Impacts of Solar PV, Battery Storage and HVAC Set Point Adjustments on Energy Savings and Peak Demand Reduction Potentials in Buildings

Dany Pamungkas[1,3], Manisa Pipattanasomporn[2], Saifur Rahman[2], Nanang Hariyanto[3], Suwarno[3]
[1]PT PLN (Persero), Jakarta, Indonesia
[2]Virginia Tech – Advanced Research Institute, Arlington, VA, USA
[3]School of Electrical Engineer and Informatics, Institut Teknologi Bandung, Indonesia
pamungkas_dg@yahoo.com

***Abstract*— This paper discusses and compares three alternatives to reduce electrical energy consumption (kWh) and peak demand (kW) in buildings, namely deployment of rooftop solar PV, battery energy storage and HVAC set point adjustments. The building model of a warehouse located in Alexandria, VA, was developed in eQUEST, and its electrical consumption was validated with metered data. To perform the overall analysis, adjustment of HVAC set points was conducted in eQUEST, while Solar PV and battery models were developed and deployed on top of the developed eQUEST building model. Overall, the method presented here can serve as a guideline for building owners to analyze energy savings/peak demand reduction alternatives, of which benefits are varied from buildings to buildings based on building sizes, electricity tariffs, climate zones and building operation.**

***Index Terms*— battery storage, energy savings, HVAC control, peak demand reductions, solar PV.**

I. INTRODUCTION

Total electrical energy consumed in the U.S. commercial sector reached 1,367,191 kWh in 2016, or 36.3% of the total U.S. electrical consumption [1]. Commercial customers are defined as buildings used for education, food sales, health care, lodging, mercantile, office, public assembly, warehouse and storate, etc. According to [2], electric utility revenues from the sales of electrical energy to commercial customers come from energy charges (72%), demand charges (25%) and customer charges (3%). Demand charges –the maximum customer kW usage achieved monthly– have become one of the key components that must be considered beside the energy charges.

Customers can implement several alternatives to reduce their monthly electricity bills, such as deploying rooftop solar PV to lower their peak demand, using battery energy storage to shift the use of electrical energy from on-peak to off-peak periods, or increasing the HVAC set points during the peak period. A solar PV system can be deployed with or without battery energy storage. Solar PV without battery is suitable for buildings that have peak demand during the day [3]. This is in contrast to the solar PV with battery where the PV power output can be stored in the battery and used when needed [4]. Battery storage is another alternative to reduce building peak demand. Battery is typically used for peak shaving and load shifting. Authors in [5] present a peak-shaving method using battery energy storage. Authors in [6] discuss a battery storage control strategy to compensate the differences of electricity price between on-peak and off-peak periods. Adjustment of HVAC set point is the other alternative that can manage energy consumption in buildings [7]. Authors in [8] develop optimization techniques to reduce the HVAC electrical energy consumption where the objective function is to minimize peak energy consumption.

Most researchers analyze the benefits of deploying supply-side alternatives (i.e., solar PV and/or battery storage) in buildings without taking into account the demand-side alternative (i.e., adjusting HVAC set point). Focusing on this issue, this paper discusses the impact of solar PV, battery storage, and HVAC temperature control on energy savings and peak demand reductions in a building. Research findings become recommendations for the building owner in selecting the best option(s) to reduce the building's electricity bills.

II. BUILDING MODEL DEVELOPMENT USING EQUEST

Under this work, a building model is developed using eQUEST [9] – a building energy simulation software – to simulate hourly building electrical load profiles.

A. Building Description

A commercial building used as office, storage, and warehouse is modeled in this analysis to represent the use of electrical energy of a commercial customer. The total building footprint area is 8,991 sqft. The building construction blueprints indicating wall/roof materials, building footprint, floor-to-ceiling heights, as well as specific details on building schedules, HVAC unit sizes, load densities and monthly electricity bills have been gathered from the building owner. The building is located in Alexandria, Virginia, U.S., and is served by Dominion Energy on the GS-2T (30 kW - 500 kW) electric tariff schedule, which is a Time-of-Use (ToU) rate [10].

B. Building Loads and Building Operation

The electrical load in this building consists of lighting, air conditioning and office equipment. The HVAC thermostat set point is set at 74°F during occupied hours and 80°F during unoccupied periods. The building operates from

Monday to Friday between 06:00 and 18:00, and on Saturdays between 06:00 and 12:00. Based on monthly electricity bills obtained from the building owner, seasonal variation can be observed, where the building energy consumption varies throughout the year. Monthly energy consumption in winter months is about 4 MWh, while that in summer months is as high as 9 MWh.

C. *eQUEST Building Modelling*

eQUEST is used to develop the model of the above building. Output of eQUEST is the hourly building energy use. Fig. 1 depicts the 3D model of the building developed in eQUEST.

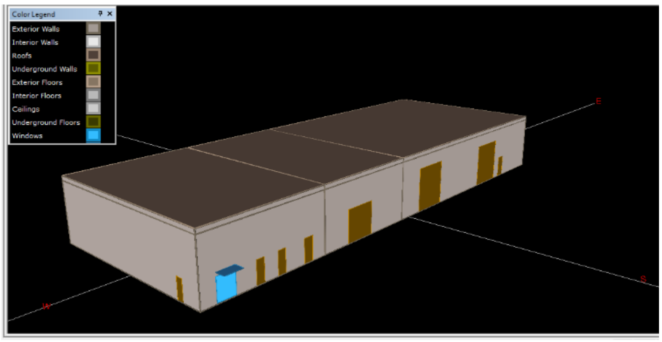


Figure 1. eQUEST building model.

The building model development uses the following information as inputs: building footprint/dimensions, building wall/roof/window/door materials, details of HVAC systems, load densities of electrical equipment, as well as building occupancy and building operation. In addition, weather data at the building location (Alexandria, VA, USA) are also used as the input to the eQUEST model. Several adjustments on the schedule of electrical equipment in the building are conducted so that the demand and energy consumption values of this building model are close enough to the building's monthly electricity bills. The output of the developed eQUEST building model, i.e., the building load profile during a one-year period, is depicted in Fig. 2.

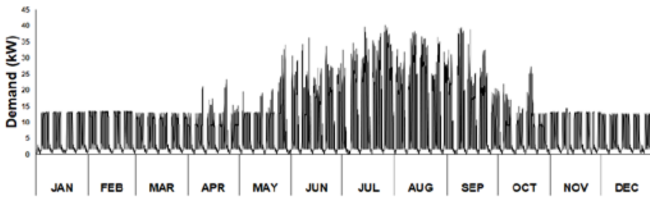
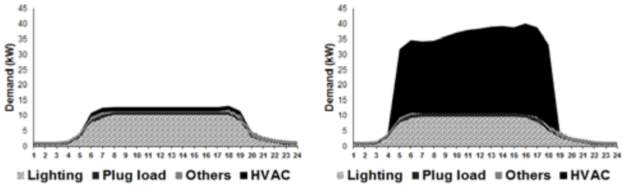


Figure 2. Simulated load profile for the period of one year (output from the building model developed in eQUEST).

As shown, the peak electrical demand reaches 40 kW in July. The lowest demand happens on weekends and holidays. It can be seen that the building electrical energy consumption in summer is higher compared to that in winter. This is contributed by the energy used by the building cooling system, which results in high building peak demand (kW) and high building energy consumption (kWh) on summer weekdays. Fig. 3 depicts a comparison between the electrical energy consumption of this building by load type on a winter weekday (January 12th) and a summer weekday (July 26th).

D. *Building Model Validation*

To validate the developed building model, the energy consumption of the simulated building model is compared to the building's monthly electricity bills. This comparision is illustrated in Fig. 4. As shown, the simulated monthly building energy consumption is deviated from the actual monthly building energy consumption by less than 5%. Hence, the developed building model is considered a good representative of the actual building.



(a) (b)

Figure 3. Building load profiles on : (a) January 12th and (b) July 26th.

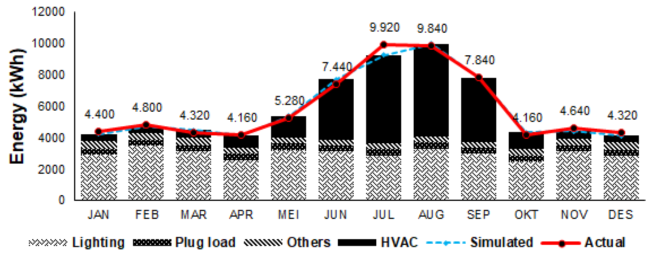


Figure 4. Comparison of the simulated monthly electricity consumption and the actual consumption from electricity bills.

III. Sizing And Operation Of Solar PV, Energy Storage Units And Method For HVAC Set Point Adjustment

In this section, sizing of solar PV and energy storage units, together with their operating strategies, are discussed. The method for HVAC set point adjustment is also described.

A. *Rooftop Solar PV*

Polycrystalline solar PV is selected for this analysis as it is the most common PV type on the market with good efficiency and good prices [11]. The usable building roof area for PV installation is calculated to be 3,528 ft2 assuming that the rooftop available area reduced by the space support equipment for the solar panel [12].

Variable solar energy data come from two sources: (i) the global horizontal irradiance (W/ft2) taken from NASA [13]; (ii) and the annual solar insolation in one-hour intervals (W/ft2) taken from National Renewable Energy Laboratory [14]. The former is used to detemine the installed power capacity of the PV generator. The latter is used to determine the PV energy generation during a one-year period.

Based on the following information: the solar catchment area (3,528 ft2), polycrystalline modul efficiency (15%), maximum solar irradiance (0.58 kW/ft2) and several derating factor [15], the maximum installed PV capacity on this building is determined at 28.93 kW.

Using the hourly solar insolation data from NREL, the power output of the solar PV during a one-year period is illustrated in Fig. 5. As shown, the maximum PV output is 25kW in March.

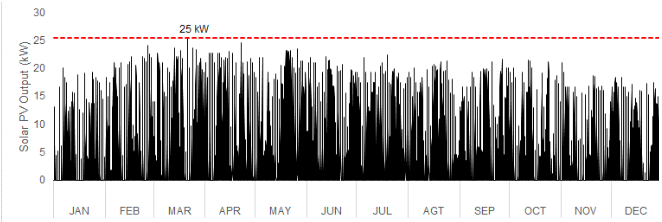


Figure 5. Hourly solar PV power output during a one-year period.

B. Battery Energy Storage

Energy storage in this analysis is of lithium-ion type. Lithium-ion battery is selected due to its popularlity and high energy density (up to 200 Wh/kg) [16].

1) Determining Battery Storage Capacity

To determine the battery capacity, firstly the demand limit value, i.e., the building demand in kW above which the battery is used for peak shaving, is determined. Typically, this demand limit level is selected at the kW level that can avoid monthly demand charge. Since the building under study does not pay for the demand charge, this study determines the demand limit level based on the percentile selection method of the total building load duration curve [17,18,19]. Specifically, this study uses 98.5 percentile selection, which implies the building load during 131.4 hours (1.5%) out of 8760 hours is supplied by the battery [19]. At 98.5 percentile, the demand limit value of this building is 34.07 kW as shown in Fig. 6.

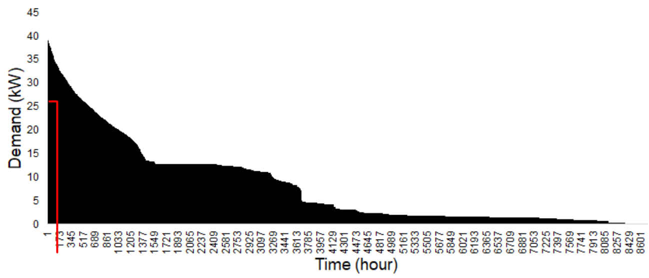


Figure 6. Demand limit selection on the building load duration curve at 98.5 percentile.

The next step is to determine the capacity of the battery using the failure plot [17]. The failure plot takes into account the number of days in a year when the battery capacity is insufficient to perform its peak shaving function. In this study, the failure plot is generated by determining the battery energy capacity (kWh) needed to perform peak shaving given the peak shaving level (kW) and the number of days in a year that the batery capacity is not sufficient for peak shaving, i.e., failed day. With a fixed number of failed days, the peak shaving level (x-axis) is varied to obtain the corresponding battery energy capacity (y-axis), of which the relationship is represented by each contour graph as shown in Fig. 7.

This study assumes that there is one day that batery capacity is not sufficient for peak shaving. Based on this information and the demand limit value selected (i.e., 34.07), the required battery capacity is determined at 38 kWh as illustrated in Fig. 7. According to [19], typical battery state-of-charge (SOC) is between 20% - 100%, or 80% of the total battery capacity. Hence, the required battery capacity is 38 kWh/0.8 = 47.5 kWh.

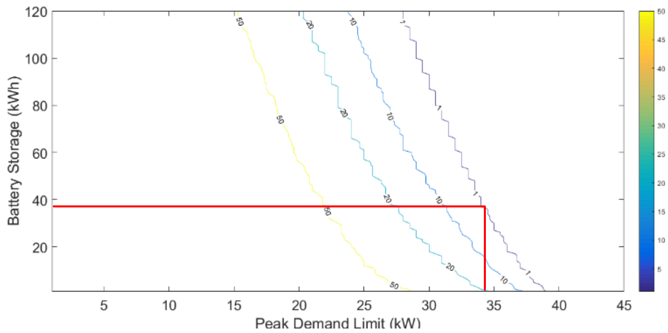


Figure 7. Failure plot of battery storage.

2) Battery Charge/Discharge Strategies

Two battery charge/discharge strategies are considered, namely the TOU-based linear optimization method [8] and the optimal peak load shaving method [7]. Note that this study assumes that battery discharge occurs only on peak days (i.e., weekdays) to reduce the number of roundtrip charge-discharge operation that may impact battery life.

- *TOU-based Linear Optimization Method*

Based on [7], the optimization problem of storage battery operation is formulated as shown in (1). This is to maximize the difference between the cost savings from peak shaving and the cost of electricity difference during off-peak charging and on-peak discharging the battery.

$$\max\left(\sum_h p_{utility,h}\times q_{psd,h}\right)-\left(\sum_h p_{utility,h}\times q_{psc,h}\right)-\left(\sum_h p_{utility,h}\times q_{utility,h}\right)\forall h$$

(1)

where,

$p_{utility,h}$: Electricity price in hour h ($/kWh)
$q_{psd,h}$: Battery discharge amount in hour h (kWh) during on-peak periods
$q_{psc,h}$: Battery charge amount in hour h (kWh) during off-peak periods
$q_{utility,h}$: Consumption from the utility in hour h (kWh)

- *Optimal Peak Shaving Method*

For each day, the optimal peak shaving level is determined according to (2). The objective function is to minimize the difference between the battery capacity and the battery energy used during charging/discharging daily.

$$\min\left|C_{batt}-\int_{t_0}^{t}(L(t)-x)dt\right|;\ \text{for } L(t)>x$$

(2)

where,

C_{batt} : Battery capacity (kWh)
x : Daily optimal peak shaving level (kW)
$L(t)$: Building load at time t (kW)

C. HVAC Set Point Adjustments

The impact of HVAC temperature set point adjustments on building electricity consumption is determined using the developed eQUEST building model. This is carried out by gradually increasing the set point by 1°F increment from 74°F (base case) to 77°F during the occupied hours. The 77°F limit is referred to the ASHRAE comfort diagram [20].

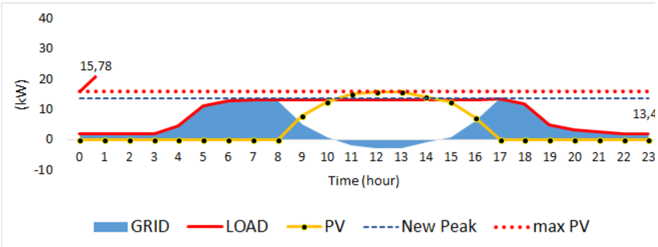
IV. Energy Savings And Peak Demand Reduction Potentials With PV, Battery And HVAC Control

Each of these alternatives is deployed separately on the building model. This section discusses energy savings and peak demand reductions in the building after deploying these alternatives.

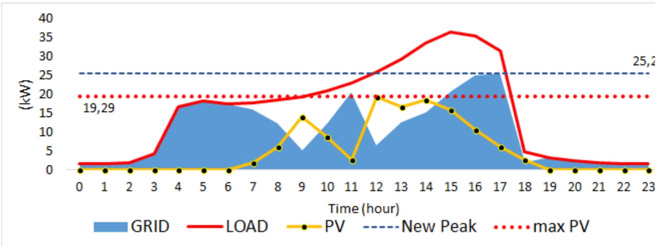
A. Solar PV Deployment

1) Impact on Daily Building Load Profiles

Solar PV output (discussed in Section III) is treated as negative load of the developed eQUEST building model. Fig. 8 illustrates the net building load after subtracting the PV output on a winter weekday (January 12th) and a summer weekday (June 10th).



(a)



(b)

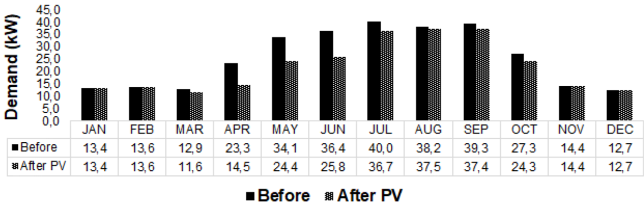
Figure 8. Net building load profile with PV on: (a) January 12th and (b) June 10th.

It can be seen that daylight hours affect the duration of solar PV power output, which is longer in Summer as compared to Winter. For example, as shown in Fig. 8(a), the PV power output duration on January 12th is from 10:00 – 17:00 (7 hours), while as shown in Fig. 8(b) June 10th, it starts from 08:00 – 19:00 (11 hours). This power output duration affects the total energy supplied by solar PV to the building, accordingly reducing daily building energy consumption.

As shown in Fig. 8(b), solar PV has its maximal power power output of 19.29 kW in the afternon at 13:00. Hence, the deployment of solar PV also reduces daily peak demand of the building.

2) Impact on Monthly Peak Demand Reductions

Fig. 9 compares the monthly maximum peak demand with and without the 28.93 kW PV unit. It can be seen that with the deployment of solar PV, the monthly peak demand reductions are found in April through October. The largest peak reduction occurs in the month of June at 10.6 kW, while no peak demand reduction is observed in January, February, November and December. The reason is the building has a morning peak in winter months and the solar PV fails to perform peak demand reduction in this condition as shown in Fig. 10.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Before	13,4	13,6	12,9	23,3	34,1	36,4	40,0	38,2	39,3	27,3	14,4	12,7
After PV	13,4	13,6	11,6	14,5	24,4	25,8	36,7	37,5	37,4	24,3	14,4	12,7

Figure 9. Monthly maximum peak demand with and without solar PV.

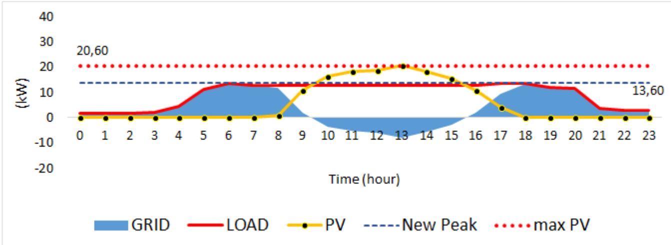
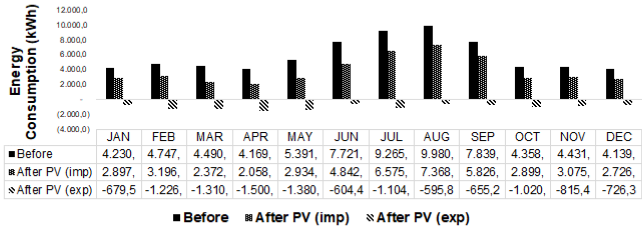


Figure 10. Net builidng load profile with PV on a winter day (February 19th).

3) Impact on Monthly Energy Savings

Energy consumption reduction after solar PV deployment varies each month, depending on the monthly solar PV power output and the building demand. Fig. 11 shows monthly building energy consumption with and without the 28.93kW solar PV.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Before	4.230,	4.747,	4.490,	4.169,	5.391,	7.721,	9.265,	9.980,	7.839,	4.358,	4.431,	4.139,
After PV (imp)	2.897,	3.196,	2.372,	2.058,	2.934,	4.842,	6.575,	7.368,	5.826,	2.899,	3.075,	2.726,
After PV (exp)	-679,5	-1.226,	-1.310,	-1.500,	-1.380,	-604,4	-1.104,	-595,8	-655,2	-1.020,	-815,4	-726,3

Figure 11. Monthly building energy consumption with and without solar PV.

As shown, with the deployment of PV, there are both energy imported from the grid (denoted as 'imp') and energy exported to the grid (denoted as 'exp'). Exporting energy occurs when the PV output exceeds the building load, which usually happens on low power consumption days, such as weekends and holidays. On such days, the PV output may exceed the building load, and thus exporting to the grid. An example is shown in Fig. 12 on Saturday August 27th.

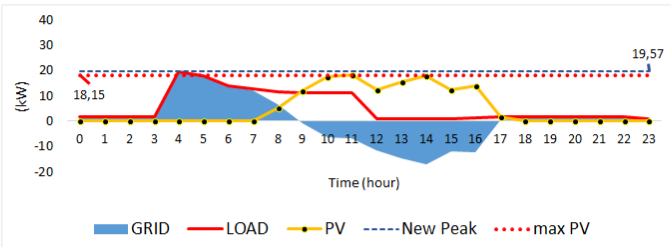


Figure 12. Net builidng load profile with PV on Saturday August 27th, showing energy exported to the grid.

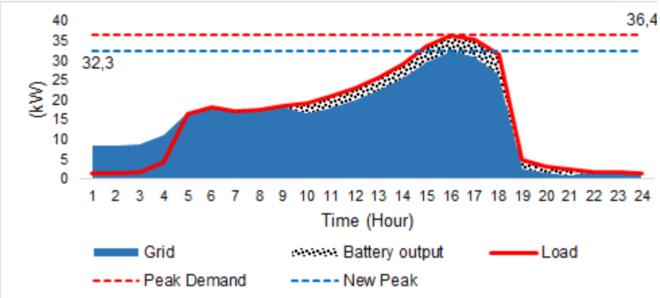
B. Battery Energy Storage Deployment

Two battery charge/discharge strategies discussed above are examined to evaluate the impact of battery storage on daily building load profiles, monthly peak demand reductions and monthly energy savings.

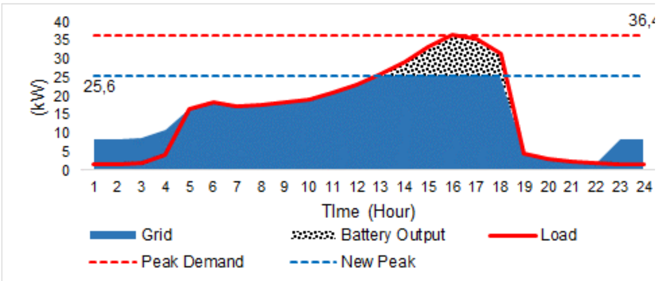
1) Impact on Daily Building Load Profiles

TOU-based Linear Optimization Method: Using (1), Fig. 13(a) illustrates the building load with battery operation on June 10th, depicting the impact of battery charge/discharge using the TOU-based linear optimization method. As shown, the charging of battery storage occurs between 23:00 and 04:00. The discharge process starts during the on-peak period between 10:00 and 22:00 in Summer (June – September) and between 07:00 and 22:00 in Winter (October – May). This follows the TOU period specified in GS-2T electricity tariff schedule. It can be seen that on this day the building peak demand with battery decreases from 36.4 kW to 32.3 kW (4.1 kW reduction).

Optimal Peak Shaving Method: Using (2) the optimal peak shaving level is determined and the battery operates to shave the building peak above this level. Fig.13(b) illustrates that the battery starts to discharge process at 13:00 when the building load exceeds the optimum peak shaving level of 25.6 kW. At 18:00 the battery storage stops discharging when the SOCmin battery is reached. The battery charges during the night time between 23:00 and 04:00. It can be seen that with the optimal peak shaving method the building peak demand decreases from 36.4 kW to 25.6 kW (10.8 kW reduction).



(a)

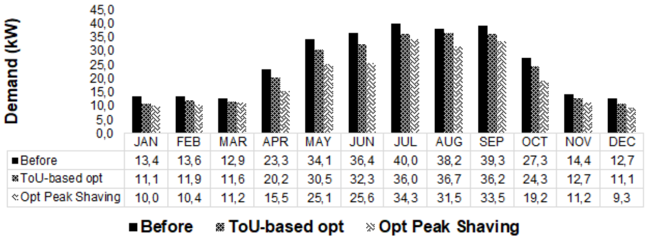


(b)

Figure 13. Net builiding load profile with battery storage on June 10th, using two different discharging strategies: (a) the ToU-based linear optimization method; and (b) the optimal peak shaving method.

2) Impact on Monthly Peak Demand Reductions

The monthly peak demand reductions as a result of battery deployment using two battery discharging strategies are illustrated in Fig. 14.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Before	13,4	13,6	12,9	23,3	34,1	36,4	40,0	38,2	39,3	27,3	14,4	12,7
ToU-based opt	11,1	11,9	11,6	20,2	30,5	32,3	36,0	36,7	36,2	24,3	12,7	11,1
Opt Peak Shaving	10,0	10,4	11,2	15,5	25,1	25,6	34,3	31,5	33,5	19,2	11,2	9,3

Figure 14. Maximum Peak Demand after battery storage deployment.

ToU-based Linear Optimization Method: From Fig. 14, the level of reductions is quite significant for the TOU-based linear optimization method in June (i.e., from 36.4 kW to 32.3 kW, a 4.1 kW reduction) and July (i.e., from 40.0 kW to 36.0 kW, a 4.0 kW reduction).

Optimal Peak Shaving Method: From Fig. 14, the monthly peak demand reductions using the optimal peak shaving method is much higher than the reductions using the TOU-based linear optimization method. The highest reduction is found in June, where the peak load reduces from 36.4 kW to 25.6 kW (a 10.8kW reduction).

3) Impact on Monthly Energy Savings

There observes is a small increase in monthly building energy consumption after deploying the battery storage. This is the effect of battery round trip efficiency, which is assumed 93%.

C. HVAC Set Point Adjustments

The base case HVAC set point of the building energy simulation model is at 74°F during the occupied period. In this analysis, the set point is increased by 1°F increment from 74°F to 77°F to evaluate the impact of HVAC set point adjustments on building energy consumption.

1) Impact on Daily Building Load Profiles

After the HVAC set point adjustment is performed, the building load is reduced compared to the base case condition. Fig. 15 illustrates the impact of this HVAC set point adjustment on July 6th. The building peak demands reduce from 34.6 kW to 34.1 kW, 33.4 kW, and 32.7 kW for the HVAC set point adjustments of +1°F, +2°F and +3°F, respectively.

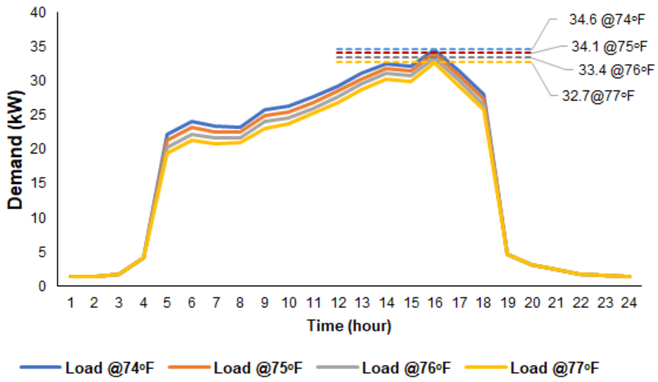


Figure 15. Building load profiles on July 6th with HVAC set point adjustments.

2) Impact on Monthly Peak Demand Reductions

HVAC set point adjustments have impact on the monthly peak demands, as shown in Fig. 16. The monthly peak demand reductions are dominant when HVAC is running in a cooling mode, especially between April and November.

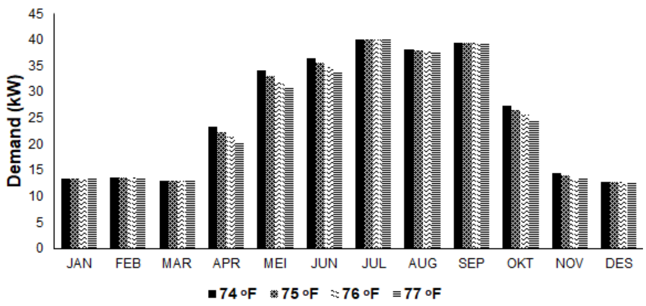


Figure. 16. Building monthly peak demands with HVAC set point adjustment.

Notice that the increase in HVAC set point results in noticable reductions in the building peak load during shoulder seasons (i.e., in April, May, June, October and November). This is because outdoor temperature is not as high in these months, hence the HVAC set point increase results in reduction in HVAC consumption, and subsequently building peak load reduction.

As the outdoor temperature is high in August, the increase in HVAC set point only results in slight reduction in the building peak load. The reason being HVAC has to operate even with the increase in HVAC set point. It is also observed there is no peak savings in July due to HVAC set point adjustment. This is because the high outdoor temperature in July which requires HVAC to operate almost all the time.

3) Impact on Energy Savings

The total annual electrical energy consumption at various HVAC set point adjustments is shown in Table I.

TABLE I. HVAC SET POINT ADJUSTMENT AND ANNUAL ENERGY CONSUMPTION

Thermostat Set Point (°F)	**HVAC Energy Consump. (kWh)**	**Reduction (%)**	**Building Energy Consump. (kWh)**	**Reduction (%)**
74	25,179.14		70,765.02	
75	24,169.35	-4.0	69,620.35	-1.6
76	23,143.37	-8.1	68,729.26	-2.9
77	22,105.65	-12.2	67,691.52	-4.3

As shown, savings in the building energy consumption is obtained with the increase of HVAC set point. Generally speaking, increasing the thermostat set point by 1°F reduces HVAC consumption by roughly 4%, and the building consumption by roughly 1.5% over a one-year period.

D. Summary of Annual Peak Demand Reductions and Energy Savings by Deploying Three Alternatives

All three alternatives result in peak demand reductions and energy savings in the building, as summarized in Table II. The solar PV option and the battery storage option with the optimal peak shaving charge/discharge strategy provide the highest building peak demand reductions, i.e., roughly 10.6kW reduction from the building peak of 34.6 kW in June, compared to the other alternatives.

TABLE II. COMPARISON OF ANNUAL PEAK DEMAND REDUCTIONS AND ENERGY SAVINGS

Method	**Maximum Peak Demand Reduction (kW)**	**Annual Energy Reduction (kWh)**
Solar rooftop PV 28.93 kW	10.6 (Jun)	23,992.0
Battery storage system (i) ToU-based Linear optimization (ii) Optimal peak shaving	 4.1 (Jun) 10.8 (Jun)	 -715.05 -715.05
HVAC control (thermostat set point increases from 74°F to 77°F)	3.24 (May)	3,073.5

With respect to energy savings, the highest reduction is found with the deployment of the solar PV alternative. The PV option reduces the annual energy consumption by 23,992kWh from 70,765kWh, a 33.9% reduction. The battery energy storage deployment increases the energy consumption by 715kWh, a 1% increase. Lastly, the 3°F increase in HVAC set point decreases the building annual energy consumption by 3,073.5kWh, or 4.3%.

V. FINANCIAL ANALYSIS

So far, the analysis indicates that all three alternatives reduce building peak demand and energy consumption. This section discusses financial analysis, considering the investment and recurring costs of solar PV/battery storage, as well as electricity bill reductions to quantify the Net Present Values (NPV) and payback periods for the three alternatives.

A. Assumptions

1) Electricity Tariff

For this analysis, the Dominion Energy's GS-2T tariff schedule is used. Under this schdule, on-peak hours are from June 1st to September 30th beween 10:00 and 22:00, Mondays through Fridays; and from October 1st to May 31st between 07:00 and 22:00, Mondays through Fridays. Off-peak hours is the time period other than on-peak hours.

The PV energy purchase price used in this study is the Dominion Energy’s Solar Purchase Price of 15 ¢ per kWh [10]. This is a special tariff rate for commercial customers who own solar PV with a capacity of less than 50 kW.

2) Installation and operational cost

Assuming that the installation costs of solar PV is $1.62/watt [22], therefore the total investment cost is $46,867 for the 28.93kW solar PV. The operational and maintenance (O&M) costs are $14/kW per year while the inverter replacement is $90/kW every 10 years [21]. In this discussion, it is assumed that the lifetime of the solar PV is 30 years [21].

The installation cost for 47.5 kWh battery energy storage is $108,526 [23]. In addition to the investment cost, the recurring costs are assumed at $294.8 per year [23] and the replacement of battery every 11 years at $244/kWh [24]. These assumptions are summarized in Table III.

TABLE III. ASSUMPTIONS ON FINANCIAL ANALYSIS OF THE THREE ALTERNATIVES

Parameter	**Solar PV**	**Battery energy storage**		**HVAC** adj. (to 77°F)
		ToU-based linear opt.	Opt. peak shaving	
Cost : (i) Investment ($)	46,867	108,526	108,526	-
(ii) O&M per year ($)	405.0	294.8	294.8	-
(iii) Equipment replacement ($)	5,207	23,180	23,180	-

3) Economical parameter

To perform the financial analysis, the interest rate and inflation rate are required. The interest rate is assumed at 4.9% while the inflation rate is assumed at 2.5%. In this discussion, these values are applied when performing the breakeven calculation.

B. Electricity Bills Reductions

Based on the building electricity tariff schedule and the monthly electricity consumption discussed above, annual electricity bills are calculated when PV, battery and HVAC set point changes are individually deployed in the building. The savings in annual electricity bills when deploying these alternatives are summarized in Table IV.

- With the solar PV option, the annual electricity bill decreases from $7,925.3 to $4,140.0 ($3,785 or 47.8% reduction) after deploying the solar PV.
- With the battery storage option, the annual electricity bill decreases from $7,925.3 to $7,395.0 ($530.3 reduction) for the ToU-based linear optimization method and decreases from $7,925.3 to $7,055.4 ($869.9 reduction) for the optimal peak shaving method.
- With the HVAC adjustment, the electricity bill reduction depends on the increase in temperature set point. For example, raising HVAC set point from 74°F to 77°F reduces the annual electricity bill from $7,925.2 to $7,609.6 ($315.6 reduction).

C. Break Even Analysis

Table V summarizes the 30-year NPV analysis, and the payback period of all three alternatives. As shown, the 30-year NPV of this rooftop solar is $26,166, while that of the battery (ToU-based and optimal peak shaving strategies) and HVAC adjustment options are $-114,151, $-106,551, $7,062, respectively. The negative NPV means there is no benefit gained on the battery energy storage deployment. The costs paid for investment and maintenance operations are not covered by the benefits gained.

Regarding the payback period, it takes 17 years to achieve a breakeven condition with the 28.93 kW solar PV. The HVAC set point adjustment option directly provides benefit from Year 1 since there are no installation and investment costs to deploy this alternative.

TABLE IV. ELECTRICITY BILLS REDUCTIONS WITH SOLAR PV, BATTERY AND HVAC SET POINT ADJUSTMENTS

Parameter	**Solar PV**	**Battery energy storage**		**HVAC** adj. (to 77°F)
		ToU-based linear opt.	Opt. peak shaving	
Benefit: Annual bill savings ($)	3,785	530	869.9	315.6

TABLE V. NET PRESENT VALUES (30-YEAR ANALYSIS) AND PAYBACK PERIOD

Parameter	**Solar PV**	**Battery energy storage**		**HVAC** adj. (to 77°F)
		ToU-based linear opt.	Opt. peak shaving	
NPV ($) (30-year analysis)	26,166	-114,151	-106,551	7,062
Payback period (years)	17	-	-	1

VI. CONCLUSION

In this paper, analysis has been performed to understand how different alternatives (i.e., rooftop PV, battery storage and HVAC set point adjustment) impact building-level load profiles, monthly peak demand reductions and monthly energy savings. This paper also includes cost-benefit analysis, in particular net present values and break-event points.

Research findings indicate that, for this office/warehouse building, while deploying the rooftop solar PV and adjusting HVAC set points provide the reduction in both electrical energy consumption and peak demand, battery storage deployment decreases the building peak demand but resulting in an increase in total kWh consumption. Due to the reduction in day-time electricity consumption, solar PV provides the largest reduction in electricity bills (47%). This is followed by battery energy storage (11%), and HVAC set point adjustment (4%). Based on the financial analysis result, the solar PV option has the breakeven point at Year 17 (with 30 years equipment lifetime). The battery storage option does not reach its breakeven point even reaching the equipment life. While HVAC set point adjustment directly provides benefits to customers from Year 1.

ACKNOWLEDGMENT

This study was supported by PT PLN (Persero) partially awarded to the corresponding author, Dany Pamungkas. The authors would like to thank faculty members at Virginia Tech - Advanced Research Institute (VT ARI) for providing guidance and facility necessary to accomplish this research.

REFERENCES

[1] U.S. Energy Information Administration, "Electric Power Annual 2016", Dec.2017.
[2] National Renewable Energy Laboratory, "How to Estimate Demand Charge Savings from PV on Commercial Buildings," September 2007 [Online]. Available: https://www.nrel.gov/docs/fy17osti/69016.pdf. Retrieved: February 2018.
[3] Al-Refai. M.A (2014). Optimal Design and Simulation of a Grid-Connected Photovoltaic (PV) Power System for an Electrical Department in University of Tripoli-Libya. *International Journal of Electrical and Computer Engineering. 8(6)*, pp 848-852.
[4] R. Hanna, J. Kleissl, A. Nottrott, M. Ferry. (2013,9). Energy dispatch schedule optimization for demand charge reduction using a

photovoltaic-battery storage system with solar forecasting. Solar Energy 103 (2014) 269–287.

[5] ABB Coorporate Research Center, Peak Shaving Control Method for Energy Storage [Online]. Available: http://www.sandia.gov/ess/EESAT/2013_papers/Peak_Shaving_Control_Method_for_Energy_Storage.pdf. Retrieved: March 2018.

[6] Udegbe. E., "Economic Modeling of The Energy Management System for A Battery-Solar Building-Integrated Microgrid: A Comparison Between Lead-Acid and Lithium-Ion Battery Systems," M.S. thesis, Dept, Energy and Mineral Eng. The Pensylvania State University. 2014.

[7] CSIRO Energy Technology, Optimal Supervisory HVAC Control: Experiences in Australia. [Online]. Available: http://docs.lib.purdue.edu/ihpbc/17. Retrieved: March 2018.

[8] Faculty of Human Life Science, Dynamic Optimization Technique for Control of HVAC System Utilizing Building Thermal Storage [Online]. Available:http://www.ibpsa.org/%5Cproceedings%5CBS1999%5CBS99_C-18.pdf. Retrieved: March 2018.

[9] DOE-2.2. Building Energy Use and Cost Analysis Program. Vol 1 : Basic. Berkeley, CA 2004.

[10] Dominion Energy, Intermediate General Service Time of Usage GS-2T [Online]. Available: https://www.dominionenergy.com/. Retrieved: November 2017.

[11] Price,G.D,"Power System and Renewable Energy, Design, Operation, and System Analysis," Momentum Press : 2014, pp. 49-80.

[12] Department of Housing and Urban Development Community Planning and Development (CPD), Renewable Energy Toolkit for Affordable Housing [Online]. Available: https://www.hudexchange.info /resources/documents/Renewable-Energy-Toolkit.pdf. Retrieved: February 2018.

[13] NASA, POWER Project Data Sets [Online]. Available: https://eosweb.larc.nasa.gov/sse/. Retrieved: February 2018.

[14] National Renewable Energy Laboratory (NREL), Solar Power Data for Integration Studies [Online]. Available: https://www.nrel.gov/grid/solar-power-data.html. Retrieved: February 2018.

[15] Nayak. C.K, Nayak. M.R. "Optimal Design of Battery Energy Storage System for Peak Load Shaving and Time of Use Pricing," Dept. of Electrical Engg. Indira Gandhi Institute of Technology, Sarang. 2017.

[16] Roberto.S, Hojgaard, H. Johan, Poul. N, "Performance and Lifetime Limiting Effects in Li-ion Batteries," Ph.D. Dissertation, Technical University of Denmark, 2016 [Online]. Available: http://orbit.dtu.dk/files/125702467/Performance_and_Lifetime_Limiting_Effects_in_Li_ion_Batteries.pdf. Retrieved: April 2018.

[17] P. Denholm and M. Hand. (2011) "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity," *Energy Policy*. 39(3). pp. 1817-1830.

[18] EPRI-DOE. Handbook of Energy Storage for Transmission and Distribution Application. EPRI. Palo Alto, CA. 2003.

[19] Leadbetter. J.C.R, "Residential Battery Energy Storage Systems for Renewable Energy Integration and Peak Shaving," M.S.thesis, Dept. Mech.Eng., Dalhousie University, 2012.

[20] Wang. S.K, "Handbook of Air Conditioning and Refrigeration" New York : McGraw-Hill, 2000. pp.161.

[21] National Renewable Energy Laboratory (NREL), Nationwide Analysis of U.S. Commercial Building Solar Photovoltaic (PV) Breakeven Conditions [Online]. Available: https://www.nrel.gov/docs/fy16osti/64793.pdf. Retrieved: February 2018.

[22] National Renewable Energy Laboratory (NREL), U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017 [Online]. Available: https://www.nrel.gov/docs/fy17osti/68925.pdf. Retrieved: February 2018.

[23] DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA, Albuquerque, CA, 2013.

[24] Turlock Irrigation District, Energy Storage Study 2014 [Online]. Available:http://www.energy.ca.gov/assessments/ab2514_reports/Turlock_Irrigation_District/2014-10-28_Turlock_Irrigation_District_Energy_ Storage_Study.pdf. Retrieved: April 2018.