Active Demand Side Management of a Grid Connected Photovoltaic Energy System using optimal Control

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Abstract: In this study, optimal energy management for a grid-connected photovoltaic-battery hybrid system was proposed to benefit customers at the demand side. The management of energy flow aims to minimize electricity cost subject to a number of constraints. Time of use (TOU) program was developed to import electricity during off-peak hours and used it during peak hours. Simulation results for the 24-hours period showed that, for a typical Auckland household load, the optimal control approach exported 9.75 kWh more electricity to the grid and imported 4.62 kWh less electricity during winter period. Further, the proposed approach imported 5.27 kWh less electricity from the grid during summer periods than the house with no controller.

Keywords: *Building energy management, energy efficiency, photovoltaic energy systems, hybrid energy systems*

1. Introduction

Global energy demand is continuously growing, the fossil resources are declining and the global warming is increasing. Many countries have opted for the adoption of measures to reduce energy consumption and encouraging transition towards renewable energy generation. This has introduced a new architecture of the energy supply system, which moves from a centralized to a decentralized energy generation. In this context, PV generation appears as the most promising alternative due to its maturity, environmentally friendly characteristics and low maintenance.

Buildings represent the largest share of energy consumption in most countries and account for nearly 40% of final energy use [1], therefore efficient energy utilization and control of energy consumption at the household level is crucial [2]. The challenging part is to match energy demand with intermittent energy generation. An active demand side management strategy is needed to optimize the use of PV source and storage and to match local energy production with consumption while insuring user comfort.

Many domestic systems installed in recent times have been grid-connected PV systems without battery storage. In this respect, the grid acts as a “battery” to backup these systems and so they do not require complex energy dispatch strategies, but rather can rely on simple load management strategies. Prioritizing the use of a PV system is the only rule when the PV energy is less than the energy requirement of the load. In contrast, battery storage brings a number of challenges to energy dispatch and load management strategies, as more complicated scenarios must be considered; such as charging the battery during the daytime, discharging during the night or when there is high demand. As a result, advanced control strategies are needed for hybrid PV-battery systems, such that the utilization of the PV array can be enhanced and the grid regulation can be improved in terms of safety and efficiency [3].

For grid-connected hybrid PV-battery systems, the changing electricity price, the timing of energy transactions, the mismatch between solar energy generation and energy demand are the main challenges and have been discussed by both [4] and [5]. Hence energy management for hybrid systems with battery storage is an issue that has attracted significant interest from researchers [6]; [7].

The control of large-scale solar energy systems has received some attention, with most researchers having considered energy management and demand response for large-scale integration of renewable energy at the utility side [8]; [9]. In this respect, numerous utility companies are investigating and implementing “smart” grids (SG) with a view to making the existing power generation system advanced, reliable, self-healing and economical.

In addition to the attention that has been paid to larger renewable electrical energy systems, a number of studies have attempted to apply similar strategies to residential scale electricity use. [10] reviewed a number of research studies on energy management controllers for smart homes where the aims were to address reducing energy consumption, peak to average ratio and energy wastage. They identified various control and pricing schemes, such as real time pricing (RTP), critical peak pricing (CPP), time of use (TOU) and day ahead pricing (DAP). In one particular study, [11] used peak to average ratio (PAR), daily energy demand, electricity cost and the hourly energy demand of shiftable electrical appliances of the consumers as the constraints in a control system. The objective function was to minimize the energy cost of the consumers through the determination of the optimal power usage and operation time of the appliances. This was achieved by shifting the high energy consuming loads to off peak hours, which helped minimize the energy consumption in the peak hours.

In a later study, [12] presented a demand side management (DSM) model for a residential energy management system in order to avoid peak formation while decreasing electricity demand and preserving user comfort levels within specified limits. In their work, three heuristic algorithms were used to evaluate the objective function. They suggested that the genetic algorithm based controller was better in term of electricity cost reduction, PAR minimization and maximization of user satisfaction than binary particle swarm optimization (BPSO). However, the computational time of the algorithm was higher. In a similar vein, [13] reduced the computational time for load scheduling in homes by introducing an evolutionary algorithm, that improved the performance (convergence rate and accuracy) of differential evolution (DE). On this basis there appears to be scope for advanced control strategies in renewable electric power systems.

In this vein, [14] studied a linear programming (LP) based model to minimize the electricity cost in a residential dwelling. In their study, a day was divided into time slots of equal lengths with different pricing rates, similar to a TOU scheme. In their LP model the home appliances were scheduled in appropriate time slots to reduce the electricity bill such that the consumer could enter the schedule detail in the LP model which would then deliver the most efficient and optimal scheduling output. [15] studied an optimal control approach to improve the performance of EMS for scheduling of energy flow for a hybrid energy system with a view to minimizing the cost of electricity and maximizing PV energy usage.

In their work to achieve maximum efficiency from photovoltaic systems using small-scale batteries and flexible thermal loads, [16] proposed four rule-based control algorithms and calculated the building energy flows and PV self-consumption ratios (the consumption of most of the PV energy within the building premises) on an annual basis. Results showed that installing batteries for local PV utilization was an attractive investment due to decreasing trends in battery cost and feed-in tariffs (FIT). In a more general sense, [17] discussed the effectiveness of a rule-based energy management strategy for a hybrid wind/PV/fuel-cell stand-alone application. In their work, real weather and load profile data were utilized such that the proposed controller managed the energy flow among different energy sources and storage units under realistic conditions.

Residential energy management systems were also studied in [18], where an optimal and automatic residential energy consumption-scheduling framework was proposed. The aim of this work was to achieve a desired trade-off between minimizing the electricity cost and minimizing the waiting time for the operation of each appliance in the households.

In a subsequent and similar study by [19], an appliance scheduling scheme for residential building energy management was proposed. This system utilized a time-varying retail pricing structure that was enabled by two-way communication infrastructure. In realising this, finite-horizon scheduling optimization problems were formulated to exploit the operational flexibilities of the thermal and non-thermal appliances, and incorporated both forecasts and newly updated information. Their simulation results showed that customers can have notable energy cost savings on their electricity bills with the time-varying pricing.

Research studies have already been conducted on grid connected renewable energy systems. However, most of these studies have focused on energy management for large scale integration of renewable energy systems at the utility side. Currently, there are very few studies reporting on the optimal energy management and DSM for small scale grid connected hybrid systems at the demand side, because hybrid systems are installed for stand-alone or back-up usage without any contribution of DSM program [20]; [21]. The focus of this paper was to analyze a comprehensive photovoltaic-battery-grid (PBG) system utilizing the Time-of-use (TOU) program; an optimal energy scheduling management algorithm of the PBG system which aims to minimize the electricity imports from the grid, maximize the energy exports to the grid, save on electricity cost and help the user to efficiently manage their generation, consumption and storage.

2. Description of the PBG system

Fig. 1 summarizes the basic principle of the optimal control for a domestic energy system where time-varying parameters (i.e. the electricity price, the comfort criteria, energy demand prediction, solar radiation prediction and occupancy) are inputs to the controller. One can see that the modelling and design effort consist of specifying a dynamic model of the domestic energy system, as well as constraints of the control problem and a cost function that encapsulates the desired behavior. At each sampling interval, these components are combined and converted into an optimization problem depending on the control framework chosen.

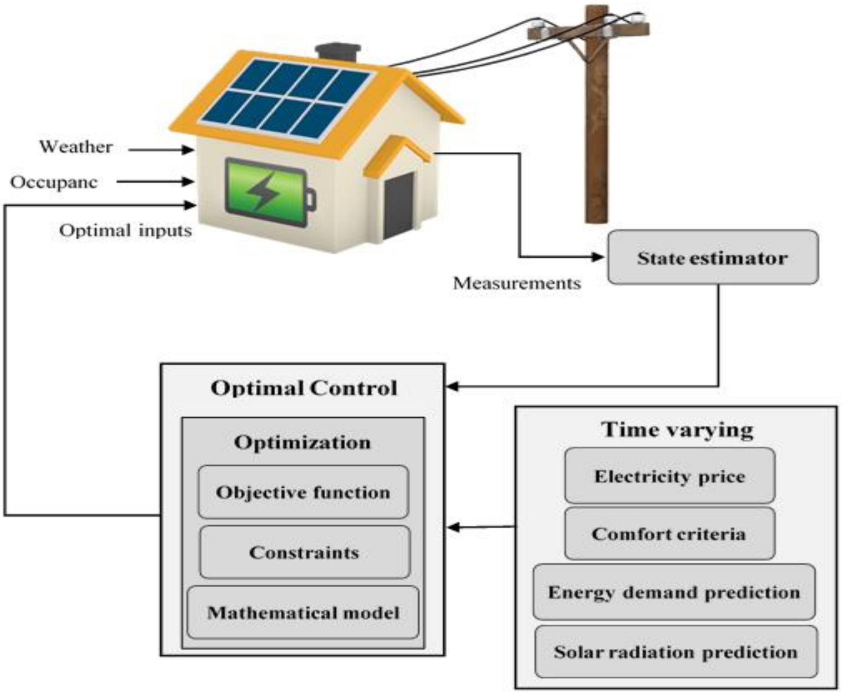

Fig. 1 PBG energy system layout

In this work, a photovoltaic-battery-grid system is proposed; where, PV energy and battery storage can be used to cover the energy demand of a house. In situations where both the PV array and the battery bank cannot satisfy energy demand; total load of the house can be reduced by shifting usage of the non-critical loads (dish washer, washing machine & dryer) in the house to periods when free energy will be available from the PV array. If the energy demand is still greater than the combined energy available from the PV and battery bank the deficit would be imported from the local grid.

At a holistic level the energy dispatching procedures are shown in Fig. 2, where the energy from the PV array, battery bank and grid are used to satisfy the load. The output energy of the PV array is used to satisfy energy demand of the house and charge the battery bank.

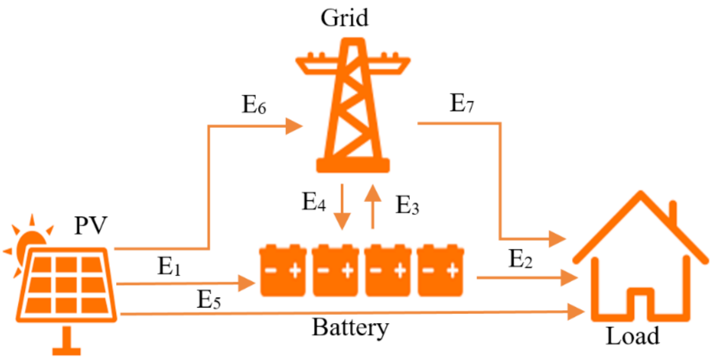

Fig. 2 Schematic of the PBG hybrid system

When the battery bank is fully charged, load demand is satisfied and excess PV energy is available, it is exported to the grid as a last priority (represented by E_3). If energy demand of the house is larger than the PV array production, the energy requirements should be met by the battery bank using E_2 or the grid energy E_7 in the case where the battery bank is fully depleted.

3. Model of the PBG hybrid system

The PV array consists of several solar cells to convert sunlight into electricity. The hourly energy output of a given area can be simply formulated as

$$E_{pv} = \eta_{pv} S_{pv} A_{pv} \tag{1}$$

where E_{pv} is the hourly energy output from the PV array. A_{pv} is the size of the PV array; η_{pv} is the efficiency of the PV array and S_{pv} is the hourly solar irradiation incident on the PV array (kWh/m^2). The hourly solar irradiation incident on the PV array is closely related to time of a day, season of the year, tilt, location, diffuse fraction etc. In this study, electricity load profiles and PV array generation data from a typical Auckland house with two adults and two children were used as shown in Table 1.

TABLE I. ELECTRICITY LOAD PROFILES OF FOUR CASES AND PV ARRAY GENERATION

Time (hours)	**Winter load (kWh)**		**Summer load (kWh)**		**PV array generation Winter (kWh)**	**PV array generation Summer (kWh)**
	Weekday	***Weekend***	***Weekday***	***Weekend***		
01	1.75	1.65	1.75	1.65	0	0
02	1.75	1.65	1.75	1.65	0	0
03	1.75	1.65	2.1	2	0	0
04	1.75	1.65	2.2	2.1	0	0
05	1.75	1.65	2.1	2	0	0
06	1.9	2.1	1.75	1.65	0	0
07	1.9	2.1	1.4	1.8	0.24	0.65
08	1.6	1.8	1.5	1.8	1.26	1.65
09	1.6	1.5	1.55	1.85	2.71	3.34
10	3.25	3.4	1.57	1.9	4	4.87
11	3.25	3.4	1.6	1.9	4.94	5.54
12	2.2	2.3	1.57	1.9	5.3	6.62
13	2.2	2.3	1.5	1.4	5.19	6.84
14	2.2	2.3	1.57	1.47	4.55	5.24
15	2.2	2.3	1.6	1.5	3.61	4.61
16	2.2	2.3	1.6	1.5	2.38	3.58
17	1.9	2.3	1.7	1.6	1.16	2.28
18	1.9	1.95	2.4	2.25	0.18	2.31
19	3.5	2.46	2.56	2.55	0	1.67
20	3.5	3.96	3.5	3.95	0	0.82
21	2.56	2.46	3.5	3.95	0	0
22	2.4	2.46	2.25	2.15	0	0
23	2.4	2.46	2.2	2.1	0	0
24	1.6	1.5	1.9	1.8	0	0

In a domestic setting, PV installations are located close to the loads so require the storage of energy at appropriate times to minimize the imbalance between generation and consumption. The charging and discharging model of the battery for the optimal control computation is given by Equation (2)

$$S_{oc}(k+1) = S_{oc}(k) + \eta_c E_1(k) - \eta_d E_2(k) \tag{2}$$

where $S_{oc}(k)$ is the state-of-charge (SOC) at sampling time k and $S_{oc}(k+1)$ is the SOC at the next hour. E_1 and E_2 are charging and discharging energies respectively. η_c and η_d are charging and discharging efficiencies respectively. Discrete model of the SOC in Equation (2) is based on the continuous model proposed in [22] where, variation of the SOC is proportional to the charging and discharging currents. According to Equation (2), the current SOC ($S_{oc}(k)$) can be expressed by the initial SOC ($S_{oc}(0)$) and can be expressed as

$$S_{oc}(k) = S_{oc}(0) + \eta_c \sum_{k=0}^{k+N_c-1} E_1(k) - \eta_d \sum_{k=0}^{k+N_c-1} E_2(k) \tag{3}$$

The SOC of the battery is subject to several constraints, such as the maximum allowable charge limit and the minimum allowable discharge limit, referred to as the depth of discharge (DOD). The lower and upper bounds of SOC are subject to the following constraint

$$B_c^{min} \leq S_{oc}(k) \leq B_c^{max}$$

where B_c^{min} and B_c^{max} are the minimum and maximum allowable SOC of the battery bank respectively.

The battery bank is charged during the day time when PV energy is available and discharged during night time. Simultaneous charging and discharging are avoided using Equation (4) in the optimal control design.

$$E_1(k)E_2(k) = 0 \tag{4}$$

When PV array production exceeds total energy demand of the house, the battery bank is set in charging mode and when total energy demand of the house exceeds PV production, the battery bank is set in discharging mode.

4. Optimal control method

An optimal control method is used to dispatch the hourly energy $E_i(i = 1, \ldots 7)$ over a day to minimize the daily electricity cost. According to the TOU program, electricity price changes over different periods according to the electricity supply cost, for example a high price for peak load period, medium price for standard period and low price for off-peak periods. Electricity prices varies among suppliers and locations therefore; the following prices are chosen as average electricity prices.

$$\rho(t) = \begin{cases} \rho_k, \;\; t \epsilon T_k, T_k = [7,10] \cup [17,20] \\ \rho_o, \;\; t \epsilon T_o, T_o = [0,6] \cup [22,24] \\ \rho_s, \;\; t \epsilon T_s, T_s = [6,7] \cup [10,17] \cup [20,22] \end{cases} \tag{5}$$

where $\rho_k = 0.195\ \$/kWh$ is the price for the peak load period; $\rho_o = 0.0244\ \$/kWh$ is the price for the off-peak period and $\rho_s = 0.0465\ \$/kWh$ is the price for the standard period.

As the objective function is quadratic, the energy flow control problem is expressed as a quadratic programing problem as given in Equation (6).

$$\min_x \frac{1}{2} x^T H x + f^T x, s.t. \begin{cases} A.x \leq b, \\ A_{eq}.x = b_{eq} \\ lb \leq x \leq ub. \end{cases} \tag{6}$$

where $H, A\ and\ A_{eq}$ are matrices and f, b, b_{eq}, lb, ub and x are vectors. $H\ and\ f$ are symmetric matrices of doubles representing the quadratic in the expression $\frac{1}{2}x^T Hx + f^T x$. A_{eq} and b_{eq} are the coefficients related with the equality constraints, A and b are the coefficients related with inequality constraints, and lb and ub are the lower and upper bounds of the variables respectively. Energy dispatch variables ($E_1(k)$, $E_2(k)$, $E_3(k)$, $E_4(k)$, $E_5(k)$, $E_6(k)$, $E_7(k)$,), energy demand ($E_L(k)$), PV energy ($E_{PV}(k)$) and state-of-charge ($S_{oc}(k)$) are transformed into the $f(x)$ format to facilitate the experiment for the optimal control as shown in Table 2.

TABLE II. ENERGY VARIABLES REPLACEMENT FOR THE OPTIMAL CONTROL APPROACH

$\boldsymbol{E_1(k)}$	$\boldsymbol{x_1(k)}$	$\boldsymbol{E_6(k)}$	$\boldsymbol{x_6(k)}$
$\boldsymbol{E_2(k)}$	$x_2(k)$	$E_7(k)$	$x_7(k)$
$\boldsymbol{E_3(k)}$	$x_3(k)$	$E_L(k)$	$x_8(k)$
$\boldsymbol{E_4(k)}$	$x_4(k)$	$E_{PV}(k)$	$x_9(k)$
$\boldsymbol{E_5(k)}$	$x_5(k)$	$S_{oc}(k)$	$x_{10}(k)$

The objective function $f(x)$ is given as

$$f(x) = \left\{ \begin{matrix} \rho(t)[w_1x_8(k) - w_1x_2(k) - w_1x_5(k)]^2 + \\ [w_2x_9(k) - w_2x_1(k) - w_2x_5(k) - w_2x_6(k)]^2 + \\ [w_3x_1(k) + w_3x_2(k)]^2 \end{matrix} \right\} \tag{7}$$

$$f = \begin{bmatrix} 0 & -w_1 & 0 & 0 & -w_1 & 0 & 0 & w_1 & 0 & 0 \\ -w_2 & 0 & 0 & 0 & -w_2 & -w_2 & 0 & 0 & w_2 & 0 \\ w_3 & w_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Constraints are given as

$$x_1(k) + x_5(k) + x_6(k) \le x_9(k)$$

$$x_2(k) + x_5(k) + x_7(k) = x_8(k)$$

$$0 \le x_1(k) \le 7\ kWh$$

$$0 \le x_5(k) \le 7\ kWh$$

$$0 \le x_6(k) \le 7\ kWh$$

and

$$0.15 \le x_9(k) \le 0.85$$

The parameters of the PBG system for the optimal control approach are given in Table 3.

TABLE III. PHOTOVOLTAIC-BATTERY-GRID SYSTEM PARAMETERS

Parameters of the PBG system	**Values**
Nominal battery capacity	25 kWh
Battery charge efficiency	90%
Battery discharge efficiency	100%
Battery's depth of discharge	25%
Initial state of charge	10 kWh
PV array capacity	7 kW

5. Results of the optimal control

In order to examine the behavior of the proposed optimal control system, a simulation of a photovoltaic-battery-grid system was undertaken using 24-hours measurements of the PV array production ($E_{PV}(k)$) and the electricity consumption ($E_L(k)$) taken from a real house in Auckland. Values of the system parameters and control parameters are listed in Table IV and Table V, respectively. Initial values of $E_1(k)$, $E_2(k)$, $E_3(k)$, $E_4(k)$, $E_5(k)$, $E_6(k)$ and $E_7(k)$ are set to zeros. Initial values of S_{oc} are set to $x_m(1) = 0.5B_c^{max}$. MATLAB® code was developed for the simulation and implementation of the proposed optimal control framework.

TABLE IV. VALUES OF THE SYSTEM PARAMETERS

Notations	Values	Notations	Values
E_1^{max}	7 kWh	E_5^{max}	7 kWh
E_2^{max}	7 kWh	E_6^{max}	7 kWh
E_3^{max}	7 kWh	E_7^{max}	+/- 7 kWh
E_4^{max}	7 kWh	B_c^{min}	10 kWh
B_c^{max}	25 kWh	η_c	0.8
η_d	1.0		

TABLE V. VALUES OF THE CONTROL PARAMETERS

Notations	Values	Notations	Values
w_1	1.0	w_2	0.2
w_3	0.8		

Fig. 3 shows PV array production for a randomly selected 24-hours period in winter and summer months along with total load of the house for weekday and weekends for winter and summer months.

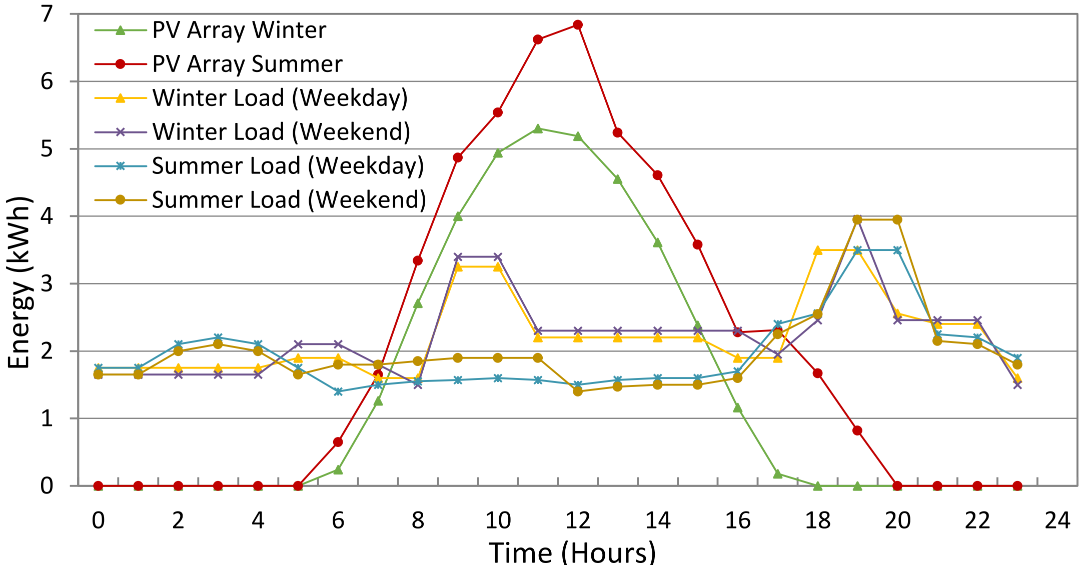

Fig. 3 PV array production and electricity load profiles for winter and summer

Fig. 4 shows energy flows from the battery ($E_2(k)$), grid ($E_7(k)$) and PV ($E_5(k)$) to satisfy electricity demand of the house. It can be seen that the proposed control system is avoiding grid imports during peak hours. During hours 17 to 20, battery has been discharged to satisfy the load. PV energy has been utilized during the day time to satisfy the load, charge the battery and export excess PV energy to the grid. Fig. 5 shows similar behavior for the winter weekend.

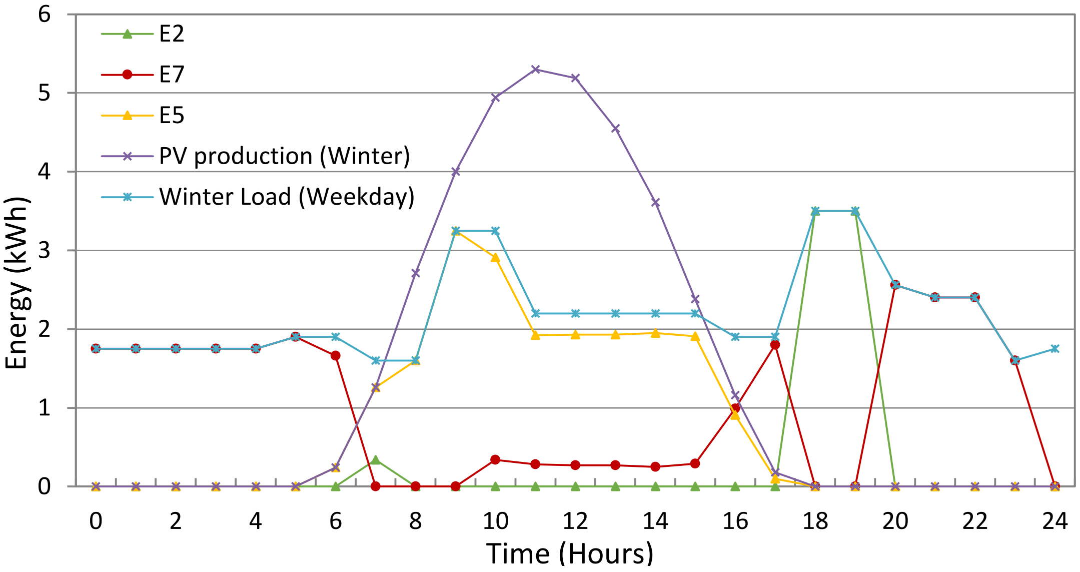

Fig. 4 Energy flow from PV, battery and grid to satisfy demand for a winter weekday

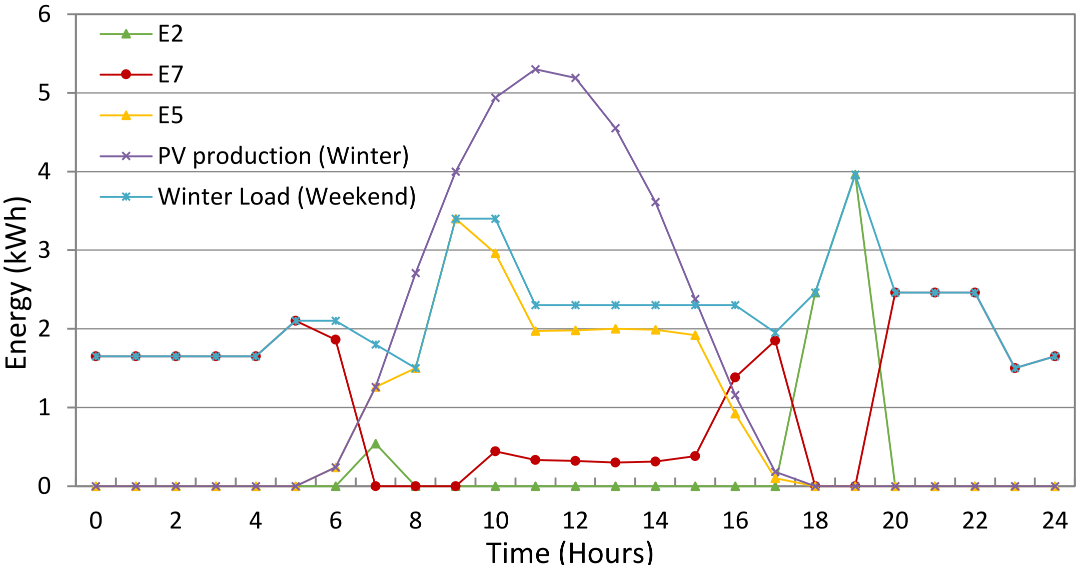

Fig. 5 Energy flow from PV, battery and grid to satisfy demand for a winter weekend

Fig. 6 and Fig. 7 shows energy flows to $(E_1(k))$ and from $(E_2(k))$ the battery bank as well as to $(E_3(k))$ and from $(E_4(k))$ the grid for a summer weekday and weekend respectively. It can be seen that battery has been charged during the day time when energy was available from the PV array and discharged during peak periods when there was no PV array production. Battery bank has also been charged from the grid $(E_4(k))$ during off-peak hours and discharged to satisfy the load when electricity prices were higher.

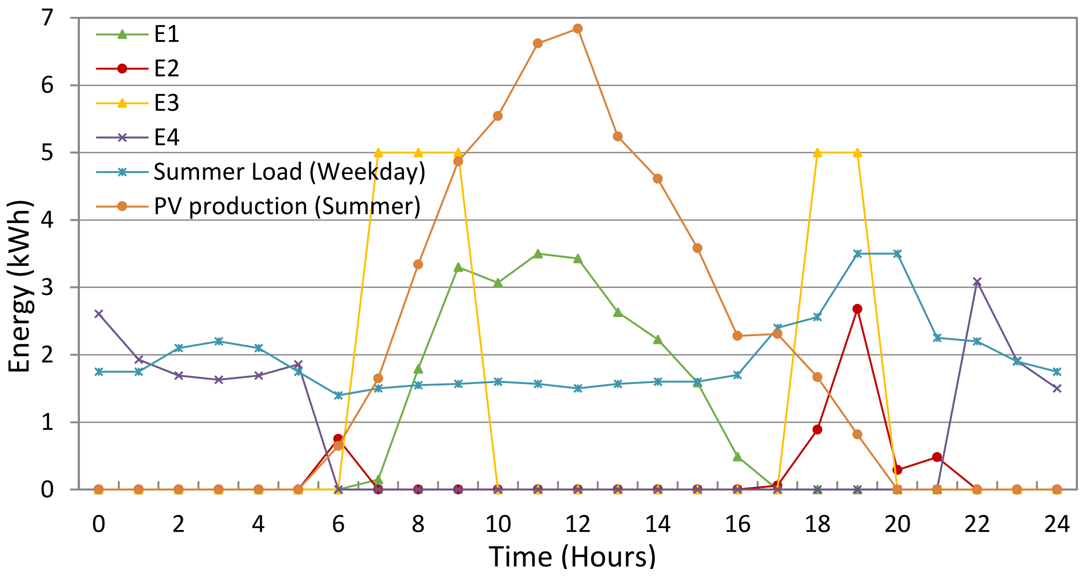

Fig. 6 Energy flows from and to the battery for a summer weekday

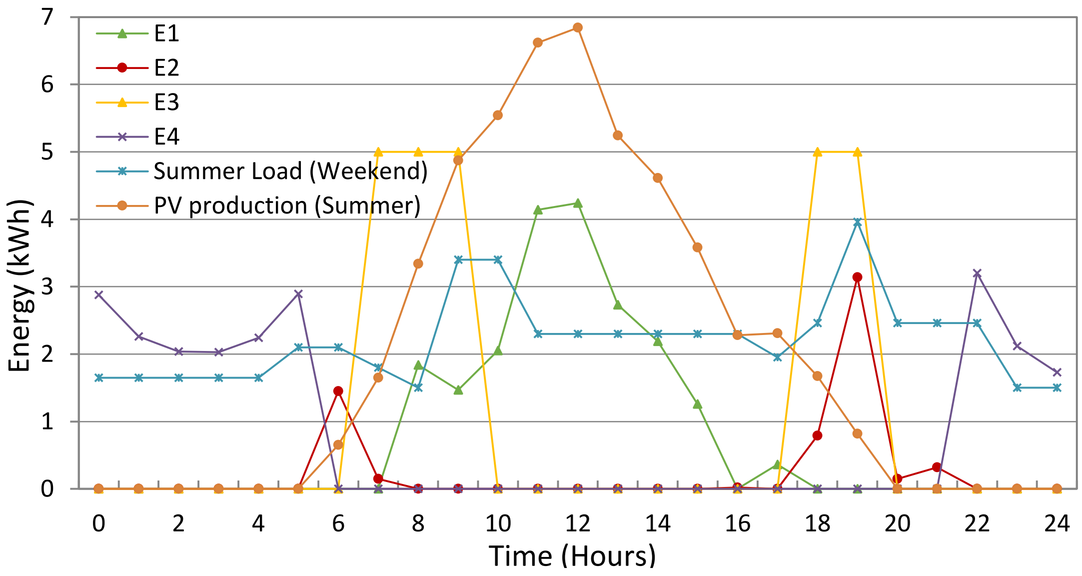

Fig. 7 Energy flows from and to the battery for a summer weekend

Table VI and Table VII shows electricity cost saving potential of the proposed controller. During the 24-hours period observed, the proposed controller managed to export 9.75 kWh more energy to the grid for the winter week while exported 3.28 kWh less energy for the summer week. Further, the optimal control approach managed to import 4.62 kWh less energy from the grid for the winter week and 5.27 kWh less energy from the grid for the summer week.

TABLE VI. ONE DAY ELECTRICITY EXPORTS/IMPORTS COMPARISON OF A HOUSE WITH AND WITHOUT CONTROLLER (WINTER)

House with controller grid exports (kWh)	**House without controller grid exports (kWh)**	**House with controller grid imports (kWh)**	**House without controller grid imports (kWh)**
22.98	13.23	26.40	31.02

TABLE VII. ONE DAY ELECTRICITY EXPORTS/IMPORTS COMPARISON OF A HOUSE WITH AND WITHOUT CONTROLLER (SUMMER)

House with controller grid exports (kWh)	**House without controller grid exports (kWh)**	**House with controller grid imports (kWh)**	**House without controller grid imports (kWh)**
25	28.28	20.76	26.03

Conclusion

In this study demand side management has been considered for a grid connected house having photovoltaic-battery installation with two adults and two children in Auckland using the optimal control method. A model for reducing electricity cost has been developed. The results show that the optimal solution to the operation of the PBG system achieves the maximal use of solar energy and battery storage. It has been shown that the optimal control approach exports 9.75 kWh more electricity to the grid and imports 4.62 kWh less electricity during winter periods than the house with PV installation but not utilizing the optimal control approach. Further, the optimal control approach exports 3.28 kWh less electricity to the grid and imports 5.27 kWh less electricity during summer periods than the house with PV installation but without optimal controller and battery storage.

In this study, only TOU was evaluated in the PBG system as an example of DSM and further work can be done to consider other DSM programs and extending the model to incorporate more renewable energy sources such as wind energy. Battery installation and its wearing cost can be included in the extended model. Solar radiation and electricity demand predictions can be utilized to plan in advance for periods of low sunshine or high energy demands.

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