THE BB&Y ZERO ENERGY HOUSE:
REPORT ON THE FIRST YEAR OF OPERATION

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ABSTRACT

BB&Y LLC has performed a deep energy retrofit on a house in Redwood City, California. The purpose of the project is to go beyond net zero energy and explore how a house can operate with zero greenhouse gas emissions. This paper summarizes the first year of operation of the dwelling, and the lessons learned. Note: This is an update on the Version 1.1, May 23, 2019 that includes a full year of PV operation, June 2018 through May 2019.

1.0 BACKGROUND

Net Zero Energy buildings generate as much energy on-site from renewable resources as they consume annually.[1] They are slowly becoming more common. California has even established an ambitious goal to have all new residential construction be Net Zero Energy by 2020.[2] This approach usually uses the grid as a giant battery so that the solar system on the house can export excess generation on sunny summer days and buy it back at night or during cloudy winter days, but netting out to zero energy use on an annual basis. The main purpose of a net zero house, however, is to reduce greenhouse gas emissions from fossil fuel generated electricity. It is clear that the electricity generation from photovoltaic arrays will reduce the need for the utility to burn fossil fuel because flexible generators can be throttled back when the sun shines. The impact of this is limited, however. First, the need to ramp fossil fuel generators to follow the variable solar output can force the grid operator to operate with higher ramp rates than desired, or force generators to operate in non-optimal conditions. More important from the perspective of limiting carbon emissions is the increasing need to curtail excess solar electricity. Curtailed renewable generation does not contribute to reducing carbon. Currently such curtailment is relatively rare, reaching 3% in 2017.[3], but it is growing rapidly. Already in May, 2019 the total curtailed renewable energy has exceeded the total for 2017.[4] California has about 15 GW of distributed and utility-scale solar out of a total load in the 30 GW range. When the solar contribution becomes sufficiently large, as it likely will be within the near future, curtailment will be the norm during summer daylight hours. In fact, it is obvious that without storage the total solar contribution will reach a limit regardless of the installed solar capacity, for it is dark about 50 percent of the year.

Another approach is needed if we wish to completely decarbonize the grid. And we do wish to do so. California law SB100 requires that utilities procure 60% of their electricity from renewable resources by 2030.[5] Former Governor Brown recently upped the ante by signing an executive order mandating statewide carbon neutrality by 2045.[6] An even more recent addition to the zero carbon movement is Excel Energy, a large utility serving eight midwestern states.[7]

Beyond increasing renewable generation, the main avenues for further carbon reduction involve storage and demand management: storage to shift daytime excess solar energy for use at night, and demand management to schedule loads such as heating and vehicle charging to daytime use. Using these techniques, it is hoped that houses such as the BB&Y house can eliminate residential carbon emissions, and at the same time provide carbon-free electricity to the grid.

A recent subtle but important change in emphasis is emerging. That is from energy to carbon.[8] People have realized that it is not energy *per se*, but carbon emissions that are the object of concern. Toward that end, we really should be talking about Net Zero Carbon Buildings, not Net Zero Energy Buildings. California is actively pursuing this goal. For example, AB3232 directs the California Energy Commission to assess the potential for California to reduce greenhouse gas emissions from residential and commercial buildings by 40 percent by 2030.[9]

When electricity use is partitioned among the major US greenhouse gas emission sectors, buildings generate the largest share at 32%. This is followed by industry at 30%, transportation at 29%, and agriculture at 9%.[10] Amazingly, when the emissions incurred in new building construction are included, the building sector contributes 39% of global emissions (these additional emissions come from the industry and transportation sectors).[11] Any program to greatly reduce greenhouse gas emissions must include buildings. Fortunately, modern building science and practice, such as those being studied under AB3232 for inclusion in California building codes, allows for very low energy consumption in new building construction. (Reducing embedded carbon requires more work, however.) Unfortunately, new buildings account for a small fraction of the building stock. This calls for an urgent need to also develop cost-effective retrofit methods that make existing buildings zero carbon. Exploring how this can be done is the goal of the BB&Y residential retrofit experiment. As discussed in Section 3, electric vehicles (EVs) will play an important role in reducing greenhouse gas emission in the transportation sector, and houses with EVs will offer unique synergistic challenges and opportunities to further reduce emissions. So far, the BB&Y house has not incorporated an EV, however.

2.0 EXPERIMENT

To explore zero carbon residential opportunities, BB&Y LLC purchased a 900 square foot, two-bedroom, one-bath house in Redwood City, California to use as a test bed. This house was built in 1948, and is typical of a large number of tract houses built in the post war era. As such, it had un-insulated walls and single-pane casement windows. Natural gas powered the furnace, stove, and water heater. The previous owner had replaced all lights with LEDs. A blower door test indicated it was quite leaky at 19 air changes per hour at 50 pascal pressure (19ACH50).

The residence was occupied for one year while plans were made for the deep energy retrofit. Figure 1 shows the energy used during this period as measured by the utility bills. Natural gas use in therms has been converted to kWh,[a] and the monthly consumption converted to average power by dividing by the number of hours in each month.[b] The effect of winter heating demand on gas consumption is readily apparent, while the small increase in electricity use in the summer is probably from the air conditioner.

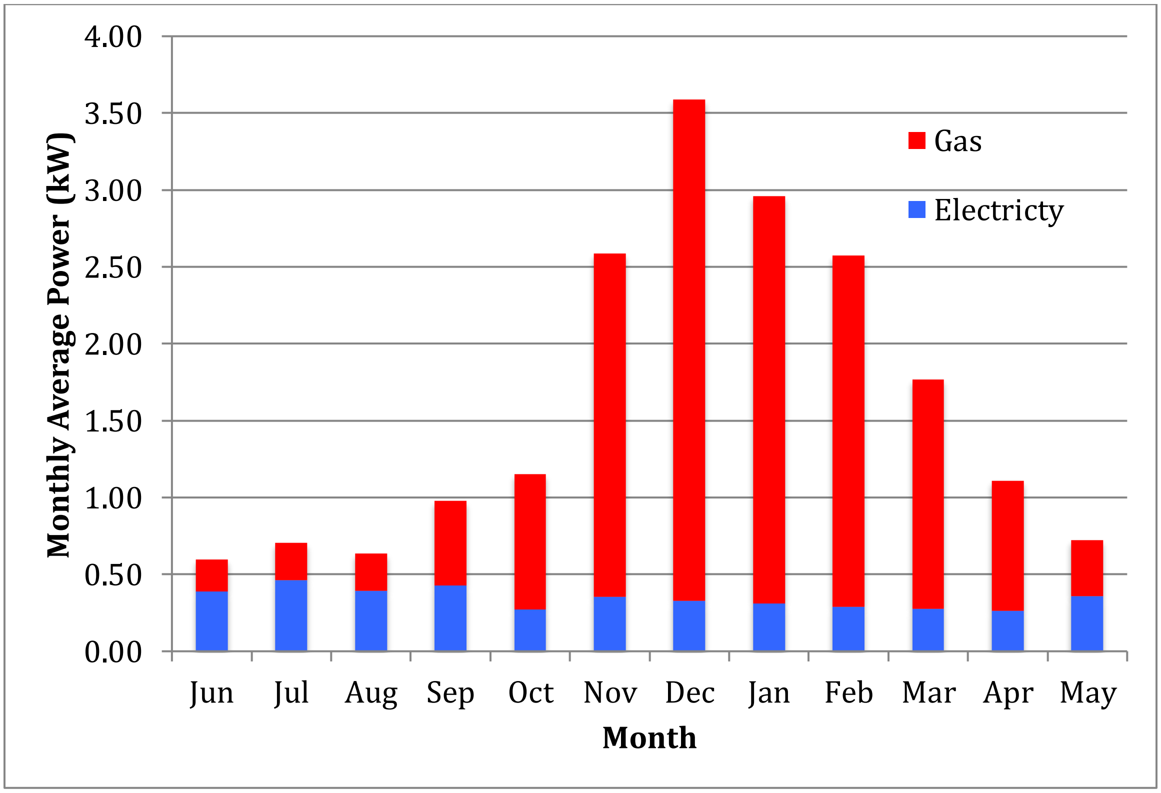

Figure 1: Original house, one-year average power consumption, June, 2016 through May, 2017.

These results are summarized in Table 1. It is interesting to note that the BB&Y house, even before renovation, emits less that 10% of the greenhouse gasses due to electricity use compared to the average US residence. This is a result of its low

[a] Using a conversion of 29.3 kWh/therm.

[b] The reader may be more familiar with presenting this data in kWh per month, or kWh per day. The use of average kW is in keeping with the output of BEOpt, and is useful in that it is independent of the days in the month. To convert to kWh per day, simply multiply by 24 hours.

electricity use and the remarkably low carbon intensity of PG&E, the local utility. PG&E emits only 0.294 pounds of CO_2 per kWh compared with the national average of 0.954.[12] The low electric consumption is likely due to the small size of the house (900 square feet), there being only one occupant, and the fact that the previous tenant converted all lights to LEDs). The results for gas use are comparable to the national average, however. Apparently, the small size and mild climate compensate for being leaky and uninsulated. Also note that the preponderance of CO_2 emission is due to the use of natural gas. Clearly a zero-carbon house cannot use natural gas.

Table 1: Summary of annual energy use and CO_2 emissions before renovation. The 2017 US national average residence is shown for comparison.

	BB&Y residence			Average US residence		
	Energy	Cost	CO2	Energy	Cost	CO2
		($)	(Metric Tons)		($)	(Metric Tons)
Electric	3037 kWh	552	0.41	10,404 kWh	1,340	4.50
Gas	382 therms	570	2.33	362 therms	349	2.21
Total		1,122	2.74		1,689	6.71

2.1 Design

We engaged a local architectural firm[13] with experience in passive house design to help work through the options and produce drawings. The house was modeled with BEOpt to explore the impact of various efficiency measures.[14] Because BEOpt does not allow for energy storage, we exported the 10-minute house energy consumption to Homer so that the overall microgrid operation could be modeled.[15]

The design process was an iterative one as the project evolved. The details of this process, along with the measurement methodologies, will be covered in a technical companion paper. One important aspect that deserves mention here, however, was the decision to go with a conditioned crawlspace. This came about because we were unable to meet our original goal of an air leakage rate of 2 air changes per hour at 50 pascals pressure difference (2ACH50). This low leakage was needed to minimize winter heating load. Recall that the starting point was 19ACH50. We sealed all the major envelope leaks that we could locate, such as old ceiling can light fixtures, fireplace flue, and the like. Even so, we reached only 8ACH50. The original house had a vented crawlspace. Most of the leakage was coming out the crawlspace. Air entered the crawlspace through numerous cracks between walls and the floor. It proved easier to seal the crawlspace vents than plug these extended cracks. This required including the crawlspace in the building air circulation system. After this change we achieved 6ACH50, which we learned is considered reasonable for a retrofit of such an old house. So we abandoned our original goal of 2ACH50, but we learned much about the process and believe that future improvements are possible. Note that the Passive House Standard is a very tight 0.6ACH50, which requires careful construction in a new house. Building to the Passive House Standard virtually eliminates the need for winter heating in the Bay Area climate. Keep in mind that for a house dependent on solar energy for all its energy needs, the winter heating months are the constraining feature. Not only is the solar resource least during these months, but the energy needs are greatest due to heating load.

With the modeling guidance we came up with the design outlined in Table 2. With these features it was expected that the house would require minimal grid support (i.e., minimal need for fossil generation). Images of the completed house are shown in Figure 2.

The PV system deserves some discussion. At 7.7 kW AC it is rather large for this small house. The array area is approximately half the house floor plan area. It will surely generate excess annual energy. It was designed as a shade structure in place of the original porch roof. As such it is horizontal. Modeling indicated that the value of having an optimally tilted array is minimal if the goal is to minimize grid reliance. This is because the critical design point is winter cloudy days where much of the insolation is diffuse. By utilizing bifacial modules, some of this diffuse component can be captured from ground reflection. Additionally, the bifacial glass-glass modules give a pleasant appearance from the porch area.

Figure 2: Images of the BB&Y house following retrofit. Top: front view. Bottom: view from back door showing solar shade structure over porch.

Table 2: Final design retrofit changes for the BB&Y Zero Carbon House

On-site Energy System

1. Install 24, Sunpreme GxB 380 bifacial PV modules, 380 W each for a total of 9.12 kW (not including backside contribution). These were mounted on solar shade structure in back of the house, which replaced the original porch cover.
2. Install SMA Sunny Boy 7.7 kW inverter.
3. Install two Tesla Powerwall II 13kWh battery packs.
4. Cap natural gas inlet, as electricity supplies all needs.

Envelope

1. Replace original single pane windows with double pane, low-e, Argon filled units.
2. Blow in 12 inches of cellulose insulation in attic
3. Seal major air leaks such as fireplace, ceiling light fixtures, and exhaust fans. Final air leakage of 6ACH50 measured. (Fresh air need was handled by installing a heat recovery ventilator air system.)

Crawlspace

1. Seal vents. Note: this eliminated the need for floor insulation.
2. Install polymer ground cover.
3. Spray 6 inches of closed cell foam on inside of foundation wall.

HVAC

1. Replace original gas furnace and electric A/C unit with Carrier 25VNA Infinity variable speed heat pump and variable speed fan coil having an HSPF of 12.
2. Install Zehnder heat recovery ventilation system, needed due to tight house.
3. Replace original gas water heater with 80-gallon heat pump version.

Washer/Dryer

1. The original house had no washer or dryer, so
2. We installed a Blomberg WM 98400 SX high efficiency washer, and a
3. Blomberg DHP 24412 W heat pump dryer (highest efficiency Energy Star dryer).

Kitchen Appliances

1. Replace all appliances with modern Energy Star units including:
2. Refrigerator: GE BPE16DTH top freezer
3. Dishwasher: Bosch SHS5AVL2UC
4. Microwave: Bosch HMV3022U
5. Electric Induction Cook Top: GE PHP9030PJBB

Lighting

1. Retain original LED units, except for replacing ceiling cans with modern air-sealed, insulation-rated units to reduce conditioned space to attic leakage.

2.2 Measured energy consumption

The retrofit renovations were largely completed by March of 2018, and the tenant reoccupied the house at that time. We now have one year of operation following the retrofit. The solar system did not become operational until May, however, so the energy requirements came from the utility until then. The PV array contribution will be presented below. Figure 3 compares the before and after electric energy consumption. For this comparison we kept the heating set-point at 68 F for both years.

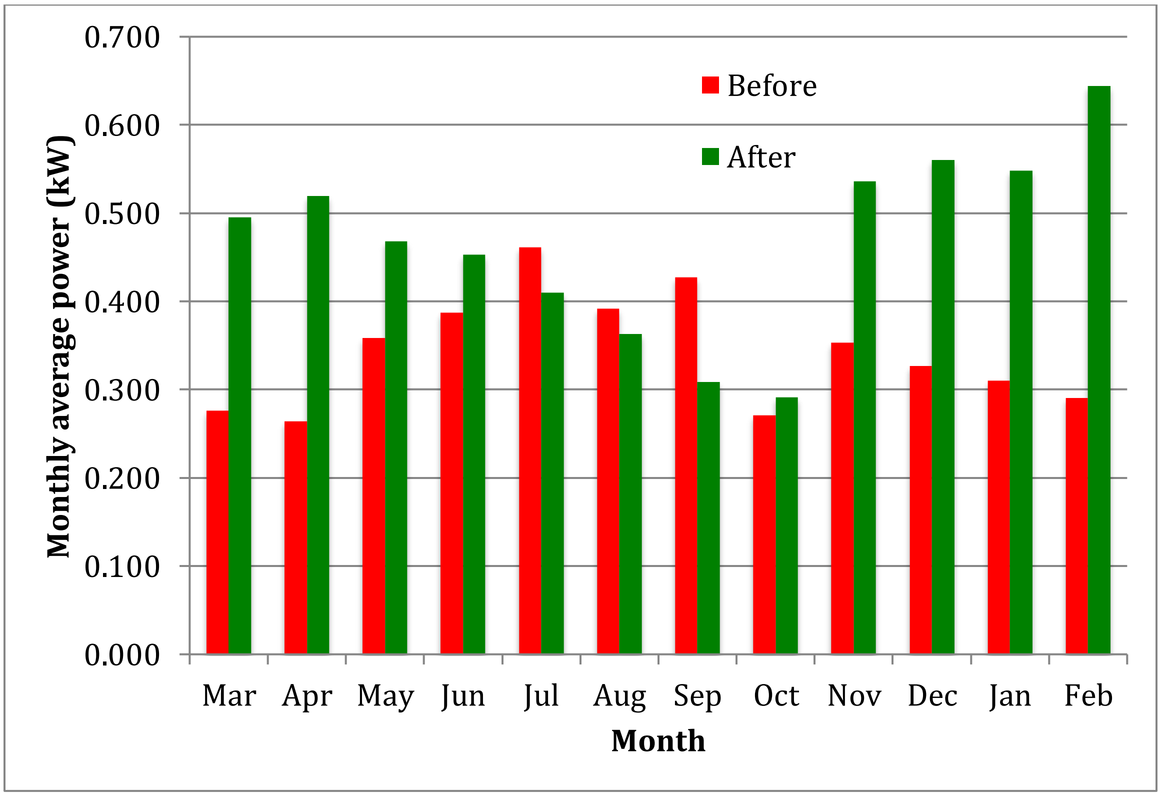

Figure 3: Comparison of the BB&Y house electric energy consumption before and after renovation. The natural gas use of the original house is not included. The retrofit house uses no natural gas. For the original house the period is June, 2016 through May, 2017. For the retrofit it is March, 2018 through February, 2019.

Note that the use of Energy Star appliances kept the overall electric consumption about the same despite adding a washer and dryer, and converting cooking and water heating and house heating to electric. Electric use increased due to heating during the heating season starting in November. Table 3 compares the before and after energy use and carbon emissions. The CO2 emission has been reduced from 2.33 to 0.54 metric tons, an 80% reduction! This is before including the carbon-free on-site solar production.

Table 3: Comparison of one-year energy use and CO_2 production before and after renovation. For the carbon emissions, it is assumed that the electricity was purchased from PG&E. In actuality, it came largely from onsite PV after May.

	Before		After	
	Energy (kWh)	CO_2 (Metric Tons)	Energy (kWh)	CO_2 (Metric Tons)
Electric	3,307	0.41	4,074	0.54
Gas	11,193	2.33	0	0.00
Total	14,500	2.74	4,074	0.54

2.3 PV and battery performance.

The PV array and battery system became operational in mid-May, 2018. Two operating modes were tested during the summer. The first was off-grid operation, effected by simply switching off the utility interconnect breaker, and the second was self-powered mode. This is a mode available in the Tesla Powerwall in which the utility remains connected, but there is no export until the battery is at 100 percent charge. The system is set to draw on the utility only when the battery drops below 5 percent charge. The system would draw from the grid if the house demand exceeds the 10 kW capacity of the two Powerwalls, however, this never happened with the selected equipment.

For the purposes of this experiment the off-grid mode proved not to be very useful. This is because the battery reached 100 percent charge in the morning during the summer, after which the inverter shut down having nowhere to send the power. This prevented comparing the PV production with modeled expectation. In addition, we lost any revenue from excess generation sales. Note: standard net energy metering tariff was not applicable as the house was a net producer starting when the array was turned on, and remained so throughout the year.

The first-year energy performance is shown in Table 4. A total of 139 kWh was required from the grid, while 7,092 kWh was exported. BB&Y received a $510.90 payment from PG&E for this export. It is best to think of 139 kWh grid use as the back-up required to cover periods of successive cloudy days during winter heating. It represents 3.7 percent of the 3,756 kWh consumed. This is slightly more than the original prediction of 3 percent largely because the heating load is greater. The carbon emissions are summarized in Table 5. The final carbon footprint is only 0.02 MT, a 99 percent reduction! This, of course, does not include any credit for the zero-carbon electricity exported to the grid. Any reasonable carbon credit for this export would make the house a net carbon sink. Shown is the credit if the solar export is displaced by flexible natural gas fueled generators, assuming the natural gas plant produces a typical 0.48 MT/MWh of CO_2.

Table 4: First year operation energy performance.

Month	House use (kWh)	PV production (kWh)	Grid Import (kWh)	Grid Export (kWh)
Jun, 2018	326	1670	0	1286
Jul	305	1577	0	1300
Aug	270	1026	0	793
Sep	222	519	0	260
Oct	217	511	0	244
Nov	386	393	85	75
Dec	417	518	15	57
Jan, 2019	408	521	34	105
Feb	433	687	6	148
Mar	351	1009	0	606
Apr	211	1300	0	1040
May	210	1445	0	1180
Total	3756	11177	139	7094

Table 4 Notes:

1. Export energy is less than PV output minus house use due to battery round trip losses.
2. PV production prior to November is compromised by periods of off-grid operation and inverter stability issues.
3. November PV output was drastically impacted by the Paradise, California wildfire due to haze and ash deposits on the array.

Table 5: Summary of annual carbon emissions.

	Original house	After energy retrofit	Including PV and battery	With export credit
CO2 (MT)	2.74	0.54	0.02	-3.41

2.4 Heating Load

Generally, January in Redwood City, California is the severest month for heating, having the most heating degree-days coupled with the least solar resource. In Figure 4 we break out the energy consumed in building heating (i.e., the energy to the heat pump) during January, as well as the remainder. As before, these values are converted to average power. It is seen that fully half the power is consumed in building heating. Since January is the critical month, this requires the PV array and battery sizes to be twice that needed if heating were not electrically powered.

Also shown in Figure 4 are the results of BEOpt modeling for January. One thing to note is that the BEOpt heating load is somewhat higher than measured. This January, however, was relatively warm. Redwood City had 442 heating degree-days, whereas the TMY weather data used by BEOpt has 508. If one simply increases the heating load by this ratio (508/442), then the corrected value shown as DD Corrected results. BEOpt made remarkably accurate predictions regarding heating requirements, 0.314 kW versus 0.322 kW. A big difference remains in the other loads, which are nearly twice measured. We don't yet have measurement sensors on all the major appliances, and so don't know the cause of this. It could simply be because BEOpt assumes more than one occupant.

Given that the heat pump has a coefficient of performance (COP) of around 4, the January heat required averages about 1.1 kWth. This compares with the original house requiring over 2 kWth. Thus, the energy retrofits discussed above, such as new windows, reduced the heating requirement by about 50 percent. We had hoped for more than this and will be looking to improvements over the coming year.

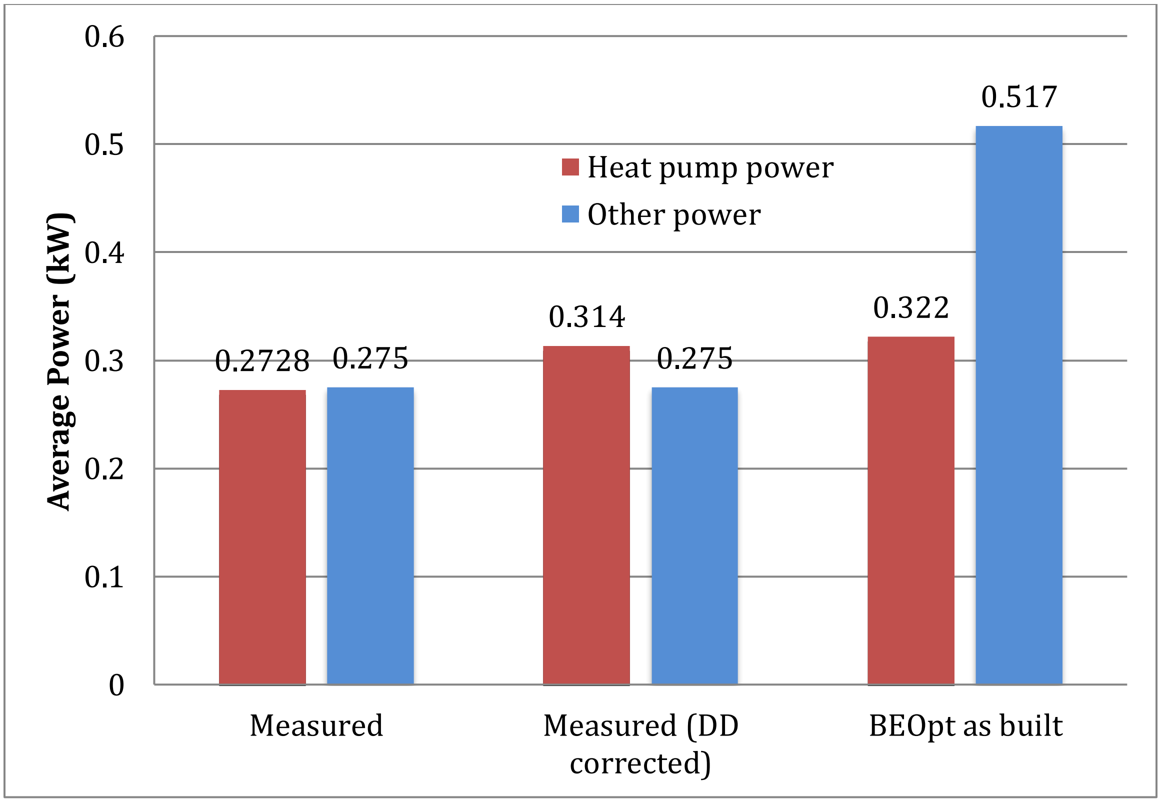

Figure 4: January average power showing the value consumed in heating as well as the remaining power. See text for discussion of the various bars.

3.0 DISCUSSION

Several lessons are immediately apparent. First, big reductions in greenhouse emissions are obtained by simply converting from natural gas heating to heat-pump electric heating. This growing trend toward what is often called "deep electrification" will have a major carbon reduction impact, especially when the light-duty vehicle fleet is also electrified (transportation being comparable to building greenhouse gas emissions).[16] Second, an array sized at about half the area of the house supplies considerable greenhouse gas-free electricity to the grid, and gives a house with very little need to draw from the grid. Such large arrays will become more and more practical and cost-effective in residential application when PV roof shingles are commonplace.

It would seem prudent to encourage the conversion from natural gas to heat pumps in a manner such that it is largely complete by 2040. A successful example of such a transition is the conversion from incandescent to LED lighting. Today, LEDs are so cost effective as to be basically a no-brainer. These days when incandescent bulbs burn out, they are most often replaced by LEDs. A goal would be to make heat pumps such a no-brainer choice any time a furnace, water heater, or clothes dryer needs replacement.

The cost of the remaining elements of the deep energy retrofit was larger than justifiable on strictly economic grounds. Of course, this was a one-off experiment. It is hoped that the economics of a deep energy retrofit can be improved through practice and learning so that it too becomes a no-brainer. One thing of note is that the tenant finds the sealed house with its constant, filtered fresh air supply via the heat recovery ventilator remarkably comfortable compared to traditional houses that rely on intermittent air leaks for fresh air. This is a hard-to-value added benefit.

The BB&Y House required 139 kWh of annual back-up energy from the grid, or less than 4 percent of the annual energy needs. It is expected that this will be further reduced in the coming year as the issues that affected November are dealt with. Additionally, there remain some heat losses that are easily eliminated. The major components are un-insulated walls in some areas and having the HVAC equipment in the vented attic. These will be corrected over the summer. Our measurements of the actual heat loss paths will be covered in a companion technical paper. We will also explore the impact of load management strategies such as time variable thermostat settings.

The main reason for the low backup requirement is the large size of the PV system at 7.7 kW_{AC}. On an annual basis this system is expected to generate three times the energy required by the house. The battery storage is also rather large at 26 kWh, which translates to 40 hours at the worst-case February consumption. The remainder, less battery losses, is exported. Under the current situation, there is clearly excess PV and battery from a purely economic perspective. In fact, the house is pretty much designed as an off-grid house would be, with three times PV and two days of battery storage. It should be noted, however, that one day the entire utility system will be effectively "off grid" when fossil fuel generation is eliminated. When this happens there will be no place for excess PV generation to go once batteries are full, and the grid operator will need the ability to curtail distributed PV as well as central station PV. In that future scenario, what was back-up power in the case of the house will have to come from the dispatchable renewables: hydroelectric, geothermal, and biomass. Given the small back up requirement, this seems eminently doable.

An alternate option would be to operate off-grid, or to "grid defect" in the terminology of the Rocky Mountain Institute's popular report.[17] In this case the back-up power could come from various sources. One likely one is from EV batteries in a vehicle-to-grid mode. Note the requirements are so infrequent, at less than two full cycles per year, that it would not impact an EV battery from a life-cycle reliability perspective. This is distinct from the more commonly explored vehicle-to-grid operating modes where the batteries are cycled daily to supply the load.

4.0 CONCLUSONS

We have shown that it is eminently feasible to convert an existing residence into a net carbon sink. The largest contribution to carbon reduction comes simply from converting all appliances to electric, and using heat pumps for home heating, hot water, and clothes dryer. Adding PV plus storage enables the house to become largely independent of the utility grid and its reliance on fossil fuel sources. Adding conventional energy efficiency measures such as double pane windows and added insulation can reduce the heating requirements by 50 percent or so, which enables reaching the zero-carbon goal with a correspondingly smaller solar system and battery.

From a high-level technical perspective, it doesn't matter whether the PV and storage are distributed on rooftops, or located in large central power plants. The ultimate mix will involve both, as multi-unit housing and much of industry do not have the space to house a large enough array. The point is that we clearly can create a carbon free residential energy system in mild climate zones. Economics and policy will dictate the optimum amount of distributed PV, central station PV, and battery storage in that future system. Despite the rapidly declining costs of PV and batteries, considerable work remains to make this a "no-brainer" cost-effective option.

It should be noted that going forward, utility providers will increasingly look to reduce nighttime load, because much of their supply will come from solar. Time of use tariffs will likely encourage this. Our experience indicates that it is very feasible to virtually eliminate nighttime use in the residential sector by a combination of energy efficiency, battery storage, and demand management. In summary we see a four-step process to eliminate greenhouse gas emissions in the building sector.

Step 1: Eliminate natural gas and electrify all house loads as efficiently as possible.

This involves converting to heat pump HVAC, hot water, and dryer, plus an induction stove. All appliances should be as efficient as is practical.

Step 2: Reduce winter heating requirement.

Winter heating load adds to the amount of PV required to power the building. But this added PV is only needed during the heating months when solar output is least, resulting in excess energy available at other times. Heating load can be reduced by upgrading the building envelope insulation and installing a heat recovery ventilator.

Step 3: Rely on renewable energy for the needed electrical supply.

PV will likely be the major source of renewable energy, but if the grid is retained many others can contribute as well; including wind, geothermal, and hydroelectric.

Step 4: Shift demand from night to day and supply sufficient storage.

Sufficient electrical storage will be needed to cover the variability of the renewable sources. This can come from many technologies including batteries and pumped hydroelectric, but nighttime demand should be reduced as much as possible through such means as thermal storage and EV charging at work.

Not long ago this aspirational goal of decarbonizing buildings would have looked technically feasible, but hopelessly expensive except for a few off-the-grid zealots. Due to rapidly declining renewable energy and battery storage prices, that is no longer the case. The issue today is how best to effect this transition from a policy and business plan perspective.

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