Energy Storage Management Strategy Based on Dynamic Programming and Optimal Sizing of PV Panel-Storage Capacity for a Residential System

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***Abstract* —In this paper, control of solar energy storage in a residential household is presented using Dynamic Programming (DP) algorithm with the objective of minimizing the overall cost of daily household load demand. The DP algorithm is designed to optimally manage the charge/discharge cycles of the household energy storage unit and maximize homeowner benefit. Moreover, the Net Present Value (NPV) is calculated and used for optimal PV panel and energy storage capacity sizing while taking into account the household load demand for different seasons and the Time-of-Use (*ToU*) electricity price. The DP based control strategy has also been compared with a heuristic control strategy which shows the superior performance of the former.**

Keywords: Energy management, energy storage, dynamic programming, Net Present Value, PV panel sizing, household load profile.

I. Introduction

With the continuing decrease in solar panel component and installation costs, solar power generation in residential applications is becoming increasingly attractive to the homeowners. The residential consumers are integrating solar power as a source of clean energy with the aim of maximizing their investment return and reducing their monthly energy cost. As a result, Photovoltaic (PV) energy is emerging as one of the most effective alternative energy options in a smart household. However, an important aspect of solar power generation is that it does not necessarily align with the household load demand. In other words, the generated peak PV power cannot be consumed by the customer effectively during daytime. On the other hand, the evening peak load demand cannot be solely met by the solar resources since solar generation is comparatively low during this time. To overcome this issue, energy storage can be added in a hybrid unit to maximize the solar power usage, however, this addition comes at a premium cost, especially, if the installed energy storage capacity is higher than the required daily needs. Thus, only a suitable combination of battery storage with the PV generation will offer the opportunity for optimal investment on a hybrid energy storage system.

Energy storage devices are typically used to smooth variations in load demand from the power grid [1]. Some proposed usage of energy storages are: ramp rate control due to power fluctuation [2], allowing users to exploit the price variations without having to shift their demand to the low-price periods [3], and regulation of grid voltage to integrate renewable energies [4]. However, from the customer's point of view, minimizing the investment cost and maximizing benefits for the overall system is the most important objective. The combination of the size of storage capacity and PV panel based on the household demand is part of the system optimization approach. In [5], the authors proposed a PV panel and storage capacity sizing method based on minimizing the back feeding power on the grid. However, they do not consider investment costs and annual savings for utilizing PV panels with storage devices.

Since Dynamic Programming (DP) ensures global minima and can be applied to both linear and non-linear systems, it has been used for capacity sizing of storage to eliminate the effect of power outages [6], unit commitment problems [7], and load regulation of households [1]. However, in these studies optimal combination of storage capacity and PV panel size based study is not considered. Taking into account the relatively high costs of battery storage and PV panels makes the optimal sizing combination of a PV panel-storage essential for ensuring the best value with optimum performance for the customer. Therefore, Net Present Value (NPV) [8] with respect to the lifetime of PV panel and storage has been utilized in this research to calculate the optimal size of a PV panel-storage hybrid system.

In this work, DP based control strategy for a smart house that includes solar energy generation with storage is proposed. DP is used to achieve maximum savings in terms of electricity purchased from the grid by controlling the storage with different combinations of PV panel sizes and storage capacities. The control strategy is also applied to load profiles of different seasons considering different Time-of-Use (*ToU*) rate structures. The DP based results are then used to calculate NPV and determine the optimal PV panel size and storage capacity combination while considering the investment cost for corresponding panel and storage. The novel contribution of this paper is to utilize DP to optimize household savings and based on the results obtained from DP, determine the optimal combination of PV panel size and storage capacity from NPV calculation.

II. Proposed Methodology

A. Problem Formulation with Dynamic Programming

A household system with a PV panel and battery storage is shown in Fig.1. To minimize the overall daily electricity purchase cost, the objective function is formulated as:

$$Minimize, J = \sum_{k=1}^{T} \left[\left(P_t - P_{PV,t} + P_{c,t} \right) * C_t \right] \quad (1)$$

$$\text{Subject to } \; -P_{c,min} \le P_{c,t} \le P_{c,max} \quad (2)$$

where J represents the objective function, C_t is the *ToU* cost at time t, P_t is considered as the day-ahead household demand,

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$P_{PV,t}$ is the solar power, and $P_{c,t}$ is the operating power of the charger for storage at time *t*. $P_{c,t}$ is positive while the storage is being charged and negative when it is being discharged within the given limits. For the state-of-charge (*SOC*) calculation of the storage, it is required to know whether it is charging or discharging [9]. The sign function *sgn* is used to represent the charging/discharging scenarios, and the SOC_t of the PV storage is calculated based on the power flow as shown below:

$$sgn = \begin{Bmatrix} 1 \ \ (P_{c,t} \geq 0) \\ -1 \ \ (P_{c,t} < 0) \end{Bmatrix} \tag{3}$$

$$SOC_t = \begin{Bmatrix} \frac{E_{b,initial}+P_{c,t}(\eta_c)_t^{sgn}\Delta t}{Q_b} \ ; t = 1 \\ SOC_{t-1} + \frac{P_{c,t}\,(\eta_c)_t^{sgn}\Delta t}{Q_b}; t > 1 \end{Bmatrix} \tag{4}$$

$$SOC_{min} \leq SOC_t \leq SOC_{max} \tag{5}$$

Here, $E_{b,initial}$ is the initial stored energy of the battery, η_c is the efficiency of the charger, and Q_b is the capacity of the battery. Since storage lifetime is considered for calculating NPV, storage degradation costs due to charging and discharging are not included in the objective function.

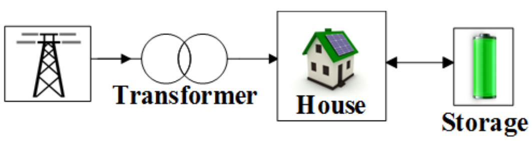


Fig. 1: Household system under study.

The problem is based on the following assumptions:

Assumption 1: The grid can only deliver power to the household. There is no back feeding of energy to the grid and no net metering compensation is provided.

Assumption 2: The storage can be charged from PV generation and it discharges only to deliver power to the household.

DP is an optimal control tool used for solving complex problems by breaking it down into sub-problems. The method uses Richard Bellman's principle and ensures global optimality [10], [11]. DP is based on Hamilton-Bellman-Jacobi (HBJ) equation. For the system of Fig. 2, the HBJ model can be written as:

$$J\big(t+1, SOC^i(t+1)\big) = \min_{soc(t+1,SOC^i(t))} \begin{Bmatrix} c\big(SOC^i(t), SOC^j(t+1)\big) \\ +J\big(t, SOC^i(t)\big) \end{Bmatrix} \tag{6}$$

In (6), *J (t, SOC^i(t))* is the optimal value obtained from the previous stage for *SOC^i(t)*. $c\left(SOC^i(t), SOC^j(t+1)\right)$ is the cost of transitioning from state SOC^i at time *t* to SOC^j at time *t+1*. The set *SOC(t+1, SOC^i(t))* defines the set of all feasible reachable points at time *t+1* on SOC^j from the current state *t*. *J (t+1, SOC^i(t+1))* is the optimal value function to go from time step *t* to next time *t+1* at SOC^j point. Therefore, the optimal point is *SOC^i(t+1)* among all possible set of *SOC^i(t))* for which the optimal value *J (t+1, SOC^i(t+1))* is obtained at point *SOC^j(t+1)*. This control strategy ensures the consideration of all possible transitions to future states to achieve cost minimization.

The solution process through DP in the context of research at hand can be visualized with the help of Fig. 2 where a three stage problem is considered for simplicity. Stage 1 defines the initial SOC where it is considered to be 0.7. While going from stage 1 to stage 2 with an increase in time, the corresponding costs are calculated for reaching different possible SOC points. A certain limit is needed to be considered for the next SOC level range based on the previous *SOC* value. To go from stage 2 to stage 3, the cost of each different possible path is calculated. For example, at stage 3 when the *SOC* is 0.7, the optimal path to reach *SOC* 0.7 is obtained by calculating and comparing the cost of all possible paths leading to *SOC* value of 0.7. Similarly, the cost for all other *SOC* points are also calculated at stage 3. Then after comparing the cost for all *SOC* points at stage 3, the point for which minimum value is obtained is determined as the most cost effective path.

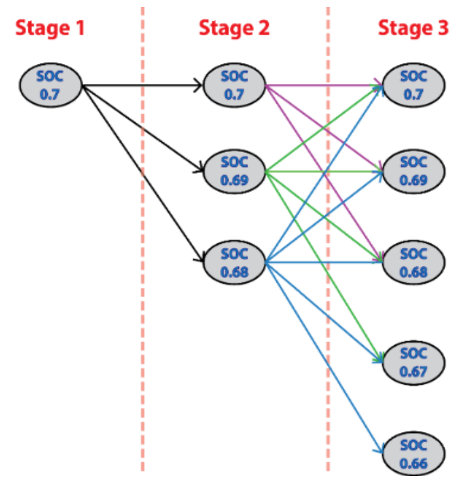


Fig. 2. Dynamic Programming with *SOC* as a state.

B. NPV based PV panel and storage sizing:

NPV is a tool used for capital budgeting to analyze the profitability of an investment. Generally, an investment with a positive NPV will be a profitable one and one with a negative NPV will result in a net loss. For the calculation of NPV, the investment cost on PV panel and energy storage, $I(Q_{PV}, Q_b)$, as well as the net annual saving from DP based control strategy, $S(Q_{PV}, Q_b)$, based on the size of PV panel, Q_{PV},and storage capacity, Q_b,are required to consider. DP based control strategy is applied to the load and PV profiles for four days of four different seasons and the obtained savings are considered as the net annual saving. From the maximum NPV, the optimal size of PV panel and storage capacity for the particular household can be found. The equation for obtaining the required optimal PV panel and energy storage can be expressed as

$$Z\,(Q_{PV}^*, Q_b^*) = \max_{Q_{PV},Q_b}\{\tfrac{S(Q_{PV},Q_b)-I(Q_{PV},Q_b)}{(1+r)^k}\} \tag{7}$$

where k is the lifetime of the PV panels in years, and *r* is the discount rate. $Z\,(Q_{PV}^*, Q_b^*)$ is the the maximum NPV which is determined for the optimal size of PV panels, Q_{PV}^*, and storage capacity, Q_b^* .

III. Simulation Results and Analysis

Simulation analysis is carried out for a typical household with a PV and storage installation to demonstrate the effectiveness of the DP technique on minimizing household cost. The parameters of the system are listed in Table I. Solar irradiance and load profiles for different seasons are shown in Fig. 3 and Fig. 4 based on the data obtained from [13] and [14]. A day-ahead scheduling is performed to determine the scheduling of the power flow of PV and storage.

Table I: System Parameters

Parameter	Value
PV panel size range	1-4 kW
Panel lifetime	20 years
Battery capacity range	0-7 kWh
Maximum operating power of the charger	1 kW
Efficiency	92%
SOC_{min}	20%
SOC_{max}	80%
Battery type	Li-ion
Battery lifetime	10 years
Battery cost range	\$150- \$350/kWh
PV panel, inverter, installation & maintenance cost	\$3.46/W [12]
Discount rate	10%

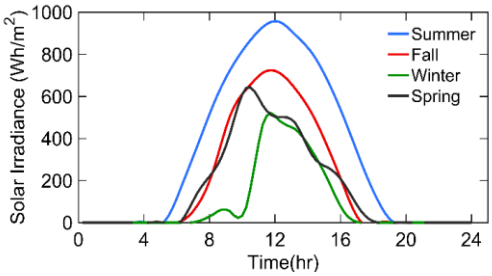


Fig. 3: Solar irradiance profiles for different seasons

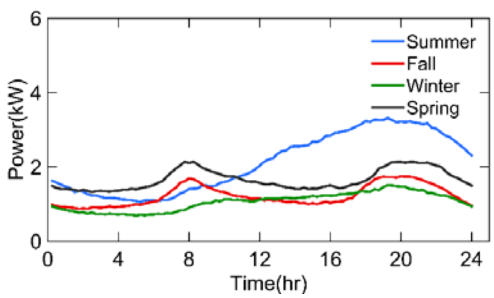
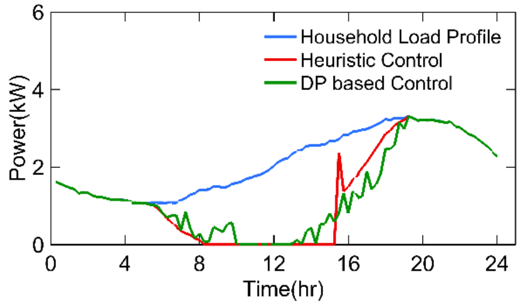


Fig 4. Household load profiles for different seasons

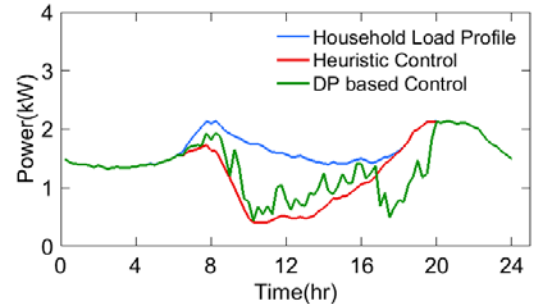
The forecasted PV and load demand data for a 24 hour period for 15 minute resolution are provided as the input to the optimization algorithm, which computes the optimal *SOC* path of the battery storage considering its constraints. Because of the variation of the load demands, PV profiles and *ToU* rate structure for different seasons, simulation results of four days of four different seasons are shown in Fig. 5. These results are shown for a 3 kW solar panel with a 4 kWh storage and *ToU* rate 1 [Appendix: Table II]. For comparison, simulation results for heuristic control are also provided. In heuristic control, the available solar energy is used to charge the storage whenever there is excess generation than demand. The storage is discharged and grid delivers power during the period when there is more demand than the available solar energy [15]. Referring to Fig. 5 (a) and (b), the results indicate that the DP based control strategy prefers to store generated PV energy during the partial-peak period which is until hour 13:00 to serve for the peak hour period. During peak period from hour 13:00 to hour 20:00 in summer and fall, the stored energy is utilized to serve the load demand. Due to this reason, the load demand from the grid for DP based control strategy is higher during the partial peak hour and lower during peak hour than the heuristic based control strategy. Similarly, according to the results of Fig. 5 (c) and (d) for spring and winter, DP based control tries to utilize the available capacity of storage to store the solar energy during the off-peak period until hour 17:00 and use this energy to serve after hour 17:00 to hour 20:00 (peak period) to reduce the electricity bill of the household owner. As a result, the load demand from the grid becomes lower than the heuristic control during hours 17:00 to 20:00 for DP based control due to comparatively higher *ToU* rate.

For the next step of the proposed strategy, the overall cost saving based on PV panel life is calculated to get the NPV for the system since solar panel installment and maintenance cost, and battery lifetime are known from Table I. Storage cost is considered as \$350/kWh. Fig. 6 shows the comparison of NPVs between heuristic and DP based control for different storage sizes with a 3 kW solar panel. It is clear from this figure that storage with an optimal control gives higher benefit than heuristic control for all sizes of storage options with a fixed panel size.

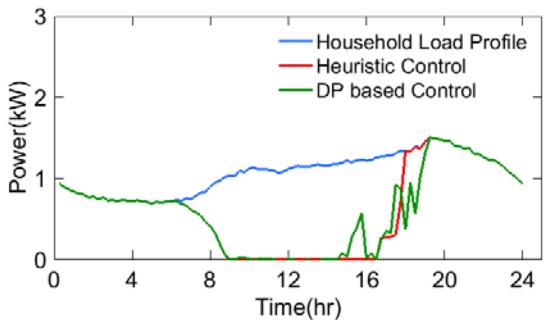
The analysis on NPV is done by varying the panel and storage sizes. For comparatively higher *ToU* rate 1 and \$350/kWh storage unit cost, the optimal sizes of the PV panel and storage capacity for the given household load demand are calculated for the DP based controlled load profiles. The result of Fig. 7 indicates that it is always beneficial to the customer to use a 3 kW PVpanel for the given household load profile irrespective of the storage size. It is also found that with an increase in the size of the PV panel, it is beneficial to add a specific size of storage to the system. However, for the lower size of PV panel, the inclusion of storage reduces NPV. Since an increase of storage size decreases the NPV, it is not beneficial to add storage when its cost remains as high as \$350/kWh. Therefore, the cost of storage is also a critical factor. As per unit cost of storage is decreasing according to [16], the effect of storage costs ranging from \$350/kWh to \$150/kWh are considered for analysis. NPV is calculated considering the DP based charge/discharge control for different storage capacity. Fig. 8 shows that NPV increases and becomes higher than \$3200 (which is the NPV without considering any energy storage) when the cost of storage decreases to \$250/kWh or less. The results also show that the NPV starts decreasing after reaching a peak with an increase in storage capacity. For both \$250/kWh and \$150/kWh storage costs, 4 kWh is the optimal size for the considered household with *ToU* rate 1 and 3 kW panel.



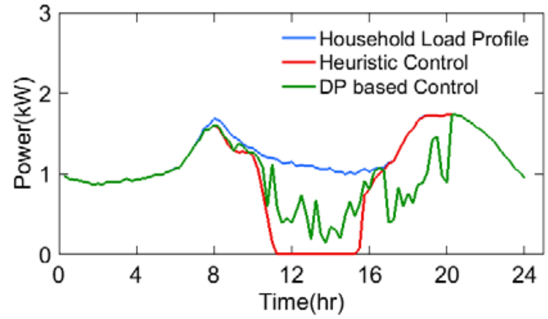
(a)Summer



(c)Spring



(b)Fall



(d)Winter

Fig. 5. Energy storage management for a household with *ToU* rate 1 for different seasons

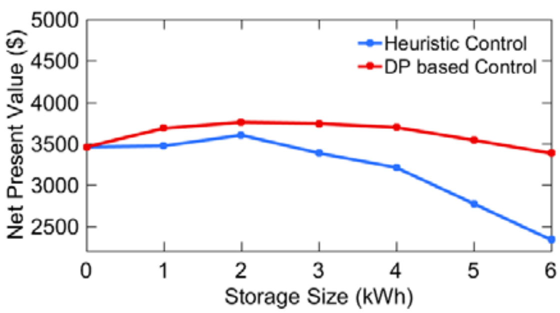


Fig. 6: Comparison of NPVs between DP and heuristically controlled PV-storage hybrid system for a 3 kW PV panel with $350/kWh storage cost.

To analyze the effect of *ToU* on NPV, in addition to the typical higher *ToU* rate 1, a typical *ToU* rate 2 (Appendix: Table III) is used that provides a comparatively lower rate and has a small deviation between off-peak and peak hour rate. The DP based control strategy is applied for different panel and storage sizes for the given household profiles and a lower storage cost of $150/kWh. The comparison among the NPVs for different panels of *ToU* rate 2 are given in Fig. 9. It can be seen that NPVs for *ToU* rate 2 cases are always negative which means that it is not always beneficial to use a PV panel, with or without energy storage, if there is less difference between peak and off peak hours or no incentives are provided to the household owner for PV generation.

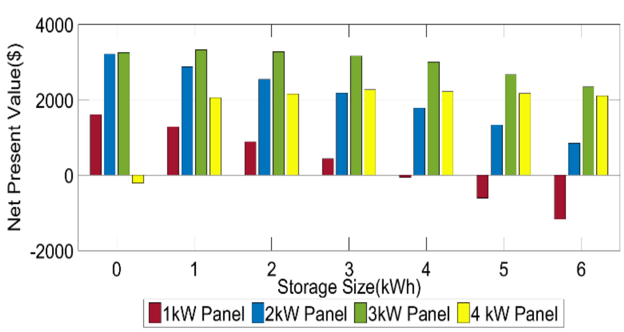


Fig. 7: NPV of the PV panel size and storage capacity system for the given household profile for $350/kWh storage cost.

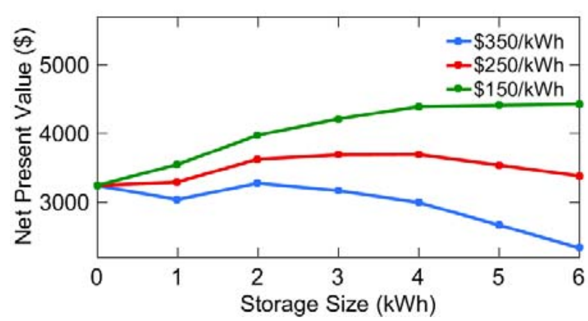


Fig. 8: Optimal size of storage for different storage per kWh costs

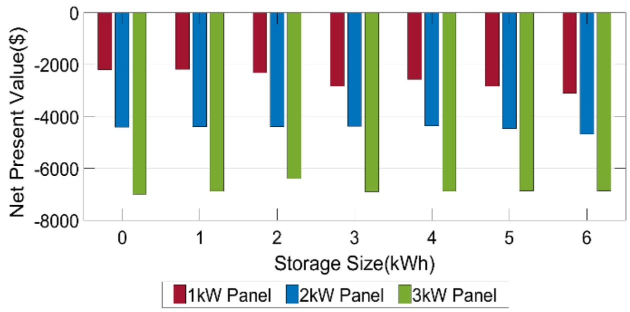


Fig. 9: Comparison of NPVs for different panel size and storage capacity for lower *ToU* rate 2.

IV. Conclusion

In this paper, an algorithm is presented based on DP for optimal control of energy storage system associated with solar power generation for a typical household. To determine the optimal solar panel size and storage capacity for a given rate structure, the results from DP have been considered for different panel and storage combinations. Moreover, NPVs for these different panel and storage sizes have been analyzed. The conclusion of the simulation analysis can be summarized as:

- If DP based control strategy is performed for energy management between storage and PV panel, then the overall NPV increases for the same size of storage.
- Due to the increase of NPV, DP based control strategy finds higher optimal capacity for storage than the heuristic control method.
- Though increasing the PV panel size means an increased amount of PV generation, it is not always beneficial. Optimal PV panel size is required to get the most economical benefit.
- With the change of storage cost, the NPV changes. A lower storage cost results in a higher NPV for the same size of storage and thus, the preferred optimal storage capacity will be higher.
- If the *ToU* rate structure is very low and no incentives are provided, then using PV panel along with storage is not cost effective even if DP based control strategy is performed and the storage cost reduces to $150/kWh.

Appendix

TABLE II:
ToU rate 1

Season	Load Type	Period	*ToU* Rate ($/kWh)
Summer and Fall (June-September)	Off-Peak	9:00 PM-9:00 AM	0.15
	Partial Peak	10:00 AM-1:00 PM & 7:00 PM-9:00PM	0.226
	Peak	1:00 PM- 7:00 PM	0.342
Spring and Winter (October-May)	Off-Peak	8:00 PM-5:00 PM	0.15
	Peak	5:00 PM – 8:00 PM	0.171

TABLE III:
ToU rate 2

Season	Load Type	Period	*ToU* Rate ($/kWh)
Summer and Fall (June-September)	Off-Peak	10:00PM-11:00 AM	0.009
	Peak	11:00 AM-10:00 PM	0.0927
Spring and Winter (October-May)	Off-Peak	11:00 AM-5:00 PM & 10:00 PM-7:00AM	0.009
	Peak	7:00 AM–11:00 AM & 5:00 PM – 9:00 PM	0.0927

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