Optimal battery sizing for hybrid photovoltaic/wind standalone system

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Abstract

For stand-alone applications, environment-friendly hybrid solar photovoltaic and wind renewable energy resources seems to be promising solutions. However, owing to the intermittency and unpredictability of renewable generation sources, battery banks are generally employed to meet the demand at all time. This paper presents a demand response model to optimize the battery bank size of standalone system. The objective of this framework is to optimize the battery storage for balancing the load demand and fluctuating renewable generation. Case studies are conducted on standalone system of a remote un-electrified household in Finland covering four seasons. The simulation results suggested that activation of demand response will optimize the battery bank capacity.

Keywords: Renewable generation; Battery bank optimisation; Demand Response; Standalone system.

Nomenclature

C_m	thermal capacity of building structure mass (J/°C)
C_a	heat capacity of air (J/°C)
H_e	Virtual conductance between external and internal temperature node points (W/°C)
H_g	Ground thermal conductance (W/°C)
H_m, H_y	Thermal conductance which allows C_m to grouped in the mass node point (W/°C)
H_x	Ventilation air heat conductance (W/°C)
$T_{n,t}^{a}$	Indoor ambient temperature of dwelling (°C)
T_t^{g}	Ground temperature (°C)

T_t^m Thermal mass temperature at time t (ºC)

T_t^{set} Set point temperature of dwelling (ºC)

T_t^x Ventilation supply air temperature (ºC)

Q_t^{hvac} HVAC power at time t (kW)

ϕ Internal temperature dead-band (ºC)

1. Introduction

In remote areas, which is difficult to be connected from the main grid, conventionally, diesel generator are utilized to serve the electrical energy requirements. However, the use of diesel generator has many disadvantages such as loss in fuel and maintenance cost, greenhouse-gas-emission and high cost of electricity [1]. In order to overcome these problems, the application of the environmental friendly renewable energy sources is quite preferred. Among renewable energy sources, both solar photovoltaic and wind play an essential role especially for small isolated/stand-alone power systems and micro grids [2]. Currently, the incorporation of battery storage is vital for such systems in order to mitigate the effect of the intermittency of the renewable energy sources.

The selection of battery size becomes a mandatory task because it influences the system reliability and cost significantly. In the previous work, optimal sizing of battery has been achieved using optimisation techniques such as genetic algorithm, artificial immune system, particle swarm optimisation (PSO), and ant colony optimisation (ACO) [3-7]. In order to avoid using excessive battery capacity, the demand response (DR) can assist the users to optimize power usage. The concept of DR is to motivate the end-use customers to change their normal consumption patterns based on the change in the price of the electrical energy over the time in order to reduce the peak demand [8-9].

Demand Response contains all intentional electricity consumption pattern modifications by end-use customers that are prepared to alter the timing level of total electricity consumption [10]. There are three general actions by which a customer response can be accomplished [11]. First, customers can minimize their electricity usage during critical peak periods when prices are high without changing their consumption pattern during other periods. This choice comprise a temporary loss of comfort. This response is achieved, for instance, when thermostat settings of heaters or air conditioners are temporary changed [12, 13]. Secondly, customers may respond to high electricity prices by shifting some of their peak demand operations to off-peak periods, as an example, they shift some household activities (e.g., dishwashers, pool pumps) to off-peak periods. The residential customer in this case will bear no loss and will incur no cost. However, this will not be the case if an industrial customer decides to reschedule some activities and rescheduling costs to make up for lost services are incurred. The third type of customer response is by using onsite generation customer owned distributed generation [14, 15]. Customers who generate their own power may experience no or very little change in their electricity usage pattern; however, from utility prospective, electricity use patterns will change significantly, and demand will appear to be smaller.

This paper presents a demand response methodology to optimize the battery bank capacity. A case study of a remote single family house in Finland is adopted where hybrid renewable energy sources, which include solar photovoltaic and wind, are considered as a primary power generation. Battery storage acts as backup to enhance the continuity of supply whereas DR is also applied in order to minimize battery storage capacity. This paper is organized as follows, Section 1 includes the introduction, Section 2 describes the presented demand response model, Section 3 depicts the system under study, Section 4 presents the simulation results and discussion, and finally the conclusions are presented in section 5.

2. Demand Response Model

This section presents an optimization model to minimize the battery bank size $E^{capacity}$ for a standalone system. The objective function can be mathematically written as

$$Minimize \quad E^{capacity} \tag{1}$$

Subjected to;

$$T_t^a = \frac{T_{t-1}^a + \frac{\Delta t}{C_a}\left[H_m T_{t-1}^m + H_e T_t^e + H_g T_t^g + H_x T_t^x + Q_t^{hvac}\right]}{1 + \frac{\Delta t}{C_a}(H_m + H_e + H_g + H_x)} \tag{2}$$

$$T_t^m = \frac{T_{t-1}^m + \frac{\Delta t}{C_m}(H_m T_{t-1}^a + H_y T_t^e)}{1 + \frac{\Delta t}{C_m}(H_m + H_y)} \tag{3}$$

$$(T_t^{set} - \frac{\phi}{2}) \le T_t^a \le (T_t^{set} + \frac{\phi}{2}) \text{ } ,\forall t \in T \tag{4}$$

$$0 \le Q_t^{hvac} \le Q_t^{hvac,\max}, \quad \forall t \in T \tag{5}$$

$$(SoC_{t+1} - SoC_t)E^{capacity} = SoC_{t_o} + (P_t^w + P_t^s - P_t^{crit} - Q_t^{hvac})\Delta t, \quad \forall t \in T \tag{6}$$

$$SoC_t^{\min} \leq SoC_t \leq SoC_t^{\max}, \ \forall t \in T \tag{7}$$

The expression (2)-(3) evaluates the electricity consumption of space heating load [16]. Whereas, the constraint (4) make sure that indoor ambient temperature do not violate the customer thermal set preferences. The constraint (5) represents the limit of rating power of space heating unit. The constraint (6) describe the characteristic of battery bank operation. Constraint (7) bounds the limit on battery bank capacity.

In the above model, all the variables but $E^{capacity}$ and SoC_{t_o} is an unknown decision variable. The problem is solved using CPLEX solver in GAMS platform.

3. Test system description

A remote single family house in Finland as shown in fig. 1 is considered where the energy consumption (kWh) for a day in each season of a year is adopted for the investigation. The household includes loads (i.e., appliances), electrical switchboard, inverter that converts dc electricity into useable AC electricity, battery charging controller and also heating loads such as space heating. The hourly meteorological data over the four seasons for outside temperature profile for four seasons is illustrated in fig. 2(a).

A Finnish household is equipped at the rooftop with wind turbine and solar photovoltaic panel of nominal powers equal to 2 and 1 kW, respectively. The total kW generated from solar PV and wind is time dependent [18] as shown in fig. 2(b) and fig. 2(c).

The expected hourly consumption patterns of these appliances are decided based on their general use. Hourly load for the four seasons is utilized for the battery sizing of the proposed standalone system. The average energy consumption for the load over summer, fall, winter and spring are 1.07, 2.64, 4.94 and 1.43 Kwh, respectively.

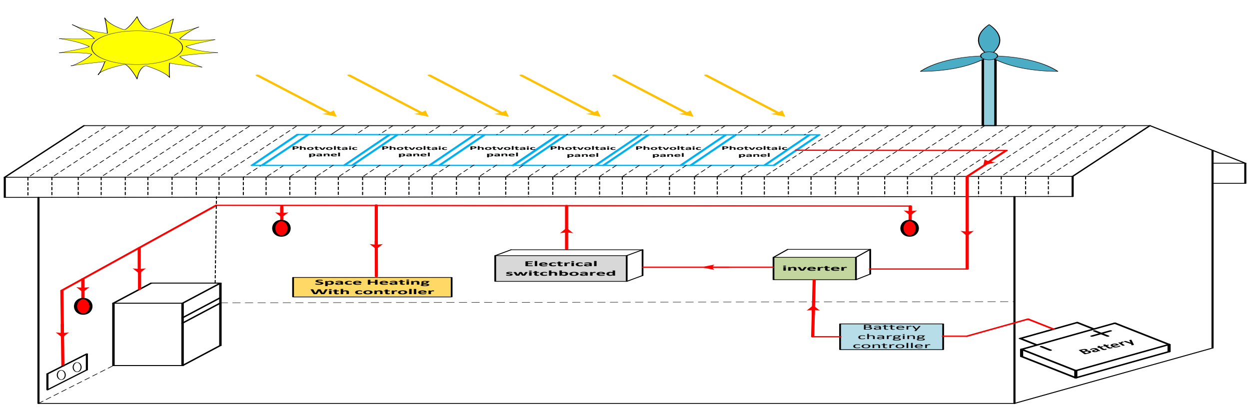


Fig. 1 An overview of the proposed system [17]

For each hour, the total power from solar and wind has been monitored. Solar PV and wind turbine represent the main supplier to the load. If their total generated power is insufficient to supply the load, the stored energy of battery will discharge to supply the load.

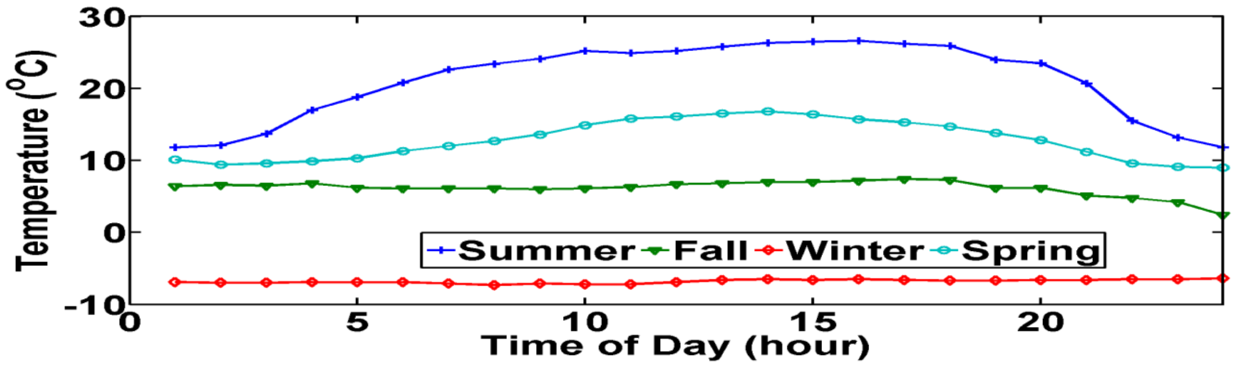


Fig. 2a outside temperature profile used in simulation

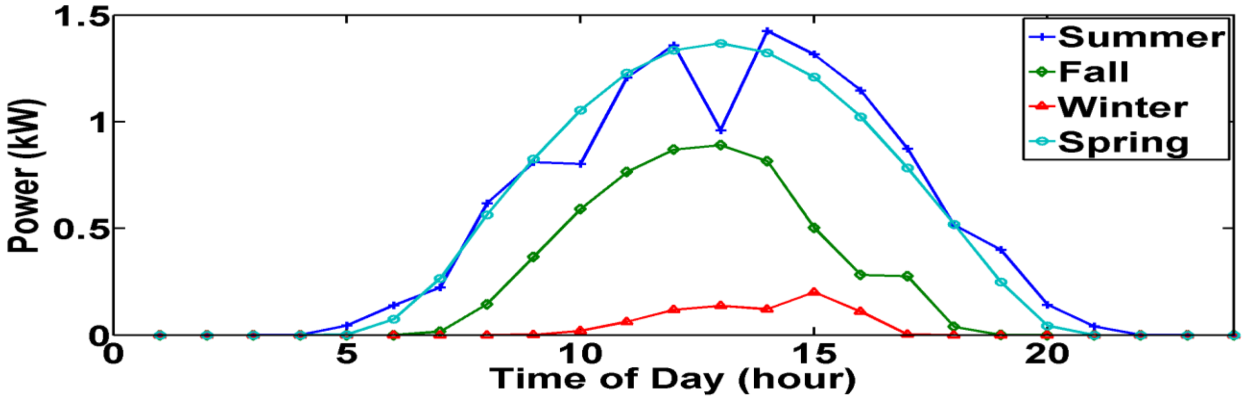


Fig. 2b Hourly generation of solar photovoltaic

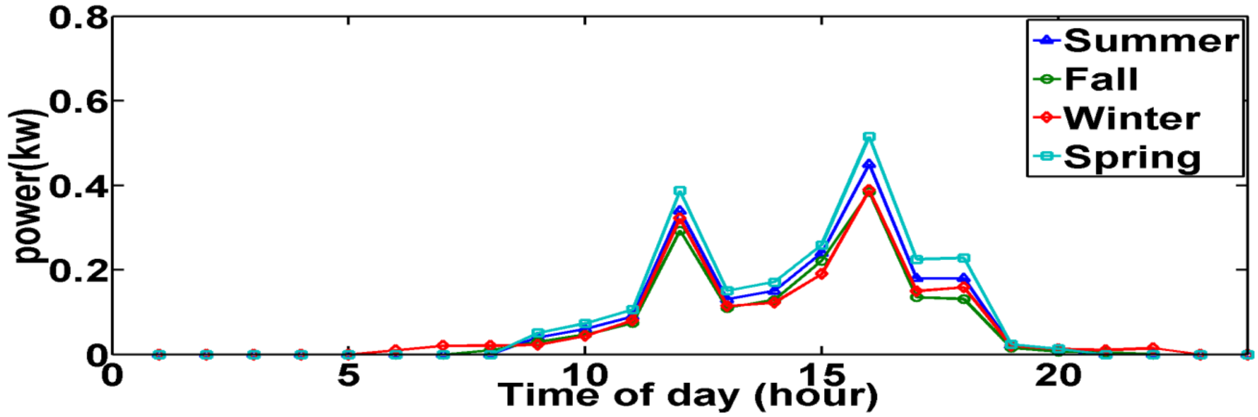


Fig. 2c Hourly generation of wind turbine

4. Simulation Results

The performance analysis of the proposed model of optimal sizing of battery is conducted. Two case studies are taken in consideration. In the first case, battery capacity size is determined without application of demand response. While in the second one demand response is implemented. Studies are conducted on representative remote un-electrified house in Finland covering different seasons.

For summer season the load demand is at its peak during 21:00 to 24:00 in the evening and the available power generated from both solar photovoltaic and wind are not sufficient to supply the load in this time Therefore, the battery is discharging during this period in order to satisfy load as shown in figs 3a and when demand response is implemented that causes shifting of some of loads. Battery size is minimized and also battery state of charge (soc) profile changed as shown in fig 3b.

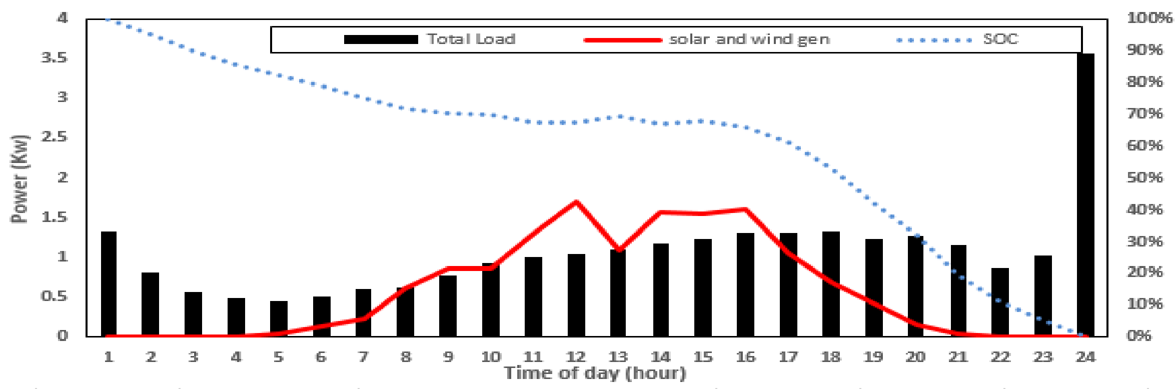
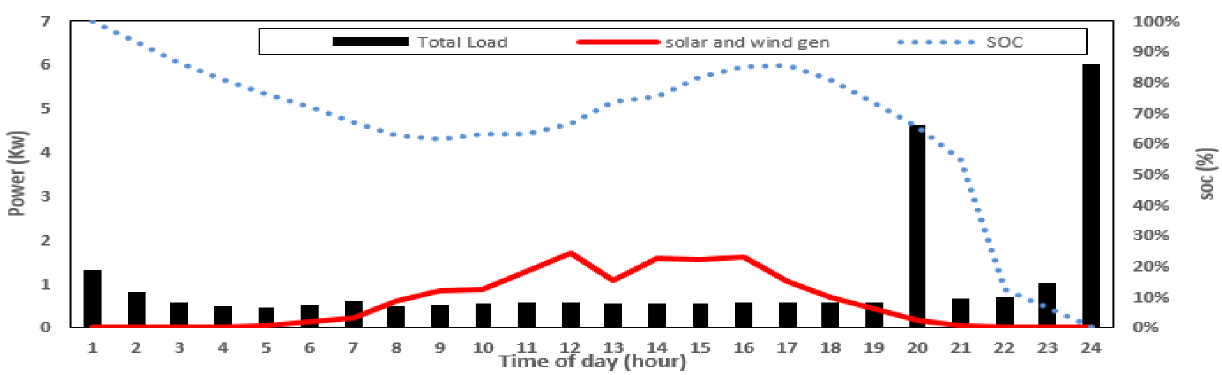


Fig. 3 Solar PV, Wind generation and battery Soc in summer (a) without DR, (b) with DR

(a)



(b)

In fall, the power from total renewable energy, load demand and battery soc without applying DR is shown in fig 4a the load demand in this season is high during the whole day as compared with summer where, the available renewable energy generation is not sufficient to cater the load in this time. To maintain the continuity of supply the battery is discharging in order to fulfil the load. The optimal sizing of battery in fall season is higher than summer due to high imbalance between load and fluctuating renewable generation Therefore, after applying DR the optimal size of battery is reduced and also changed due to shifting some loads as shown in fig. 4b

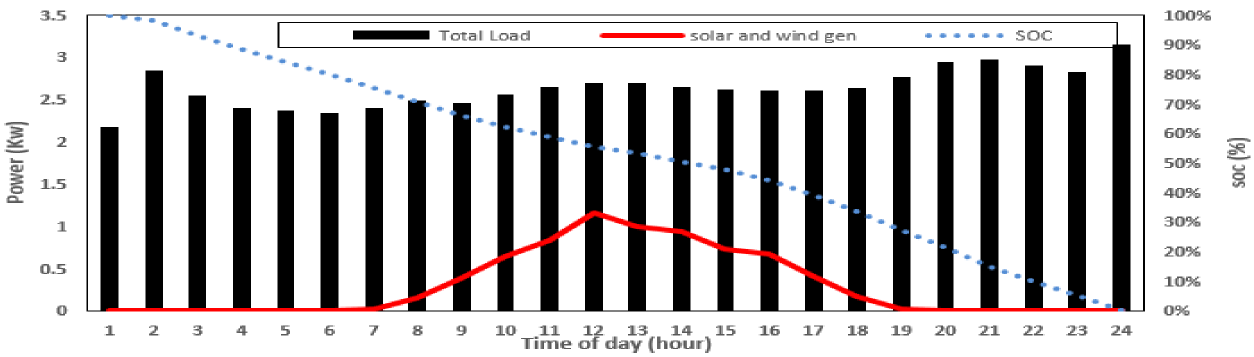
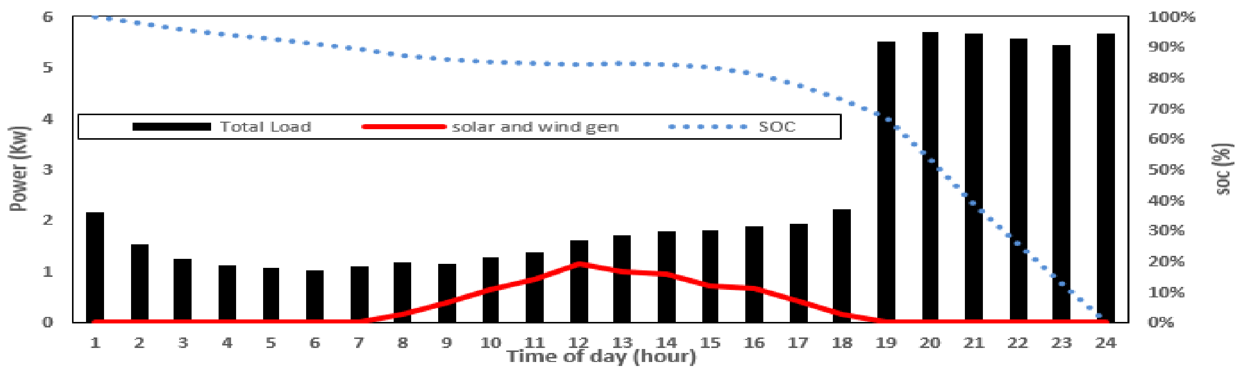


Fig. 4 Solar PV, Wind generation and battery Soc in fall (a) without DR, (b) with DR

(a)



(b)

During winter season the load demand becomes higher than fall and summer seasons and due to less power extracted from both photovoltaic and wind generation, Battery works as a backup generation and discharges in order to avoid any disconnection of load. The optimal size of battery in this case before and after applying DR is the highest one as compared to other seasons and this due to shifting of load becomes a difficult task for customer but with demand response implementation this size of battery is reduced but with a small value as shown in figs 5a &5b.

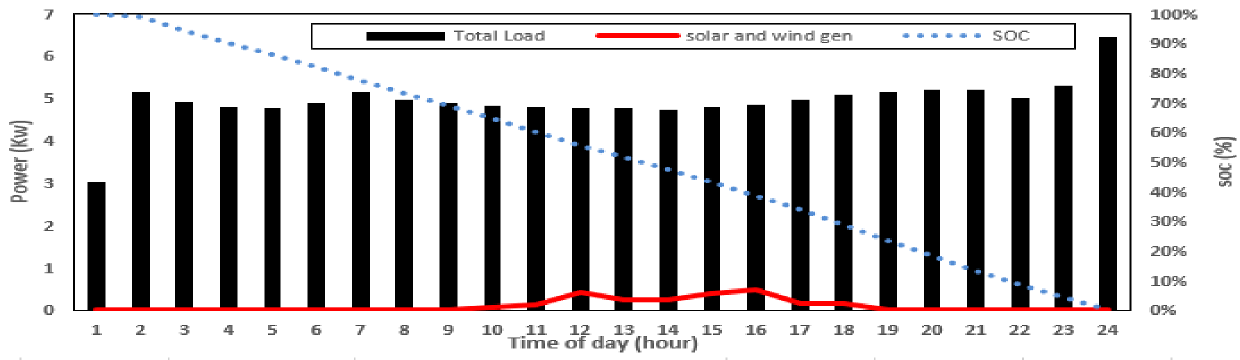
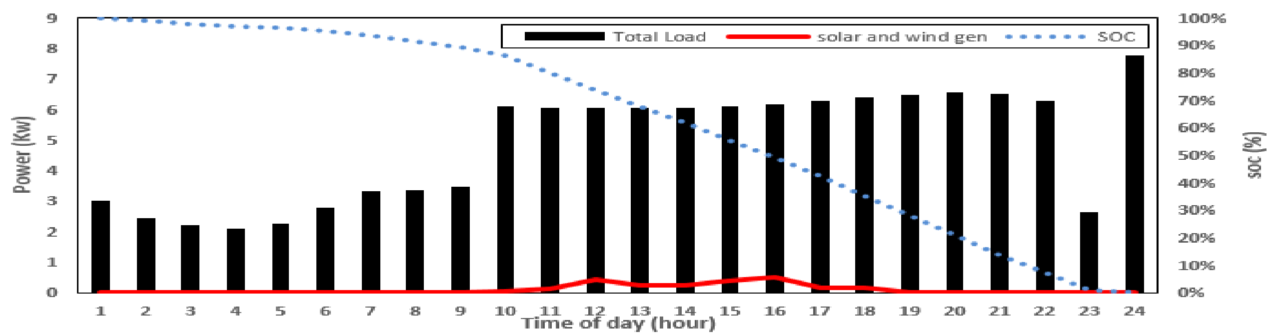


Fig. 5 Solar PV, Wind generation and battery Soc in winter (a) without DR, (b) with DR

(a)



(b)

For spring season the power extracted from both solar photovoltaic and wind are seemed enough to satisfy the load demand in period 10:00 to 17:00 so the battery is charging in this period while in the other periods the load demand is higher than total renewable energy generation therefore the battery is discharging in those periods as shown in fig 6a. Demand response is applied and optimal size of battery is minimized the battery soc profile is intermediate between summer and fall season as shown in fig 6b.

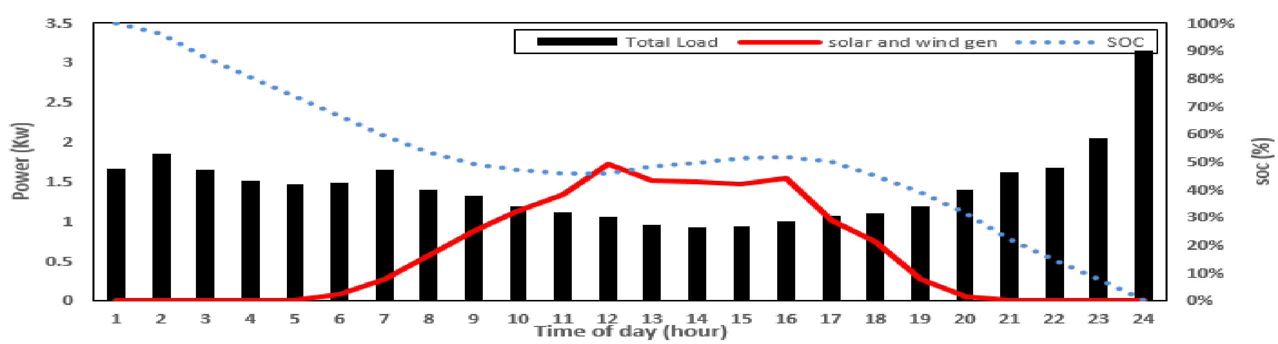
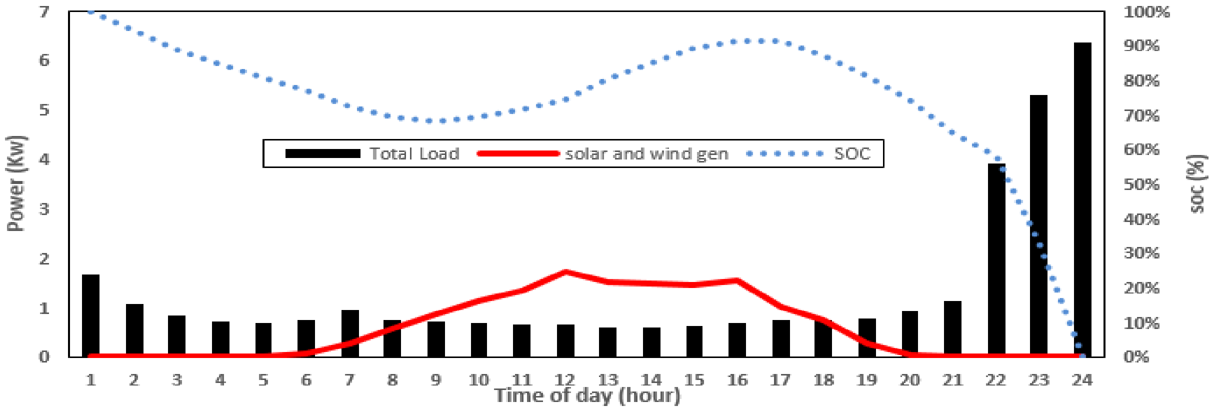


Fig. 6 Solar PV, Wind generation and battery Soc in spring (a) without DR, (b) with DR

(a)



(b)

As can be seen from the results, during winter the improvement is small as compared to other seasons. The reason is that demand response potential is the lowest during extreme weather as load shifting opportunities are minimum. Whereas during milder temperatures, for instance in spring and summer, space heating load can be prepone or postpone for a few hours, hence reducing the need of extra capacity of battery to smooth the supply-demand imbalances as shown in table 1.

Table 1 Demand Response Effect

Season	**Battery sizing optimization (kW)**		**Reduction Ratio (%)**
	Without Demand Response	*With Demand Response*	
Summer	**15.15**	**11.52**	**24%**
Fall	**42.45**	**37.28**	**12%**
Winter	**78.34**	**74.95**	**4.3%**
Spring	**19.33**	**14.36**	**26%**

5. Conclusions

In this paper, the optimal sizing of battery incorporating both hybrid solar photovoltaic and wind for an un-electrified house in Finland is presented. Real data of solar PV, wind, outdoor temperature and load is implemented in simulation. The optimization has been solved on GAMS platform. The simulation results suggest demand response reduces installed battery capacity in all seasons. Results proves that activation of demand response has a significant effect on battery sizing.

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