

The Effect of High Efficiency Building Technologies and PV Generation on the Energy Profiles for Typical US Residences

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Abstract: The penetrations of high efficiency technologies and photovoltaic (PV) generation are increasing in the residential sector. Technologies such as improved insulation and efficient HVAC systems significantly affect the energy profile of a house. This effect varies due to climate characteristics, i.e. temperature, solar radiation, relative humidity, and wind speeds. The effect of other technologies, such as efficient water heaters, lighting, or kitchen appliances, is mainly governed by human behavior, which may be represented by a schedule. This paper studies the performance of both climate-influenced and scheduled household devices among different levels of efficiency through combined computational and experimental methods. Three houses were constructed by the Tennessee Valley Authority and were outfitted with robots that mimicked the occupation of a family. The houses represented three categories of residences, namely, typical builder, retrofit, and near net-zero-energy. With the energy and weather data collected from 2009 to 2014, a total of four house energy models were developed to account for equipment changes throughout the years. The studies performed using these models considered the behavior of the HVAC systems, PV system, and water heaters as well as climate effects.

Index Terms—Heating, ventilation, and air-conditioning (HVAC), Photovoltaic (PV), Water Heater (WH), House Energy Model (HEM), Virtual Power Plant (VPP), Smart Home, Smart Grids.

I. INTRODUCTION

In the US, the residential sector contributes 21.8% of the total energy consumption with around half being the energy use of heating, ventilation, and air-conditioning (HVAC) systems [1]. Therefore, significant opportunities exist for energy savings through the implementation of advanced technologies in residences, most notably efficient HVAC systems. Other improvements, especially water heaters with high efficiencies and local solar photovoltaic (PV), can also reduce the electricity required from the grid.

Previous studies for the optimization of electricity usage and distributed generation utilized energy models for commercial buildings or large facilities rather than for residential buildings [2] [3]. In a study for a simulation of a warehouse considering PV generation, battery storage, and the HVAC system, it was found that the use of PV paired with battery energy storage was the most effective at reducing the building peak time load, and HVAC set point control showed a peak load reduction in the shoulder months and in daily profiles [4].

The influence of the HVAC system on a building's energy profile has also been shown through simulations of oversized HVAC replacements [5]. Higher efficiency appliances may also contribute to energy savings in a house [6]. This paper studies the influence of different HVAC systems on residential buildings as well as effects from local PV and other in-house devices, such as water heaters, lighting and appliances.

In 2008, the Tennessee Valley Authority (TVA) began a technology demonstration project with technical support from Oak Ridge National Laboratory (ORNL). Three houses were constructed side-by-side in Knox County, TN to represent three energy profiles: typical builder construction, retrofit efficiency, and near net-zero-energy (NZE) design (Fig. 1). Human habitation was physically simulated within the houses through the operation of equipment and appliances by robots, emulators, and other typical interfaces such as a programmable thermostat. Scheduling was based on the National Renewable Energy Laboratory (NREL) Building America house simulation protocols [7].

Data for weather, domestic hot water (DHW) draw, and energy usage was collected hourly from 2009 to 2014. The project developed a basis for the analysis of technologies across a spectrum of energy efficiency, including HVAC systems, water heaters, construction materials and techniques, appliances, and residential solar PV systems. Individual circuits were monitored to develop this data set and newer technologies like smart plugs may be incorporated in future projects to provide more detailed measurements [8].



Fig. 1. The near net-zero-energy (NNZE) house front (a) and back (b). TVA robotic devices are controlled to mimic realistic human behavior. Also shown is a HPWH used in the retrofit house (c), a shower emulator (d), and a refrigerator with programmed arms (e) that operate according to automatic schedules.

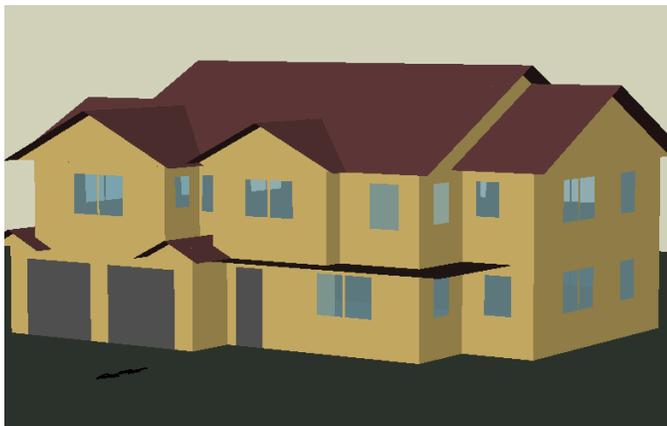
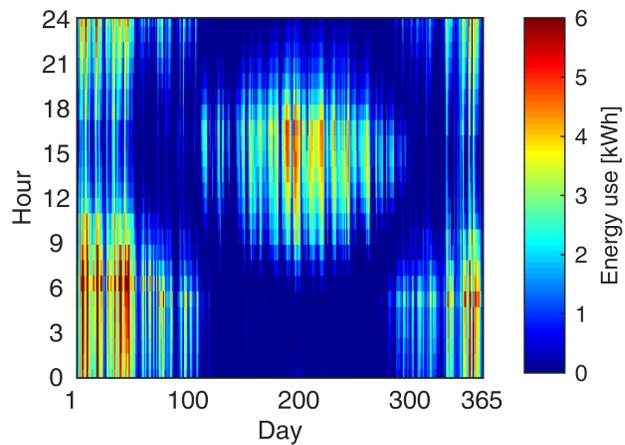


Fig. 2. Example BEopt simulation model for the typical construction house type. All models follow a very similar floor plan but different construction materials and techniques.

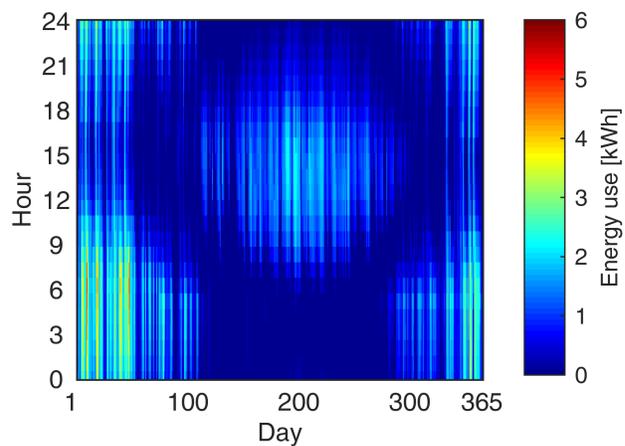
II. HOUSE ENERGY MODELING

In this study, four house models were developed based on the physical characteristics of the TVA robotic houses and calibrated against the measured data from the project. These models included a typical builder house with a SEER 13 single stage heat pump (Build13S) and the same builder house with a SEER 19 variable capacity heat pump (Build19S). The other two models were of a retrofit house with improved insulation, better windows, and a highly efficient SEER 20.5 variable speed heat pump (Retrofit) and a house built from the beginning to be near NZE on an annual basis with a SEER 16 dual stage heat pump (NNZE).

HVAC systems account for nearly half of the total energy usage of a typical house [1], [9]. Upgrading the HVAC system can considerably reduce its energy use (Fig. 3). This paper



(a)



(b)

Fig. 3. Hourly energy usage for the HVAC system of the simulated typical builder house (a) and the hourly energy difference between the HVAC systems of the builder house and the NNZE house (b) based on Knoxville, TN TMY3 weather data.

compares HVAC technologies among the houses using the typical meteorological year (TMY3) weather [10].

An external PV module was also developed and calibrated against the TVA project's measured data to enable the analysis of PV performance in different locations. Since schedule-based in-house devices, such as lighting and appliances that use domestic hot water (DHW), are minimally affected by climate, experimental measurements from the TVA project alone are used directly for their analyses.

The residential building models assessed in this paper were developed with a process that utilizes the Building Energy Optimization Tool (BEopt) (Fig. 2). The NREL developed BEopt with the same simulation engine as EnergyPlus, a widely used open-source whole-building energy modeling (BEM) engine [11]. Specifically, BEopt takes in the physical characteristics of the building floor plan and construction details, notably type of attic insulation, wall insulation, wall stud, windows, roof as well as appliance and equipment efficiencies. The software factors in other necessary information, like occupancy and

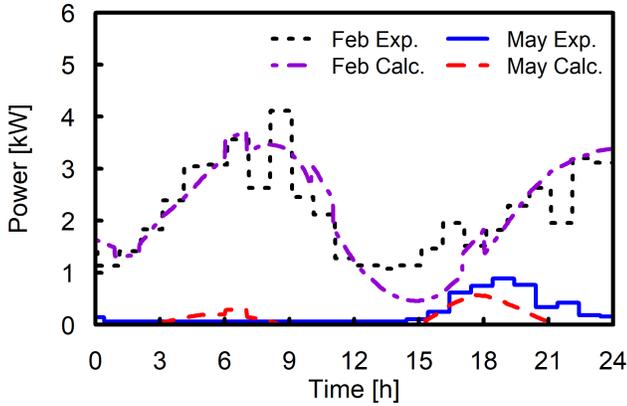


Fig. 4. HVAC system power for a high energy use, heating-only February day and a low energy use day in May with a mixture of heating and cooling.

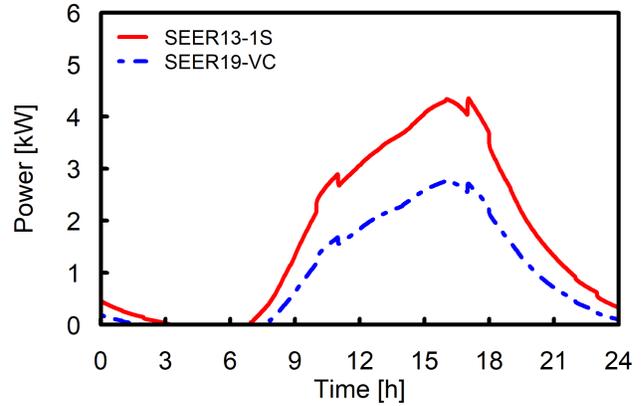


Fig. 5. Power for the HVAC systems in the Build13S and Build19S models. Both were simulated using Knoxville TN, TMY3 weather data on an example summer day.

weather data per the location of the building, and produces a very detailed input data file (idf) that was further tuned in EnergyPlus [12].

III. ENERGY EFFECTS CONSIDERING HVAC AND BUILDING TECHNOLOGY

The HVAC models used in this study employed weather data collected from an onsite weather station during two example years. Data from 2010 was utilized for models Build13S and NNZE, while 2013 data was for Build19S and Retrofit. It is important to have actual local weather data due to the HVAC system's high sensitivity to climate. Accurate modeling of an HVAC system requires a small timestep to capture highly transient behavior [13]. Considering this, the models were simulated at a timestep of one minute. The actual measured energy use and weather data were recorded with the resolution of one hour. This mismatch prevented model calibration at smaller timesteps, but was satisfactory for the analysis of monthly energy usage.

Once the initial BEopt models for the robotic houses were converted into EnergyPlus models, a significant effort was made to minimize difference between actual measured and simulated energy usage of the HVAC components. A variety of factors were considered, including material thermal mass, attic and wall insulation, HVAC coefficient of performance (COP), etc.

After various tests, the best versions of the models, which are used in this study, kept the same values as specified by TVA except for the COP ratings of the HVAC systems, which were adjusted to minimize error between measured and simulated HVAC system energy usage. For the two models that were based on 2013 data, monthly energy use was brought to within 15% difference of the measured values, a limit that followed ASHRAE Guideline 14 [14].

It was notably challenging to reduce error for certain "shoulder" months such as April, May, and October due to their very low energy usage and mixture of both heating and cooling. It should also be noted that such error is exacerbated

Table I
ENERGY USAGE AND PEAK POWER FOR DIFFERENT HVAC SYSTEMS IN THE HOUSE MODELS WITH KNOXVILLE, TN TMY3 WEATHER

House model	Annual total energy [kWh]	Peak hourly power [kW]
Build13S	9,699	10.5
Build19S	7,131	8.9
Retrofit	5,467	6.9
NNZE	4,148	5.7

when increased solar heat gain and mild temperatures occur simultaneously, which is due to the models underestimating the effect of the solar heat gain. This phenomenon occurred in 2010, which caused the other two models based in that year to have shoulder month energy use error outside of the 15% goal. In this study, the errors from the shoulder months were considered minimal because the energy usage of those months were only 1% to 7% of the annual total.

The measured and calculated HVAC power for two example days is provided for Build19S in Fig. 4. The February day had a measured total daily energy use of 51 kWh, and a total error of 1% when compared to the model. For the May day, 5 kWh and 45%, respectively. The higher error for the shoulder month is typical due to the mild temperatures.

After each of the four HVAC system models were calibrated based on actual energy use and weather measurements, they were simulated for an entire year based on Knoxville, TN TMY3 weather data so that the technologies may be generally compared under the same weather conditions. Since Build13S and Build19S were the same building energy model, the effects of the HVAC component alone may be observed (Fig. 5).

As anticipated, the SEER 19 variable capacity heat pump was much more energy efficient than the SEER 13 single stage heat pump with annual HVAC system energy savings of 2,568 kWh or 26% (13% of the total house use) and a 15% reduction in HVAC system hourly peak (Table I).

When the HVAC system and building construction are both

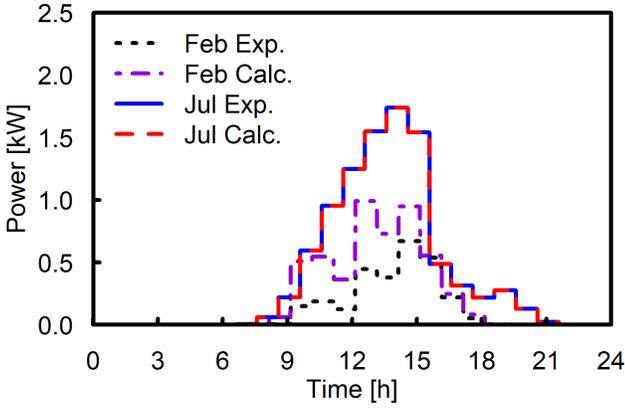


Fig. 6. Example daily PV power for the typical case of very low daily energy error and the rare case of higher error which is likely due to differing solar radiation between the irradiance sensor and actual PV panel.

improved, as shown in the comparison between cases Build13S and NNZE, the HVAC system annual total energy usage and hourly peak may be reduced by 57% and 46%, respectively.

IV. PV PERFORMANCE FOR DIFFERENT GEOGRAPHICAL LOCATIONS

An external PV module was modeled and calibrated against the measured hourly average power generation for the 2.5kW rooftop solar PV system on the NNZE house (Fig. 1b). The DC power output of the PV module was determined as follows:

$$P_{dc} = \left[\left(\frac{\gamma}{1000} \right) P_r \right] \left[1 - \left(\frac{k_p}{100} (T_{cell} - 25^\circ C) \right) \right], \quad (1)$$

where P_{dc} is the DC power output [W], γ , the solar irradiance [W/m^2], P_r , the rated PV array dc power [W], k_p , the temperature coefficient of maximum power [$\%/^\circ C$], T_{cell} , the temperature of the PV cell [$^\circ C$], calculated by

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^\circ C}{0.8} \right) \left(\frac{\gamma}{1000} \right), \quad (2)$$

where T_{amb} is the outdoor ambient temperature [$^\circ C$] and NOCT is the nominal operating cell temperature [$^\circ C$].

The AC power output of the module is calculated by considering losses as:

$$P_{ac} = P_{dc} * E_i * E_m * E_d, \quad (3)$$

where P_{ac} is the AC power output with E_i , E_m , and E_d as efficiencies considering losses due to the inverter, interconnection of modules with nonidentical properties, and dirt accumulation on the panels, respectively.

With T_{amb} and γ measured onsite hourly, average power output was calculated at the same timestep using the proposed PV module and compared to the actual values. Even though PV generation experiences significant transient behavior from variable weather conditions, an hourly timestep was found to be satisfactory for studies down to the daily level (Fig. 6).

When considering days in the example year of measured data with error above 0.1 kWh between calculated and mea-

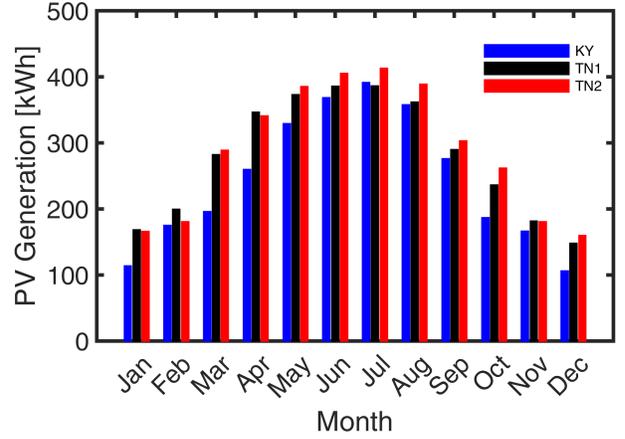


Fig. 7. Monthly total PV generation for TN1 (Knoxville, TN), TN2 (Memphis, TN), and KY (Bowling Green, KY) locations.

Table II
AVERAGE HOURLY SOLAR RADIATION, TOTAL ANNUAL PV ENERGY GENERATION CALCULATED ON AN HOURLY BASIS, AND CF FOR SIMULATED LOCATIONS BASED ON TMY3 WEATHER

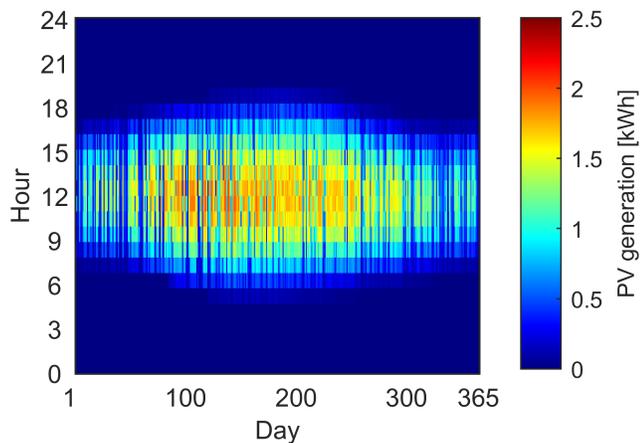
Location	Radiation [W/m^2]	PV [kWh]	CF [kW]
Bowling Green, KY	154.9	2,927	13.4
Bristol, TN	174.5	3,392	15.5
Chattanooga, TN	178.8	3,313	15.1
Columbus, MS	182.2	3,345	15.3
Knoxville, TN	178.3	3,359	15.3
Memphis, TN	187.2	3,475	15.9

sured PV power output, only about 7% have a percent error above 10%. These days are likely due to the irradiance sensor and solar panels experiencing different solar radiation from weather effects such as cloud cover. At a monthly comparison, the results are satisfactory with error only ranging from approximately 1% to 6%.

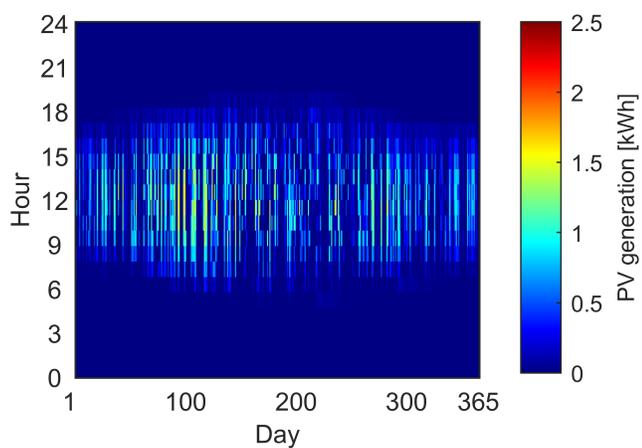
The performance of a simulated 2.5kW PV system was determined for six different locations over an entire year using TMY3 weather after the proposed PV module was calibrated based on onsite measured data. The annual PV generation and

Table III
PV RATINGS (kW) REQUIRED TO ACHIEVE NZE FOR HOUSES OF DIFFERENT TYPES IN ALL SIMULATED LOCATIONS

Location	Build13	Build19	Retrofit	NNZE
Bowling Green, KY	18.4	16.3	11.1	8.3
Bristol, TN	14.5	13.1	8.9	6.5
Chattanooga, TN	14.2	12.5	8.4	6.4
Columbus, MS	15.4	13.3	8.9	7.3
Knoxville, TN	14.8	13.1	8.9	6.7
Memphis, TN	14.4	12.4	8.3	6.8



(a)



(b)

Fig. 8. Hourly PV energy generation of the simulated 2.5kW PV system in Memphis, TN (a) and the hourly energy difference between system simulations in Memphis, TN and Bowling Green, KY (b). All simulations were based on TMY3 weather data.

calculated capacity factor (CF) as well as average hourly solar irradiance, which is for illustration purposes only and not for calculations, are provided (Table II).

As expected, the most northern location, Bowling Green, KY, had the smallest CF while one of the most southern, Memphis, TN, had the highest value (Fig. 7). To further illustrate the significant relationship between geographical location and PV generation, the full simulated year of PV generation in Memphis, TN is provided along with the hourly energy difference between the simulations in Memphis, TN and Bowling Green, KY (Fig. 8).

The PV system rating required for each building energy model to be considered NZE on an annual basis was determined for multiple locations [15]. The typical Build13S house ranges from 14.2 kW to 18.4 kW. The NNZE house has a much lower range of 6.4 kW to 8.3 kW (Table III). This illustrates that both the geographical location and the house type have a significant influence on the PV rating required for a house to be considered NZE.

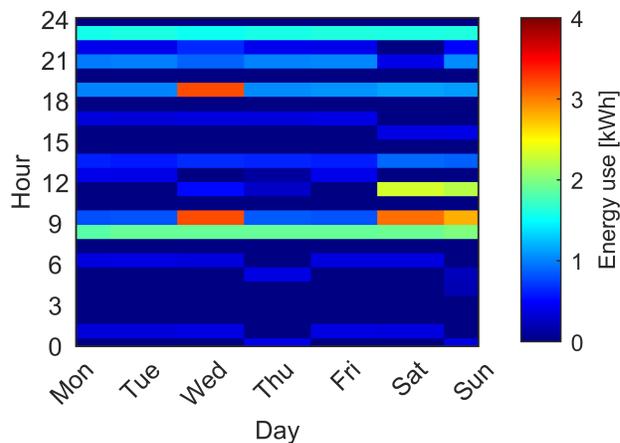


Fig. 9. Example week for the electric water heater (EWH) schedule.

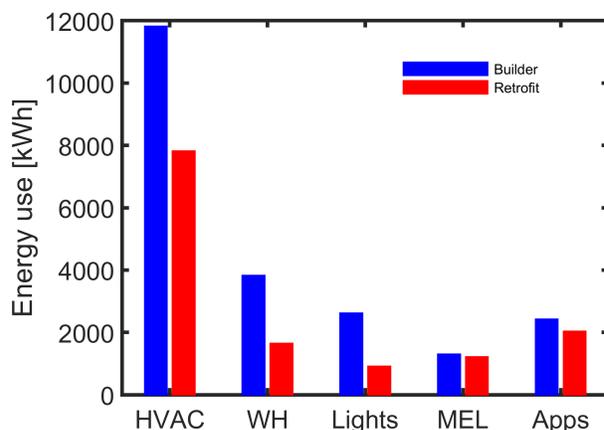


Fig. 10. Total actual measured energy usage of the HVACs, water heaters (WH), lights, miscellaneous electric load (MEL), and appliances (Apps) within the typical builder and retrofit houses for the year of 2010. The HVAC is consistently the highest individual energy user, while the water heater is always the second highest.

Since the actual 2.5kW solar system took up nearly a third of the roof space of the CC3 example house, it would be fair to assume that a typical house of this size could only support, at best, a PV system of around 9kW maximum (Fig. 1b). Therefore, only the Retrofit or NNZE house types in certain locations would be able to realistically support a PV system large enough to be NZE.

V. WATER HEATERS AND OTHER APPLIANCES

The measured loads in Fig. 10 shows that Water heaters (WH) are typically the second most energy using individual component of a house, after the HVAC system. This is another opportunity to realize significant energy savings through changing a single appliance. Since the energy usage of WHs is decisively dependent upon human behavior, the study of the component was based upon measured data. Inside the TVA robotic houses, automated systems implemented schedules to represent the use of DHW and appliances [16]. DHW

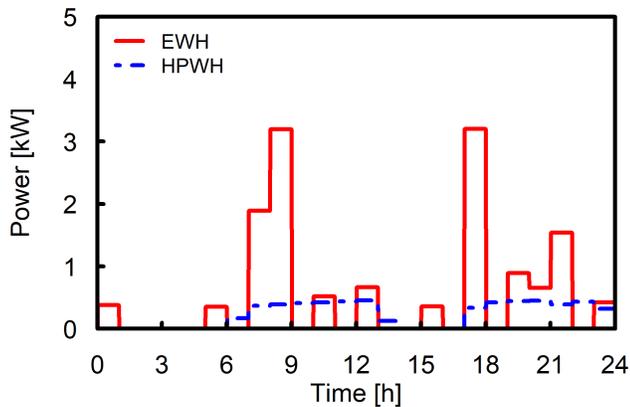


Fig. 11. Power for the typical builder house EWH and the retrofit house HPWH during an example day in 2010.

use schedules in the project were derived from the Building America House Simulations Protocol [7].

According to the measured energy use of the WHs in the builder and retrofit houses in 2010, it was found that upgrading from an electric water heater (EWH) with typical appliances to a heat pump water heater (HPWH) with EnergyStar appliances yielded remarkable results in energy use reduction. Over the entire year, the 50 gallon HPWH in the retrofit house used a total of 2,179 kWh (57%) less than the EWH in the typical builder house. This is due to the better appliances as well as the improved technology of the HPWH (Fig. 11).

VI. CONCLUSION

There is significant opportunity for reducing energy use in the residential sector through high efficiency technologies and for increasing distributed PV generation. This study illustrates this through the experimentation and simulation of buildings, HVAC systems, and PV energy models as well as through comparison of schedule-based in-house devices such as water heaters and appliances. It was shown that an HVAC system upgrade alone, without any changes to the building, can reduce energy use of the HVAC by 26% or by 13% of the total house's energy use.

With better construction materials and improved techniques, HVAC energy savings can more than double to 57% with a 46% reduction in HVAC system peak hourly power. It was shown that this combination may reduce the PV rating that is required for a house to be considered NZE by up to 55%, depending on location. For the simulation locations, it was determined that only the Retrofit or NNZE house designs could support enough rooftop solar PV panels to be considered fully NZE over an entire year. It was also shown through experimental methods that HPWH technology with better appliances can use up to 57% less energy than an EWH with typical appliances over an example year. This reduction is very significant since the WH is the second most energy using device in a typical house.

VII. ACKNOWLEDGMENT

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