging fruit – the replacement of propane with an ASHP and PV. The boundary conditions used are intentionally conservative; for example, the relatively low PV yield and lack of current subsidies, however the results are positive such that future work can be motivated to further examine the details of PV and heat pump systems in North America.

From a techno-economic viewpoint, new research could identify heat pump performance requirements, i.e. minimum seasonal COP, for a range of markets. This approach could also help identify locations where GSHP might be more advantageous than ASHP. More also needs to be known about the ability for existing households to incorporate heat pumps. In this study, the peak hourly load of the Low Efficiency house rose from 2.1 to 17 kW, suggesting that additional costs in upgrading electrical service to the building may be necessary.

In the same vein, the impact of heat pumps at scale on existing electric grids needs further research. It is likely that grid investments will be needed if heating and transportation are to be electrified [73]. The need for peak shaving could promote distributed

batteries, which would also benefit PV self-consumption, but further complicates the optimization of building energy systems. Emergency grid outage backup provides a third demand for batteries, which is increasingly critical when buildings rely entirely on electricity. The large influence of electricity sellback price on the size of the PV system underscores the importance of policy to foster distributed generation, and indicates that low-cost electrical storage could play a major role in encouraging the use of HP and PV.

From a policy perspective, the results suggest heat pumps do not necessarily need investment incentives to replace propane furnaces. If electrical upgrades are necessary, however, then subsidies could help overcome adoption barriers. More critical will be the design of electricity rates that can promote both HP and PV, thereby balancing the incentives for utilities and consumers. Previous work comparing PV+HP to natural gas demonstrates how existing net metering policies are already economically beneficial for customers [21]. This relationship could be complicated by carbon taxes, which would benefit heat pumps by making propane more expensive, but could also make electricity more expensive. Further research into rate setting policies and business models are needed to understand the impact a transition to PV+HP at scale could have on utilities.

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.

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Appendix. A: Model descriptions

A collection of energy modeling tools are utilized to generate hourly thermal demand profiles that are converted into energy supply using simplified boiler and heat pump models. The final thermal and electrical profiles at each electrification level are simulated using HOMER Pro 3.13 [74] for the parametric PV analysis and calculating key performance indicators. For brevity, a high-level summary of the models and boundary conditions are presented here, with all details and motivations provided in the linked [MethodsX article](#).

Location/Climate

Climate data is generated using Meteonorm 7.3.1 [75] with Copper Harbor, Michigan as the representative location (47.4687 N, 87.8927 W) representing International Energy Conservation Code Zones 6 and 7 [76] and Köppen-Geiger zone Dfb [77]. Snow losses in cold climates have been shown to be meaningful at low tilt angles [78–80], therefore snowfall is assumed to cause a fixed percentage of losses for an entire day selected at random. The resulting daily loss patterns and total losses are comparable to empirical measurements [79].

Energy Demand

Energy uses within residences have been divided into three categories – appliances, domestic hot water (DHW), and space heating. The modeled household has two occupants, the most common occupancy rate in cold/very cold regions [81], and

170 m² of conditioned area, which corresponds to the average Mid-western home size for two people [82].

An activity based model by Widen et al. [83,84] is used to generate a one-minute synthetic load profile for appliance use, which is summed into hourly values. Total annual demand is 3937 kWh and is comparable to the U.S. average for two-occupant households [85,86].

Synthetic hot water usage profiles are generated using the CREST Demand Model v2.2 [87] for two occupants based on one-minute activity patterns. This creates slightly different demand patterns from day-to-day, but the average water-volume draw-off per hour, remains nearly constant throughout the year. Total hot water demand is 66 L per person per day, the approximate median for two-occupant households [88].

Space heating and cooling demands are modeled using IDA-ICE [89]. The three envelope efficiencies use the same geometry of a single-floor, 170 m² dwelling. The houses are classified by Low-, Mid-, and High-Efficiency, and are differentiated by envelope U-values and infiltration rates. The High-Efficiency home also uses ventilation heat recovery, further lowering demand from the mid-efficiency building.

Total annual demand for the Low-, Mid-, and High-Efficiency envelopes are 27.5, 12.8, and 7.6 MWh/yr, respectively, corresponding to specific heating demands of 162, 75, and 45 kWh/m²/yr. Peak heating demand occurs in February where outdoor temperatures reach −20.9 °C leading to peak powers of 22.1, 13.9, and 6.7 kW_{th} for the Low, Mid, and High, respectively. Cooling demands are much lower and are predominantly experienced during July and August. Peak cooling demand occurs in August and are 2.85, 3.67, 2.73 kW_{th} for Low, Mid and High, respectively.

Energy Supply

Energy supply is modeled with individual devices for DHW and space heating (i.e. no combined units) based on commercially available products. Heating distribution is done with air since it is the most common in cold climates [90] and allows the same infrastructure to be use for heating and cooling. The distribution systems themselves are not considered part of the costs since they are assumed equivalent between technologies and/or would already be in place in the case of a retrofit.

A 95% AUFE, two-stage condensing propane furnace model is assumed, but applied with 90% efficiency for both SH and DHW in HOMER [91]. This accounts for real world losses missed in the AUFE standard [92] and is comparable to other studies [30,37,61]. Separate furnace capacities are specified for each envelope efficiency, as shown in [Table A1](#) with their associated prices [93–95]. The DHW tank is a 50 gallon (189 L), 36,000 BTU/h (10.5 kW) model and common for all efficiencies [96]. The nominal propane price applied is the 5-year U.S. average at \$0.585/L, and is a balance between Midwestern and Northeastern prices of \$0.444/L and \$0.784/L, respectively [97].

The heat pumps are modeled using a black box approach based on performance maps, which define the coefficient of performance with sink and supply temperatures [98]. Here the 2D map is simplified into a 1D curve where COP is based exclusively on outdoor temperature (T_a), defined by Equation [A\(1\)](#). The hourly electrical

Table A1
Propane equipment capacities and prices.

Application	Capacity (kW)	Installed Price (\$)
High Efficiency	13.1	3950
Mid Efficiency	17.6	4100
Low Efficiency	25.8	4350
DHW	10.5	1500

demand is found by dividing thermal loads by the COP. The resulting annual COP (i.e. seasonal performance factor) is 2.3 and compares conservatively to the cold-climate heat pump studies listed in Ch. 2.

$$COP = 0.0015T_a^2 + 0.1T_a + 2.7 \quad (A1)$$

For the DHW heat pump, an ASHP integrated, 50 U.S. gallon (189 L) hot water tank model in Polysun 11.2 [99] is used with a top node tank temperature of 55 °C. It relies on the same performance map model, but the tank recharging occurs about once per day, providing temporally appropriate electrical loads. SPF of the hot water tank is 3.1 resulting in an annual electricity use of 568 kWh.

Unit prices for each heat pump are shown in Table A2 are based on the 285–570 \$/W range in [100] and the peak capacities. The heating capacities are the same as the propane furnaces and prices are limited to equipment and installation, same as the propane equipment. The hot water tank is priced using a commercial product from the same manufacture as the propane tank with the same assumed installation cost [101].

Retail electricity prices vary considerably by region and utility, with the Midwestern and Northeastern 2020 averages being 0.131 and 0.166 \$/kWh, respectively [102]. A nominal price of \$0.150/kWh is used here. A self-consumption/net-billing model is used for PV, where generation used in the building offsets purchases at the retail price and overproduction is sold to the grid at another price. Grid sale prices are most often between 0.070 and 0.103 \$/kWh in conjunction with avoided costs [103–105], and a nominal \$0.100/kWh price is used here.

The PV modules are modeled with specifications from Sun-Power's E20-327 [106] and modeled on the AC bus with an 85% performance ratio [107,108]. The modules face due south with a 30° tilt, resulting in a 1124 kWh/kW_p first year yield. A 30-year system lifetime is assumed in conjunction with most developers [109] and long-term module studies [110,111]. PV capital costs are a function of capacity and taken from p.27 in [112] and reduced by 15% to account for the consistent reduction in prices over time [112,113]. Annual operation and maintenance costs are \$15/kW/yr [114].

Key performance indicators

Primary energy supply (PES) provides a metric to compare on-site fuel combustion and electricity generation with off-site electricity generation. The final energy supply (FES) is converted into PES using Equation A(2) based on the physical energy content method [115], which includes site-to-source (η_s) and conversion (η_c) loss factors for each fuel multiplied by the relative share in the electricity portfolio (ϕ). The electricity grid is assumed to have a 5% transmission loss (η_g). The summed product of these variables is the inverse primary energy factor (PEF⁻¹). Full details on electricity portfolio assumptions are given in the linked [MethodsX](#) article, with a final PEF⁻¹ of 0.389 is calculated, equivalent to a PEF of 2.568 for baseline grid electricity. Primary energy supply of propane is found using the final energy demand, 0.900 device efficiency, and an additional source-to-site loss of 0.869 [116].

Table A2

Heat pump equipment capacities and prices.

Application	Capacity (kW)	Unit Price (\$/kW)	Installed Price (\$)
High Efficiency	13.1	420	5500
Mid Efficiency	17.6	380	6700
Low Efficiency	25.8	360	9300
DHW	8.5	–	1700

$$PES = \frac{FES}{\sum (\eta_s \eta_c \phi) \eta_g} = FES * PEF \quad (A2)$$

The main indicator applied in the results is primary renewable energy fraction (PREF) to measure the total renewable supplied to the homes including electricity and heating. This is the ratio of primary energy supply from renewables, both from the grid and rooftop PV, to the total PES. When on-site solar PV is present, only the self-consumed portion is included in the electricity supply portfolio. Overproduction is sold and considered part of the overall grid portfolio, where it is diluted to effectively zero.

Carbon dioxide equivalent (CO_{2-eq}) GHG emissions factors (EF) vary by region, therefore an average of the three U.S. cold-climate regions are applied to fossil fuel sources [117] and the remaining from [118]. Since wind and PV capacities are largely new construction, lifecycle emissions are applied while the others use operational emissions given that the embedded emissions are already released. The summed emissions factor of the baseline grid supply is 0.468 kg_{CO_{2-eq}}/kWh_{el}. GHG emissions for propane combustion are 1927 kg/m³, including site-to-source and combustion emissions [116].

Total life cycle cost (TLCC) is defined by Equation A(3). All variables include the summation of equipment investment (C_0), operational expenditures like electricity, propane, and maintenance (O_y), revenues from the sale of PV overproduction (R_y), and the salvage value of equipment that does not reach end of life (S_L). Over the economic lifetime (L) of the system, all costs occurring in year (y) are discounted back to the present with rate (d).

$$TLCC = C_0 + \sum_{y=1}^L \left[\frac{O_y - R_y - S_L}{(1+d)^y} \right] \quad (A3)$$

The economic lifetime is 20 years to coordinate with the typical lifetime of heating system equipment, a long-term inflation rate of 2%, and a real discount rate of 2% [71,119].

Technical indicators specific to the PV system include:

- Solar Fraction, the ratio of all PV generation to total electricity load
- Self-Consumption, the ratio of PV generation used in the building to total generation
- Self-Sufficiency, the ratio of self-consumed generation to total electricity load

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