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# Economic Analysis of Demand Side Management with Residential PV System and Energy Storage System

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**Abstract:** Renewable energy sources (RESs) as distributed generation (DG) have an important place on distribution networks (DNs) in recent years. RESs are being used for voltage stability, low power losses and low energy cost. Two way energy transmission is possible after the development of smart distribution girds and different electricity tariffs can be applied for customers at different times of day. PV modules are growing rapidly for residential applications and PV modules applications are becoming widespread together with technological improvements. Because of the raw material continuity problem of PV modules, energy storage systems (ESSs) can be used at residential PV applications. In this paper, economical effect of the residential PV system for customer is investigated and ESS is used with PV system for more efficient PV usage. The charge/discharge timing of ESS has been set to obtain a minimum electricity bill for one home. Then we used distribution network to analyse the impact of the residential PV application. For this purpose, it was accepted that 25 per cent of homes at distribution network have residential PV and ESS (RPVESS).

**Keywords:** PV Modules, Energy Storage Systems, Demand Management, Distribution Network, Electricity Price

# Konutlarda PV ve Enerji Depolama Sistemiyle Talep Yönetiminin Ekonomik Analizi

**Öz:** Dağıtık üretim olarak yenilenebilir enerji kaynakları, son yıllarda dağıtım şebekelerinde önemli bir yere sahiptir. Yenilenebilir enerji kaynakları; gerilim kararlılığı, düşük güç kaybı ve düşük enerji maliyeti için kullanılmaya başlanmıştır. Akıllı dağıtım şebekelerinin geliştirilmesinden sonra iki yönlü enerji aktarımı ve müşteriler için günün farklı saatlerinde farklı elektrik tarifeleri uygulanabilir hale gelmiştir. PV modüller konut uygulamaları için hızla büyümekte ve PV modül uygulamaları teknolojik gelişmelerle birlikte yaygınlaşmaktadır. PV modüllerin hammadde sürekliliği sorunu nedeniyle, konut PV uygulamalarında enerji depolama sistemleri kullanılabilir. Bu çalışmada, müşteriler için konut PV sisteminin ekonomik etkisi araştırılmış ve daha etkin PV kullanımı için PV sistemi ile birlikte enerji depolama sistemi kullanılmıştır. Enerji depolama sisteminin şarj / deşarj zamanlaması, bir ev için elektrik faturası minimum olarak ayarlanacak şekilde belirlenmiştir. Daha sonra konut PV uygulamasının etkisini analiz etmek için dağıtım şebekesi kullanılmıştır. Bu amaçla, dağıtım şebekesindeki evlerin yüzde 25'inin konut PV ve Enerji Depolama Sistemi'ne (RPVESS) sahip olduğu kabul edilmiştir.

**Anahtar kelimeler:** PV Modül, Enerji Depolama Sistemleri, Talep Yönetimi, Dağıtım Şebekeleri, Elektrik Fiyatları

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## 1. Introduction

DG units are becoming more popular after the development of the smart grid and because of the declining fossil fuel sources; renewable energy is an important part of the DG. RESs can produce safe, efficient and environmental energy for DNs as DG. The houses are became a power generation areas with development of the RESs. Because of these reasons, individual energy production has begun to be supported by many governments. The development of the PV arrays has begun to take attention for residential applications [1-10]. PV arrays are a DC power source based on ambient temperature and solar irradiation level. There are too many works about the mathematical modelling of PV cell. One diode mathematical model is the basic PV model and it is used at the most of works [11-14].

Demand management (DM) is another popular subject in literature. DM can help to shave peak load with scheduling the operation of deferrable loads. Especially price based demand management is generally used for decreasing the energy cost. Rooftop PV units has been proposed for DM in many works. Deferrable load can be shift from peak time to solar power generation time for DM [15-21].

Energy storage systems can be used both in distribution networks and in residential applications with renewable energy sources for DM applications. PV cells generate electricity depending on the weather conditions. Along with the three-time tariff application, different price tariffs began to be applied at different times of the day. While there are three different price applications for day, peak and night, the most expensive energy is provided at the peak time. Since PV panels cannot produce energy at peak time, using energy storage systems in residential PV applications will contribute to cheaper energy supply. Thus, the rate of utilization of PV panels is much lower when the electricity consumption is highest. Therefore, with the use of energy storage systems, it will be possible to optimize the use of PV panels in distribution networks [22-24].

The purpose of this study is to explore the utility of PV panels, which are becoming increasingly widespread, to customers and distribution companies along with residential applications. We proposed a DM option without load shifting, we used ESS with PV systems to feed peak load. For this purpose, a yearly energy saving and cost research has been done for a house with solar panel and energy storage system. The daily energy production was determined with the prepared PV model and the produced energy was transferred to the energy storage system for usage in the peak time. As a result, utility on annual electricity bill has been put forward. Then, it is assumed that nearly 25% of the houses in the distribution network are using PV and ESS system, and the effect on distribution network was investigated. Cost and total load comparisons are shown with these case studies.

## 2. PV and ESS based Residential System

In recent years, bidirectional power flow is become possible at lots of countries. Besides self-energy generation for homes is a popular subject in the world. PV panels have an important place about these developments. Rooftop PV systems is began to became widespread. PV systems can provide energy to the locations which are far from the DN as base stations, general lightening, homes etc. Except those, PV systems are become popular for self-energy production and demand management applications.

PV cells consist of semiconductor materials and produce DC voltage depending on ambient temperature and solar irradiation. The working principle of PV cells is similar to the p-n junction diode. PV cell can be modelled with current source, parallel diode, and parallel and series resistance. One diode model electrical equivalent circuit for PV cell is given in Figure 1. Output current which is depending on photon current, diode current and parallel resistance current is given in (1).

$$I = I_{ph} - I_d - I_p \tag{1}$$

$I_{ph}$ is photon current whish is given in (2), $I_d$ is diode current which is given in (3) and $I_p$ is parallel resistance current which is given in (4). Eq. (5) and (6) are necessary to calculate (2) and (3).

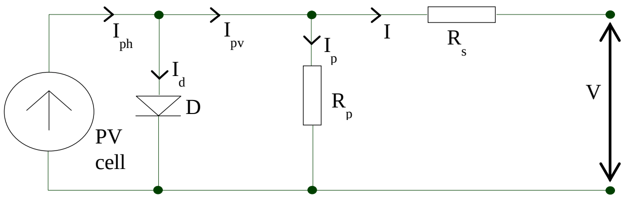



**Figure 1.** PV Cell Electrical Equivalent Circuit [25]

$$I_{ph} = N_p * \frac{G_T}{G_{Tref}} * \left[ I_{ph_{ref}} + K_i \left( T_C - T_{C_{ref}} \right) \right] \tag{2}$$

$$I_d = N_p * I_s * \left[ e^{\frac{q\left(V + I\frac{N_s}{N_p}R_s\right)}{N_s n k N_c T_C}} - 1 \right] \tag{3}$$

$$I_p = \frac{V + I\frac{N_s}{N_p}R_s}{\frac{N_s}{N_p}R_p} \tag{4}$$

$$I_s = I_{s_{ref}} * \left[ \left( \frac{T_{C_{ref}}}{T_C} \right)^3 * e^{\frac{qE_g}{nk} * \left( \frac{1}{T_{C_{ref}}} - \frac{1}{T_C} \right)} \right] \tag{5}$$

$$I_{s_{ref}} = \frac{I_{sc_{ref}} + K_i (T_C - T_{C_{ref}})}{e^{\frac{q\left(V_{oc_{ref}} + K_v\left(T_C - T_{C_{ref}}\right)\right)}{n k N_s T_C}} - 1} \tag{6}$$

Kyocera KC200GT PV module is used as solar power generation module and electrical specifications for this panel are given in Figure 2. Maximum power is 200 W for one module. Voltage is 26.3 V and current is 7.61 A at maximum power point. 4 modules are used for creating rooftop PV system.

## ■ Specifications

| ■ Electrical Performance under Standard Test Conditions (*STC) | |
|---|---|
| Maximum Power (Pmax) | 200W (+10%/−5%) |
| Maximum Power Voltage (Vmpp) | 26.3V |
| Maximum Power Current (Impp) | 7.61A |
| Open Circuit Voltage (Voc) | 32.9V |
| Short Circuit Current (Isc) | 8.21A |
| Max System Voltage | 600V |
| Temperature Coefficient of Voc | $-1.23\times10^{-1}$ V/℃ |
| Temperature Coefficient of Isc | $3.18\times10^{-3}$ A/℃ |

*STC : Irradiance 1000W/m², AM1.5 spectrum, module temperture 25℃

| ■ Cells | |
|---|---|
| Number per Module | 54 |

**Figure 2.** KC200GT PV Module Electrical Specifications [26]

Solar irradiation and ambient temperature at 2016 are used with one-hour time interval for Kayseri in Turkey. Both of these data are measured in Develi in Kayseri by Meteorology Kayseri Regional Directorate. Equations (1)-(6) are used for solar power generation. The modelled PV module is simulated and daily peak power and generated energy for one year is shown in Figure 3.

| PV Nomenclature | | | |
|---|---|---|---|
| $I$ | PV Cell Output Current | $E_g$ | Bandgap Energy |
| $I_{ph}$ | Photon Current | $T_C$ | Cell Temperature |
| $I_d$ | Diode Current | $T_{C,ref}$ | Reference Cell Temperature |
| $I_p$ | Parallel Resistance Current | $R_s$ | Series Resistance |
| $I_s$ | Diode Saturation Current | $R_p$ | Parallel Resistance |
| $I_{s,ref}$ | Reference Saturation Current | $N_p$ | Parallel Module Number |
| $I_{ph,ref}$ | Reference Photon Current | $N_s$ | Series Module Number |
| $V$ | Output Voltage | $N_c$ | Cell Number |
| $G_T$ | Solar Irradiation | $V_{oc,ref}$ | Reference Open Circuit Voltage |
| $G_{T,ref}$ | Reference Solar Irradiation | $I_{sc,ref}$ | Reference Short Circuit Current |
| $q$ | Electron Charge-1.6*$10^{-19}$ C | $K_i$ | Short Circuit Current Temperature Coefficient |
| $k$ | Boltzmann's Constant-1.38*$10^{-23}$ J/K | $K_v$ | Open Circuit Voltage Temperature Coefficient |
| $n$ | Ideality Factor | | |

Maximum power of PV module is 200.933 W in 17th July and minimum power is 15.447 W in 07th January. Total yearly energy is 365.826 Wh.

Hourly load power for one home is calculated with (7) and PV power is calculated based on the $G_T$ and $T_{amb}$ (8). T is the total hour of the year 2016, so total hour is 8764. Yearly total PV power is described with (9). Because of the solar and meteorological variability generated PV power is not always stable. PV size is determined with (11) based on yearly home load.

$$P_{total} = \sum_{t=1}^{T} P_{home\_load}(t) \quad t = 1,2,3,4 \ldots \ldots T, \ T = 8784 \tag{7}$$

$$P_{PV}(t) = f\big(G_T(t), T_{amb}(t)\big) \quad t = 1,2,3,4 \ldots \ldots T, \ T = 8784 \tag{8}$$

$$P_{PV\_T} = \sum_{t=1}^{T} P_{PV}(t) \tag{9}$$

$$PV_{module\_size} = \frac{P_{total}}{P_{PV\_av}} \tag{10}$$

Most of the distribution companies have three-time tariff for different hours. Most expensive time is peak hours and electricity bill can be decreased with demand management. Load shift is one of the DM strategies. Deferrable load can shift to day time or night time to use cheaper energy. Another strategy can be using the ESS. Solar power can be stored with ESS and stored energy can be used at the peak time. Thus, peak load can be feed without DN. New electricity bill is given in (11). Energy saving with RPVESS can be find with (12).

$$B_N = \sum_{d=1}^{D} E_1(d) * b_1 + \sum_{d=1}^{D} E_2(d) * b_2 + \sum_{d=1}^{D} E_3(d) * b_3, D = 366 \tag{11}$$

$$\sum_{m=1}^{M} B(m) - B_N, M = 12, \tag{12}$$

$B_N$ is new electricity bill, B is the monthly electricity bill, $E_1$, $E_2$ and $E_3$ are the daily energy consumption for different electricity price tariff zone, $b_1$, $b_2$ and $b_3$ are the electricity prices.

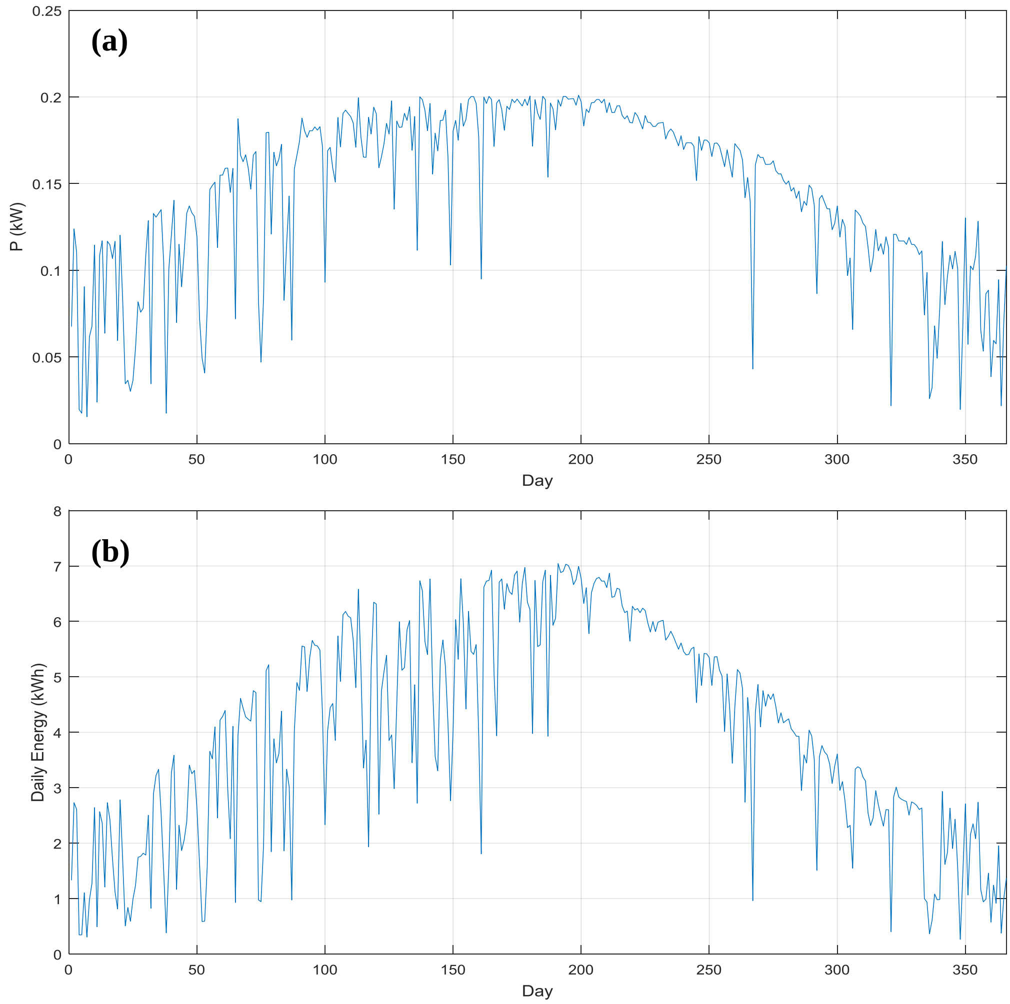



**Figure 3.** (a) Daily Peak Power of PV Module, (b) Daily PV Module Energy

**Table 1.** Yearly Electricity Bill and Energy Consumption

| Month | Electricity Bill | Energy Consumption kWh |
|---|---|---|
| January | 14.63 | 125 |
| February | 10.41 | 89 |
| March | 12.29 | 105 |
| April | 14.86 | 127 |
| May | 18.03 | 154 |
| June | 17.81 | 152 |
| July | 15.47 | 132 |
| August | 16.88 | 144 |
| September | 11.38 | 97 |
| October | 15.47 | 132 |
| November | 13.13 | 112 |
| December | 11.36 | 97 |
| **Total** | **171.7 $** | **1466 kWh** |

Monthly energy consumption and electricity bill for one house are given in Table 1.

Yearly energy of one house is 1466 kWh and total bill is 171.7 $. Economic benefit of the RPVESS is calculated with equation 13. Electricity price tariff of TEDAS in 2017 is given in Table 2 [27]. An optimization strategy of demand management for decreasing electricity bill is presented in Figure 4.

**Table 2**. Electric Price Tariff of TEDAS [27]

| Electric Price Tariff with Distribution Fee (cent/kWh) | | |
|---|---|---|
| **Day ($b_1$)** | **Peak ($b_2$)** | **Night ($b_3$)** |
| 0.093877 | 0.141984 | 0.059123 |

## 3. Case Studies

PV array and grid-tie inverter are used for residential application. 4 units KC200GT solar panels are used. Savior SSIN3200W inverter is selected for energy conversation. Inverter specification is given in Table 3. 2 units Ritar DG12-150 battery is used as ESS. RPVESS installation cost is given in Table 4. Electricity bill which is calculated with single-time tariff of a low load house in Kayseri is used. PV model is simulated for daily energy production. PV energy is used at day time and extra energy is stored with ESS to peak time usage. 25 per cent of PV energy is set not be use and stored at ESS. 10 per cent of PV energy is accepted as energy conversion losses. New electricity bill is calculated with three-time electricity tariff for monthly and yearly with equation (11). Electricity bill is given in Table 5.

**Table 3.** Inverter Specifications

| Inverter Specification | SSIN3200W |
|---|---|
| Input Voltage | 90-280 V |
| Output AC Voltage | 230 V ±5% |
| Maximum Efficiency | 93% |
| Maximum PV Array Open Circuit Voltage | 105 V |
| Maximum Solar Charge Current | 50 A |

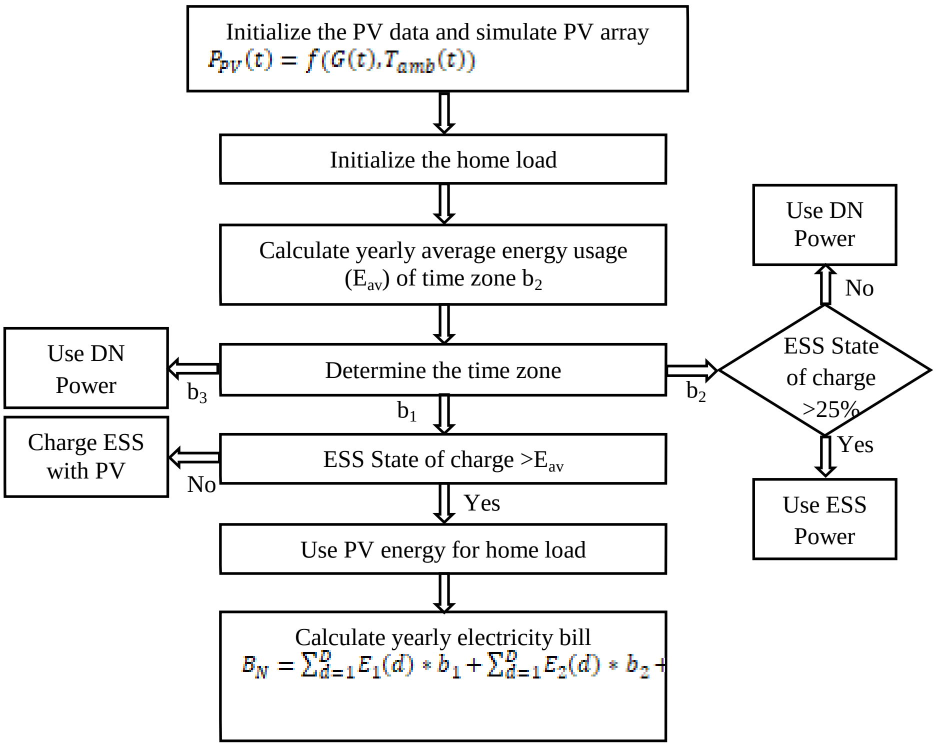



**Figure 4.** Optimization Strategy of Electricity Bill

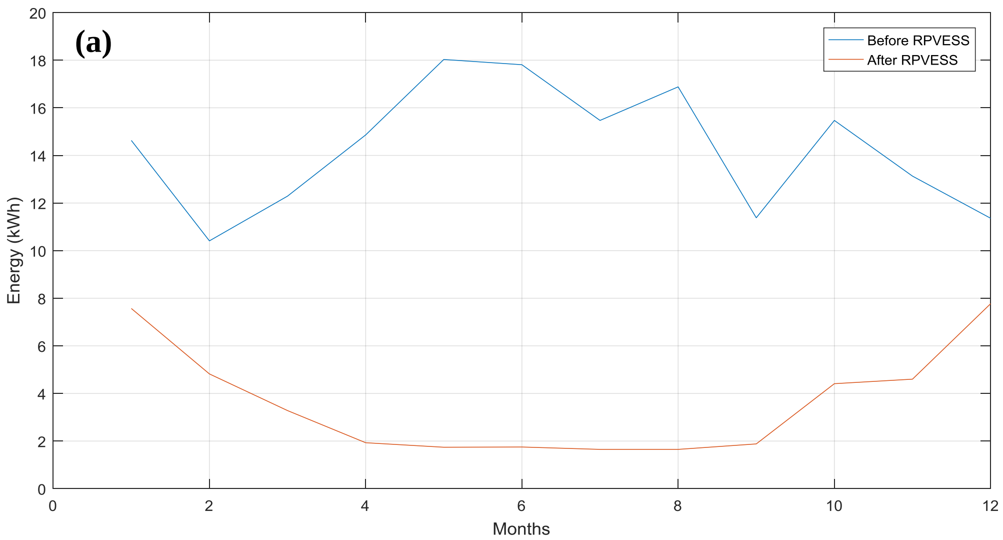
**Table 4.** Installation Cost

| | **Cost** |
|---|---|
| PV Module | 880 $ |
| Inverter | 470 $ |
| ESS | 650 $ |
| **Total** | **2000 $** |

**Table 5.** Yearly Electricity Bill and Energy Consumption with RPVESS

| **Month** | **Electricity Bill** | **Energy Consumption kWh** |
|---|---|---|
| January | 7.57 | 74.89 |
| February | 4.82 | 51.32 |
| March | 3.28 | 39.54 |
| April | 1.93 | 29.28 |
| May | 1.74 | 28.50 |
| June | 1.75 | 28.17 |
| July | 1.65 | 27.83 |
| August | 1.65 | 27.83 |
| September | 1.88 | 29.32 |
| October | 4.41 | 47.40 |
| November | 4.60 | 49.25 |
| December | 7.77 | 76.54 |
| **Total** | **35.46 $** | **509.87 kWh** |

Total energy consumption and electricity bill are given in Figure 5. Total bill is decreased 136.24 $ and total energy consumption is decreased 956.13 kWh for one year as expected.



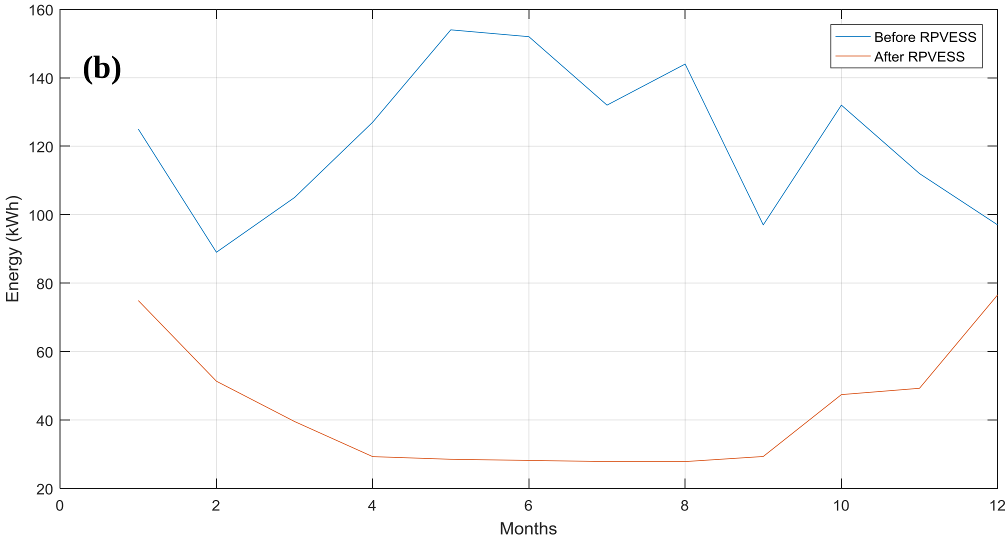



**Figure 5.** (a) Electricity Bill Comparison, (b) Energy Consumption Comparison

Second case study is about distribution network. The optimization strategy that is shown in Figure *4* is used at this case study. It is assumed that 25 per-cent of the houses have RPVESS at 33 bus DN as shown in Figure 6. Line and load data of DN is given in Table 6. Total distribution network energy and total yearly energy loss is given in Figure 7. New electricity bill is calculated with three-time electricity tariff for yearly with equation (11). After RPVESS usage, total electricity bill is decreased from 1980036 $ to 1753584 $. Both of them are calculated with three-time tariff.

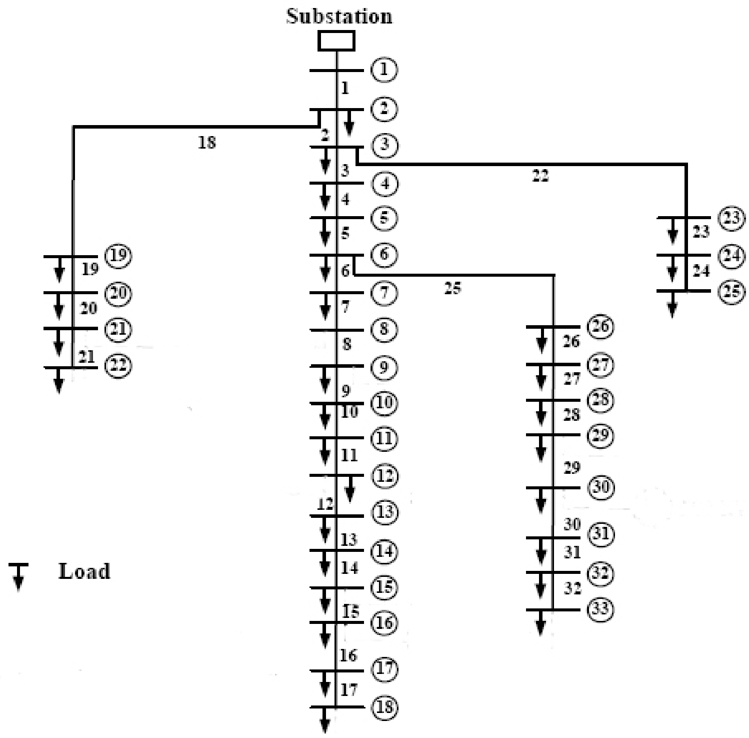
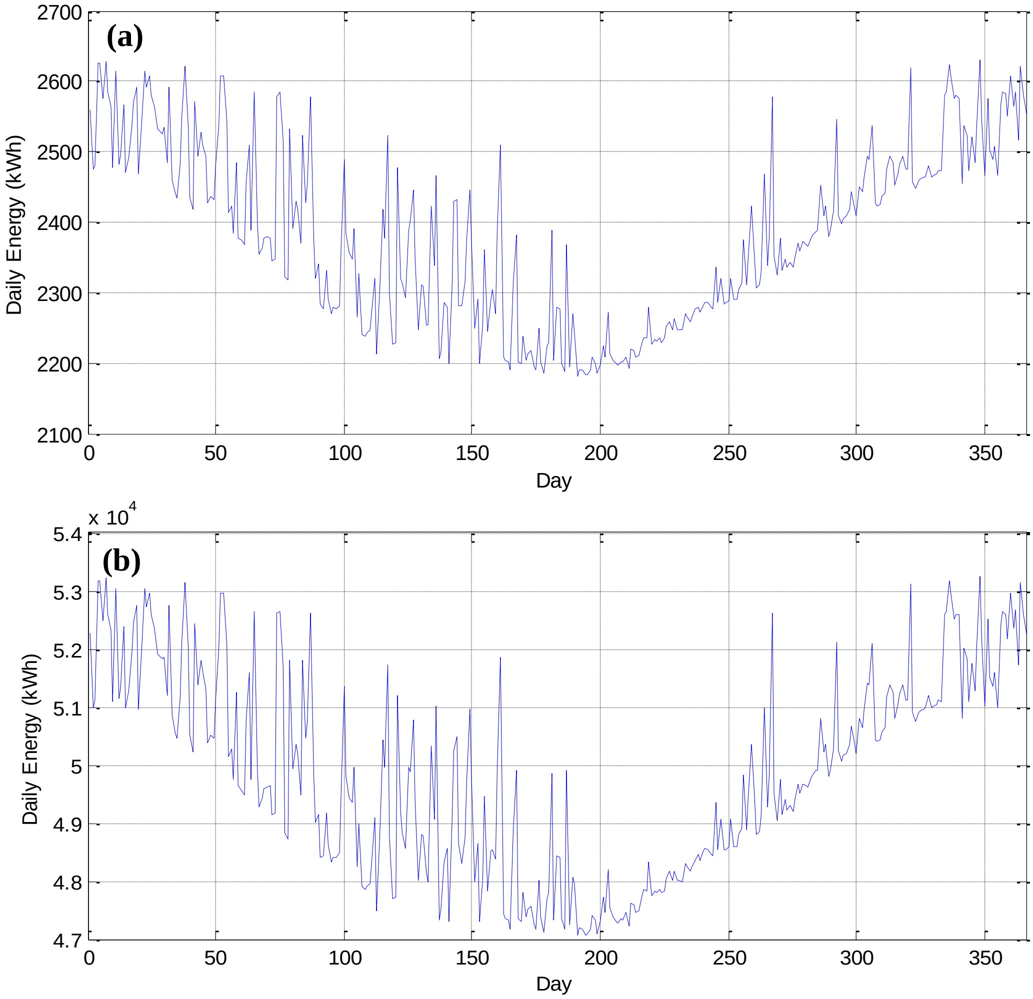



**Figure 6.** 33 Bus Distribution Network [28]




(b)

**Figure 7.** (a) Yearly Energy Loss, (b) Yearly Total Energy

## 4. Conclusion

Energy efficiency is one of the most important part of the energy saving. Demand management applications aim to benefit energy saving and load shifting is the most used method for DM. After the development of the renewable energy sources, PV panels are begun to take a place for residential energy production. In this paper, a demand management option as residential PV system and ESS without load shifting is proposed and economical effect of the RPVESS is investigated. First, RPVESS is applied to one home and yearly PV generation and energy consumption is performed. Generated PV power is optimized to decrease electricity bill and economical effect of RPVESS is analysed for one home. Electricity bill is decreased nearly 80%. Then, 33 bus DN is used for distribution network analyse and it is assumed that 25% of total homes are used RPVESS. Yearly energy consumption is decreased 11.437% and total distribution network loss is decrease 10.0151%.

These results are showing us the importance of the PV system usage and the necessity of the residential systems. While renewable energy sources have an important place in energy production, the produced energy must be used efficiently. Residential PV system usage will not be enough in the coming years, different demand management options will have an important place in energy planning studies. This study provides an energy planning option for optimum PV system usage. Thus, produced energy on RPVESS will be used an optimum way for decreasing electricity bill. This work will help us in future studies on demand energy management.

## APPENDIX

**Table 6.** Line Data and Load Data of 33 Bus Distribution Network

| 33 BUS DISTRIBUTION NETWORK LINE DATA AND LOAD DATA [25] | | | | | | | |
|---|---|---|---|---|---|---|---|
| LINE DATA | | | | | LOAD DATA | | |
| Branch No | Sending Bus | Receiving Bus | R | X | Bus No | $P_L$ (kW) | $Q_L$ (kVAr) |
| 1 | 1 | 2 | 0.0922 | 0.0470 | 2 | 100 | 60 |
| 2 | 2 | 3 | 0.4930 | 0.2511 | 3 | 90 | 40 |
| 3 | 3 | 4 | 0.3660 | 0.1864 | 4 | 120 | 80 |
| 4 | 4 | 5 | 0.3811 | 0.1941 | 5 | 60 | 30 |
| 5 | 5 | 6 | 0.8190 | 0.7070 | 6 | 60 | 20 |
| 6 | 6 | 7 | 0.1872 | 0.6188 | 7 | 200 | 100 |
| 7 | 7 | 8 | 0.7114 | 0.2351 | 8 | 200 | 100 |
| 8 | 8 | 9 | 1.0300 | 0.7400 | 9 | 60 | 20 |
| 9 | 9 | 10 | 1.0440 | 0.7400 | 10 | 60 | 20 |
| 10 | 10 | 11 | 0.1966 | 0.0650 | 11 | 45 | 30 |
| 11 | 11 | 12 | 0.3744 | 0.1238 | 12 | 60 | 35 |
| 12 | 12 | 13 | 1.4680 | 1.1550 | 13 | 60 | 35 |
| 13 | 13 | 14 | 0.5416 | 0.7129 | 14 | 120 | 80 |
| 14 | 14 | 15 | 0.5910 | 0.5260 | 15 | 60 | 10 |
| 15 | 15 | 16 | 0.7463 | 0.5450 | 16 | 60 | 20 |
| 16 | 16 | 17 | 1.2890 | 1.7210 | 17 | 60 | 20 |
| 17 | 17 | 18 | 0.7320 | 0.5740 | 18 | 90 | 40 |
| 18 | 2 | 19 | 0.1640 | 0.1565 | 19 | 90 | 40 |
| 19 | 19 | 20 | 1.5042 | 1.3554 | 20 | 90 | 40 |
| 20 | 20 | 21 | 0.4095 | 0.4784 | 21 | 90 | 40 |
| 21 | 21 | 22 | 0.7089 | 0.9373 | 22 | 90 | 40 |
| 22 | 3 | 23 | 0.4512 | 0.3083 | 23 | 90 | 50 |
| 23 | 23 | 24 | 0.8980 | 0.7091 | 24 | 420 | 200 |
| 24 | 24 | 25 | 0.8960 | 0.7011 | 25 | 420 | 200 |
| 25 | 6 | 26 | 0.2030 | 0.1034 | 26 | 60 | 25 |
| 26 | 26 | 27 | 0.2842 | 0.1447 | 27 | 60 | 25 |
| 27 | 27 | 28 | 1.0590 | 0.9337 | 28 | 60 | 20 |
| 28 | 28 | 29 | 0.8042 | 0.7006 | 29 | 120 | 70 |
| 29 | 29 | 30 | 0.5075 | 0.2585 | 30 | 200 | 600 |
| 30 | 30 | 31 | 0.9744 | 0.9630 | 31 | 150 | 70 |
| 31 | 31 | 32 | 0.3105 | 0.3619 | 32 | 210 | 100 |
| 32 | 32 | 33 | 0.3410 | 0.5320 | 33 | 60 | 40 |

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