GreenPeaks: Employing renewables to effectively cut load in electric grids

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***Abstract*—Reducing the carbon footprint of energy generation is an important part of ongoing sustainability efforts. To cut carbon footprints, electric utilities are incentivizing renewable energy integration through net metering and introducing time-of-use pricing plans to cut demand peaks, as peaks significantly contribute to both generation costs and carbon emissions. Net metering is one of the most popular means of integrating distributed renewable generation in the grid. However, the current net metering approach doesn't effectively cut demand peaks because renewable harvest peak and demand peaks are out of sync. Furthermore, as several states impose net metering subscriber limits of less than 1% of the peak, net metering isn't even close to realizing the full potential of renewable integration in the grid. To address these limitations, we present GreenPeaks, an energy storage based renewable integration system to enhance net metering. GreenPeaks employs energy storage to intelligently move a fraction of harvested energy to peak intervals and accumulate any surplus harvest. We evaluate GreenPeaks using consumption data from real homes. Our results show that GreenPeaks reduces grid-wide peak by 12% in contrast to net metering's 2%, while reducing the electricity generation costs by more than 40%.**

I. INTRODUCTION

2016 was the warmest year since modern recordkeeping began in 1880; according to NASA, 2016 was the third year in a row to set a new record for highest global average temperature. The temperature increase is principally driven by increased carbon dioxide and other human-made emissions into the atmosphere. One of the major contributors to the emissions is electricity generation. In 2016, about 35% of the total energy-related CO2 emissions in the U.S. were from the electric power sector [4]. To reduce the carbon footprint of electricity generation and cut costs, utilities and states are transitioning towards more sustainable renewable energy sources such as the wind and solar energy and striving to cut peak demands.

The U.S. Department of Energys (DOE) Sunshot Initiative proposes to have solar energy account for 14% of all electricity generated in the US by 2030 and 27% by 2050. To facilitate this transition electric utilities and states are encouraging customers to deploy onsite renewables. For instance, as of January 1, 2017, all new buildings of 10 stories or fewer in San Francisco must be built with solar panels included. Currently, net metering is one of the most popular approaches that allows customers to integrate their onsite renewable deployments with the electric grid. It allows customers to generate onsite electricity (e.g., using solar panels); generated energy is used to satisfy customers demand, and any surplus generation is sold back to the grid. In its current form, net metering has two crippling limitations: 1) it doesnt adequately cut peaks, as energy harvest peaks and demand peaks are out of sync; for instance, solar power harvest peaks earlier in the day, but household peak demands typically occur around dinner times; 2) many states impose subscriber limit to less than 1% of the peak thus severely restricting renewable integration and peak shaving from net metering; for instance, Washington state caps the use of metering at 0.5% the 1996 peak load [2].

Peak shaving is vital for taming both electricity costs and carbon footprint. Demand peak impacts capital costs by dictating the installed generation capacity and transmission and distribution infrastructure capacity, as these must be provisioned for serving the peak. Additionally, as the transmission and distribution losses are proportional to the square of the current, higher peak demand results in higher distribution losses. Besides, frequently, the peak loads cannot be served using base load generators that are continuously running. Hence, utilities need to dispatch extra "peaking" generators to satisfy the peak demands. These "peaking" generators frequently operate on fossil fuels like natural gas and oil([8]) which leave greater carbon footprints compared to several base load electricity generators such as hydroelectric plants, nuclear plants, solar power, etc [1]. Furthermore, because of the costs associated with building efficient power plants, the peaking generators are inefficient compared to the base load plants [8].

To overcome the limitations of net metering, effectively shave peaks, and cut electricity bills we present GreenPeaks. GreenPeaks enhances the naive net metering with intelligent energy storage to shift harvested energy to peak times and store unusable/unsellable surplus for later consumption. The online battery charging-discharging algorithm in GreenPeaks extends the PeakCharge algorithm [20] to incorporate renewable energy. Like PeakCharge, GreenPeaks strives to keep the home's net instantaneous grid power consumption close to the target average consumption; renewable harvest is used as follows:

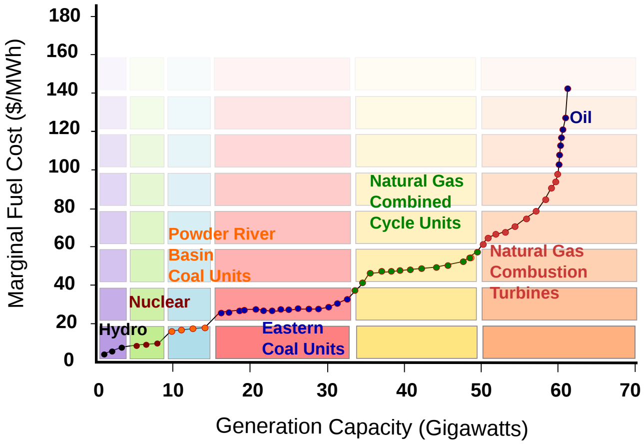


Fig. 1: The marginal cost to generate electricity increases as the demand increases. Data from [14].

if the home's instantaneous demand is above target average, the harvested energy is used to bring it down to the average, any remaining harvest is stored. If the demand is below target average, renewable energy is stored; if all the harvest cannot be stored, the surplus is consumed. The harvest that can neither be stored nor consumed, is sold back to the grid.

Experimental evaluation on real world power consumption data from several homes show that compared to net metering GreenPeaks can boost peak reduction by up to 500% and further reduce generation costs by up to 300%. Additionally, GreenPeaks can cut user electricity bills up to 5.8% exceeding net metering's savings by more than 200%.

II. BACKGROUND

A. *Utility's generation costs*

Figure 1 shows a utility's marginal costs of operating generators in the southeast U.S. [14]. The figure demonstrates that the electricity generation costs mount rapidly (and non-linearly) as the demand peak increases. Peaks also contribute to transmission and distribution losses since these losses are proportional to the square of the current. Roughly 10 to 20% of generation costs in the U.S are incurred servicing top 100 hours of peak demand annually [22]. We use the data in Figure 1 to derive the demand-cost function for GreenPeaks evaluation. We derive the function by scaling the real demand-cost data presented in the figure (taken from the Federal Energy Regulatory Commission report [14]) to match the peak demand in our home traces (described in the Evaluation section).

B. *Variable electricity pricing*

To reduce peak demand on their grids, many utilities are transitioning from classic flat electricity pricing to more market-based, variable pricing plans such as time-of-use (ToU) pricing and day-ahead real-time pricing plans. These variable pricing plans have a higher electricity price during high demand intervals and a lower price during low demand periods thus incentivizing customers to lower their consumption during peak-periods. Such pricing plans are being used in several places, e.g., Ontario Energy Board offers time-of-use electricity pricing based on three usage periods—off-peak (6.5 ¢/kWh), mid-peak (9.5 ¢/kWh), and on-peak (13.2 ¢/kWh) [23]. Similarly, Pacific Gas and Electric Company too offers time-of-use electricity pricing [24]. Besides, under the residential real-time pricing programs in Illinois, utilities charge customers for their hourly consumption based on the wholesale hourly market price of electricity [15]. Furthermore, to curtail the peak demands from commercial customers, utilities impose peak surcharge on their tallest demand peak across the billing cycle, such as in [5]. Hence, in addition to paying for the total energy consumption ($/kWh price), the customers pay for every kW of their tallest peak demand ($/kW).

As argued in [20], we believe achieving effective peak shaving from renewable integration requires re-designing both pricing plans and solar integration algorithms. Hence, we evaluate GreenPeaks under a hybrid pricing plan, similar to the one used in [20], where the customers are charged for both total energy consumption in the billing cycle ($/kWh component) and tallest peak ($/kW component); the energy consumption is billed using ToU pricing similar to the one employed by Ontario Energy Board [23]; we adopt the peak surcharge based on the study presented in [20].

C. *Net metering*

Currently, net metering is the most common way utilities compensate customers for going solar [3]. It allows customers deploy solar panels and harvest energy; homes consume the harvested energy to satisfy their energy needs; any surplus harvest is fed (sold) back to the grid and customers get credit in their electricity bill for this energy. If the harvested energy is insufficient, homes can draw the deficit from the grid as usual [29].

D. *GreenPeaks architecture*

Figure 2 depicts GreenPeak's architecture, which enhances the net metering architecture to leverage energy storage. The architecture utilizes a discharge controller (similar to [30]) to programmatically limit the rate of draw from the battery. To shave peaks and achieve target consumption level at the home it is essential to limit the battery's rate of discharge using discharge controller; otherwise, by default the rate of discharge is dictated by the home's instantaneous consumption. A gateway server continuously monitors 1) home's consumption via an in-panel energy monitor, 2) battery's state of charge, 3) electricity prices via the Internet, and 4) solar harvest using current transducers. Based on the monitored values, the server periodically (every 5 minutes) determines 1) the fraction of harvested energy to be stored, and 2) the fraction of harvest to be consumed immediately. The server also decides how much of the home's demand should be drawn from the grid and how much from the energy storage. The in-panel meter in the architecture is the standard bi-directional meter used in net

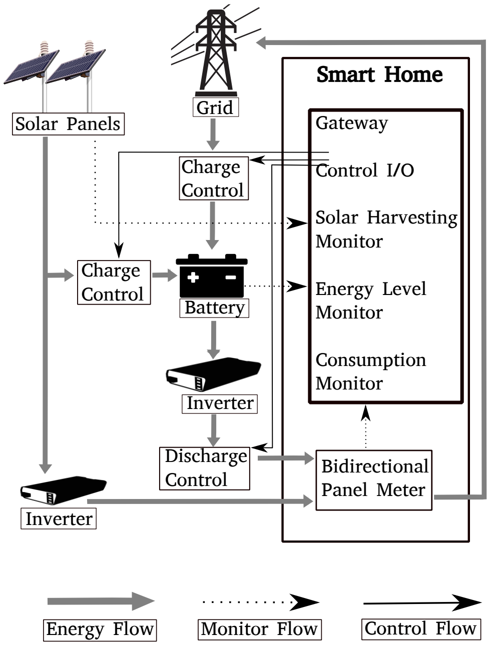


Fig. 2: GreenPeaks system architecture.

metering. After satisfying the home's instantaneous demand and charging the battery, any surplus is sold back to the grid.

Energy storage: With the advent of several off-the-shelf home energy storage solutions—such as Teslas Powerwall [9]—enhancing net metering with energy storage is easily achievable in practice. There are several more similar products, e.g., [6], [7]. However, to keep this study generic and independent of specific commercial products, we assume the homes use sealed lead-acid batteries. We assume the combined round-trip efficiency of the battery and inverter is 80% [26]; to elongate the battery lifetime, we restrict the battery's depth-of-discharge to about 50% (as done in [18]) and limit the maximum charging rate to $C/4$ ("C" is the usable battery capacity); this is well within the maximum permissible charging rate of $C/3$ [17].

III. PROBLEM STATEMENT

Although energy storage and onsite renewable generation can cut peaks and reduce costs, the choice of when and how to use the harvested energy presents interesting tradeoffs and challenges. Using the harvested energy as and when it is generated can lower the instantaneous consumption from the grid and cut costs, but may not shave peaks effectively—as energy harvest and consumption peaks could be out of sync. Instead, if we store the harvested energy for later use, we can cut peaks by using the stored energy during peak times. However, storing the energy results in additional losses due to battery inefficiencies, hence we get to use a smaller fraction of the total harvest. Further, as determining the peak size and occurrence time is difficult, employing stored energy for maximum peak reduction is challenging.

In this work we address the problem of deploying energy storage and solar panels at homes to cut their peak demands and bills. We define the problem as follows. Given the home's current and past power demand, current solar harvest, and electricity pricing plan the problem is to design an online renewable integration algorithm to determine: 1) the fraction of current solar harvest to be consumed immediately and the fraction to be stored, 2) the fraction of home's demand to be consumed from the grid and the fraction to be drawn from the energy storage so as to reduce the home's electricity bill and peak demand while ensuring the aggregate grid-wide consumption profile becomes grid-friendly as more and more homes adopt solar harvest.

IV. GREENPEAKS ALGORITHM

In this section, we propose two algorithms, namely, the home-oriented method and GreenPeaks that efficiently utilize the harvested solar energy to reduce the energy consumption from the grid. Our main contribution is GreenPeaks, an algorithm that builds on our prior work PeakCharge [20] and smartly leverages the solar energy harvested locally to reduce the peak energy consumption from the grid. We assume that time is divided into intervals and all algorithms (i.e., Peak Charge, net metering, the home-oriented method and GreenPeaks) execute continuously making decisions at the beginning of each interval. In our experiments, we consider time intervals of 5 minute durations. In the evaluation section, we demonstrate that GreenPeaks, in addition to reducing the peak energy consumption, results in generation cost savings for the utility companies and monetary savings for the customers.

A. *PeakCharge*

We first provide a brief overview of the PeakCharge algorithm [20]. PeakCharge uses an online battery charging-discharging algorithm to lower electricity bills in the presence of variable pricing plans with peak surcharge. To minimize the peaks, PeakCharge strives to keep the home's electricity consumption close to its target daily average consumption. If the home's demand is above the target average, PeakCharge draws a fraction of the demand from the energy storage so as to bring down the net consumption from grid to the target average. Similarly, when the consumption falls below the target average, it charges the battery at a rate needed to bring up the net consumption to the average. Depending on the price differential between the off-peak and peak intervals and the peak surcharge, PeakCharge can also some times charge or discharge the battery greedily to maximize cost savings. Details of PeakCharge algorithm can be found at [20].

B. *Home-oriented Method*

In the home-oriented method, the harvested solar energy is used to directly satisfy the home's current power demand and any surplus energy (left after consuming the harvested energy towards current home demand) is sold back to the grid. The harvested energy is never stored in the battery and not used to charge the battery even if the battery is empty. Instead, the battery is charged from the grid. For charging and discharging the battery, home-oriented method leverages the PeakCharge algorithm [20]. Thus the home-oriented method serves as a baseline approach that simply combines the harvested solar energy and the PeakCharge algorithm to shave the peak consumption and cut electricity bills.

C. GreenPeaks

GreenPeaks is a peak-centric algorithm that focuses on flattening the home's consumption profile using solar harvest and energy storage. As it is difficult to accurately predict the size and occurrence of peaks, GreenPeaks adopts a heuristic approach. Employing solar energy and batteries, it strives to keep the instantaneous net grid power draw of a home close to its target daily average consumption. For instance, if a home's daily energy consumption is 24 kWh, the target average power consumption would be 1 kW. Hence, in this case, GreenPeaks will strive to keep the home's instantaneous power draw from the grid around 1 kW throughout the day. By flattening daily power consumption profile to the target average, GreenPeaks shaves the peaks.

GreenPeaks has three possible energy sources to satisfy the home's power demand: solar harvest, electric grid, and the energy storage device (battery). At any given point in time, harvested solar energy is used as follows: If the home's power demand is above the target average, the harvested energy is used to flatten the demand to the average. For example, if the target average is 1 kW, but home's current power need is 1.3 kW, 0.3 kW of the solar harvest would be fed into home so as to bring down its net grid power draw to 1 kW (the target average). Any remaining harvested energy after flattening the demand is stored in the battery. However, if the harvested energy is insufficient to flatten the demand to average, we will use up all of it to achieve the best possible flattening. If the home's instantaneous demand is below the target average, the harvested energy is directly stored in the battery. In case the battery gets full, any surplus harvested energy is used towards satisfying the home's current power demand. At any point in time, if there is surplus solar harvest after satisfying current home demand and charging the battery, it is sold back to the grid. GreenPeaks' approach to using solar harvest is summarized in Algorithm 1.

To use the stored energy (in battery) for peak shaving and bill reductions, GreenPeaks adopts PeakCharge's approach, which is summarized next. The decision of charging the battery from the grid or using the stored energy for satisfying the home's power needs is primarily based on the current price of electricity, peak penalty, and home's current demand. Let's assume the cost of electricity during low-price intervals is C_L \$/kWh, electricity's cost during high-price intervals is C_H \$/kWh, battery efficiency is e, maximum battery charging rate is X_{max} kW, peak surcharge is P \$/kW, and length of low-price interval is T hour. Given these values, if the monetary benefit of charging the battery greedily from the grid during low-cost period and using the stored energy during high-cost periods is greater than the peak penalty incurred from greedy battery charging, greedy battery charging during low-cost periods would save money for the customer. Otherwise, peak-centric charging and discharging would be more economical. In other words, if the inequality in equation 1 holds, greedy charging-discharging is beneficial, else peak-centric charging-discharging is warranted.

$$eX_{max}C_HT - X_{max}C_LT > X_{max}P \tag{1}$$

GreenPeaks employs the above insight while charging/discharging the battery from the grid. In summary, GreenPeaks uses the battery as follows:

- Given the electricity price is low and home's current demand is below target average, greedily charge the battery (from the grid) at maximum rate if 1 holds. Otherwise, charge the battery from the grid at a rate so as to bring up the net grid power draw to the target average demand.
- Given the electricity price is low and home's current demand is above target average, greedily charge the battery (from the grid) at maximum rate if 1 holds. Else, discharge/draw power from the battery so as to bring down the home's net grid power draw to the target average.
- Given the electricity price is $high$ and home's current demand is below target average, greedily draw power from the battery at full rate (max up to the home's current demand) if 1 holds. Otherwise, do nothing.
- Given the electricity price is $high$ and home's current demand is above target average, greedily draw power from the battery at full rate (max up to the home's current demand) if 1 holds. Otherwise, draw power from the battery so as to bring down the home's net power draw to the target average.

If there are more than two price intervals in electricity pricing plan, each interval is classified as "low" or "high" based on whether its price is lower or higher than average. In this case C_L and C_H are calculated by taking the average of the cost per period weighted by the length of the period.

Algorithm 1 GreenPeaks Algorithm

```
for each time interval do
    if demand $\geq$ average then
        if (harvested energy $\geq$ demand - average ) then
            flatten demand to average
            if (harvested energy available) then
                charge battery until fully charged
                remaining energy used to satisfy home's demand
        else
            decrease demand to extent possible
    else
        charge battery until fully charged
        remaining energy used to satisfy home's demand
    if (surplus harvested energy) then
        sell surplus energy back to the grid
```

V. EVALUATION

In this section, we compare the performance of GreenPeaks with the proposed home-oriented method, net metering, and PeakCharge [20] on household power consumption traces for 114 apartments for a week (February 1 to February 7, 2016) [10] and harvested solar power traces collected in the same geographical region for the same time period [25] and demonstrate that GreenPeaks outperforms the other approaches. As the harvested solar power and the household power consumption trace values are not in the same order, we scale the solar power generation traces for our experiments such that the harvested energy is 20% of the daily average demand across all the homes.

The default value of the experimental parameters used in this paper is similar to our prior work [20]. Battery capacity C is 50% of the daily average consumption of the homes, which is in line with the findings of [20], where authors showed that a battery with usable capacity greater than 20% of the daily average consumption was sufficient to get maximum peak reduction at individual homes. We assume a battery efficiency of 80%, which is similar to the efficiency rating for VRLA/AGM lead-acid batteries in a Department of Energy report [26]. We use a peak demand surcharge of U$2.0 for a 30 minute window around the highest peak of the day; as several electricity utilities charge customers for 30 minute peaks (such as [5]), we do the same. The maximum battery charging rate in our experiments is C/4, i.e., the battery charges to full capacity in 4 hours, which translates to roughly a C/8 rate for a battery used at 45% depth-of-discharge (DOD). The C/4 maximum charging rate is within the maximum possible charge rate of C/3 for sealed lead-acid batteries [17]. As mentioned earlier, we evaluate GreenPeaks under a hybrid pricing plan, similar to the one used in [20], where the customers are charged for both total energy consumption in the billing cycle ($/kWh component) and tallest peak ($/kW component); the energy consumption is billed using ToU pricing similar to the one employed by Ontario Energy Board [23], which offers time-of-use electricity pricing based on three usage periods—off-peak (6.5 ¢/kWh), mid-peak (9.5 ¢/kWh), and on-peak (13.2 ¢/kWh).

A. Qualitative Results

Before presenting performance results, we present some qualitative results to help the reader appreciate the nuances of the PeakCharge and GreenPeaks algorithms. Figure 3(a) shows the average power consumption of a single household for a particular day. From this figure, we observe that the peak demand for this day is approximately 6000 Watts. Figures 3(b) and 3(c) show the energy consumption of the same home from the grid using the PeakCharge and the GreenPeaks algorithms respectively. In both scenarios, the battery capacity is 10kWh. From Figure 3(b), we observe that for this particular day, PeakCharge is successful in shaving some peaks, but is unsuccessful in shaving the tallest peak. In comparison, GreenPeaks that intelligently combines the harvested solar energy and the PeakCharge algorithm is successful in shaving all peaks and reducing the peak energy consumption to the average. These figures demonstrate that while PeakCharge is capable of flattening some peaks by leveraging on-site batteries, additional reduction in energy drawn from the grid can be obtained by intelligently utilizing the harvested solar energy.

In Figure 4, we compare between the average aggregate raw demand for all apartments considering the entire week and the aggregate demand using the PeakCharge and GreenPeaks algorithms. This figure demonstrates that GreenPeaks can reduce the aggregate peak demand for the entire grid and not just for an individual home. Additionally, from an electric utility's perspective, as GreenPeaks can flatten the overall energy consumption, it can result in significant generation cost savings. We investigate the peak reduction and generation cost savings in greater detail next.

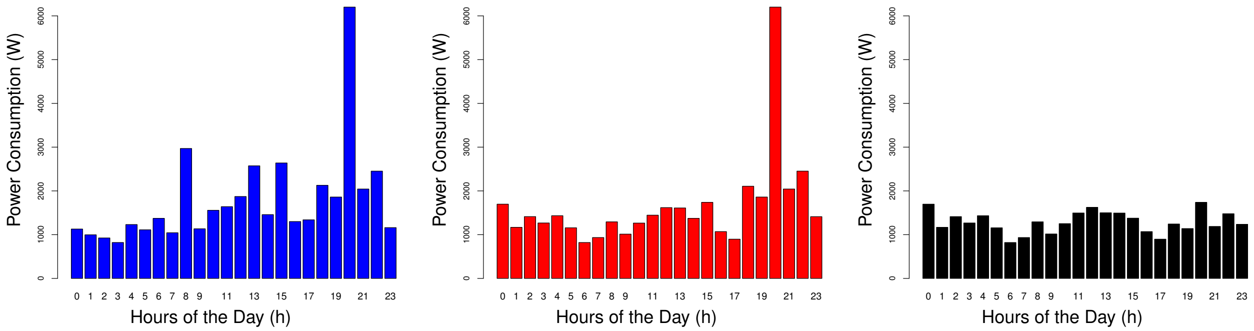
B. Generation Cost Savings and Peak Reduction

In Figures 5 and 6, we investigate the aggregate generation cost savings and the aggregate peak reduction across the grid, respectively, as the battery capacity increases. Battery capacity at individual homes is varied from 0% to 100% of the average daily energy consumption across all homes. We observe that generation cost savings and peak reduction increase sharply and then flatten out when the battery capacity reaches approximately 50 - 60%; this happens because a home's total consumption is fixed. Adding more storage after a certain point can't reduce the peak further. The figures also show that GreenPeaks can provide significantly higher peak reduction and generation cost savings in comparison to the other approaches,e.g., GreenPeak's generation cost savings exceeds that of net metering by up to more than 300%.

Figures 7 and 8 demonstrate that the aggregate generation costs and peak demand across the grid steadily decreases as a greater fraction of homes adopt GreenPeaks. Similar to Figures 5 and 6, here too, GreenPeaks achieves best savings compared to the other approaches. For instance, GreenPeaks boosts aggregate peak reduction by more than 900% compared to net metering. Besides, the high generation cost savings shows the incentive for the utility companies to encourage customers to harvest solar energy locally and to use on-site batteries.

C. Benefit to Customers

Results presented thus far in the paper have demonstrated the potential benefits for the utility companies. In Figure 10, we show the potential savings from the customer's perspective. Figure 10(a) shows the average peak energy reduction for individual homes, while Figure 10(c) shows the dollar savings per day for the customers. We observe that GreenPeaks results in greater daily dollar savings compared to net metering—up to more than 370%. Our experiments demonstrate that GreenPeaks benefits both utility companies and customers and can thus be easily deployed in practice.



(a) Raw Demand (b) After using PeakCharge (c) After using GreenPeaks

Fig. 3: Average hourly power consumption of a representative home

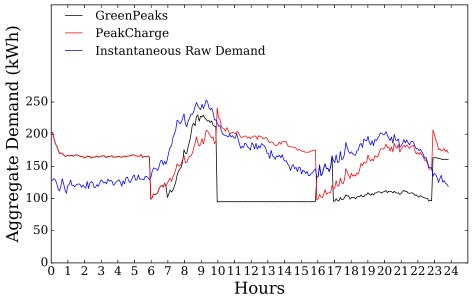


Fig. 4: Aggregate raw demand and aggregate demand after applying GreenPeaks

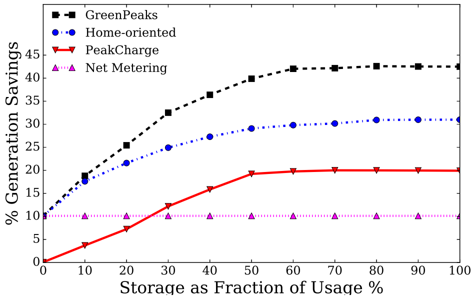


Fig. 5: Generation cost savings vs. battery capacity

D. *Discussion on Peak Demand Surcharge*

We conclude the evaluation section with a discussion on the peak demand surcharge. The PeakCharge algorithm that runs at the core of the GreenPeaks algorithm uses a peak penalty to regulate the charging/discharging behavior of the battery. In Figure 9, we investigate the impact of the peak penalty on the GreenPeaks algorithm. As expected, small values for the peak demand surcharge cause the algorithm to charge and discharge the battery greedily, resulting in a higher rebound peak than the original raw demand. However, as the peak penalty increases,

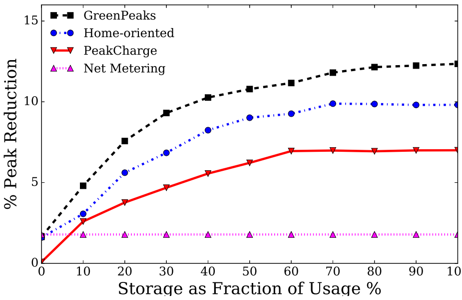


Fig. 6: Peak reduction vs. battery capacity

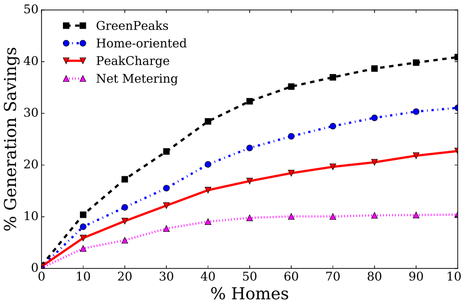


Fig. 7: Generation cost savings vs. percentage of homes with battery

both the PeakCharge and GreenPeaks algorithms starts behaving in a peak-centric manner, by flattening the demand to the average energy consumption. Our experiments show that peak penalty values greater than 0.6$/kW are sufficient to make the algorithms operate in the desired manner.

VI. RELATED WORK

A lot of research on demand-response in the grid using energy storage has focused on cutting costs for customers exploiting variable electricity pricing. For example, Daryanian et al. [13] first presented an optimization approach to cut

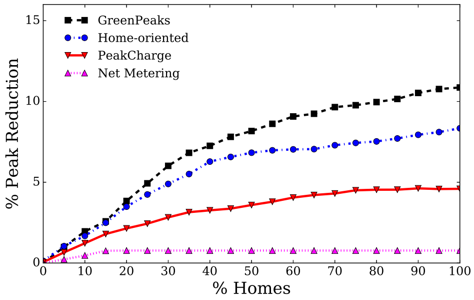


Fig. 8: Peak reduction vs. percentage of homes with battery

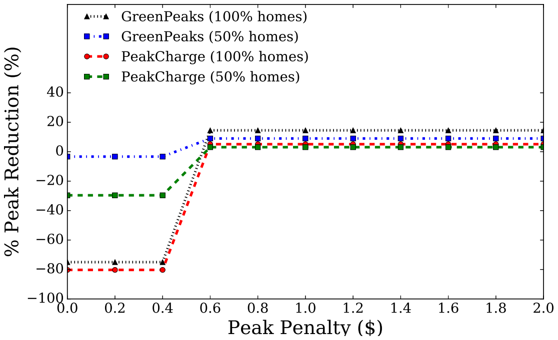
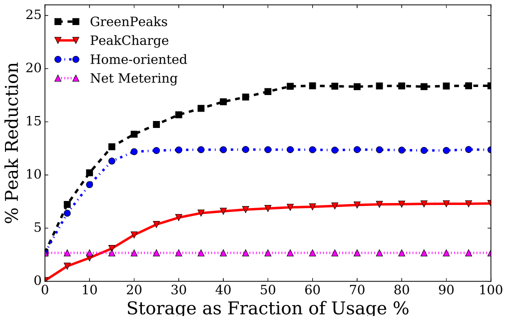


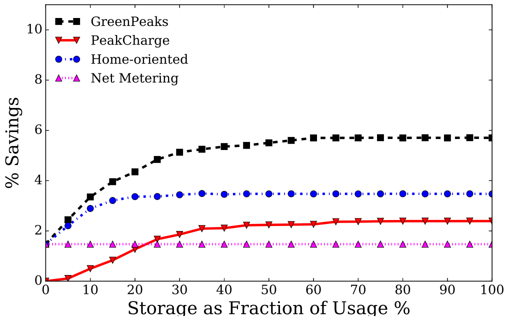
Fig. 9: Rebounding peaks in the grid by Increasing the peak demand surcharge.

electricity bills in presence of spot electricity prices. Similarly, authors in [18] proposed a linear optimization solution to minimize electricity bills using a battery under variable prices. Van de ven et al. [28] model the problem as a Markov Decision Process and claim that there is a threshold-based stationary cost-minimizing policy. If the power demand is independent and identically distributed, the policy is optimal. In our work, we take more empirical approach using consumption traces from real homes, solar panel generation, and market-based rate plans. Over and above, all the aforementioned approaches focus only on employing storage for bill reduction. In contrast, our work additionally focuses on renewable energy integration to achieve its goals. Further, as shown in [12], approaches that greedily use energy storage for cost reduction can lead to an increase in the aggregate grid-wide peak demand. This is not a limitation of our work, as GreenPeaks strives to keep the home's consumption close to its target average. Besides, in [21] authors have proposed to deploy energy storage across the distribution network hierarchy to cut the peak demands and lower utility's electricity distribution costs. On the contrary, our work focuses only on deploying storage and renewables at homes to lower their bills.

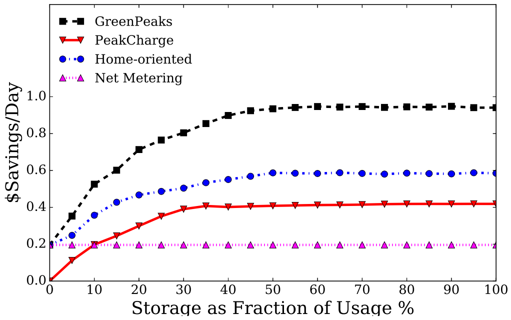
Researchers have also proposed scheduling and controlling home appliances to cut peak demand and energy bills at homes. [11] proposes to flatten a home's electricity consumption profile by scheduling the background loads such as A/Cs, refrigerators, and dehumidifiers. Likewise, authors in [27]



(a) Percentage peak reduction



(b) Percentage savings



(c) Dollar savings

Fig. 10: Customer gains vs. variation in battery capacity

define the notion of household appliance elasticity and use this to reduce peak demands by solving an optimization problem. Authors in [Smart thermostat] propose to intelligently adjust the AC temperature set point to cut power draw from the grid during peak demand intervals. Our work does not schedule the home appliances or modify their operation in any way. The peak shaving and bill reductions are achieved by intelligently combining energy storage, solar harvest, and grid energy under the given pricing plan.

There has also been work combining energy storage and renewable harvest at homes, e.g., [19] proposes to combine renewable harvest and energy storage to cut home's electricity bills; [19] essentially cuts bills by storing cheap energy for use in high-cost intervals. GreenPeaks is fundamentally different from these approaches in that it strives to keep the home's net consumption close to its target average as opposed to shifting consumption from low-cost periods to high-cost using batteries. Authors in [16] show that profitability of storage based solar systems is significantly influenced by the location and subsidies.

The closest work to our approach is presented in [20], where authors present an online algorithm (PeakCharge) to reduce electricity costs in the presence of dynamic prices and the peak demand surcharge. However, PeakCharge only employs energy storage to achieve its goal, whereas GreenPeaks integrates both energy storage and renewable harvest into the home's consumption.

VII. CONCLUSION

In this paper we presented GreenPeaks to enhance today's net metering with intelligent energy storage to 1) effectively shave peak demands, 2) cut electricity generation costs, 3) lower user electricity bills, and 4) allow for higher renewable energy integration in the grid. GreenPeaks employs an online algorithm to intelligently satisfy the home's immediate demand using differing fractions of energy from renewable harvest, energy storage, and the grid in the presence of variable electricity pricing with peak surcharge. We evaluated GreenPeaks using real power consumption traces from homes. Our results show that GreenPeaks can lower electricity generation costs by up to 42% and cut grid-wide peak demands by up to 39%. Additionally, individual homes can save up to more than 80 ¢/day in their electricity bills.

Currently, we have devised and evaluated GreenPeaks algorithm for residential buildings. In the future, we would like to extend GreenPeaks for deployment in commercial buildings. Techniques presented in this paper may need an extension for commercial buildings as they exhibit different kind of consumption patterns, e.g., wide peaks as opposed to tall narrow demand peaks. Besides, the electricity bill savings presented in this work do not account for the cost of the battery, solar panels, labor, etc. We would like to conduct a long-term return-on-investment analysis for GreenPeaks accounting for all the costs.

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