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DOI
10.1016/j.enconman.2019.112156

Publication date
2019

Document Version
Final published version

Published in
Energy Conversion and Management

Energy Conversion and Management 201 (2019) 112156

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Daily-seasonal operation in net-zero energy building powered by hybrid renewable energies and hydrogen storage systems

Hasan Mehrjerdi[a,*], Atif Iqbal[a], Elyas Rakhshani[b], Jose Rueda Torres[b]

[a] Electrical Engineering Department, Qatar University, Doha, Qatar
[b] Electrical Sustainable Energy Department, Delft University of Technology, Delft, Netherland

ARTICLE INFO

Keywords:
Hydro energy
Hydrogen storage system
Mixed integer linear model
Net-zero energy building
Solar energy

ABSTRACT

The net-zero energy buildings are often supplied by renewable resources and energy storage systems. These energy resources have different seasonal and daily patterns of power production. Their output power is also uncertain. This paper aims to study these issues including daily-seasonal operation patterns, uncertainty, and cogeneration of various renewable resources and storage systems. These issues are investigated at net-zero energy building supported by renewable resources (i.e., solar energy, hydro energy, and fuelcell) and energy storage systems (i.e., hydrogen storage system). The uncertain parameters of the model are solar-hydro-load powers. The model minimizes the investment cost on solar system. The plan finds optimal sizing and operation for solar, hydro, hydrogen, and fuel-cell. The cooperation of hydrogen storage and fuelcell is optimized to level the uncertainty. The surplus of energy is fed into water electrolyzer to produce hydrogen and the fuelcell consumes the hydrogen to produce electricity. The seasonal operation is dealt by cogeneration of hydro-solar systems. The proposed plan installs 73 kW solar panel. The hydrogen storage system is charged at hours 7–17. When hydro power is increased to 39 kW, the building does not need the solar energy. The proposed model decreases the Carbon Dioxide by about 39546 kg. The model also reduces the total cost by about 50.3%.

1. Introduction

Nowadays, the traditional energy resources are limited and the purpose is to develop substituting resources like renewable energies. The renewable resources have been rapidly developed over the recent years and they are broadly integrated into the electrical systems [1], microgrids [2], and buildings [3]. The small-scale and large-scale buildings are the proper targets to utilize these capacity resources [4]. The various sorts of renewable energies are utilized in the electrical systems including wind [5], solar [6], hydro [7], hydrogen [8], and geothermal. However, the most common ones are the wind and solar energies [9].

The applications of renewable energies need proper energy management tools to handle their characteristics such as parametric uncertainty [10]. The energy management in the buildings is addressed through home energy management system (HEMS). The HEMS is an efficient tool to fix energy issues in the consumer side rather than the generation side [4]. The HEMS includes various techniques and technologies to improve energy consumption in the buildings [3]. The different objectives may be defined for HEMS such as energy cost reduction, reliability and security improvement, energy loss reduction, self-healing and resilience operation, and well-being of people [11]. In HEMS, the building may be connected to grid (grid-tied) or it can operate on islanding state (off-grid). In the off-grid systems, the energy of the building must be supplied by available capacity resources in the building [12]. In [12], the energy of off-grid site is supported by electric vehicles, hydrogen vehicles, solar panels, fuelcell, and diesel generator.

The net-zero energy building (NZEB) is an off-grid building and its energy is optimized by HEMS [13]. The NZEB does not receive energy from the electrical network and its energy is supplied by distributed energy resources such as wind turbine, solar panels, fuel-cells, diesel generator, or micro hydro turbines [14]. However, the purpose is to supply the whole energy of the building by renewable energies in order to achieve a zero carbon building [15]. The NZEB may also be integrated with electric and fuelcell vehicles [9]. The NZEB can also be part of the smart grids [16]. The NZEB always includes the uncertainty which must be handled. The stochastic methods and Monte Carlo model may be applied to handle the uncertainty. Such uncertainties also make impact on the CO2 emissions caused by the building. The studies show that the uncertainty and CO2 emissions are the important parameters in life cycle assessment [17].

One of the necessary equipment in the NZEB is the energy storage

* Corresponding author.
E-mail address: Hasan.mehrjerdi@qu.edu.qa (H. Mehrjerdi).

https://doi.org/10.1016/j.enconman.2019.112156
Received 5 August 2019; Received in revised form 3 October 2019; Accepted 6 October 2019

Nomenclature

Parameter and variable	Description
ICs	Investment cost on solar system ($)
PSP_n	Rated power of solar system (kW)
C_{sp}	Price of solar system ($/kW)
$TL^{sc,se,ti}$	Total load of building (kW)
$PLD^{sc,se,ti}$	Power of load (kW)
$PWE^{sc,se,ti}$	Power of water electrolyzer (kW)
sc, SC	Scenario index, set of scenarios
se, SE	Season index, set of seasons
it, IT	Time interval index, set of time intervals
$TG^{sc,se,ti}$	Total generation of building (kW)
$PSP^{sc,se,ti}$	Power of solar system (kW)
$PHT^{sc,se,ti}$	Power of hydro system (kW)
$PFC^{sc,se,ti}$	Power of fuelcell (kW)
$Bch^{sc,se,ti}$	Binary variable for charging state [0,1]
$Bdh^{sc,se,ti}$	Binary variable for discharging state [0,1]
$Ch^{sc,se,ti}$	Charged hydrogen into storage tank (kg)
$Dh^{sc,se,ti}$	Discharged hydrogen from storage tank (kg)
K_h^e	Conversion factor between electricity and hydrogen
PFC_n	Rated power of fuelcell (kW)
PWE_n	Rated power of water electrolyzer (kW)
$\eta_{wf}^{sc,se}$	Efficiency of water electrolyzer and fuelcell (%)
$Hy^{sc,se,ti}$	Stored hydrogen in the storage tank (kg)
Hy_0	Initial hydrogen inside the storage tank (kg)
Hy_n	Capacity of hydrogen storage tank (kg)
$WHT^{sc,se,ti}$	Flow of input water to hydro turbine (m^3/s)
g	Gravitational acceleration equal to 9.8 (m/s^2)
W_d	Density of water equal to 1000 (kg/m^3)
H_{HT}	Height of water (m)
ηHT	Efficiency of hydro turbine (%)
PHT_n	Rated power of hydro turbine (kW)
WHT_n	Rated flow of input water to hydro turbine (m^3/s)

system [18]. Since the NZEB is often supplied by renewable power, it needs further technologies to deal with renewable volatility [19]. The energy storage systems are efficient technologies to handle such volatility [20]. The different configurations of renewable energies and energy storage systems have been operated in NZEB. For instance, the solar-battery [21], wind-battery [22], and pumped-hydro systems [23] are the proper combinations for buildings. Both the electrical and thermal storage systems are useful in NZEB [24]. The thermal energy is often stored into the storage tank through phase change material [24].

The hydrogen storage system is also the proper technology to utilize hydrogen in the buildings [25]. The hydrogen storage system can be used to buffer the volatility of renewable energies [26]. In such systems, the volatility of renewable energy is converted and stored in hydrogen form. The hydrogen is afterward fed into the fuelcell to produce electricity [27]. Such procedure properly levels the surplus and shortage of renewable energy and levels the energy pattern [28]. The hydrogen energy utilization can result in zero emission building, where, the photovoltaic system and hydrogen production process are cooperated to produce energy [29]. The hydrogen is often produced through electrolyzing water and the required energy for water electrolyzer is taken from renewable energy resources [30]. Such procedure is known as power to gas [31].

The energy management systems always incorporate the uncertainties of renewable energies. These uncertainties should be properly modeled and dealt with. There are various methods to model the uncertainty in the energy management systems such as chance-constrained model predictive control that has been applied for energy management in microgrids considering uncertainty [32]. The risk-constrained energy management [33], robust optimization [34], and control-based optimization [35] are the other common techniques to

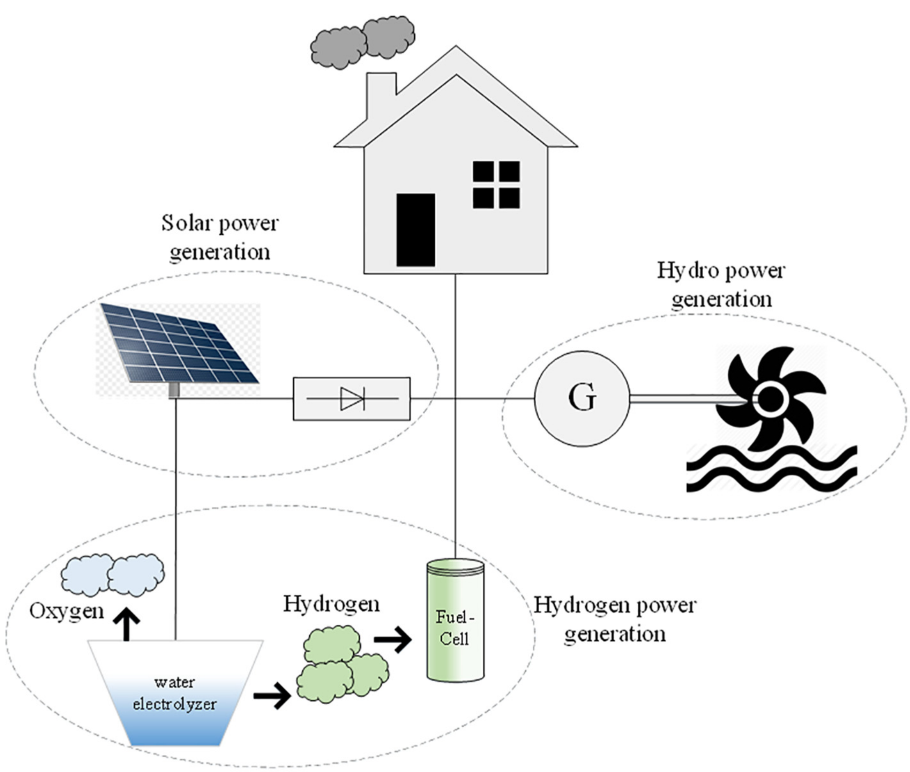

Fig. 1. Net-zero energy building equipped with solar-hydro-hydrogen-fuelcell.

handle the uncertainty.

1.1. Contributions and innovations of paper

The energy management in the building includes several issues because of renewable energy integration. The produced power by renewable resources is different from one day to another day and their daily pattern must be modeled and studied. As well, the energy pattern is different from one season to another season and the seasonal pattern needs to be studied. The energy profile of the renewable energies is also uncertain and the uncertainty management techniques are required. All of these issues become more complicated when different energy resources are simultaneously operated.

In this regard, this paper aims to model and study all of these issues simultaneously. A net-zero energy building is modeled and equipped with hydrogen storage system, fuelcell, solar system, and micro hydro turbine. The uncertainty, daily operation, and seasonal operation of these resources are considered. The solar power, hydro power, and load demand are modeled including volatility and uncertainty. The seasonal operation is also modeled to demonstrate the useful cogeneration of hydro-solar generating systems. In the summer, the solar energy can support the hydro energy and in the winter the shortage of solar energy is supplied by hydro energy. The volatility of energy in the solar-hydro-load systems is mitigated by hydrogen-fuel cell system.

The main contributions of the paper are highlighted as follows;

- The NZEB is supported by solar-hydro-hydrogen-fuelcell systems.
- The daily and seasonal operations, uncertainty, and cogeneration of all capacity resources are simultaneously modeled and included.
- The solar power, hydro power, and load demand are the uncertain parameters and modeled by Gaussian distribution function.
- The seasonal operation is simulated to demonstrate the cogeneration of hydro-solar systems.
- The cooperation of the hydrogen storage system and fuelcell is optimized to smooth out the uncertainties.
- The stochastic programming minimizes the investment cost on solar energy system while it finds the optimal level of solar power with the determination of optimal operating patterns for the hydrogen storage system and fuelcell.

2. Methods

In this section, the methodology of the paper is developed. The proposed net-zero energy building is introduced and mathematical formulation of the problem expressed.

2.1. Proposed net-zero energy building

Fig. 1 shows the infographic of the net-zero energy building. The building is equipped with solar panels and hydro turbine. The hydro turbine is connected to the generator to produce electricity. The output DC power of the solar panels is converted to AC power through interfacing DC-AC converter and fed into the building. The solar power also runs the water electrolyzer. The water electrolyzer converts solar energy to hydrogen. The hydrogen is stored in the storage tank. The fuelcell may use the stored hydrogen and produce electricity when the generated electricity is less than the demand [36]. Such system (hydrogen storage and fuelcell) can properly smooth out the volatility and uncertainty in the generated energy by hydro and solar systems [37].

The seasonal cooperation of hydro and solar generating systems is also modeled and simulated to deal with their energy issues. The main issue associated with hydro-solar generating systems is their seasonal pattern. The solar energy is high in the summer but low in the winter. On the other hand, the hydro energy is high in the winter and low in the summer. As a result, these two resources can compensate each other if they are operated together. In the summer, the solar energy supplies lack of hydro energy and in the winter, the hydro system compensates the solar energy shortage.

The proposed model supplies all the energies of the building by renewable energy resources resulting in zero environmental contamination with a reliable operation. The hydro-solar generating system produces renewable energy and the energy storage system levels the renewable volatility.

2.2. Mathematical formulation of the problem

The problem aims to operate hybrid generating systems including solar-hydro-hydrogen-fuelcell in NZEB. The objective function of the plan is to minimize the investment cost on solar panels as presented by (1).

$$ICs = \mathrm{PSP}_n \times C_{sp} \tag{1}$$

The total energy consumption in the building is calculated by (2). It includes the energy consumed by load and water electrolyzer. The total generated energy in the building is also calculated by (3). It comprises the produced energy by solar, hydro, and fuelcell systems. The total generated energy must be equal to the total consumed energy at each time interval as confirmed by (4) [4].

$$TL^{\mathrm{sc,se,ti}} = \mathrm{PLD}^{\mathrm{sc,se,ti}} + \mathrm{PWE}^{\mathrm{sc,se,ti}} \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{2}$$

$$TG^{\mathrm{sc,se,ti}} = \mathrm{PSP}^{\mathrm{sc,se,ti}} + \mathrm{PHT}^{\mathrm{sc,se,ti}} + \mathrm{PFC}^{\mathrm{sc,se,ti}} \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{3}$$

$$TL^{\mathrm{sc,se,ti}} = TG^{\mathrm{sc,se,ti}} \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{4}$$

The hydrogen storage system and fuelcell are operated to smooth out the energy uncertainty. When, the generated energy is more than the consumed energy, the water electrolyzer is operated to charge the hydrogen into the hydrogen storage tank. On the other hand, when the generated energy is less than the consumed energy, the fuelcell is operated to discharge the hydrogen from the hydrogen tank and to produce electricity. As a result, there is a charging-discharging operation pattern for the hydrogen storage system. At each time interval, the hydrogen storage system is allowed to operate only on one of the charging or discharging states. This point is modeled through (5) to (7) [7].

$$Bch^{\mathrm{sc,se,ti}} + Bdh^{\mathrm{sc,se,ti}} \le 1 \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{5}$$

$$Bch^{\mathrm{sc,se,ti}} = 1 \Rightarrow \begin{cases} Ch^{\mathrm{sc,se,ti}} \ge 0 \\ Dh^{\mathrm{sc,se,ti}} = 0 \end{cases} \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{6}$$

$$Bdh^{\mathrm{sc,se,ti}} = 1 \Rightarrow \begin{cases} Ch^{\mathrm{sc,se,ti}} = 0 \\ Dh^{\mathrm{sc,se,ti}} \ge 0 \end{cases} \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{7}$$

The produced power by fuelcell is specified by (8) and the rated power of fuelcell is denoted by (9). The consumed power by water electrolyzer is modeled in (10) and its rated power is given by (11) [1].

$$Ch^{\mathrm{sc,se,ti}} = PFC^{\mathrm{sc,se,ti}} \times K_h^e \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{8}$$

$$PFC^{\mathrm{sc,se,ti}} \le PFC_n \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{9}$$

$$Dh^{\mathrm{sc,se,ti}} = PWE^{\mathrm{sc,se,ti}} \times K_h^e \quad \forall\, sc \in SC,\ se \in SE,\ it \in IT \tag{10}$$

$$PWE^{sc,se,ti} = PWE_n \quad \forall\, sc \in SC,\, se \in SE,\, it \in IT \tag{11}$$

The efficiency of the hydrogen storage system is defined as (12). The stored hydrogen at each time interval is calculated by (13). The initial hydrogen inside the hydrogen tank is modeled in the problem by (14) [3].

$$\eta_{wf}^{sc,se} = \frac{\sum_{ti \in TI}(Dh^{sc,se,ti})}{\sum_{ti \in TI}(Ch^{sc,se,ti})} \quad \forall\, sc \in SC,\, se \in SE \tag{12}$$

$$Hy^{sc,se,ti} = Hy^{sc,se,ti-1} + Dh^{sc,se,ti} - (Ch^{sc,se,ti}/\eta_{wf}^{sc,se}) \quad \forall\, sc \in SC,\, se \in SE,\, it \in IT \tag{13}$$

$$Hy^{sc,se,ti1} = Hy_0 + Dh^{sc,se,ti1} - (Ch^{sc,se,ti1}/\eta_{wf}^{sc,se}) \quad \forall\, sc \in SC,\, se \in SE,\, it \in [it1] \tag{14}$$

The capacity of the hydrogen tank is limited to its maximum capacity as specified by (15). As well, the initial hydrogen for next day operation must be available. In (16), it is confirmed that the energy at the final time interval is available for feasible operation in the next day.

$$Hy^{sc,se,ti} \le Hy_n \quad \forall\, sc \in SC,\, se \in SE,\, it \in IT \tag{15}$$

$$Hy^{sc,se,ti24} \ge Hy_0 \quad \forall\, sc \in SC,\, se \in SE,\, it \in [it24] \tag{16}$$

The produced power by the hydro turbine is calculated by (17). It is clear that the produced power depends on the turbine height, efficiency, and input water flow. The produced power may be limited by rated power of hydro turbine as indicated in (18). As well, the input water flow may be limited by the physical constraints on the hydro system structure as shown by (19) [38].

$$PHT^{sc,se,ti} = WHT^{sc,se,ti} \times g \times W_d \times H_{HT} \times \eta HT \quad \forall\, sc \in SC,\, se \in SE,\, it \in IT \tag{17}$$

$$PHT^{sc,se,ti} \le PHT_n \quad \forall\, sc \in SC,\, se \in SE,\, it \in IT \tag{18}$$

$$WHT^{sc,se,ti} \le WHT_n \quad \forall\, sc \in SC,\, se \in SE,\, it \in IT \tag{19}$$

The rated power of solar energy system is also defined as (20).

$$PSP^{sc,se,ti} \le PSP_n \quad \forall\, sc \in SC,\, se \in SE,\, it \in IT \tag{20}$$

3. Results and discussions

In this section, the results are presented and the proper descriptions given about the results and findings. First, the test system is introduced and the data presented. Then the outputs of the problem are studied and analyzed.

3.1. Illustrative test case

A net-zero energy building equipped with solar panels, hydro turbine, hydrogen storage, and fuelcell is considered as case study to simulate the given model. The load power is 30 kW and its daily-seasonal profile is given in Fig. 2 [39]. The loading profile follows different patterns during various seasons. The on-peak loading hours are seen at hours 18–22 during seasons 1–3. But in the winter (season 4), the on-peak loading hours are shifted back to hours 16–18. The maximum demand for energy is during the summer and the minimum demand for energy is during the fall.

It is really difficult to determine the exact level of power for a building because the small-scale buildings can have about 10–15 kW demand and the large-scale buildings can have about 50–60 kW demand. The common level of power for buildings is between about 10 kW to 60 kW. As a result, this paper takes 30 kW power for the test case.

The daily-seasonal solar energy profile is shown in Fig. 3 [4]. The solar energy is increased in the summer and decreased in the winter. The maximum solar energy is harvested during day hours from 10 to 16. In the initial and final hours, 1–5 and 21–24, the solar energy is zero.

The hydro power is 5 kW and its daily-seasonal profile is given in Fig. 4 [40]. The hydro energy is increased in the winter and decreased in the summer because of the weather conditions and seasonal variation of water volume [41]. As a result, Fig. 4 shows that the volume of water (i.e., hydro energy) is on the maximum during winter and minimum during summer.

The efficiency of the hydrogen storage system is equal to 60% and the initial hydrogen inside the hydrogen tank is two kilograms.

The price of solar panels is 1200 $/kW. The conversion factor between hydrogen and electricity in the fuelcell and electrolyzer is 40 kWh electricity per 1 kg hydrogen with 60% efficiency. The solar power, hydro power, and load demand are modeled by Gaussian distribution [38]. A large set of scenarios is generated by sampling from these uncertain distribution functions and the scenario reduction technique is applied to reduce number of scenarios to 10 scenarios as listed in Table 1 [1].

3.2. The selected data

In order to have the realistic outputs in the simulations, the input data to the model have to be real. In this paper, the data are taken from reputable references and they are the real world data. For instance, in the real markets, the price of solar system is about 1000–1300 $/kW in different countries. Accordingly, this study has considered 1200 $/kW for solar panels. This point is also correct about the other data in the paper. As a result, the accurate data in the simulations make the outputs realistic.

The proposed model is prepared as a planning-package to design the net-zero energy buildings. This package gets input data from the user (planner) and solves the problem. This toolbox can be used to design the net-zero energy building in every location based on the local data. The planner can easily change the input data and get the new outputs according to the desired data. As a result, the input data cannot cause limitation of the toolbox.

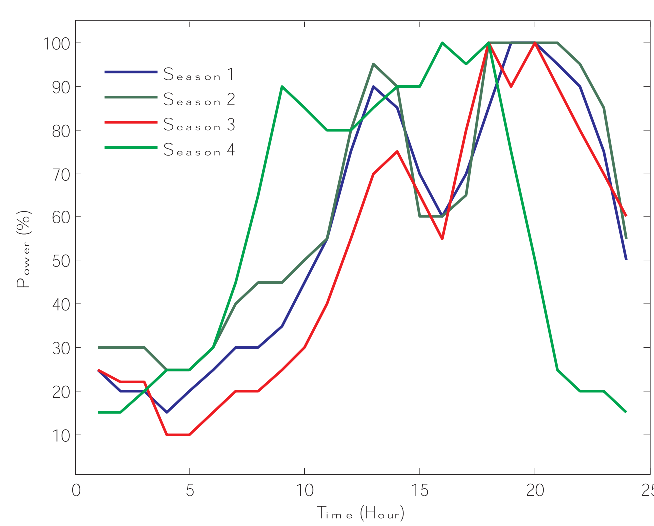

Fig. 2. Daily-seasonal load power profile. (Season 1: Spring; Season 2: Summer; Season 3: Fall; Season 4: Winter).

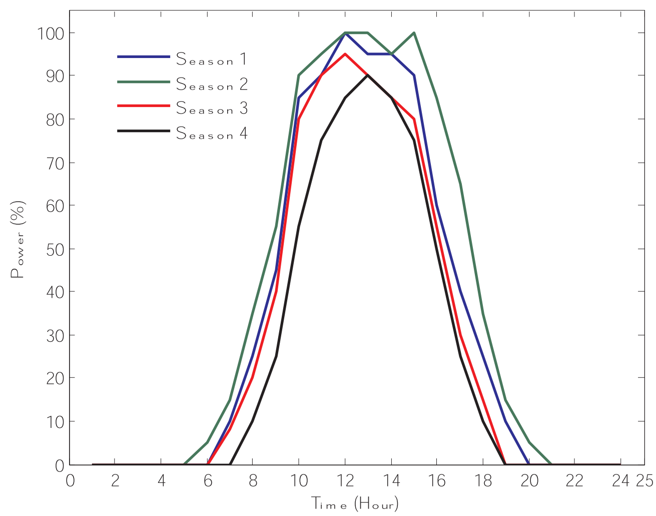

Fig. 3. Daily-seasonal solar energy profile. (Season 1: Spring; Season 2: Summer; Season 3: Fall; Season 4: Winter).

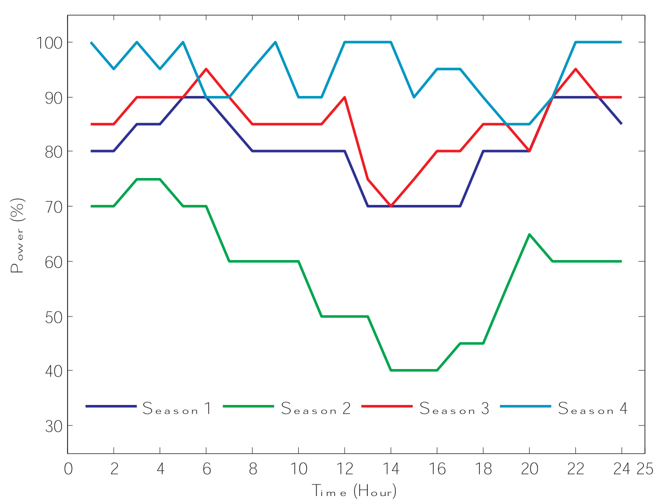

Fig. 4. Daily-seasonal hydro energy profile. (Season 1: Spring; Season 2: Summer; Season 3: Fall; Season 4: Winter).

3.3. Outputs of the model

The NZEB is modeled and simulated in GAMS software. The optimal Levels of the design variables are listed in Table 2. The required power of solar energy system is 73 kW and capacity of hydrogen storage tank is optimized on 12.3 kg.

3.4. Equilibrium of energy

The optimized capacity resources cooperate with each other to supply the energy demand under all seasons of the year as listed in Tables 3–6. Table 3 presents the power equality in the building at season 1 under scenario 1. It is confirmed that the generated power at each hour is equal to the consumed power. At hours 7–17, the produced energy is more than the load, as a result the excess energy is converted to the hydrogen by water electrolyzer. On the other hand, when solar energy is zero, the energy shortage is supplied by the fuelcell. The total energy consumption is 794.3 kWh and it is equal to the total energy generation during 24 h. Such equilibrium emphasizes on the accuracy of the given model and simulations. The total level of power shows that the significant part of energy is supplied by solar system where 70% of the energy is supplied by solar panels, about 17% is supplied by fuelcell, and 13% is fed by hydro system. The electrolyzer needs a large amount of energy to produce hydrogen.

Table 1
Scenarios of performance based on the uncertain parameters.

Hour	Scenario									
	1	2	3	4	5	6	7	8	9	10
1	1	0.82	1.25	0.71	1.1	1.46	1.5	1.03	0	1.5
2	1	1.01	1.27	1.18	1.23	1.01	0.76	1.4	1.32	0.46
3	1	0.94	1.38	0.69	1.5	0.78	0.66	0.62	0.96	0.79
4	1	0.75	0.91	0.99	0.38	1.29	1.32	0.93	0.49	1.5
5	1	1.09	1.37	0.15	1.26	0.39	1.37	1.15	1.48	0.3
6	1	1.09	1.06	0.38	1.05	1.27	1.15	0.77	1	1.32
7	1	0.91	0.67	0.99	0.99	0.91	0.23	1.17	1.5	0.94
8	1	1.08	0.83	1.34	0.74	1.5	0.64	0	0.3	0
9	1	0.8	1.21	0.51	0.95	0.71	0.54	1.28	0.43	1.14
10	1	0.81	1.4	1.2	1.26	1.19	0.73	1.28	1.29	1.44
11	1	0.83	0.73	1.15	1.16	1.05	0.59	1	0.4	1.48
12	1	0.98	0.97	0.82	0.4	0.51	1.22	0.79	1.08	0.58
13	1	0.92	0.85	0.99	1.34	1.39	1.5	0.74	0.73	0.99
14	1	1.29	1.42	1.5	1.09	0	0.87	0	1.5	1.47
15	1	0.99	0.8	0.58	1.5	0.12	1.29	1.5	1.29	1.4
16	1	1.08	1.3	1.14	0.58	0.41	1.4	1.38	0.73	0.71
17	1	1.09	0.86	1.06	0.73	1.5	1.07	0.35	0.57	0.05
18	1	1.06	1.17	1.1	0.34	1.44	0.86	0.11	0.73	1.2
19	1	1.03	0.7	1	1	0.44	0.72	0.77	1.5	1.24
20	1	1.19	1.34	1.08	1.37	0.92	0.39	1.41	0.97	1.5
21	1	0.83	0.5	0.92	0.82	0.67	0.86	1.5	0.86	0
22	1	1.25	1.07	0.49	0.81	1.1	1.08	1.32	0.87	0.73
23	1	1.1	1.09	0.82	0.89	1.5	0.9	1.46	1.5	1.33
24	1	0.83	0.82	1.07	0.94	0.61	1.11	1.5	0	0.92

Table 4 introduces the power equilibrium in the building at season 2 under scenario 1. At season 2, the solar energy is more than season 1 and the hydro energy is less than season 1. As a result, the shortage of hydro energy is compensated by solar energy. As well, more solar energy is converted to hydrogen and fuelcell produces more power. The total value of energy consumption-generation shows that the most demand for energy is in season 2. The electrolyzer and load consume approximately equal levels of the energy (each one about 50%). The solar system, fuelcell, and hydro system supply about 74%, 18%, and 8% of energy, respectively.

Table 5 presents the power equality in the building at season 3 under scenario 1. In this season, the hydro energy is increased and the solar energy is reduced compared to season 2. However, the equilibrium of energy at all time-intervals is confirmed. As well, the hydrogen storage system successfully shifts energy from hours 4–19 to the other day hours. In this season, the consumed energy is reduced compared to season 2. The load and electrolyzer consume about 50% of energy. The solar energy system supplies the most portion of the energy. However, the solar energy is reduced compared to season 2 and the hydro power increases its output to compensate the solar energy as a result.

Table 6 reports the power equality in the building at season 4 under scenario 1. In this season, the hydro energy is high and the solar energy is low compared to the other seasons. The shortage of solar energy is compensated by hydro power. The operation of hydrogen system (water electrolyzer and fuelcell) is different from the previous cases in order to compensate lack of the solar energy. At most of the hours, the hydro energy can successfully supply the demand and the solar energy is

Table 2
Optimal levels of the design variables.

Design variables	Optimal Level
Investment cost on solar system ($)	87,600
Power of solar system (kW)	73
Rated power of water electrolyzer (kW)	86
Rated power of fuelcell (kW)	41
Capacity of hydrogen storage tank (kg)	12.3

Table 3
Power equality in the building at season 1 under scenario 1.

Hour	Consumption		Generation		
	Load power (kW)	Electrolyzer power (kW)	Solar power (kW)	Hydro power (kW)	Fuelcell power (kW)
1	7.5	0	0	4	3.5
2	6	0	0	4	2
3	6	0	0	4.25	1.75
4	4.5	0	0	4.25	0.25
5	6	0	0	4.5	1.5
6	7.5	0	0	4.5	3
7	9	2.55	7.3	4.25	0
8	9	13.25	18.25	4	0
9	10.5	26.35	32.85	4	0
10	13.5	52.55	62.05	4	0
11	16.5	53.2	65.7	4	0
12	22.5	54.5	73	4	0
13	27	45.85	69.35	3.5	0
14	25.5	47.35	69.35	3.5	0
15	21	48.2	65.7	3.5	0
16	18	29.3	43.8	3.5	0
17	21	11.7	29.2	3.5	0
18	25.5	0	18.25	4	3.25
19	30	0	7.3	4	18.7
20	30	0	0	4	26
21	28.5	0	0	4.5	24
22	27	0	0	4.5	22.5
23	22.5	0	0	4.5	18
24	15	0	0	4.25	10.75
Total	**409.5**	**384.8**	**562.1**	**97**	**135.2**
	Total consumption = 794.3 kW		**Total generation = 794.3 kW**		

Table 4
Power equality in the building at season 2 under scenario 1.

Hour	Consumption		Generation		
	Load power (kW)	Electrolyzer power (kW)	Solar power (kW)	Hydro power (kW)	Fuelcell power (kW)
1	9	0	0	3.5	5.5
2	9	0	0	3.5	5.5
3	9	0	0	3.75	5.25
4	7.5	0	0	3.75	3.75
5	7.5	0	0	3.5	4
6	9	0	3.65	3.5	1.85
7	12	1.95	10.95	3	0
8	13.5	15.05	25.55	3	0
9	13.5	29.65	40.15	3	0
10	15	53.7	65.7	3	0
11	16.5	55.35	69.35	2.5	0
12	24	51.5	73	2.5	0
13	28.5	47	73	2.5	0
14	27	44.35	69.35	2	0
15	18	57	73	2	0
16	18	46.05	62.05	2	0
17	19.5	30.2	47.45	2.25	0
18	30	0	25.55	2.25	2.2
19	30	0	10.95	2.75	16.3
20	30	0	3.65	3.25	23.1
21	30	0	0	3	27
22	28.5	0	0	3	25.5
23	25.5	0	0	3	22.5
24	16.5	0	0	3	13.5
Total	**447**	**431.8**	**653.35**	**69.5**	**155.95**
	Total consumption = 878.8 kW		**Total generation = 878.8 kW**		

converted to hydrogen. In this season, the solar energy is on the minimum level and on the other hand the hydro energy is on the maximum level. Such cogeneration helps the system to supply the load demand when one of the resources is not functioning with maximum capacity.

Table 5
Power equality in the building at season 3 under scenario 1.

Hour	Consumption		Generation		
	Load power (kW)	Electrolyzer power (kW)	Solar power (kW)	Hydro power (kW)	Fuelcell power (kW)
1	7.5	0	0	4.25	3.25
2	6.6	0	0	4.25	2.35
3	6.6	0	0	4.5	2.1
4	3	1.5	0	4.5	0
5	3	1.5	0	4.5	0
6	4.5	0.25	0	4.75	0
7	6	4.34	5.84	4.5	0
8	6	12.85	14.6	4.25	0
9	7.5	25.95	29.2	4.25	0
10	9	53.65	58.4	4.25	0
11	12	57.95	65.7	4.25	0
12	16.5	57.35	69.35	4.5	0
13	21	48.45	65.7	3.75	0
14	22.5	43.05	62.05	3.5	0
15	19.5	42.65	58.4	3.75	0
16	16.5	27.65	40.15	4	0
17	24	1.9	21.9	4	0
18	30	0	10.95	4.25	14.8
19	27	0	0	4.25	22.75
20	30	0	0	4	26
21	27	0	0	4.5	22.5
22	24	0	0	4.75	19.25
23	21	0	0	4.5	16.5
24	18	0	0	4.5	13.5
Total	**368.7**	**379.04**	**502.24**	**102.5**	**143**
	Total consumption = 747.74 kW		**Total generation = 747.74 kW**		

Table 6
Power equality in the building at season 4 under scenario 1.

Hour	Consumption		Generation		
	Load power (kW)	Electrolyzer power (kW)	Solar power (kW)	Hydro power (kW)	Fuelcell power (kW)
1	4.5	0.5	0	5	0
2	4.5	0.25	0	4.75	0
3	6	0	0	5	1
4	7.5	0	0	4.75	2.75
5	7.5	0	0	5	2.5
6	9	0	0	4.5	4.5
7	13.5	0	0	4.5	9
8	19.5	0	7.3	4.75	7.45
9	27	0	18.25	5	3.75
10	25.5	19.15	40.15	4.5	0
11	24	35.25	54.75	4.5	0
12	24	43.05	62.05	5	0
13	25.5	45.2	65.7	5	0
14	27	40.05	62.05	5	0
15	27	32.25	54.75	4.5	0
16	30	11.25	36.5	4.75	0
17	28.5	0	18.25	4.75	5.5
18	30	0	7.3	4.5	18.2
19	22.5	0	0	4.25	18.25
20	15	0	0	4.25	10.75
21	7.5	0	0	4.5	3
22	6	0	0	5	1
23	6	0	0	5	1
24	4.5	0.5	0	5	0
Total	**402**	**227.45**	**427.05**	**113.75**	**88.65**
	Total consumption = 629.45 kW		**Total generation = 629.45 kW**		

3.5. Operation of the hydrogen storage system

The produced hydrogen by water electrolyzer (charged hydrogen) and the consumed hydrogen by fuelcell (discharged hydrogen) are depicted in Fig. 5 under all seasons. It is clear that the hydrogen storage system (including water electrolyzer, storage tank, and fuelcell) shows various charging-discharging patterns under different seasons. In seasons 1 and 3 (spring and autumn), the operation patterns are approximately similar. Because the water flow and sunshine are almost similar at these seasons. In season 2 (summer), the hydro power is low and sometimes unavailable but the solar power is high. As a result, the hydrogen storage system tries to convert the excess of solar energy to hydrogen and stores it. The results show that the hydrogen storage system charges the hydrogen tank at day hours. On the other hand, in season 4 (winter), the hydro power is high but the solar power is low. Therefore, the operation of hydrogen storage system for converting solar energy to hydrogen is reduced.

Fig. 6 shows stored hydrogen inside the hydrogen storage tank. It is clear that the operation patterns in seasons 1 and 3 are approximately similar. But seasons 2 and 4 show different operation patterns. The hydrogen is often stored in the day hours when the solar energy is available and it is consumed in the night times when the solar energy is not available. The building has a different loading profile at season 4 as well as the operational pattern of hydrogen system is different in this season. The maximum stored hydrogen is approximately 12 kg and it is seen at season 2, hour 17. The charging-discharging operation of hydrogen storage system helps the building to deal with energy unavailability and volatility.

3.6. Scenario analysis

The uncertainties of solar, hydro, and load powers make significant impacts on the operation of hydrogen storage system. Fig. 7 shows the consumed power by electrolyzer at hour 15 and the produced power by fuelcell at hour 21 under all scenarios of performance. It is clear that they change their operation patterns to deal with uncertainty and their powers are changed together with scenarios. Such operation handles the uncertainties of solar, hydro, and load powers and empowers the building to operate under such uncertainties. Under scenario 4, the uncertainty level is low, and the electrolyzer reduces its operation. Under scenario 5 and 10, the generated power is increased because of solar volatility and the electrolyzer converts this excess of power to hydrogen. The cooperation of electrolyzer and fuelcell helps the building to deal with energy intermittency. When the energy is not enough, the fuelcell operates to produce electricity. On the other hand when the energy is more than demand, the electrolyzer operates to store the energy in the hydrogen form.

3.7. Analyzing the hydro energy

The hydro power plays a major role in the building and supplies a big part of the energy. In order to show the impacts of hydro energy in the building, the building under various hydro powers is simulated and the results are summarized in Table 7. The building excluding hydro power (i.e., hydro power equal to zero) cannot continue to operate and the model is infeasible. In other words, the solar and hydrogen systems cannot supply the demand without hydro system. Together with increasing the hydro power, the required solar power is reduced.

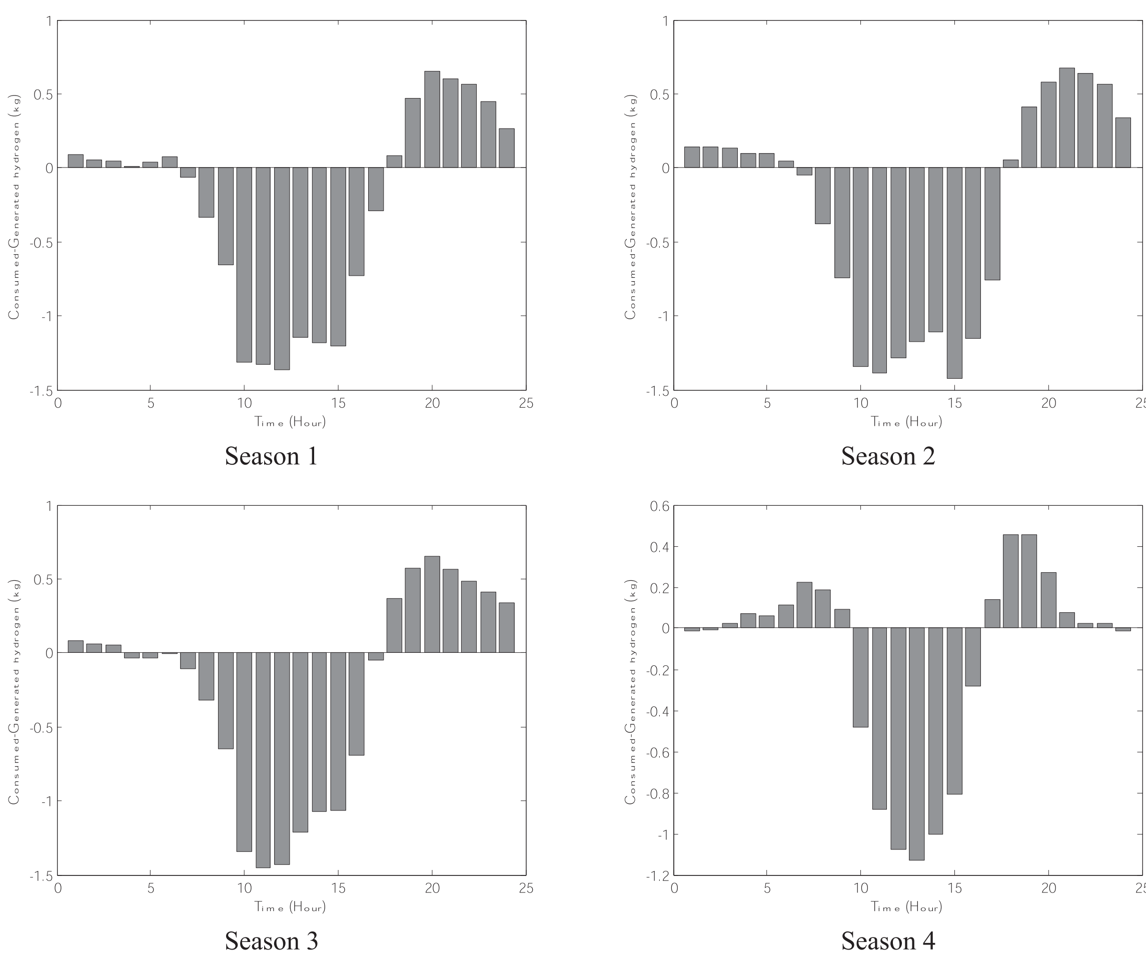

Fig. 5. The consumed and produced hydrogen under all seasons.

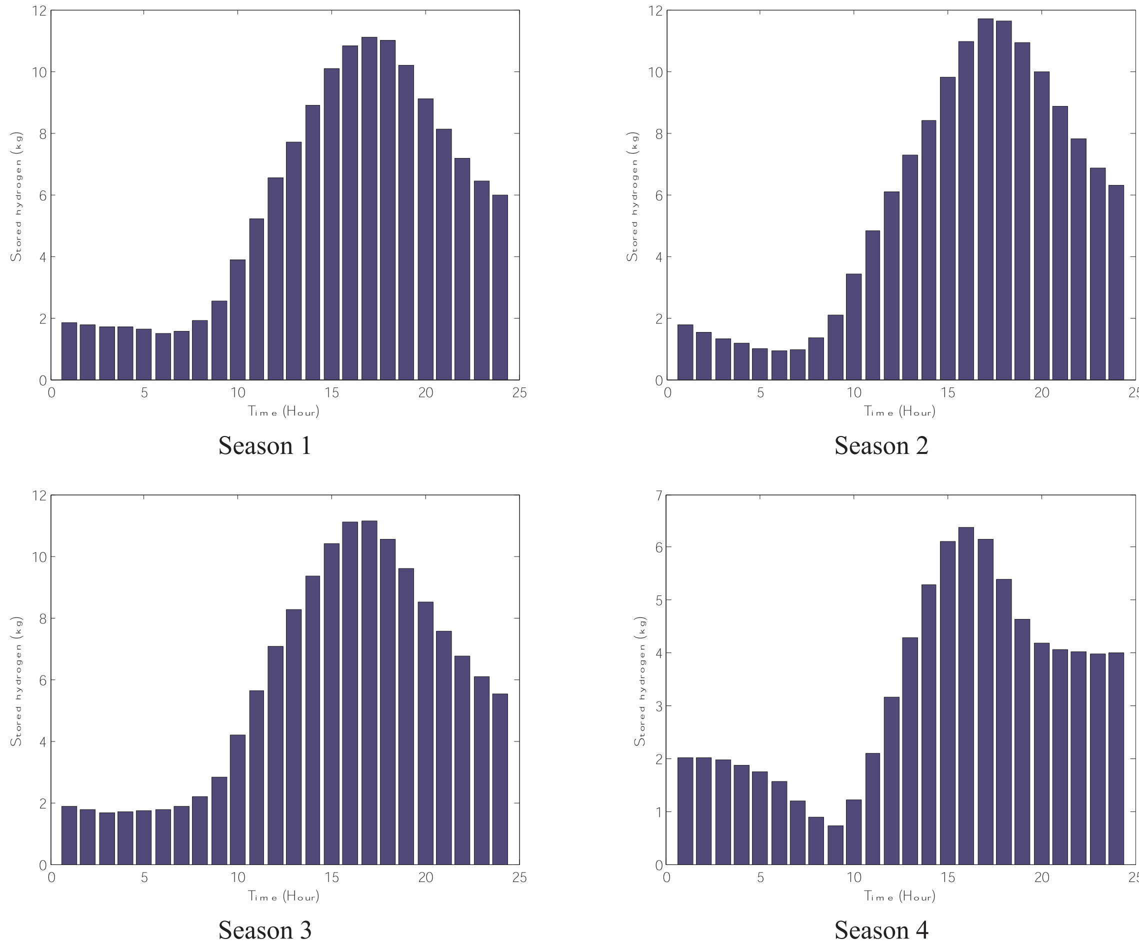

Fig. 6. The stored hydrogen under all seasons.

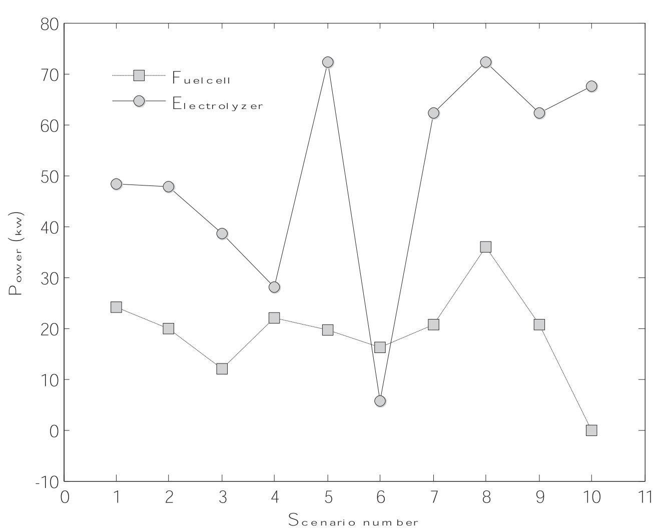

Fig. 7. Consumed power by electrolyzer at hour 15 and generated power by fuelcell at hour 21 under all scenarios of performance.

Eventually, if the hydro power is 39 kW, the solar system will not be required. It means that the hydro power equal to 39 kW can supply the load demand together with hydrogen storage and the building does not need the solar panels.

Table 7
Optimal levels of the design variables under different hydro powers.

	Hydro power (kW)				
	0	1	5	10	39
Investment cost on solar system ($)	Infeasible	118,800	87,600	62,400	0
Power of solar system (kW)	Infeasible	99	73	52	0
Rated power of water electrolyzer (kW)	Infeasible	120	86	64	52
Rated power of fuelcell (kW)	Infeasible	41	41	36	18
Capacity of hydrogen storage tank (kg)	Infeasible	17.8	12.3	9.3	14.9

3.8. Analyzing efficiency of the hydrogen storage system

The efficiency of hydrogen storage system is also an important factor in the model. Fig. 8 shows that the required solar power is reduced along with increasing the efficiency of hydrogen storage system. As ideal hydrogen storage system without energy losses (i.e., efficiency equal to 100%) needs the least solar power. This achievement demonstrates that the high efficiency hydrogen storage system is required to make the model more economical.

However, in this paper the efficiency is set on 60% to have realistic outputs. The efficiency of hydrogen storage units by using a 350 bar compressed gas storage is about 47% [42]. The heat released during the hydrogen conversion can also be converted to electricity in the fuelcell that increase the overall efficiency to about 66% [42]. As a result, 60% efficiency for hydrogen storage is realistic.

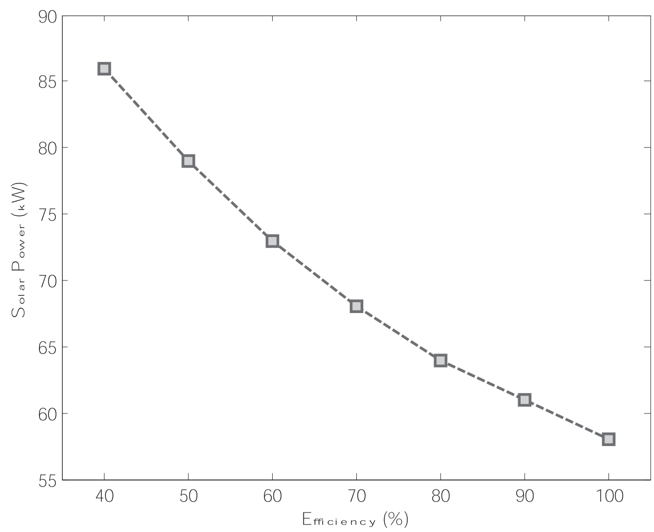

Fig. 8. Required solar power versus efficiency of hydrogen storage system.

Table 8
Sensitivity analysis of the parameters.

	Investment cost on solar system ($)
Nominal operating condition	87,600
Increasing load by 5%	99,600
Increasing hydro power by 5%	79,200
Increasing price of solar panels by 10%	96,300
Increasing efficiency of hydrogen system by 10%	84,000

Table 9
Seasonal reduction in CO2 by the designated building.

Season	Reduction in the released CO2 (kg)
Season 1	35,743
Season 2	39,546
Season 3	33,648
Season 4	28,325

Table 10
Seasonal oxygen release by the designated building.

Season	The released O2 into the atmosphere (kg)
Season 1	6926
Season 2	7772
Season 3	6822
Season 4	4094

It should be noted that the technical and economic assessment of hydrogen storage systems demonstrate that the hydrogen is the cost-efficient energy carrier and the metal hydrides are the promising solutions for future hydrogen economy [43]. The cost of hydrogen storage system depends on the storage method. It is required to include various factors in order to optimize a hydrogen storage system. In practice, this has to be considered for every specific condition and general consideration may be misleading [44].

3.9. Sensitivity analysis

The accuracy of the model is confirmed by several sensitivity analysis on the parameters as listed in Table 8. The outputs show that increasing load by 5% results in more investment cost by about 14%. Increasing hydro power by 5% reduces the investment cost by about 10%. Increasing price of solar panels increases the planning cost and increasing efficiency of hydrogen system reduces the planning cost. The trends of the simulations emphasize on the accuracy of the model.

3.10. Environmental analysis

The proposed model for NZEB utilizes the non-polluting energy resources and significantly reduces the environmental pollutions, i.e., CO2. In order to calculate the CO2 pollution released by the building, it is assumed that 0.5 kg of CO2 is produced for every kilowatt hour of electricity consumed by the building. The seasonal reduction in the released CO2 by the building is listed in Table 9. It is demonstrated that the building considerably decreases the contaminating gases. As well, the main reduction is in the summer (season 2) because the highest demand for energy is in this season. On the other hand, the lowest demand for energy is in season 4 (winter) and the reduction in the released CO2 is minimum.

The designated building not only reduces the released CO2, but also releases oxygen (O2) into the atmosphere and helps the environment. In order to calculate the produced O2 by the building, it is assumed that water electrolyzer converts 40 kW hours of electricity to 1 kg of H2 and 8 kg of O2 from 9 kg of water. This operation is seen in the commercially available electrolysis systems. According to this operation, the seasonal oxygen released by the designated building is calculated and listed as Table 10. The O2 production depends on the water electrolyzer operation. In the on-peak season (season 2), the water electrolyzer has more operation and the produced O2 is consequently increased.

3.11. Economic analysis

The designated building is supported by hydrogen storage, hydro, and solar systems. The building is supplied by these energy resources and does not receive any energy from the grid. The energy cost of the building is therefore zero. However, the building needs an initial investment cost to install the aforementioned energy resources. In order to analyses the economic aspects of the given model, the average lifetime of energy resources is considered equal to ten years and the analysis is presented for ten years time period over their lifetime. Two cases are assumed; in the first case, the building receives energy from local energy resources and it does not receive energy from the electrical grid. This case is the proposed model for net -zero energy building. In the second case, the building receives its energy from the electrical grid and

Table 11
Economic analysis on investment and energy costs.

	Case 1	Case 2
	Building receives energy from local energy resources	Building receives energy from grid
Total investment cost on energy resources ($)	205,000	0
Annual energy consumption (kWh)	274,526	274,526
Annual cost of energy consumption ($)	0	41,178
Total cost in 10 years ($)	205,000	411,780
Total cost in 10 years (%)	49.7%	100%
Salvage value	Yes	No

it does not need to install the energy resources. Table 11 summarizes the economic analysis for the mentioned cases. The results reveal that both models have similar annual energy consumption. But the first case supplies energy by available energy resources and the second case supplies energy by electrical grid. The proposed NZEB (first case) reduces the total cost by about 50.3%. As well, the salvage value of the energy resources can be considered for the proposed model as an extra profit. In the proposed model, the return on invested capital is about 4 years.

4. Conclusions

A NZEB equipped with hydrogen storage system, solar panels, and hydro turbine was modeled and investigated. The model was implemented and solved by GAMS software. The simulation results showed that the required power of solar energy system is 73 kW and the optimal capacity of hydrogen storage tank is 12.3 kg. As well, the rated power of water electrolyzer and fuelcell were optimized by the program. The equilibrium of power under all hours and seasons was confirmed. It was demonstrated that the hydrogen storage system converts the excess of solar energy to the hydrogen at day hours when solar energy is available such as hours 7–17. On the other hand, during night time when the solar energy is zero, the hydrogen is converted back to electricity by fuelcell in order to compensate the energy shortage. Such charging-discharging process damps out the uncertainties of solar, hydro, and load powers. The cogeneration of hydro-solar systems was also studied. It was addressed that during summer time when hydro power is low, the energy shortage is supplied by solar system and during winter time when solar power is low, it is compensated by hydro energy. It was shown that the electrolyzer and fuelcell change their operation patterns to deal with uncertainty and their powers are alerted in conjunction with scenarios of performance. The results demonstrate that the building without hydro cannot continue to operate. Together with increasing the hydro power, the required solar power is reduced. The building with 39 kW hydro power does not need the solar energy. The required solar power is reduced along with increasing the efficiency of hydrogen storage system. The conducted error analyses also emphasize on the accuracy of the model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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