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Case Report

Evaluation of Home Energy Efficiency Improvements in a Hot Desert Climate in Northwestern Mexico: The Energy Saving vs. Money Saving Conflict

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Abstract: Reducing household energy consumption is one of the most important strategies used to decrease fossil fuel consumption and greenhouse gases emissions, and to encourage renewable energy utilization. Most energy conservation strategies in the domestic sector are aimed at preferential loans, i.e., purchasing renewable electricity or to improve the efficiency of home appliances, such as air conditioning and lighting. However, despite the relative economic successes of these technologies, they have not had expected impacts in regard to energy consumption. In this work, the authors analyzed the consumption patterns of two equivalent households—one was adapted with improved thermal insulation and a 1.2 kW photovoltaic system to reduce consumption from the electrical grid. The results show that dwellings where no improvements were made registered lower electric energy consumption, due the fact that users were aware that no strategy had been implemented, and its consumption; hence, electricity payments depended solely on one's attention over the electronic device operations. On the other hand, energy conservation strategies in households promotes confident and relaxed attitudes toward the use of energy, leading to lower energy billings, but a higher gross energy consumption.

Keywords: household energy consumption; rebound effect; energy efficiency; renewable generation

1. Introduction

Energy consumption in modern society is closely related to a "life quality" concept, particularly when analyzing consumption patterns in residential sectors [1–3]. In developed countries, household energy consumption accounts for nearly 20% of total consumption. This trend is expected to increase due to population and economic growth, urging implementation of well-targeted (and focused) energy saving strategies [4–6].

Reducing residential energy consumption is one of the most effective strategies used to decrease greenhouse gas (GHG) emissions [7–9]. By improving energy efficiency and modifying energy consumption habits, the following savings and benefits could be achieved:

- Reduction in electricity production costs by preventing usage of emergency power plants at peak hours.
- Important changes in consumption habits are motivated by positive behavior reinforcement via a decrease in electricity and fuel payments, encouraging an energy saving culture that promotes the idea of "consuming what is needed and not what is afforded", and recognizing energy as a limited and scarce resource that must be conserved and rationally utilized.

- Decreased pressure of transmission and distribution electrical systems, extending the lifespans of their components, reducing failure susceptibility, and avoiding premature expansions in the grid, which allows investments into improved efficiency equipment and renewable energy utilization.

Residential energy consumption could be reduced via a number of well-established strategies aimed at increasing efficiency or improving energy consumption habits [10,11]. This efficiency increase is generally accomplished by incorporating modern equipment, capable of performing the same duties of older devices, but with lower energy consumption, such as new refrigerator technologies, heating, ventilating, air conditioning systems, and illumination devices. Moreover, in this category, it is possible to include all modifications performed to a system to meet the expectations of users (in regard to low energy consumption), such as building thermal envelopes, modifications to increase natural light utilization, increasing or reducing heat gains (according to weather conditions), and implementing passive strategies to improve thermal comfort. On the other hand, when considering changes in consumption habits, the most frequently used strategies are related to rational utilization of resources, such as optimum temperature adjustments in cooling and heating devices, preventing operation of appliances and illumination in empty rooms, and proper utilization of laundry and drying machines [12,13].

Another energy saving approach involves incorporating household renewable energy sources. Renewable generation systems would not only affect the family (by reducing energy expenses), but also diversify the energy supply, allowing the family to take advantage of domestic energy sources. Solar energy and wind power are among the fastest growing renewable energy sources. In the last 10 years, more than 370 GW of wind power generators and 177 GW of photovoltaic (PV) systems were installed worldwide [14], with PV being the best option in areas with low wind and high sunlight (e.g., the north of Mexico and south of USA). Depending on regional electricity fares, short return rates could be accomplished, motivating users toward PV technologies [15–17].

Despite the growth (and indisputable advantages) of photovoltaic systems, there are non-technical issues related to the consumption habits of users (which are essentially holding back the large-scale impacts of photovoltaics in the domestic sector). The rebound effect is a well-known phenomenon in economics and has recently received great interest in the energy field. Studies have analyzed the effects of incorporating photovoltaic systems in extreme climates, such as in a hot desert. The rebound effect is associated with an energy consumption increase, derived from a reduction in costs, due to the use of high-efficiency equipment or energy generation through renewable sources, such as photovoltaic systems [18,19].

Typically, it has been observed that households that utilize high-efficiency equipment see increases between 24% and 36%, with respect to the energy consumption recorded before improvements [20–22]; direct rebounds between 15% and 21% have been estimated in homes that incorporate energy generation through photovoltaic systems [23–25].

It is not yet clear what the effects are from climate, average income, or dwelling characteristics, on the rebound effect, related to incorporating photovoltaic systems; however, certain trends can be perceived [26–28]:

- The percentage of the rebound effect in mild and warm climates is generally greater than the rebound observed in hot desert weather. However, due to the higher installed electrical load, consumption (in kWh) in hot climates becomes more relevant.
- Income level has an effect inversely proportional to the rebound effect. Middle or lower class families respond with increased consumption when decreases in energy costs are observed. On the other hand, in sectors with high levels of income, the effect is less dramatic, as in these sectors, there are no economic “restrictions” for energy consumption before the energy reduction costs, due to the incorporation of photovoltaic systems.
- In tariff schemes, where the billing costs are reduced as a result of incorporating photovoltaic systems, users tend to increase their consumption; while in schemes

where the users receive compensation, thanks to the amount of energy delivered to the network, consumption tends to remain unchanged or even decreases.

In Mexico, several programs have been implemented (through government financial support) to reduce residential energy demand. The most representative include incandescent lamp substitutions, replacing inefficient air conditioning and refrigeration systems, and credits to improve residential thermal insulation [29].

Nevertheless, the impact of the above-mentioned strategies is, generally, only evaluated by a reduction in energy payments and its feasibility is determined by the return on investment, without verification of the consequences in consumption habits and gross energy demand (before renewable generation). In this work, we evaluated energy saving strategies and the generation of renewable energy sources in residential sectors, in order to determine the effects between energy efficiency improvements/renewable energy generation and household consumption habits, in middle class, hot, desert weather, to provide new insights for energy savings programs.

2. Experimental

Two identical, one-story, new houses were equipped and analyzed to determine the social and economic effects of energy-efficiency improvement strategies and renewable energy generation systems. The houses were built with concrete block walls and beam and vault roofs. Both houses had identical dimensions and occupancies, with construction areas of 65 m^2 (700 sq. ft.); both were inhabited by two adults.

The improved house (from now on, referred to as "IH") was conditioned with 2 inches of expanded polystyrene insulation plates (on the roof and walls). It also featured an air conditioning system with a seasonal energy efficiency ratio (SEER) of 13—equivalent to 13 KBTU/kWh—and a nominal capacity of 2 refrigeration tons (RT—24,000 BTU/h), a refrigerator of 615 dm^3 (18 cu ft), a ceiling fan of 150 W, and 8 LED lamps (5 W each). In order to evaluate the effects of renewable generation on the users' consumption habits, the IH was equipped with a PV generation system equivalent to 1.2 kW. The PV system was initially coupled with a 1700 W_{DC} Sunny Boy inverter, but it failed due to the high roof temperatures; it was replaced by Enphase M200 microinverters and then connected to the grid through a General Electric bidirectional meter.

The control house (CH), with dimensions and construction characteristics similar to the previous house, was only covered with 1 inch of insulation (in both the roof and four walls). It was also equipped with an AC 13 SEER a 2 RT capacity, (24,000 BTU/h), a refrigerator of 615 dm^3 (18 cu ft), a ceiling fan of 150 W, and 8 fluorescent lamps (20 W each). The households—in regard to TVs, cellphones, and computers, in both scenarios—had a total equivalent electric load.

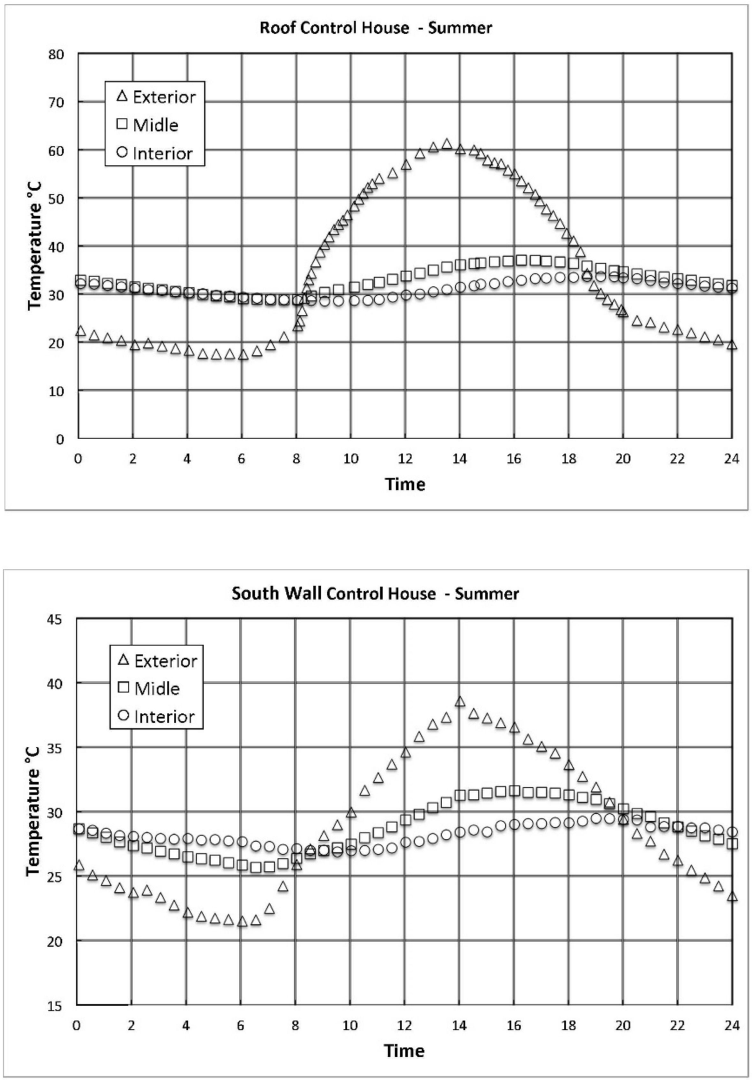
In the IH, the energy delivered by the PV system and the consumption from the grid were continuously measured with G-Meter Energy Monitoring (GreenNet) and the energy quality was validated with a Fluke 434 analyzer. In the CH, the same measurements were conducted, excluding the PV contribution.

3. Temperature and Energy Measurements

Both the control and improved houses were equipped with 18 type K thermocouples (Chromel/Alumel); six were placed in the roof in two different spots. The 12 remaining sensors were distributed in the walls of the four sides of the houses, recording temperature every 10 min. In each measured spot, both in the ceiling and walls, the thermocouples were arranged in groups of three—one in the exterior to sense outer surface temperature, another in the interior, and the last one in the middle, in order to determine the efficacy of the thermal envelope.

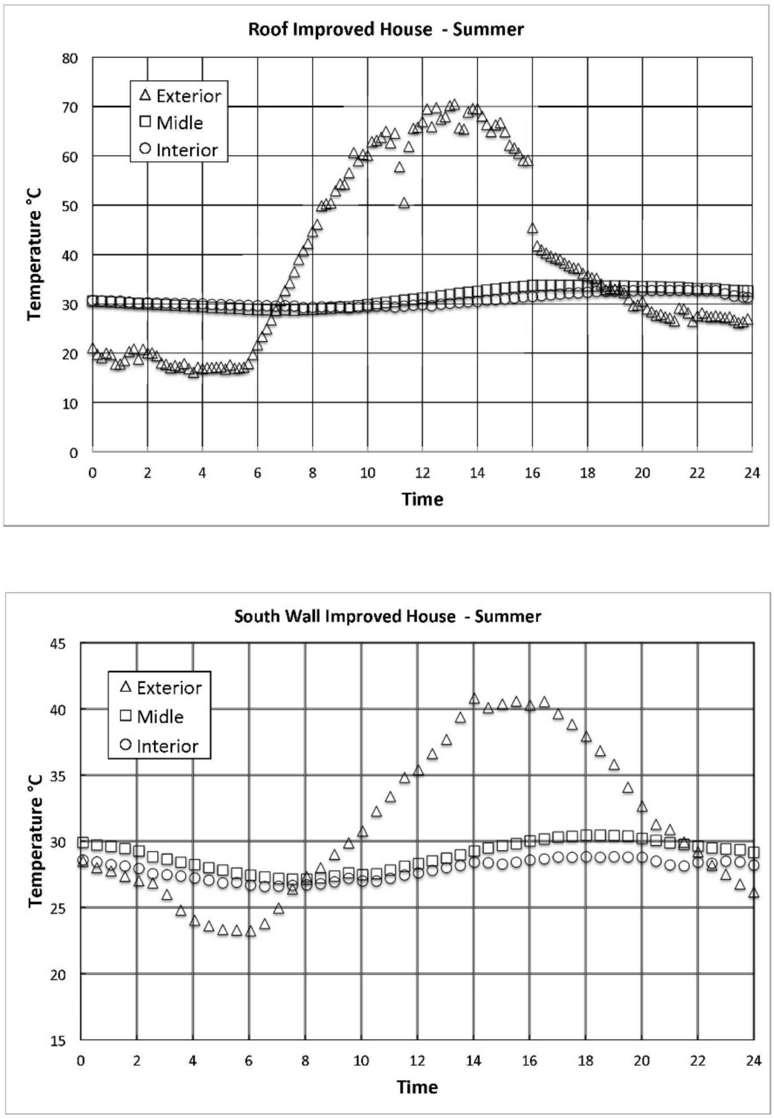
4. Results

The indoor and outdoor household temperatures, as well the temperature after the insulation in roofs and walls of both buildings, were recorded. The most dramatic effects due to direct solar exposure were observed in roofs and in south facing walls, as displayed in Figure 1a,b; where a comparison is shown between the temperature measurements in the roof and walls for the CH and IH in a day during the summer.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. Comparison between the temperature measurements in the roof and walls for the CH (**a**) and IH (**b**) during a day in the summer.

When comparing the exterior, middle, and interior temperatures in the roof and walls of CH and IH, the effect of the enhanced thermal insulation in the IH is visible, considering that, during the peak hours in the summer, the inner roof temperatures in the IH barely exceed 30 °C, despite the exterior temperatures being above 70 °C. Although the average indoor surface temperatures for both scenarios were similar (31 °C and 30 °C for the control and improved house, respectively), and responded to the set point adjustment to 25 °C in both cases, the CH experienced higher and undesirable fluctuations in the interior temperature, causing discomfort and increasing the air conditioning electric consumption. Another important fact was that, in both the roof and walls, the higher exterior temperatures were recorded in the improved house. This effect is due to the fact that the thicker insulation layer prevents heat transfer to the interior, leading to greater accumulation of heat on the exterior side of the building.

In winter, the thermal insulation effect was analyzed in the south facing wall of both the control and the improved house. Figure 2 shows the temperature measurements outside, inside, and in the middle of the wall after the insulation layer in a typical, partially cloudy day.

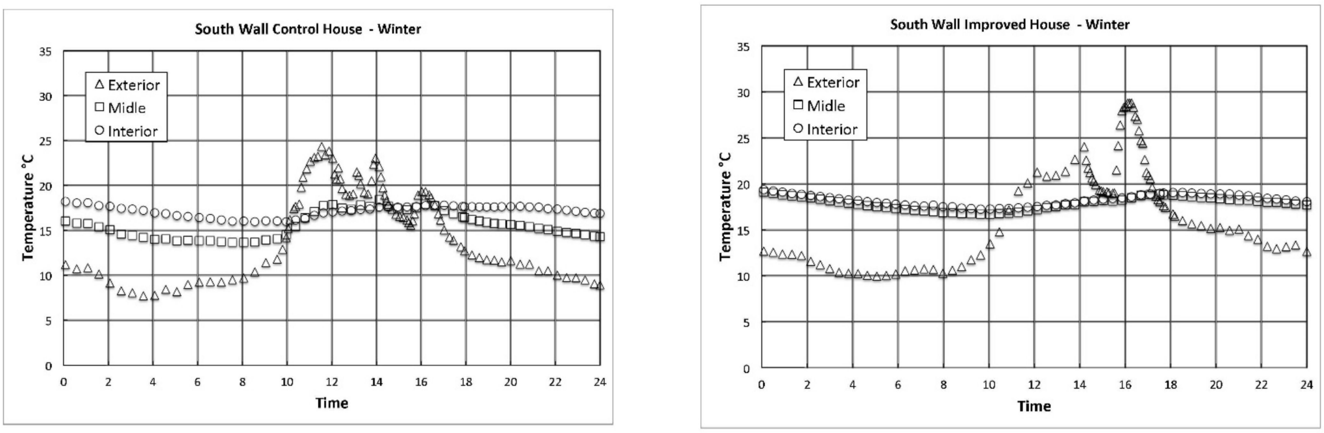


Figure 2. The temperature profiles for south facing walls in CH and IH.

Figure 2 shows that the lower thermal insulation in CH allowed undesirable thermal exchange with the external environment, increasing the heat lost and leading to uncomfortable temperature variations in room temperature. However, in this case, as neither of the analyzed buildings had heating devices, the low temperature in winter had no effect on electric energy consumption.

The electric energy consumption for IH is shown in Figure 3, displaying the gross consumption, the PV generation, and the energy difference taken from the grid. Figure 4 presents a comparison between the gross consumption of IH and CH with data displayed in Tables 1 and 2.

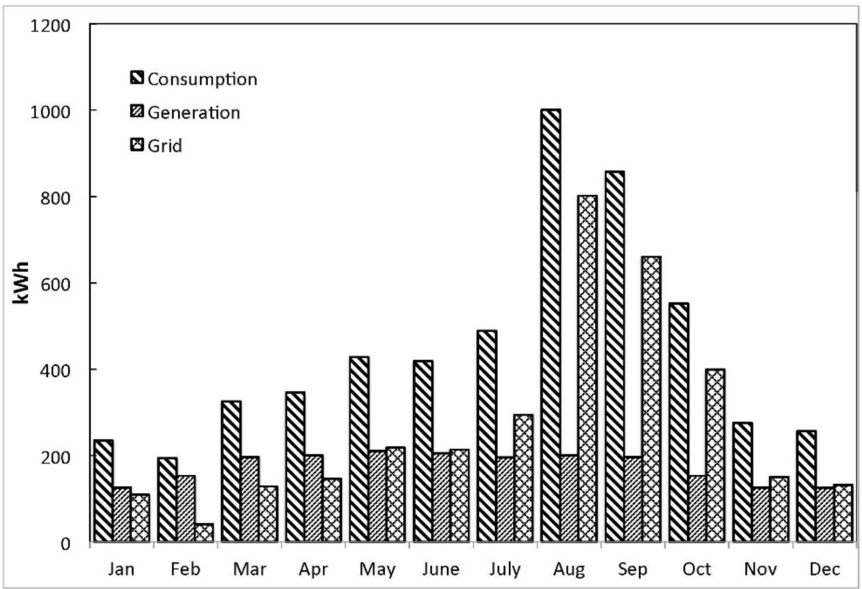


Figure 3. Consumption, PV generation, and grid consumption in IH recorded for 1 year.

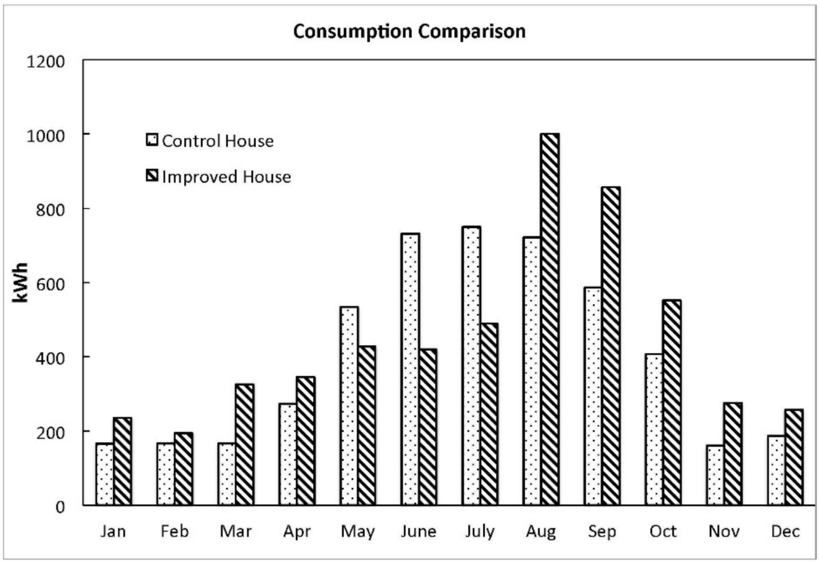


Figure 4. Comparison of Energy consumption for CH and IH.

Table 1. Consumed and generated energy plotted in Figure 3.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Consumption	235	194	325	346	428	419	489	1001	857	552	276	257
Generation	126	153	197	200	210	205	195	200	197	153	126	125
Grid	109	41	128	146	218	214	294	801	660	399	150	132

Table 2. Consumption comparison both buildings.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Improved	235	194	325	346	428	419	489	1001	857	552	276	257
Control	166	167	167	273	534	732	750	722	587	407	161	187

In Figures 3 and 4, one could observe a typical consumption pattern for households located in hot desert climates, with a considerable increment in demand during summer related to the air conditioning utilization. From November to April, the consumption is controlled almost exclusively by the illumination and amenities, such as television and computers, with an average demand during this period of 164 and 449 kWh for the CH and the IH, respectively. In the IH, the PV generation remained reliable throughout the year, with values ranging from 126 to 210 kWh, with an average of 174 kWh.

When analyzing the consumption profiles of the control and improved houses in Figure 4, one could notice that, except for the first month of the hot season, CH maintained a lower consumption than the IH. The latter is described as a typical rebound effect, if considering the fact that the "economic theory" governs consumption behavior, where demand is related to the final cost of electricity to the householder. The later becomes evident when analyzing the consumption increase from August in IH, just after the users received relatively cheap electric bills due to the PV contribution during the first months of the hot season. Similar observations were reported in previous works [23,24,26], where it was observed that energy efficiency improvements and renewable energy generation had a negative psychological effect on consumers, promoting confident and relaxed attitude regarding the use of energy, leading to higher gross consumption. Whereas in dwellings where no improvements were performed, the users remained prudent and vigilant with electricity consumption. As they were aware that no strategy had been implemented, the demand (and hence payments) depended solely on the level of attention paid to electric device operations. Furthermore, special attention should be paid to the fact that any increase in tariffs that seeks to discourage energy waste would seriously damage (economically) low-income families, particularly in developing countries. A more successful approach appears to be implementing a revenue scheme for those who have the potential to "generate in excess", rather than modifying the cost of energy [28,30].

5. Conclusions

Two equivalent dwellings were analyzed in order to compare the energy consumption effects of PV generation and insulation improvement in one dwelling. The results show that, under weather conditions in the south of the EEUU and in the north of Mexico, two inches of expanded polystyrene is needed to avoid uncomfortable variations in indoor temperatures that lead to increases in energy consumption, particularly in the hottest season. Regarding the incorporation of PV generation systems in the domestic sector, it was observed that the reduction in electricity billing caused by PV contributions resulted in a negative effect in users, leading to an increase in gross energy consumption. A new approach is necessary—one that not only focuses on high efficiency and energy saving devices, but also implements strategies to improve user consumption habits, promoting the idea of "consuming what is needed and not what is afforded".

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