Minimization of Residential Electricity Bill using EMS

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Abstract

As global energy demand continues to rise, integrating renewable resources has emerged as a practical solution. However, handling the intermittency of renewables presents a challenge. An effective approach is optimizing energy management, specifically Solar PV panels and energy storage, alongside the primary utility. In this study, we use linear optimization to minimize residential electricity bills over one year. The approach schedules energy use based on solar power availability, energy storage system (ESS) state-of-energy (SoE), and dynamic tariffs, efficiently utilizing resources. Testing the impact of a smart energy management system (EMS) across three scenarios shows significant cost reductions compared to static tariffs, proving the EMS's real time benefits.

1. Introduction

According to the European Union (EU) Energy Technology Strategy, consumers, or energy end-users, are anticipated to hold a central position in the future energy landscape. An effective strategy for actively engaging consumers revolves around the continual adoption and integration of PV panels. PV energy has demonstrated its feasibility for consumers, primarily attributed to policy incentives and the decreasing costs associated with it [1].

Recently, sustainable development has been facilitated by the integration of Renewable Energy Resources (RERs) into power systems. RERs are incorporated into the system through decentralized microgrid projects, necessitating efficient technological solutions for information sharing between distributed energy resources (DERs) and consumers [2]. An essential component of a smart grid, the EMS is a system that can be characterized as A control approach and system for sharing information, guaranteeing the efficient provision of energy from both the generation and distribution aspects while minimizing costs. [3].

While RERs offer numerous advantages in addressing energy scarcity issues, they face challenges related to intermittent, stochastic, and unpredictable energy generation. Therefore, integrating ESS alongside RERs can be an attractive solution. [4]-[5].

A significant amount of research focuses on the implementation of EMS and the development of optimization algorithms to minimize costs. These efforts take into account dynamic electricity tariffs and aim to optimize the efficient use of energy resources [6].

The application of simulations based on optimization in economic load dispatch (ELD), demand side management (DSM) and unit commitment (UC) approaches within existing power systems contributes to sustainable development. These simulations help optimize the allocation of resources, improve energy efficiency, and reduce operational costs, all of which are vital aspects of achieving sustainability in power generation and distribution [7]–[9].

An optimization method based on mixed-integer linear programming approach is presented in references [10]-[11], aiming to reduce the real time operational costs of a RES and battery microgrid at Aalborg University's campus. The EMS based fuzzy logic controller provides an equal distribution of available electricity from renewable resources while also implementing different contingency plans that may arise owing to the intermittent nature of renewable energy supplies[12]. In addition, reference [13] introduces a combination of the optimizer based MIDACO and MATPOWER to minimize grid power imports while maximizing PV usage. The system has created an improved self-sufficient EMS for an electric vehicle charging station (EVCS) that operates independently as a separate load. To adapt to the changing availability of RERs, a two-level optimization model that incorporates wind energy is introduced in reference [14]. This model aims to minimize operational expenses within a day-ahead electricity market, with a primary focus on minimizing disruptions for end-users. The adoption of optimization-driven demand response (DR) and EMS has gained global recognition, supported by emerging communication systems and advanced metering infrastructure (AMI) [15]. These approaches yield more practical and financially valuable decisions in the context of demand response marketing.

All of these approaches aim to optimize energy usage while managing real time electricity costs efficiently. However, these methods often neglect to consider the two-way information exchange between the EMS and the ESS. This involves not only charging or discharging the ESS based on the availability of solar energy but also considering the fluctuations in real-time grid electricity prices. Hence, the primary objective of this research is to address this aspect. This is achieved by presenting an optimization approach based on linear programming. The purpose of this approach is to devise a scheduling strategy that effectively manages the energy generation and consumption patterns of loads over a one-year period. This scheduling approach takes into account both the availability of PV energy and the dynamic variations in grid electricity prices.

The remainder of this paper is organized as follows. In Section 2, the methodology of the proposed approach is introduced. Section 3 provides mathematical formulation of EMS. Section 4 discusses the plausible scenarios and results. The paper is concluded with Section 5.

2. Methodology

The residential-type load shown in Fig. 1 varies on an hourly basis and is connected to the distribution grid. To reduce demand by activating the grid, the system incorporates an ESS and a PV. The battery stores extra energy from PV source during periods of high solar energy production and also from the grid when electricity rates are more cost-effective. During daylight hours, PV power is readily available, and the customary practice is to fulfill the entire load using PV energy. Once the load is met, any excess energy is directed towards recharging the battery. The SoE of the battery is monitored by the EMS. If the SoE exceeds the upper limit, the extra energy is sold to grid. During the peak evening period when there is generated power from PV, the primary focus of the EMS is to assess the battery's SoE level. If the SoE surpasses the lower limit, the load is powered from the stored energy within the ESS. Furthermore, if there is an excess of energy after fulfilling the peak-hour demand, the ESS also supplements the grid with energy. The discharge of the battery during peak hours leads to a notable reduction in the electricity bill by reducing grid energy consumption. As a result, the battery is replenished from the grid to sustain a robust SoE level.

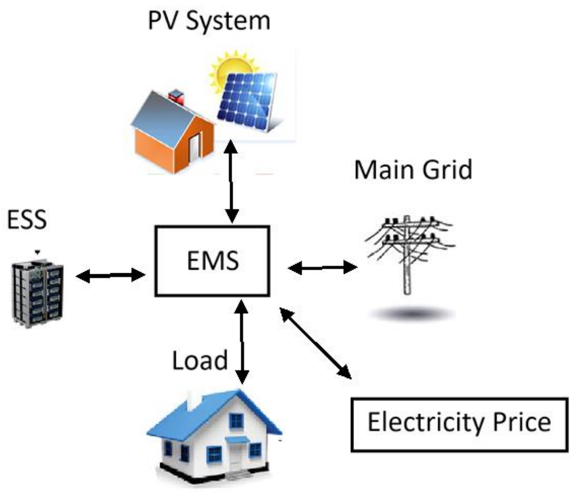

Fig. 1. Overview of the EMS system.

3. Problem Formulation

This section describes the mathematic expressions for the model. Table 1 describes the symbols used in mathematical formulation.

Table 1. List of Symbols

Symbols	Description
C	Total electricity bill in period t [₺]
λ_t	Electricity price bought from the grid and sold to grid in period t [TL/kWh]
$P_t^{Buy,Grid}$	Total power bought from grid in period t [kW]
$P_t^{Sell,Grid}$	Total power sold to grid in period t [kW]
$P_t^{Used,PV}$	PV power used in period t [kW]
$P_t^{Sell,PV}$	PV power sold to grid in period t [kW]
$P_t^{T,PV}$	PV power produced in period t [kW]
$P_t^{DissCh,ESS}$	ESS discharging power in period t [kW]
$P_t^{Ch,ESS}$	ESS charging power in period t [kW]
$P_t^{Used,ESS}$	ESS power used in period t [kW]
$P_t^{Sell,ESS}$	ESS power sold to grid in period t [kW]
P_t^{Load}	Demand power of residential in period t [kW]
SoE_t^{ESS}	State-of-energy of the ESS in period t [kWh]
$SoE_t^{Ini,ESS}$	Initial state-of-energy of the ESS [kWh]
CR^{ESS}	Charging rate of ESS [kW]
$SoE^{Min,ESS}$	ESS minimum value SoE [kWh]
$SoE^{Max,ESS}$	ESS maximum value SoE [kWh]
DR^{ESS}	Discharging rate of ESS [kW]

3.1. Objective Function

The optimization objective function to minimize the electricity bill is given in Eq. (1).

$$C = min \sum_t^N (\lambda_t . P_t^{Buy,Grid} - \lambda_t . P_t^{Sell,Grid}) \quad (1)$$

In Eq. (1), electricity usage cost by grid is subject to changes over time based on Time-of-Use (ToU) prices, defined as λ_t and energy flow between grid. Beginning with $t = 1$, the optimization horizon is divided into N discrete steps with one-hour intervals.

3.2. Problem Constraints

To minimize grid usage and maximize the utilization of PV and ESS, in Eq. (1) described the optimization problem must adhere to the following equality constraints. The equilibrium of power is expressed in Eq. (2) for each time interval, designated as t. The left side of Eq. (2) illustrates the origin from which the essential power is sourced to the households, while the right side portrays the appliances and systems that consume the needed electricity.

$$P_t^{Buy,Grid} + P_t^{Used,PV} + P_t^{Used,ESS} = P_t^{Load} + P_t^{Ch,Batt} , \forall t \quad (2)$$

In Eq. (3), ($P_t^{Sell,Grid}$) represents the power sold to the grid. ($P_t^{Sell,PV}$) and $P_t^{Sell,ESS}$ denotes the power sold to grid by PV and ESS respectively. The total sales power to the grid ($P_t^{Sell,Grid}$) equals the summation of these two expressions

$$P_t^{Sell,Grid} = P_t^{Sell,PV} + P_t^{Sell,ESS}, \forall t \quad (3)$$

In Eq. (4), the total generated power from PV value ($P_t^{T,PV}$) is equal to the total power used for the load ($P_t^{Used,PV}$) and the power sold by the PV ($P_t^{Sell,PV}$). This equation is repeated for each time period *t*.

$$P_t^{T,PV} = P_t^{Sell,PV} + P_t^{Used,PV} , \forall t \quad (4)$$

The ESS constraints are outlined in Eq. (5) - (9). Eq. (5) specifies that the power discharged by the ESS matches the total power consumed and sold by the ESS. Meanwhile, constraints in Eq. (6) - (7) impose restrictions on the charging and discharging power of the battery.

$$P_t^{Used,ESS} + P_t^{Sell,ESS} = P_t^{DissCh,ESS}, \forall t \quad (5)$$

$$0 \leq P_t^{Ch,ESS} \leq CR^{ESS}, \forall t \quad (6)$$

$$0 \leq P_t^{DissCh,ESS} \leq DR^{ESS}, \forall t \quad (7)$$

$$SoE_t^{ESS} = SoE_{t-1}^{ESS} + P_t^{Ch,ESS} - P_t^{DissCh,ESS}, t > 1 \quad (8)$$

$$SoE_t^{ESS} = SoE_t^{Ini,ESS}, t = 1 \quad (9)$$

$$SoE^{Min,ESS} \leq SoE_t^{ESS} \leq SoE^{Max,ESS}, \forall t \quad (10)$$

In Eq. (8), The SoE is specified. Eq. (9) represents the initial SoE status, while Equation (10) signifies the upper and lower limits of the ESS SoE. This limitation serves to prevent deep discharges and extend the lifespan of the battery The ESS level (SoE_t^{ESS}) ranges from 15% to 85%. If the energy level drops below the lower threshold, the battery switches to a charging mode, depending on the generation of PV energy. In cases where PV energy is unavailable, the EMS checks if the electricity price is low to initiate the charging process. If SoE_t^{ESS} exceeds the upper limit, the EMS ceases battery charging. To meet the current load demand, the grid must draw any excess power, as indicated in Eq. (8). The effect of various parameters can be observed in Figure 2. Optimization techniques are employed to ensure the efficient utilization of energy, aiming to reduce electricity costs.

4. Case Studies

In this study, a residential user profile characterized by an average hourly consumption of 3.5 kW is used over the course of one year. Solar PV panels, consisting of 2 strings and 8 series, provides a 5 kW output capacity. Furthermore, the ESS is equipped with a rated capacity of 5 kWh, demonstrating an overall efficiency of approximately 96%.

The PV panel production data has been obtained by conducting a simulation at a specific location within the boundaries of Kastamonu province using the Pvsyst 7.4 program.

Residential load data has been randomly generated in the Matlab R2022a to have an average of 3.5 kWh.

The values for the three-term tariff, as shown in Table 2, have been taken into account as the electricity purchase and sale prices with Value Added Tax (VAT).

EMS simulations have been carried out via Matlab R2022a.

Table 2. Electricity prices according to hourly time slots [16]

Time Intervals	Price
06:00 - 17:00	2.28 TL/kWh with VAT
17:00 - 22:00	3.35 TL/kWh with VAT
22:00 - 06:00	1.43 TL/kWh with VAT

In this section, monthly electricity bills have been calculated for 3 different scenarios. The details are provided below.

4.1. Scenario with Grid alone

In this scenario, the house is connected to the grid. Loads are powered by the grid. There are no RERs or ESS. The load demand fluctuates with time, resulting in grid power supply that aligns with the same pattern.

Electricity consumption profile and monthly electricity bill are shown in Fig. 2 and Table 3 respectively. Total calculation of electricity bill at the end of one year period is as about 6,122.20 TL/month.

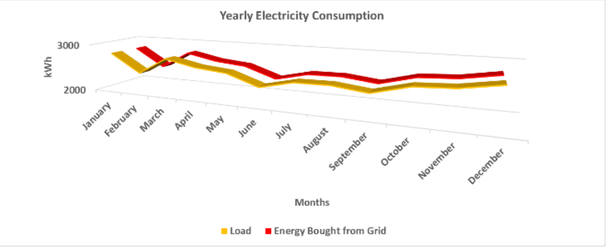

Fig. 2. Yearly Electricity consumption.

Table 3. Yearly electricity bill and load

Months	Total Load (kWh)	Monthly Electricity Bill (₺)
January	2803.04	6,666.16
February	2416.631	5,706.06
March	2773.416	6,573.81
April	2642.079	6,210.33
May	2582.012	6,058.63
June	2358.797	5,535.63
July	2515.979	5,911.60
August	2526.659	5,928.49
September	2449.555	5,758.28
October	2632.163	6,206.22
November	2669.117	6,321.16
December	2789.619	6,590.05
Total	31159.067	73,466.42

4.2. Scenario with Grid and PV

In this scenario, a PV RES acts as a grid compensator, but a storage system is still not in use. When there is PV available, the loads are directly powered by the PV system. Any excess PV generation, beyond what's required to meet the load demand, is sold to the grid. This is stated by the negative grid power, as depicted in Fig. 4. Consequently, the cost of electricity decreases, as evidenced by the declining trend in the curve showing the power purchased from the grid in Fig. 3.

Finally, grid dependency is reduced to some extent by solar penetration. A reduction in grid energy consumption results in a decrease in the total electricity bill to approximately 4,619.81 TL/month. The monthly invoice amounts are included in Table 4.

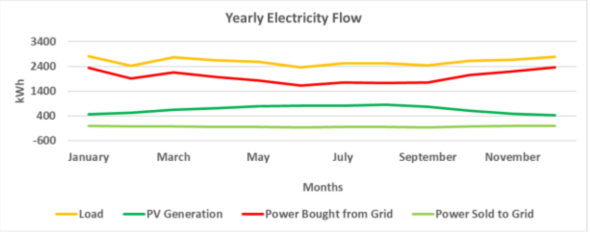

Fig. 3. Yearly electricity flow with PV and grid.

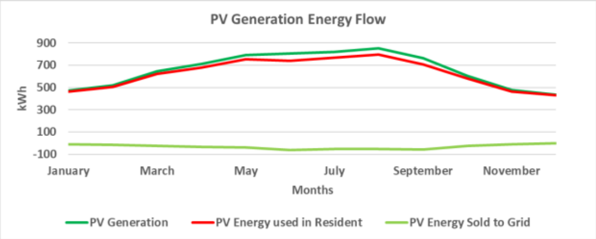

Fig. 4. PV generation energy flow.

Table 4. Yearly electricity bill and net grid power flow

Months	Net Grid Power Flow	Monthly Electricity Bill (₺)
January	2330.1555	5,587.98
February	1896.2487	4,519.59
March	2127.8945	5,101.38
April	1929.0324	4,580.05
May	1792.0152	4,251.74
June	1555.8892	3,695.09
July	1698.0734	4,035.35
August	1676.7499	3,983.51
September	1685.3613	4,014.49
October	2027.5708	4,827.74
November	2194.0312	5,237.97
December	2356.6396	5,602.86
Total	23269.6617	55,437.74

4.3. Scenario with Grid, PV and ESS

The last scenario involves the integration of an ESS. This particular case undoubtedly offers the lowest achievable cost for meeting the load demand while minimizing grid power usage.

The initial SoE of the ESS stands at approximately 50%, and it operates with a maximum charge rate of 5.67 W and a minimum discharge rate. If the EMS determines that the SoE falls below the upper charging constraint, PV will charge the battery during daylight hours, as indicated by the highlighted box. In the early morning and late at night, when grid electricity rates are more affordable, the battery replenishes its charge by sourcing power from the grid.

When the EMS identifies surplus power within the ESS following the fulfillment of load demands, this surplus power is sold to the grid. This strategy leads to a decrease in the overall monthly electricity expenses, lowering it to 4,210.04 TL/month.

In Fig. 5 shows the energy flow that occurred on a day in August. In Fig. 6, on the other hand, depicts the battery's SoE for the same day.

Table 5, on the other hand, presents the monthly grid-to-net energy flow and the corresponding monthly invoice amount.

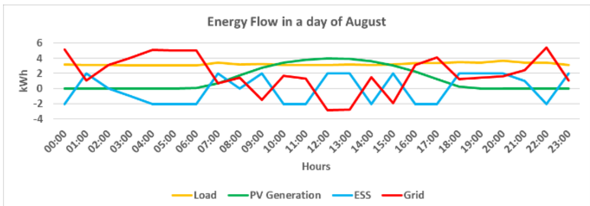

Fig. 5. Electricity flow in a day of August.

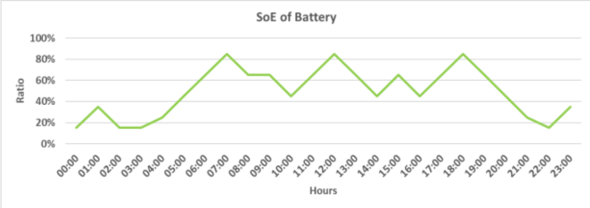

Fig. 6. SoE of a day in August.

Table 5. Yearly Electricity Bill and Net Grid Power Flow

Months	Net Grid Power Flow	Monthly Electricity Bill (₺)
January	2326.6555	5,166.34
February	1896.2487	4,143.27
March	2127.8945	4,684.74
April	1929.0324	4,176.85
May	1792.0152	3,835.10
June	1555.8892	3,291.89
July	1698.0734	3,618.71
August	1676.7499	3,566.87
September	1685.3613	3,611.29
October	2027.5708	4,411.10
November	2194.0312	4,834.77
December	2354.6396	5,179.52
Total	23264.1617	50,520.43

4.4 Comparison

Table 6 below shows the monthly electricity bill amount without the PV panel and battery, and the respective changes in the bill when the PV panel is added to the system and when both the PV panel and battery are added.

To compare to Case 1, the EMS without ESS results in a 24.54% reduction in the electricity bill in Table 6. The EMS centered around optimization techniques. (Scenario 3) achieves cost reductions of 31.23% and 8.87% compared to Scenario 1 and Scenario 2, respectively. It is confirmed the satisfactory results of Scenario 3 in response to dynamic pricing strategies such as real time pricing or ToU.

Table 6. The monthly impact of the battery and PV panel to bill.

Months	Monthly Bill without PV and ESS (₺)	Reduction of the Monthly Bill with PV Panel	Reduction of the Monthly Bill with PV Panel and ESS
January	6,666.16	-16.17%	-22.50%
February	5,706.06	-20.79%	-27.39%
March	6,573.81	-22.40%	-28.74%
April	6,210.33	-26.25%	-32.74%
May	6,058.63	-29.82%	-36.70%
June	5,535.63	-33.25%	-40.53%
July	5,911.60	-31.74%	-38.79%
August	5,928.49	-32.81%	-39.84%
September	5,758.28	-30.28%	-37.29%
October	6,206.22	-22.21%	-28.92%
November	6,321.16	-17.14%	-23.51%
December	6,590.05	-14.98%	-21.40%
Total	73,466.42	-24.54%	-31.23%

5. Conclusions

In this research, the optimization method enables the practical use of RERs and ESS as versatile grid assets. Even in its preliminary stages, the EMS utilized in this study displays dynamic capabilities for managing demand in response to ToUpricing structures. In future investigations, distinct priority levels can be allocated to individual appliances within the established EMS to improve the optimization of how they use energy.

The effective of linear programming optimization approach can be further improved by integrating artificial intelligence methodologies and formulating dedicated Multi-objective Optimization strategies. Additionally, constraints such as line capacity limits and generation constraints for Distributed Energy Resources (DERs) can be incorporated seamlessly. To fully harness the potential of RERs, it is conceivable to combine wind energy turbines alongside solar arrays.

6. References

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