Home Retrofit Results In Net Positive Energy Operation

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Residential energy consumption in the U.S., excluding renewables, is approximately 9.1 QBtu (9×10^{18} J)[1] based on 2015 data. In 2018, residential CO_2 emissions were approximately 345 million metric tons.[2] These numbers will continue to increase as the population grows if measures to prevent it are not put in place. However, ambitious actions such as load reduction and use of renewables will greatly slow down if not reduce these environmental impacts.[3] This article presents a case study in which an existing home was retrofitted to achieve net positive energy (i.e., the home generates more energy than it consumes) and rely 100% on renewables. It achieved net positive energy (NPE) in 2019. Modifications mainly targeted load reduction, high-efficiency HVAC equipment and primary energy source shift using renewables (solar).

Materials

Test House: Private Residence in Western Wisconsin

The subject of this study, a private residence in Polk County, Wis., is a premanufactured home built in 1997. Polk County, Wis., is in IECC Climate Zone 6,[4] which corresponds to a cold winter and warm-humid summer. This type of construction was chosen due to limited time and the challenge of implementing new construction in a less populated and rural area. The home was delivered in three pieces, halves split along the long axis and a roof "cap" that allowed for a more conventional roof pitch. It measures 16.4 m × 7.9 m (53.8 ft × 25.9 ft), with 130 m^2 (1,399 ft^2) of occupancy area; it was placed on a poured concrete foundation with the long axis facing southwest (*Figure 1*).

The interior consists of three bedrooms, two bathrooms and a great room area containing living, dining and kitchen spaces on the main floor. Exterior walls are 2 in. × 6 in. timber insulated with R-19 fiberglass batt insulation. The ceiling is insulated with R-38 insulation.

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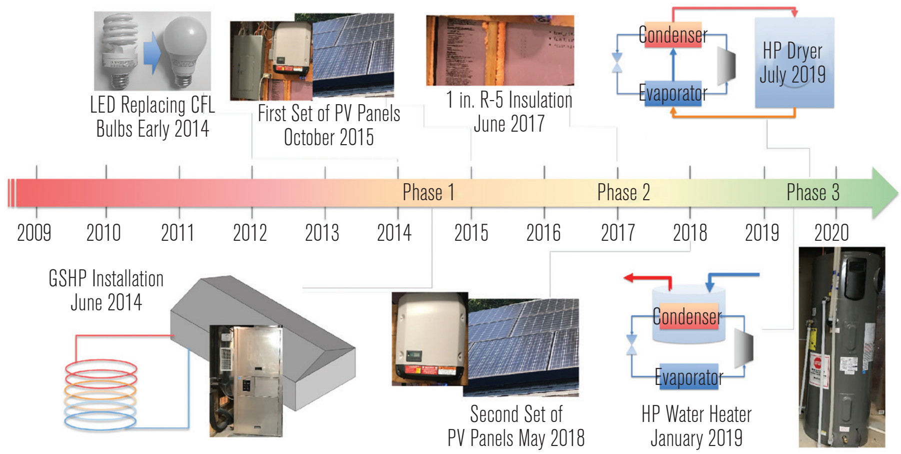
Windows are dual pane. Original appliances included a standard efficiency liquefied propane (LP) gas furnace, LP gas hot water heater, LP gas dryer, an electric range/oven and no AC.

The home also includes a fireplace with maximum capacity of 35 kBtu/h (10 kW) and rated at 63% efficiency with outdoor intake air. However, the fireplace is mostly decorative. The thermostat setting for heat is 62°F (17°C) while unoccupied.

This second home is occupied approximately 25% of the time, mostly during spring/summer/fall, but also some during winter, with the number of occupants ranging from six to 25. In 2020, the occupancy increased to nearly 45% of the time due to the COVID-19 pandemic.

FIGURE 1 Home before (left) and after (right) renovations.

FIGURE 2 NPE retrofit timeline.



Five-Year Net Positive Energy Timeline

An ideal net zero energy (NZE) (i.e., the home generates as much as it consumes) or net positive energy (NPE) new construction includes a structured four-step sequential process of planning, load reduction, high-efficiency equipment and renewables.[5] Retrofit projects may include all these elements, but not necessarily in a structured way.

In this case study, the retrofit features were not planned ahead of time, but are organized in a five-year timeline (*Figure 2*) that can be loosely split into three main phases: 1) load reduction; 2) primary energy source shift; and 3) phased down use of fossil fuels.

The baseline began in 2006 by installing CFL to replace incandescent light bulbs. The first phase started in 2014, with LED replacing the CFL light bulbs and the installation of a 3 ton (11 kW), R-410A ground source heat pump (GSHP) that uses four, 140 ft (43 m) wells. The GSHP is mainly used for heating; cooling mode use is negligible due to comfortable breezes off the lake during the warmest part of the summer.

Heat pumps have a coefficient of performance (COP) of at least 3, which means they are at least three times more efficient than gas or electric heating, since the latter two have a conversion efficiency less than 1. That results in substantial load reduction, as is discussed in the next section.

During the second phase, between 2015 and 2018, 6.7 kW of solar photovoltaic (PV) panels were installed in October 2015, with an additional 4.9 kW of solar PV installed in May 2018. In June 2017 1 in. (25 mm) R-5 insulation was applied to the aboveground portion of the concrete foundation when siding was replaced. The new insulation covered approximately 40% of the exposed foundation.

The last phase began in January 2019 when a 50 gallon (189 L) heat pump water heater (HPHW) was installed in the basement. Finally, in July 2019, a heat pump dryer (HPD) was installed, eliminating the need for LP gas.

In 2019, the home achieved NPE and became fossil fuel free after all heating systems migrated to heat pumps. The total investment, including deductions from state and federal incentives, was approximately $41,000 as summarized in *Table 1*.

Analysis

In the five years prior to starting the NPE timeline (2009 to 2014) the total energy use averaged 18 MWh per year, with 80% of that from thermal energy (E_t) as LP consumption. The estimate is based on monthly meter readings of kWhE_e and LP refill volume* (91.5 kBtu/gallon ≈ 27 kWh/gallon [25.5 MJ/L ≈ 7 kWh/L][6]). The start of using the GSHP resulted in an approximately 47% reduction in the total energy use (*Figure 3a*) in 2015 compared to the average of five years prior; while the electricity (E_e) net use increased by 60% (*Figure 3a*), there was 80% reduction of LP use (*Figure 3a*). A local LP price increase occurred in 2014 due to a shortage in supply, resulting in the cost spike shown in *Figure 3b*.

The purple bar with dashed contour in *Figure 3a* corresponds to the LP consumption reduction due to the GSHP. In *Figure 3a*, the yellow bars with dashed contours represent the amount of electrical load offset by the solar PV panels, while the blue bars with solid contours represent grid electricity use. Starting in 2016, the first set of PV panels was sufficient to produce more electricity than the house consumed, and surplus was returned to the grid. The total solar generation is the sum of the yellow and blue bars starting in 2016.

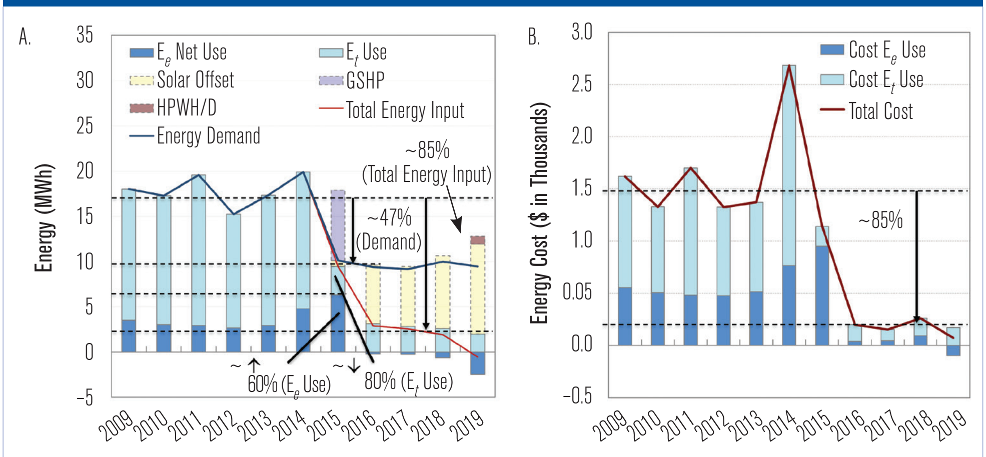
The total energy use—represented by the solid, dark blue line in *Figure 3a*—was relatively constant between 2014 and 2019. The solid red line in *Figure 3a* corresponds to the net energy input (electricity + LP) from suppliers; in 2019, it became negative—i.e., achieved NPE—with the addition of the second set of PV panels. Finally, despite the relatively small LP gas use in 2019, the HPWH and dryer eliminated the need for fossil fuel from 2020 onward.†

The energy costs fell by more than 80%, from an average of $1,500/year to less than $200 in 2019. The surplus from the PV panels in 2019 was equivalent to a $100 credit, with a surplus in energy costs being generated in 2020 onward. More than 85% energy and cost consumption reductions were achieved after the NPE timeline began in 2019 (*Figure 3*). Although not captured in *Figure 3*, between mid-2019 and mid-2020, when the home was fully electric, the net positive generation was 3,156 kWh—26% greater than 2019 alone.

TABLE 1 Summary of investments.

ITEM	GROUND SOURCE HEAT PUMP	PV PHASE 1	PV PHASE 2	HEAT PUMP WATER HEATER	HEAT PUMP DRYER	TOTAL
Installation	$5,638	$22,000	$ 13,000	$170	–	$ 40,808
Equipment	$7,685	–	–	$1,371	$1,405	$ 10,461
Well Drilling: Four, 140 ft Wells	$9,260	–	–	–	–	$9,260
Wisconsin Focus on Energy Program	–	($2,400)	($1,560)	–	–	($3,960)
30% Federal Tax Credit	($6,189)	($5,880)	($3,432)	–	–	($15,501)
Total	$16,394	$13,720	$8,008	$1,541	$1,405	$41,068

FIGURE 3 Yearly outlook: a) energy; b) energy cost from external suppliers.



*The LP tank did not need to be refilled monthly. The assumption used is for uniform consumption, and the amount attributed to each month is proportional to the number of days of each month in-between refills.

†Despite the fireplace's negligible use throughout the years, in 2019 approximately 0.15 cord of ash, maple and oak woods were used for supplemental heating. The estimated energy use due to firewood burning was approximately 2 MMBtu (2.1 GJ) or 600 kWh. This amount is equivalent to 5% of total energy demand and 30% of the LP use in 2019. This value is not accounted for in *Figure 3*, due to high uncertainty in its estimate, and it is possible that the home was NPE by a smaller margin.

Discussion

The return on investment (ROI) as of 2020 will be 14 years assuming the home will be on average net zero in the coming years‡ and that the electricity cost for this home is, according to the utility bills, \$0.17/kWh (*Table 2*). For the current national average electricity cost of \$0.13/kWh,[6] the ROI, including government incentives, would be approximately 20 years, but it may vary depending on local costs.[7] While these ROIs are not particularly attractive—although not prohibitive either—there are ways one could reduce overall investment at Phase 1 by focusing more heavily on load reduction. A leak-tight and well-insulated home will consequently reduce HVAC use, thus reduce overall energy demand, so fewer PV panels could be required.

In the home featured in this case study, the construction was inefficient from the start with respect to infiltration and insulation from the perspective that construction just met code in 1997. The structure was not "tightened" nor insulated beyond that code, and these infiltration and insulation issues were not tackled in the beginning, which corresponded to greater energy demands and equally greater investments.

Triple-pane windows may reduce the U-factor by 30% to 50% compared to double-pane windows,[8] and higher-grade insulation material for external walls and attic may add at least incremental insulation. For homeowners, however, these modifications will add value to the home so that despite the seemingly slow cash return, a substantial fraction of the investment will be converted into asset. In the long term, the return could be greater than 100% if the home is consistently NPE, since in the long run the energy generation credits could surpass the investments.

Sustainability Options: Efficient Homes and Electric Vehicles

The cost of a sustainable residence and personal transportation can be in fact very similar. State-of-the-art full electric vehicles (EVs) consume on average 0.25 kWh_e/mile (0.16 kWh_e/km),[9] while internal combustion engine vehicles (ICEV) consume on average 1.34 kWh/mile (0.83 kWh/km), assuming 25 mpg (11 km/L)[10] and gasoline's lower heating value in the range of 112 kBtu/gallon to 116 kBtu/gallon (31 MJ/L to 32 MJ/L).[11] The average mileage per year in the U.S. is approximately 13,500 miles (21 726 km),[12] which corresponds to 3,375 kWh and 18,000 kWh consumption for EV and ICEV, respectively. The average cost for a lower-end EV model currently on the market varies between \$30,000 to \$40,000. Therefore, the cost of replacing an ICEV with an EV is on the order of \$2/kWh, disregarding any tax benefits and subsidies for EVs. The GSHP in the home of the present study reduced the energy consumption approximately 8,500 kWh at an approximate cost of \$1.90/kWh; the PV panels offset 9,500 kWh from the grid at an approximate cost of \$2.20/kWh. In summary, the home investments toward an NZE or NPE are of the same order of magnitude as investing in an EV.

If one is determined to reduce their carbon footprint, switching to EVs and NZE/NPE retrofit are virtually equally reachable options. The greater the up-front investments in load reduction (insulation/infiltration), the lower the total investment per kWh as discussed above, and potentially less than an EV.

TABLE 2 Average energy cost for the home by year.

YEAR	E_e COST (\$/KWH)	E_t COST (\$/KWH)	TOTAL ENERGY COST (\$/KWH)
2009	0.16	0.07	0.09
2010	0.17	0.06	0.08
2011	0.17	0.07	0.09
2012	0.19	0.07	0.09
2013	0.18	0.06	0.08
2014	0.17	0.11	0.13
Average	0.17	0.07	0.09

Conclusions

This article presented a case study for a real-life application of retrofitting a home to achieve NPE. A timeline of five years included implementing the following: energy demand reduction by using technologies such as GSHP, primary energy shift with PV panels, and elimination of fossil fuel demand with a heat pump water heater and heat pump dryer. The modifications made between 2014 and 2019 resulted in an overall NPE and 100% renewable home in 2019 with an approximate investment of \$41,000.

This home is partially occupied throughout the year, but when it is occupied, the number of occupants is high. Furthermore, the thermostat is set to maintain the

‡The 12-month rolling average as of 4/14/20 was +2,926 $kWhE_e$ surplus, with three high-power generating summer months to come. That would complete 12 full months since adding the heat pump dryer, so NZE is a conservative assumption.

house at 62°F (17°C) throughout the winter regardless of the number of occupants. More than 85% energy and cost consumption reductions were achieved in the five years after the NPE retrofit began compared to the five years prior.

Assuming the home sustains a consistent NZE consumption, a simple payback analysis shows that the ROI for the national average electricity cost to be approximately 20 years. The ROI for this home, however, may be considerably reduced if the home maintains a good NPE margin. While the investment amount and ROI might not yet be attainable to the average homeowner in the U.S., it is comparable to investing in an EV. The market for the latter is steadily increasing and although investing in an EV will have great environmental and economic impact, NPE/NZE for retrofit or new constructions can have similar, if not greater, contributions for the same or potentially lower cost per kWh.

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