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Simulation of a ZEB Electrical Balance with aHybrid Small Wind/PV

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Abstract Electricity production from modern renewable technologies (wind energy, solar energy, water power in small scale, and geothermal energy) is growing rapidly worldwide. In addition to the large-scale power generation, applications in the residential sector is also of interest which are classified into stand-alone systems (without connecting to the grid) and grid-connected systems. Zero energy building (ZEB) is a concept based on minimized energy demand and maximized harvest of local renewable energy resources. In this paper, the electrical energy consumption of a typical residential building is modeled. In addition to the electrical grid, the house is connected to a hybrid wind turbine and photovoltaic array together with a battery storage system. The cost of electricity purchased from the electrical grid was optimized to its minimum level. The results showed that, considering a load profile with 21.675 kWh of daily consumption, a 3 kW PV array with a 2 kW wind turbine and a 5 kWh battery could save 96% of the monthly electricity bill; from 2’377 to 66’960dollars. Excluding battery storage, this saving was reduced to 74%.

Keywords: *Zero Energy Building (ZEB), energy storage, Energy Cost Optimization*

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1. Introduction

Today, it is obvious that modeling and simulation has an important role in the area of system engineering. Description of the experimental behavior of the system is not always possible. The main reasons may be the unavailability of the inputs and outputs, dangerous testing condition, high cost of testing, noncompliance of the system time constants with the human dimensions and lack of clarity of the experimental behavior of the system due to the disturbance. This will become more important in the field of renewable energies, so that almost no renewable system is being studied under real or laboratory condition before the computer simulation is performed. On the other hand, the use of the new renewables in both small and large electricity generation is growing rapidly. Because of the high cost of building construction, any innovative idea should be already modeled to assure that the system is really beneficial.

A *Net Zero Energy Building*(NZEB) is simply defined as a building in which the electricity or heat from renewable energy resources can supply the same highly reduced energy demands. Such buildings’ annual energy need can be supplied by one or more conventional or modern distribution energy systems such as electricity grid, district thermal system, gas pipe network, biomass and biofuels distribution networks [1]. The electrical components of a NZEB may be summarized as following [2]:

- *Smart Meter:* It is a gateway between the building and the smart electrical grid.
- *Heat Pump:* It reduces the energy required for interior heating.
- *Battery Storage:* It serves as the backup energy during power failure or on-peak hours.
- *Solar Photovoltaic and Small Wind Turbine:* they serve as the supplementary power generation to meet the house energy demands.
- *High Efficiency Lighting:*Modern CFL, LED, OLED require less energy.
- *Home Energy Manager:* It controls and optimizes the energy flow in the house.

Figure 1 shows a schematic of the prescribed system and the *building boundary system* which energy compares to flows and canflow in and out of the system [3]. Building boundary comprises of *physical* and *balance* boundaries. Depending on renewables generated *on-site* or *off-site*, the physical boundary may vary. Also, it includes the size ranging from a single and small house to a group of buildings. Heating, cooling, ventilation, lighting and appliances can be mentioned as different energy uses and balance boundary associated with these types of energies used for writing the energy balance for our system. Here, we confine our study to balance boundary which encompasses small wind, photovoltaic array, battery and electricity grid. The model presented here exactly shows what a home energy manager does in Figure 1 to optimize the cost of electricity purchased from the grid.

Figure 1. Schematic of the energy flow exchange between the energy-efficient building and different electricity components

1.1. Battery Storage

Electrical storage battery is a needful part of renewable power systems particularly, small wind turbines and photovoltaic and is defined as a device which allows electricity to flow in both directions: inside and outside.

In the ZEB approach, battery storage is an essential component of the standby, emergencybackup services and electric vehicles which is the concept known as vehicle-to-building (V2B) and vehicle-to-home (V2H) technology. They are able to provide beneficial storage capacity to both vehicle and the building owners by lowering cost of the electric vehicles, reducing building'spurchased energy and enabling reliable emergency power systems.

The *State of Charge* (*SOC*) of a rechargeable battery (also, known as secondary battery) at any time is defined as

$$SOC = \frac{C}{C_{rated}} \tag{1}$$

where C is the remaining capacity and C_{rated} is the rated capacity both measured in Ampere-hours (Ah) which means delivering C/k Amperes in k hours [4].

1.2. Photovoltaic & Small Wind

The efficient solar to electrical energy conversion using photovoltaic (PV) cells is one of the promising solutions for the global future energy demand. *Solar cells* are capable of converting the solar radiation into the electrical direct current (DC) through the so-called effect called photovoltaic. *Photovoltaic modules* or *photovoltaic panels* are made of the multiple interconnected solar cells. Owing to its low output power to meet the requirement of the house demands, *photovoltaic arrays* are usually utilized which are the linked collection of photovoltaic modules. To be applicable for household devices, the array output DC power should be converted to an alternative current (AC) via a device called *inverter*. Solar arrays electrical power are generally measured in watts (*W*), kilowatts (*kW*) and sometimes megawatts (*MW*) [5]. As illustrated in Figure 2, the array power generation varies from zero to its maximum value throughout the day.

Arotational flow driven machine which converts the kinetic energy from the moving air (wind) into the mechanical energy is called a *wind turbine*. Using a generator, the output mechanical energy is converted into the useful electricity. The relationship between the extracted mechanical power and the wind speed can be shown by a plot called a *power curve*. Figure 3 illustrates an idealized wind turbine power curve. The operating limits of a wind turbine is characterized by *cut-in* and *cut-out* speeds.

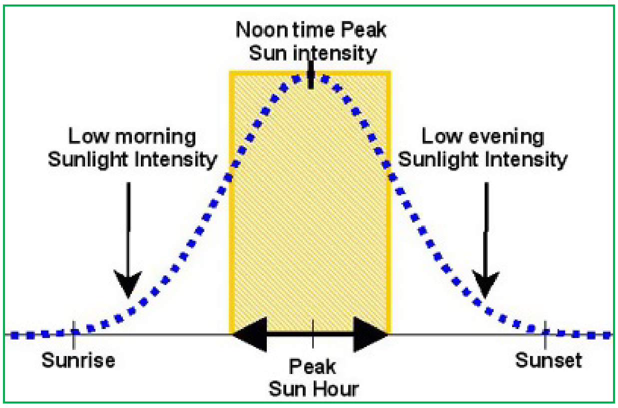


Figure 2. Typical electricity PV generation profile [6]

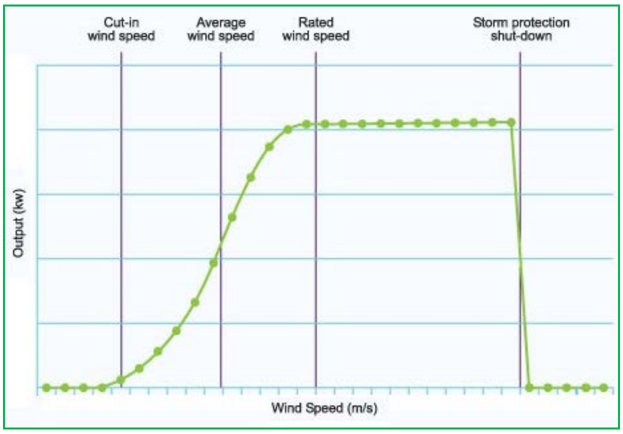


Figure 3. Idealized wind turbine power curve [7]

It can be seen from Figure 3 that the power curve is divided into four distinct zones:

- *Before cut-in wind speed* consists of low wind speeds which there is not sufficient torque exerted by the wind on the turbine blades to make them rotate so no power can be extracted.
- *Between cut-in and rated wind speed* is a transition region mainly concerned with keeping rotor torque and noise low and can be expressed as

$$P = \frac{V - V_{in}}{V_{out} - V_{in}} \times P_{rated} \tag{2}$$

where P is the extracted power (W), P_{rated} is the rated turbine power (W), V is the wind speed (m/s), V_{in} is the cut-in speed (m/s) and V_{out} is the cut-out speed (m/s).

- *Between rated and cut-out wind speed* which is relevant to higher wind speeds, the turbine design limit the output power to a maximum level (rated output power) and no further rise will happen in the extracted power.
- *After cut-out speed (storm protection shut-down)* there is a risk of damage to turbine structure and the control system stops the rotor.

1.3. Smart Meter

During the day, the *smart meter* has the option of charging various rates which are split into three separate periods according to demand for electricity: *off-peak* (low demand), *mid-peak* (moderate demand) and *on-peak* (high demand). The lowest prices are usually at night, on weekends and on holidays and are different throughout summertime and wintertime. Figure 4 shows a typical time-of-use price periods and is used in the model of the current study. Table 1 shows the assumed electricity rates in the current study.

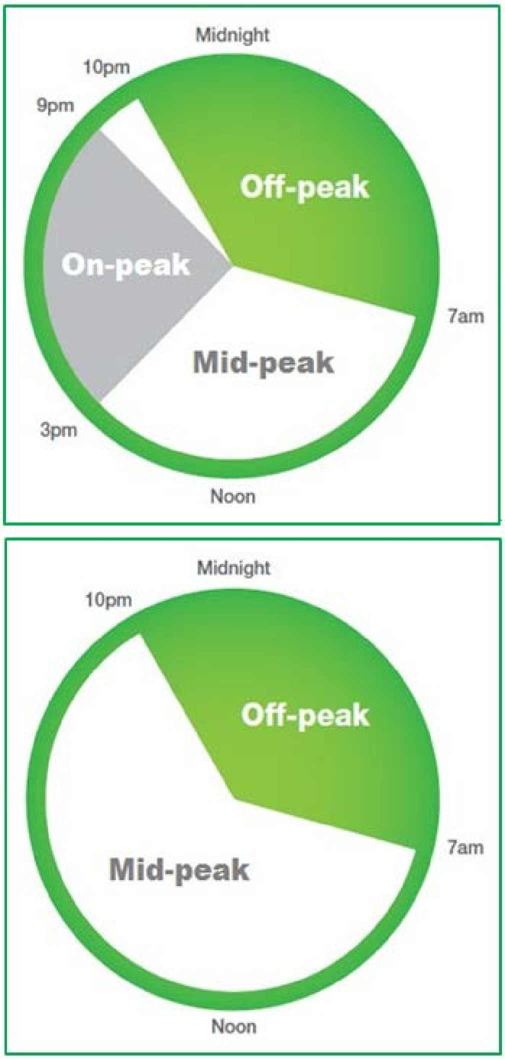


Figure 4. Hourly separate periods of electricity demand for weekdays (up) and weekends (down) [8]

Table 1. Rates of electricity in different periods (values of B_i) [9]

Period	Off-peak	Mid-peak	On-peak
Price (*cent/kWh*)	7.2	10.9	12.9

2. Model Equations

At each point of the time t_i (here, we consider each point as an hour) where $0 \le i \le 24$, we can write the energy balance on the building system boundary as

$$E_w(t_i) + E_{pv}(t_i) + E_g(t_i) = E_b(t_i) + E_c(t_i) \quad (3)$$

where E is the energy exchanged during 1 hour and the subscripts w, pv, g, b and c stand for wind turbine, photovoltaic panel, electrical grid, battery and the home energy demand, respectively. For the case of the battery, the exchanged energy is identical to its charging when $E_c < 0$ and discharging when $E_c > 0$, in other words

$$E_b(t_i) = E_{bc}(t_i) - E_{bd}(t_i) \quad (4)$$

where c and d denotes charging and discharging, respectively.

Taking the battery capacity into account, we can associate the state of the charge (*SOC*) and the exchange energy as following

$$SOC(t_i)C_{rated} = E_b(t_i) + SOC(t_{i-1})C_{rated} \quad (5)$$

where the value of SOC is always between its minimum and maximum levels.

$$SOC_{\min} \le SOC \le SOC_{\max} \quad (6)$$

The battery fault can be a reason for not assigning the values 0 and 1 to the minimum and maximum values of the SOC. As the second reason, the system owner probably like to ensure that there is always a charge remnant $SOC_{\min}C_{rated}$ left in the battery. Eq. (2) is the simple case in which the battery efficiency considered to be 100% during charging and discharging. The more typical case can be written as (5).

$$E_b(t_i) = E_{bc}(t_i)/\eta_c - \eta_d E_{bd}(t_i) \quad (7)$$

where η_c and η_d are the battery efficiencies in charging and discharging modes, respectively.

The daily price of purchased electricity $B(cent)$ can be calculated using

$$B = \sum_{i=1}^{24} B_i \quad (8)$$

where $B_i(cent/hour)$ is the rate of electricity at the time t_i. Values of B_i can be found in Table 1. Assuming a constant daily trend throughout a month, the monthly electricity bill is calculated. The aim of the current simulation is to find the minimum value of B denoted by $B_{\min}$.

Assumed value for the two first terms in Eq. (2) is depicted in Figure 5 and Figure 6. The PV array has a nominal power output of $3kW$ and the small wind turbine specifications can be found in Table 2.

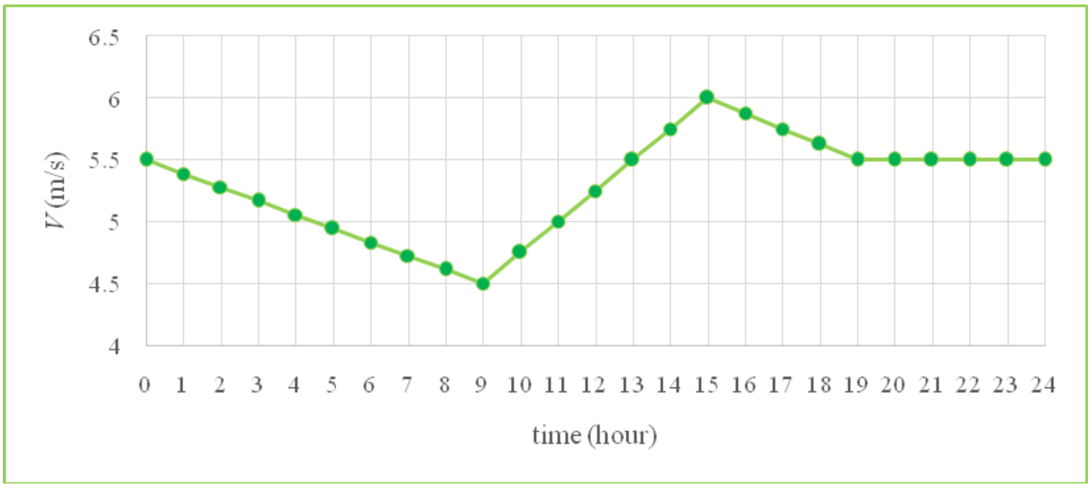


Figure 5. Distribution of daily wind speed at turbine height used for the turbine power output [11]

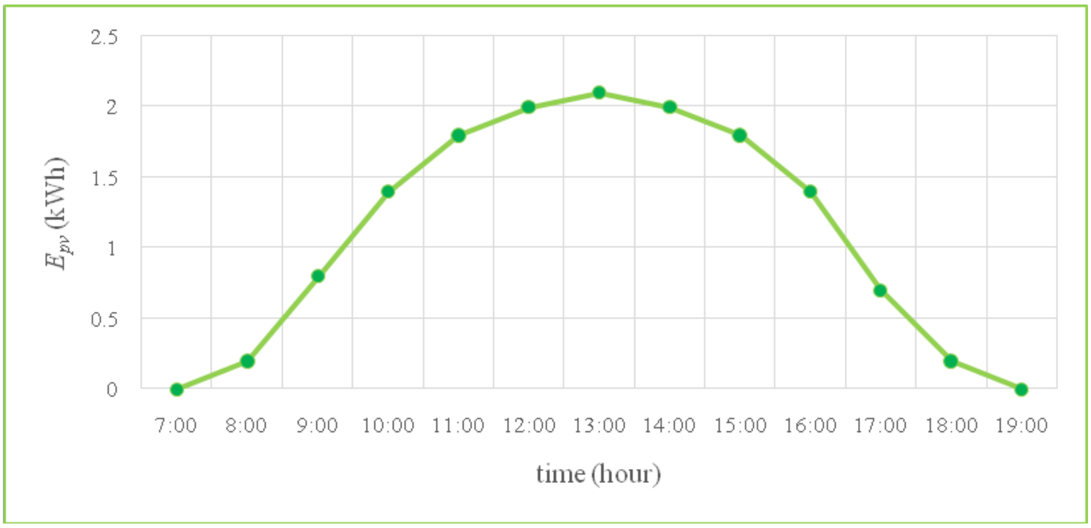


Figure 6. Distribution of hourly photovoltaic energy generation [12]

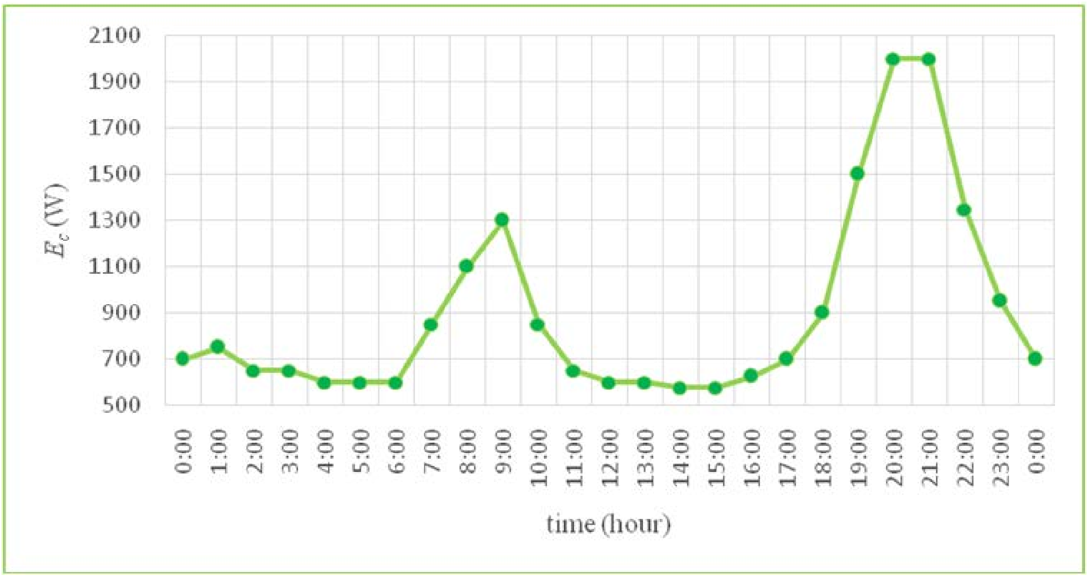


Figure 7. Distribution of hourly energy consumption for a typical family [13]

Table 2. Small wind turbine characteristics [10]

Tanfon FD-2000			
$V_{in}\,(m/s)$	$V_{out}\,(m/s)$	$P_{rated}\,(kW)$	Rotor Diameter (m)
3.5	9.0	2.0	3.2

Table 3. Battery specifications

η_c	η_d	C_{rated}	SOC_{min}	SOC_{max}
0.9	0.9	5 kWh	0	1.0

In this study we considered a typical family which consumes electricity similar to what can be seen in Figure

8. more information about load profile patterns can be found in ref. (14).The values of constants in Eqs. (5) and (6) in the model can be found in Table 3.

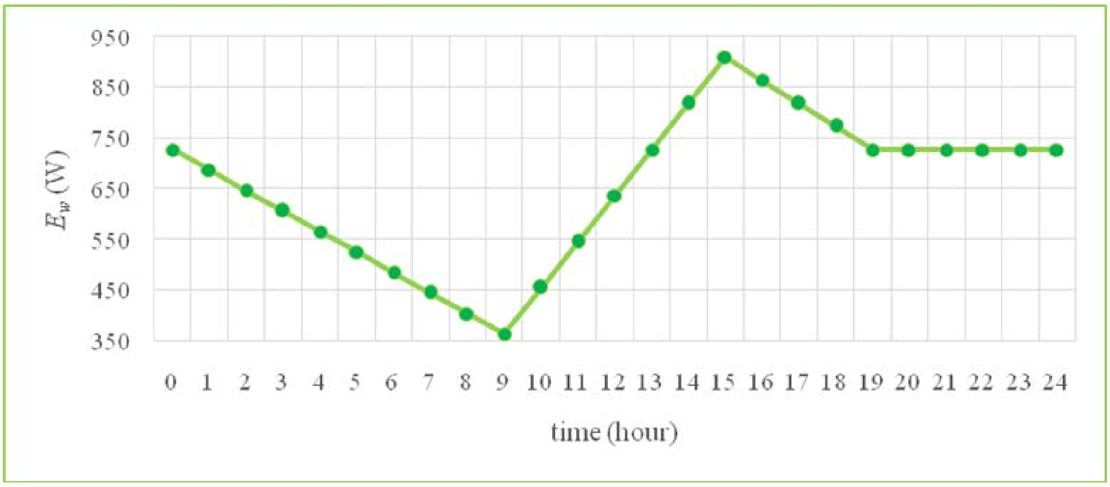


Figure 8. Distribution of daily wind turbine power used in the model

3. General Algebraic Modeling System

Equations (3) to (8) comprise a linear system of equations which can be solved using the *General Algebraic Modeling System* (GAMS) which is a high level modeling system [15] and is very similar to fourth generation programming systems. The procedure is carried out according to the defined algorithm by the software. It is capable to globally solve linear programs as well as finding local optima of nonlinear programs. In this software, the programmer can build models which are expressed in simple and concise algebraic statements to find the optimum value of a predefined function. Here, the statements are very similar to the model equations (3) to (8) except for its initial condition is required by the software to solve the problem more efficiently. We put the value of $E_w(t_i)$ at $t_i = 0$ o be $500kWh$ as can be seen in Figure 11. The available input data for wind, PV and the energy consumption along with the rate periods are imported to the system defining tables which pertains to each energy supplies/demands.

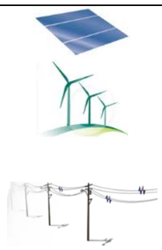
4. Results

The hourly wind turbine output power $E_w(t_i)$ is calculated using Eq. (2) and Figure 5. The output power is shown in Figure 8 and is used in the model equations. Modeling the equation systems in GAMS, the monthly electricity bill B is calculated in three cases:

- *Case I*: In presence of RET (*renewable energy technology*) with battery storage. In this case, there is a minimum value of B.
- *Case II*: In presence of RET without battery storage. Here, no minimum value of B exist.
- *Case III*: In absence of RET.

It is assumed that the daily trend of energy consumption depicted in Figure 7 continues for all the other days throughout a month. Figure 9, Figure 10, Figure 11 illustrates the simulation results. As Table 4 shows, using all elements can save 96% in electricity cost while 22% of this reduction owes to the battery storage. The more the battery storage capacity was used the more the improvement is seen in the energy saving through shifting high amount of energy from off-peak to the on-peak hours.

Table 4. Simulation results for daily prices for different cases

Case	I	II	`III
Elements			
Daily Price ($)	79.24	608.26	2’232
Monthly Price ($)	2’377	18’240	66’960

5. Conclusion

Zero Energy Building(ZEB) is a modern concept which deals with providing the electrical or thermal energy from renewable energy resources to supply the buildings’ annual energy demands. However ZEBs have different aspects, current research investigated them with electrical approach as the part of building balance boundary.

A simple model was developed to encompass the balance boundary aspect of a nearly zero energy building and the electricity cost was optimized to its minimum level using the GAMS software. Three different modes (RET with storage, RET without storage, conventional non-ZEB) were simulated to show how each element affect the monthly electricity bill. Electricity bill were calculated to be 2’377, 18’240 and 66’960 dollars per month for each of the previous cases, respectively. Hourly variations of each energy flow were shown in different graphs. Besides free resources of renewable energies, the electrical energy storage which shifts the high-cost hours to the low-cost ones, is the main reason for this reduction.

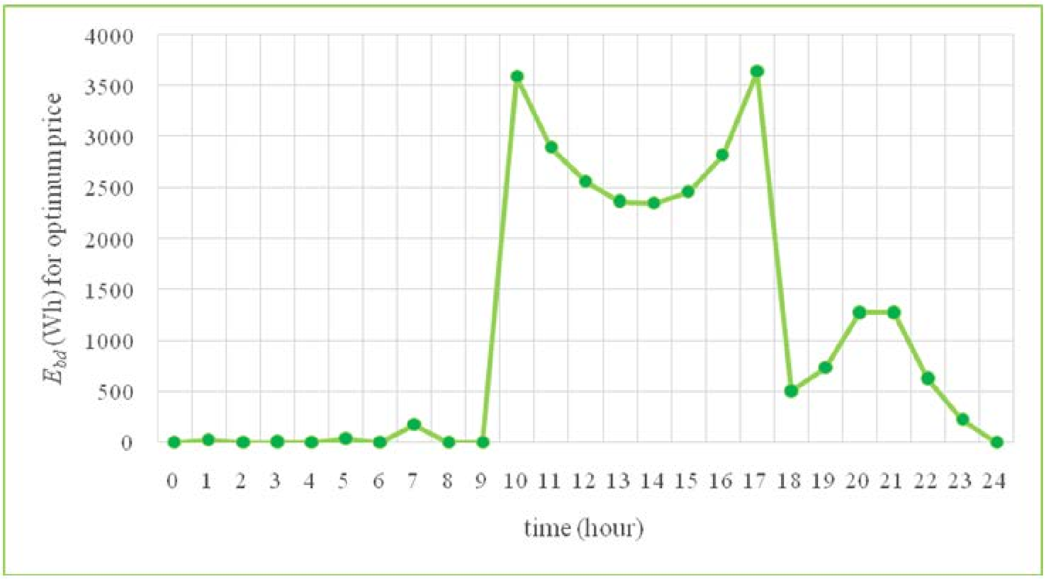


Figure 9. Simulation results for hourly variations of power flow into the balance boundary of the building through battery storage in case I

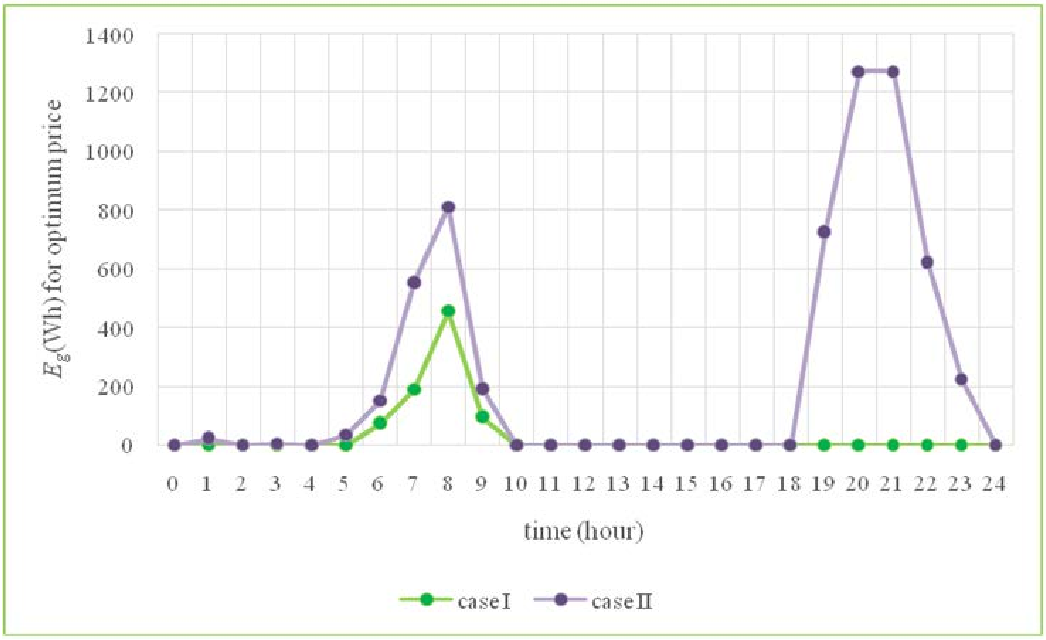


Figure 10. Simulation results for hourly variations of power flow into the balance boundary of the building through electricity grid in cases I and II

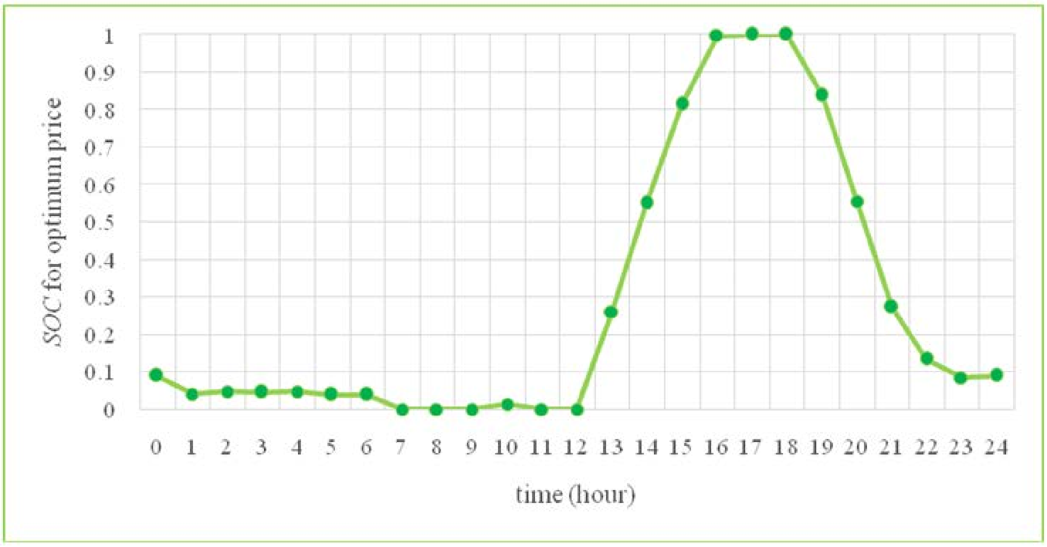


Figure 11. Simulation results for hourly variations of battery state of charge (*SOC*) in case I

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