Optimal Investment Strategy in Photovoltaics and Energy Storage for Commercial Buildings

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Abstract—In order to attain higher degrees of energy efficiency and lower energy consumption costs, buildings stakeholders are installing local photovoltaic (PV) renewable generation and energy storage (ES). The stakeholders, however, need to determine the sizing capacity of these resources in order to economically invest. The sizing of the resources result in to investment costs, which must be economically justified for them in the long-run. This only occurs if the savings obtained from the resources surpass the investment costs. An optimization model can incorporate these criteria along with the consideration of the time value of money and various battery techno-economic parameters (e.g. life expectancy, efficiencies, and costs) to determine the optimal capacities. The results show the value of the proposed model in assisting the stakeholder investment process.

Index Terms—Investment Strategy, Energy Storage, Photovoltaic Sizing, Buildings, Capacity Sizing

I. INTRODUCTION

The energy consumption from commercial buildings account for 40% of the total carbon emission in the U.S [1]. In order to decrease emissions, investments in renewable resources, energy storage, and energy efficiency are being implemented by the public and private sectors [2]. Large number of buildings, e.g. universities, strive to minimize their consumption of energy in an attempt to minimize their electricity bill. The energy usage, however, is a necessity to maintain the comfort of the occupants. On the one hand, energy efficiency programs can be implemented but the reduction is limited because the loads in the building still must operate and consume energy. On the other hand, installation of renewable resources, such as photovoltaic (PV) panels, can decrease the net energy consumption and effectively reduce the costs incurred by the building.

PVs are an effective renewable resource for buildings because solar radiation is the highest during the daytime when building occupancy is at large and the lowest during the nighttime when occupants are less likely to be in the building. However, the prediction uncertainty of solar radiation and the fast up/down rate of power change due to blockage of the panels, e.g. clouds, make PVs difficult to integrate into existing infrastructure [3]. These issues are manageable if PVs are partnered with energy storage (ES). ES has the ability to charge energy when there is an excess and discharge at times when there is a need [2]. Therefore, the fast up/down rate of power change of PVs can be mitigated with ES acting as a load or supply when required. In addition, the uncertainty in PVs radiation prediction is also mitigated, since ES can moderate the excess and shortage of PV output. The advantages of PVs will be highly dependent on hourly, daily, and seasonal weather variations. The combined management of PVs and ES enable buildings to not only reduce their carbon emission but also reduce their costs. In order to obtain these cost savings, however, the capacity sizing of PV and ES must be determined.

The sizing of these resources have been the subject of a number of works in literature. In [4], a non-linear optimization model is developed to determine the sizing of a PV installation considering the initial investment. However, it does not consider the operations of PV in reducing demand. An optimal investment strategy to determine ES capacity is developed in [5] while considering reliability criterion. However, the investment only considers the benefits obtained from the ES without considering whether the investment will obtain a return for the stakeholder. The work in [6] determines the sizing of ES and thermal storage devices in buildings subject to technical constraints and costs. The conclusion in [6] indicated the cost of battery investment is currently too high, however, they consider only the lump-sum investment and ignore the long-run monetary benefits obtained from ES. Since these resources are long-term investments, a tool is required that not only considers the lump-sum investment, but the long-run payoff and benefits of reduced electricity costs.

This work determines the optimal sizing of PVs and ES for commercial buildings. The investments are only considered if payback is possible in the expected return on investment (eROI) horizon preset by the stakeholders. The optimization model uses time value of money analysis on the initial investment and savings obtained from PVs and ES to determine the optimal capacity. The model also considers the techno-economic parameters (e.g. life expectancy, efficiencies, and costs) of different battery technologies in order to determine the best-suited technology for the application.

The main contributions of the paper are:

- Optimization tool for the sizing of ES and PVs based on the eROI. The investment strategy is economically justified in the long-run.
- Models of different battery technologies considering their techno-economic parameters.

The rest of the paper is organized as follows. Section II describes the building entity and stakeholder, ES, and PVs. Section III explains the optimization model. Section IV discusses the results and Section V concludes the paper.
II. BUILDINGS, ENERGY STORAGE, AND PHOTOVOLTAICS

A. Commercial buildings

The stakeholders’ responsibility is to overlook the daily operations of commercial buildings and reduce energy consumption. It is in their best interest to invest in renewable resources to offset the energy consumption. This will not only reduce their energy bill but may identify the buildings as energy efficient.

In order to determine if investments in the resources are justified, the stakeholders need to determine their expected return on investment ($eROI$) time. The $eROI$ is the number of years they expect to obtain a return on investment in the ES and PV installations. This value is used in time value of money analysis, which is embedded into the optimization to determine if investing in the resources is beneficial. Depending on the value of $eROI$, e.g. a few years versus decades, the optimization model invests in different capacity of ES and PV. The stakeholders can perform the analysis using any preset value of $eROI$ to study the optimal capacity of ES and PV, type of ES technology, savings from offsetting energy consumption, and the typical ES charge/discharge schedule.

B. Photovoltaic (PV) and energy storage (ES) system

The optimization model determines the sizing of PV capacity. The model considers the PV investment cost, maximum capacity that can be installed in the buildings, and the payback time. The investment cost includes the price of PV which include the balance of system and the panel price in a per-energy basis [2]. The maximum capacity that can be installed is a function of the weight and space limitations.

To reduce the energy consumption, the ES must charge and discharge during the appropriate periods. However, to be economically beneficial, hourly differences in electricity prices are required. This will then allow buying electricity during low-price periods in order to sell during high-price periods, also known as energy arbitrage [7]. The investment decisions rely on the techno-economic parameters, such as price, efficiencies, and capacity to power ratio (CPR). The ES price includes the price of installing one kWh of capacity. The charging/discharging efficiency decreases the amount of energy the stakeholders can use for their own benefit and thus may require additional capacity to recoup the losses. Another parameter considered is the CPR, which states for each unit of energy capacity, how much power can be drawn from the batteries. For example, a 24 kWh battery with 3.3 kW power rating has a CPR = 7.3, which requires several hours in order to be fully charged because of its low-power rating. In terms of arbitrage, a lower CPR is beneficial. The model considers these parameters for different battery technologies, e.g. Lithium-Ion, Zinc Bromine, among others. The stakeholders must know the benefits of each technology to determine the specific one or many technologies, e.g. test-bed, worth investing in.

III. INVESTMENT MODEL

The investment model minimizes the investment costs by translating demand costs, total investment costs, energy arbitrage benefits, and PV benefits into a typical cost that would be expected to occur on an average day, i.e. 24 hours. By doing so, the cost savings obtained from ES and PV need to outweigh the costs on a daily basis. If this is not the case, then investing in either resource is not economically justified.

This optimization model can be formulated as follows:

\[
\text{minimize} \quad c^D + ic^{PV} + ic^{ES} - r^{PV} - r^{ES} \tag{1}
\]

In equation (1), in terms of cost, $c^D$ is the cost of supplying the power demand, $ic^{PV}$ is the PV investment cost, and $ic^{ES}$ is the ES investment cost, and in terms of revenue, $r^{PV}$ is the revenue obtained from PVs, and $r^{ES}$ is the revenue from energy arbitrage. The cost of supplying power is defined as:

\[
c^D = \Delta t \sum_{(t \in T)} \tau_t \cdot D_t \tag{2}
\]

Where $\tau_t$ is electricity tariff for time period $t$ in the set of periods $T$, $D_t$ is the demand of buildings, and $\Delta t$ is the time interval. The investments costs for PV are formulated as:

\[
ic^{PV} = \frac{c^{PV}}{365 \cdot eROI} \cdot SC \tag{3}
\]

Where $c^{PV}$ is the purchase price of PVs, and $SC$ is the optimal PV energy capacity. This equation determines the lump-sum investment of PVs and calculates into a daily cost over the horizon of the $eROI$. This same calculation is also performed for the lump-sum investment in ES systems:

\[
ich^{ES} = \sum_{(b \in B)} \frac{c^{ES}_b}{365 \cdot eROI} \cdot R_b \tag{4}
\]

Where $c^{ES}_b$ is the price of battery technology $b$ in set of technologies $B$, and $R_b$ is the optimal battery capacity. Each battery technology $b$ has a maximum cycle life which can be translated to an approximate number of years $Y_b$ [8]. This is explicitly modelled in equation (4), with $R_b = \left(\frac{eROI}{Y_b}\right)$, which determines the number of replacements that are required for the specific technology over the horizon. The energy arbitrage benefits obtained from the ES system is formulated as follows:

\[
r^{ES} = \Delta t \sum_{(t \in T)} \sum_{(b \in B)} \tau_t \cdot \left( p_{t,b}^{dsg} \cdot \eta_b^{dsg} - p_{t,b}^{chg} \right) \tag{5}
\]

Where $p_{t,b}^{dsg}$ and $p_{t,b}^{chg}$ are the charge and discharge powers for each battery technology $b$, respectively, and $\eta_b^{dsg}$ is the discharge efficiency. In order for the battery to discharge and sell energy to the grid, prior charging must occur. However, buying energy to charge batteries is a cost and thus arbitrage only occurs if economically beneficial. On the other hand, the PVs energy output can be sold to the grid or be used to offset the consumption of the buildings as shown in equation (6):

\[
r^{PV} = \Delta t \sum_{(t \in T)} \tau_t \cdot (SC \cdot \alpha_t) \tag{6}
\]

In equation (6), the per-unit PV output $\alpha_t$ is a representative normalized curve for the PV production, which is then scaled by $SC$ to obtain the PV power output at each time period $t$. This is then used to determine the revenue with tariff $\tau_t$.

\[
\text{soc}_{t,b} = \text{soc}_{t-1,b} + \eta_b^{chg} \cdot p_{t,b}^{chg} \Delta t - p_{t,b}^{dsg} \Delta t \quad \forall t \in T, b \in B \tag{7}
\]

\[
p_{t,b}^{dsg} \leq \frac{BC_b}{CPR_b} \quad \forall t \in T, b \in B \tag{8}
\]

\[
0 \leq p_{t,b}^{dsg} \leq \frac{BC_b}{CPR_b} \quad \forall t \in T, b \in B \tag{9}
\]

\[
0 \leq p_{t,b}^{chg} \leq \frac{BC_b}{CPR_b} \quad \forall t \in T, b \in B \tag{10}
\]
The objective function in (1) is subject to several constraints. Constraints (7) to (10) manage the technical characteristics of each battery. In (7), the energy state-of-charge (SoC) \( soc_{b,t} \) in the current period is dependent on the state at the previous period, charge power, and discharge power. The SoC, however, cannot decrease below \( \beta_{b} min \cdot BC_{b} \), where \( 0 \leq \beta_{b} min \leq 1 \). Similar rationale applies in constraint (8) for the increase of the energy SoC above the maximum value. The SoC ceiling protects against the risk of setting the battery on fire and the minimum avoids rapid degradation [9]. In constraint (9), the charging power must be less than the maximum power determined by \( \frac{BC_{b}}{BC_{b}^{max}} \). Again, this same rationale applies to the discharge power in constraint (10).

The next set of constraints (11) and (12) are specific to the space and weight requirements in the location where the resources will be installed. In (11), the summation of the optimal capacities for all battery technologies cannot exceed the total allowed capacity \( BC^{total} \). In (12), the PV capacity is limited by the total allowed capacity \( SC^{total} \). These values are pre-set by the stakeholders.

\[
\sum_{b \in B} BC_{b} \leq BC^{total} \quad (11)
\]

\[
SC \leq SC^{total} \quad (12)
\]

Since investment in renewable resources must be justified economically, future value, present value, and annuity analysis are included in the optimization. It is assumed the cost savings obtain an interest rate \( i \) (e.g. from a bank) over the \( eROI \) horizon. To justify the investments, the future-value of the total savings need to exceed the future-value of the investment costs. Otherwise, it is not economically justified.

The equation to determine the cost savings annuity \( A \) translated to a future value is formulated as follows, [10]:

\[
A^{savings} = 365 \cdot (r^{ES} + r^{PV}) \left[ \frac{(1 + i)^{eROI} - 1}{i} \right]
\]

The daily typical revenue obtained from PVs \( r^{PV} \) and energy arbitrage \( r^{ES} \) is changed into a yearly revenue and then calculated to an annuity-based future value at the end of the \( eROI \) period. This represents the total estimated cost savings obtained over the \( eROI \) period. The investment costs’ future value is formulated as follows:

\[
F^{invest} = \left[ \sum_{b \in B} \left( r^{bat}_{b} \cdot BC_{b} \right) \cdot R_{b} + \left( r^{PV} \cdot SC \right) \right] (1 + i)^{eROI}
\]

Where the total investment cost of ES and PVs is translated into a future value at the end of the \( eROI \) period, while obtaining an interest rate (e.g. from a bank). In the optimization model, constraint (13) needs to hold in order for the investments to be justified, where the savings must be greater than the investments in the long-run.

\[
A^{savings} \geq F^{invest} \quad (13)
\]

A. Electricity tariffs

The investment strategy is dependent on the electricity tariffs because they determine the cost savings that may be obtained. The tariffs used in this work consist of flat prices, real-time prices (RTP), time-of-use (ToU), and high demand charge (HDC) tariffs [11]. Power utility companies use the HDC tariff, which include an energy and demand price, with commercial buildings because they have large demand peaks during the workday (i.e. peak periods) and minimal demand during the night (i.e. offpeak periods) [12]. This tariff encourages power reduction. On the other hand, RTP represents the behavior of prices at the wholesale market plus an additional profit margin for the utility. ToU tariffs usually have a low-price and a high price block, however, multiple price blocks can also exist, and flat tariffs are not time-dependent.

The flat, RTP, ToU tariffs use objective function (1) subject to constraints (7)-(13). However, the HDC tariff model is formulated as follows:

\[
\text{minimize } c^{D} + i c^{PV} + i c^{ES} - r^{PV} - r^{ES} + \tau^{peak} \cdot p^{peak} + \tau^{offpeak} \cdot \sum_{h \in T} p^{offpeak}
\]

Subject to:

Constraints (7) - (13)

\[
p^{peak} \geq D_{n} - \sum_{(b \in B)} p^{dng}_{b,n} \quad \forall n \in T
\]

\[
p^{offpeak}_{b} \geq D_{h} - p^{peak}_{b} - \sum_{(b \in B)} p^{dng}_{b,h} \quad \forall h \in T
\]

The power price is separated into off-peak periods \( h \in T \) and peak periods \( n \in T \). Each off-peak period where the power \( p^{offpeak}_{h} \) is greater than the peak power \( p^{peak} \) incurs a penalty priced at \( \tau^{offpeak} \). Objective function (14) has two terms representing the power charges. The first term shows the peak power cost with tariff \( \tau^{peak} \) and the second is the off-peak power cost with tariff \( \tau^{offpeak} \). The HDC tariff model is subject to constraint (16), which determines the maximum power consumption during the peak time periods \( n \). During these peak periods, the ES system can discharge and reduce the maximum consumption. The off-peak power is determined by constraint (17). This determines the additional power on top of \( p^{peak} \). Similar to constraint (16), the ES system can also reduce the off-peak power by discharging.

IV. CASE STUDY

In order to represent typical tariffs, historical data from the Pennsylvania-Jersey-Maryland (PJM) market was used [13]. The typical RTP tariff \( \tau_{n} \) was obtained using the K-means clustering approach [14], which determines a profile that best characterizes the historical data and is shown in Figure 1a. The ToU tariff was adjusted according to the RTP and is also shown in Figure 1a. The flat tariff was the average of the RTP at 50.7 $/MWh. The HDC tariff has an off-peak energy price \( \tau_{h} = 43.2 $/MWh \), peak energy price \( \tau_{n} = 63.8 $/MWh \), off-peak demand charge \( \tau^{offpeak} = 260 $/MW \), and peak demand charge \( \tau^{peak} = 980 $/MW \) [12]. The off-peak periods are between 0000 to 0545 and 2215 to 2400 hrs, and the peak periods are between 0600 to 2200 hrs.

The historical demand data was obtained from University of Washington’s smart meter [15] for a subset of buildings and a typical curve \( D_{t} \) was created using clustering (Figure 1b). The same clustering approach was applied to obtain the typical photovoltaic per-unit output \( \alpha_{t} \) as shown in Figure 1b with historical data obtained from [16].

Table I summarizes the values of the battery parameters.
ToU, PV output, and space limitations. The optimization was performed over capacities and the maximum SoC is \( \beta \) due to weight. By investing in renewable resources, cost savings may be obtained. The technologies used in the model include Lithium-Ion (Li-ion), Sodium Sulfur (SS), Advance Lead Acid (ALA), Zinc Bromine (ZB), Nickel Cadmium (NC), Vanadium Redox (VR), and recycled electric vehicle (rEV) batteries. The rEV are based on the Li-Ion technology with more frequent replacement time \( Y_b \) and their reduced capacity \( \beta \). For each battery, the minimum SoC was enforced to be \( \beta_{min} = 0.15 \) of the optimal battery capacities and the maximum SoC is \( \beta_{max} = 0.95 \). The price of PV \( p_{PV} \) is \( [800 \ 600 \ 500 \ 400] \) $/kWh representing future advancement of technology. The maximum allowable capacity for PV and ES was 100 kWh each due to weight and space limitations. The optimization was performed over 96 periods of 15-minute (\( \Delta t \)) each. The interest rate \( i \) was 5% compounded yearly \( [20] \). The model is a linear program (LP) implemented in GAMS 24.0 and solved using CPLEX \([21]\).

### A. Impact of tariffs on the investment strategy

By investing in renewable resources, cost savings may be obtained by either off-setting the energy consumption or by selling energy directly to the grid. However, the savings depend on the tariff structure the stakeholders are under. By setting the stakeholders’ eROI to a large horizon of 60 years, varying the PV price from 800 to 400 $/kWh representing the improvement of PV technology in the forthcoming years, and using ES parameters from Table I, the optimal PV and ES capacity is shown in Figure 2 for different tariffs. Figure 2a shows the optimal capacities under the RTP tariff, Figure 2b for the ToU tariff, Figure 2c for the flat tariff, and Figure 2d for the HDC tariff. Under RTP (Figure 2a) and ToU (Figure 2b) tariffs, no capacity investments occur for ES. This is the case because ES requires the purchase of energy during low-price periods in order to sell later to the grid during high-price periods. In this case, the price difference between low-price and high-price periods are not large enough and thus do not justify investments. On the other hand, under these same tariffs, investment in PV occur for all prices except for 800 $/kWh. Unlike ES, PV generates energy directly from the solar radiation. This then provides the cost savings which over the large eROI horizon is able to recover the investment costs. However, at 800 $/kWh the cost savings obtained are not enough and so no investments are made.

As for the flat tariff in Figure 2c, ES investments do not occur because the tariff is the same in all periods of the day and thus no arbitrage revenue can be obtained. At prices of 800 and 600 $/kWh, PV investments do not occur because the total costs are too large to be recovered. However, investments occur for 400 and 500 $/kWh because selling energy to the grid at the flat tariff allows cost recovery. The HDC tariff yields investments in both PV and ES. The HDC energy price is similar to the flat tariff and thus investments in both ES and PV do not occur for PV prices of 800 and 600 $/kWh. However, as PV technology improves and prices decrease to 500 and 400 $/kWh, investments in ES are economically justified. This is the case due to the additional demand charges in the HDC tariff, which are incurred during peak power periods. The batteries can be used to discharge and reduce the peak powers thus reducing the total incurred costs.

The results in Figure 2 show tariffs have a major impact on the stakeholders’ investment strategy. In addition, the PV price needs to be lower than 800 $/kWh for all tariffs in order to invest. The HDC tariff results in both PV and ES investments and was used to analyze the remainder of the results.

### B. Effect of eROI on the investment strategy

This section analyzes the effect on the investment strategy if the eROI is varied from 0 to 60 years with a step of 0.25 years. A low eROI shows the stakeholders want a faster return whereas a higher eROI shows they are long-term investors. Figure 3a shows optimal PV capacity as a function of the eROI for a PV price of 400 and 500 $/kWh. Any higher price of PV does not yield ES investments (Figure 2d). An eROI of 0 represents the time when lump-sum investments are made. At a PV price of 400 $/kWh, the capacity is zero for eROI < 15 years, because it is too low for a return. However, the PV capacity increases if eROI \( \geq 15 \) years, which indicates the stakeholders would obtain a return on the investment. Similar rationale applies for a PV price of 500 $/kWh, however the increase occurs later at eROI \( \geq 30 \) years because its takes more savings revenue to recover the investments.

Figure 3b show the ES capacities at a PV price of 400

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**TABLE I**

<table>
<thead>
<tr>
<th>Battery Technology Parameters</th>
<th>( C_{PV}^{b} ) ($/kWh)</th>
<th>( n_{charged/kg} )</th>
<th>( C/P R_b )</th>
<th>( Y_b ) (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-ion</td>
<td>225</td>
<td>0.90</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>SS</td>
<td>500</td>
<td>0.75</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>ALA</td>
<td>425</td>
<td>0.85</td>
<td>4</td>
<td>10</td>
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<tr>
<td>ZB</td>
<td>290</td>
<td>0.60</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>NC</td>
<td>300</td>
<td>0.65</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>VR</td>
<td>620</td>
<td>0.65</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>rEV</td>
<td>150</td>
<td>0.90</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

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**Fig. 1.** RTP and ToU tariff in (a), and demand and PV profile in (b).

**Fig. 2.** (a) Energy capacity for ES and PV under RTP, (b) ToU, (c) flat, and (d) HDC tariffs with varying PV prices.
Li-ion batteries are a better investment. However, due to the overall increase in costs. The ES investments require $/kWh. Unlike Figure 3b, VR battery investments do not occur due to overall increase in costs. The ES investments require eROI ≥ 30 with only Li-ion being justified.

Li-ion technology yields investments due to its high efficiency, high lifetime, and relatively low price. As for VR batteries, they have a high lifetime and low CPR, however, due their high price they are not justified for replacements in the long-run. Even though recycled EV batteries are based on Li-ion technology, they do not yield investments. This is the case because of the replacement time of 5 years as compared to a new Li-ion battery of 15 years and thus it is more economical to purchase new batteries. Other batteries in Table I are not worthwhile investments because their techno-economics require improvement.

V. CONCLUSION

The proposed optimization framework enables stakeholders to assess if investing in photovoltaics and/or energy storage capacity is economically justified in the long-run. The stakeholders set their expected return on investment time eROI representing the number of years they are willing to wait in order to recoup costs from the savings obtained from the resources. The proposed methodology incorporates time value of money, techno-economics of the resources, and electricity tariffs to determine a justified strategy.

Results show the economics of PV yield large investments in capacity. This is the case because PVs can either offset energy consumption or be sold to the grid. On the other hand, techno-economics of ES do not yield large capacity investments. With a high stakeholder eROI, e.g. 60 years, the total capacity of PV is 23.9% of the peak consumption in the buildings, whereas ES is less than 1% due to power rating limits. This occurs because ES is dependent on the structure of electricity tariffs. The ES must purchase energy during low-price periods and sell during high-price periods. Thus, if the price difference between these periods is not large enough then cost savings will not be enough to recoup investment costs. Results also show that real-time, time-of-use, and flat tariffs only enable investment in PV and not ES. However, with high demand charge tariffs, ES is beneficial to reduce the additional demand charge costs. Since tariffs are an externality for stakeholders, techno-economics must be further improved for ES investments to be justified.

REFERENCES