Renewable Energy 156 (2020) 183–192

Contents lists available at ScienceDirect

Renewable Energy

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

Peer-to-peer home energy management incorporating hydrogen storage system and solar generating units

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ARTICLE INFO

Article history:
Received 1 June 2019
Received in revised form
19 March 2020
Accepted 16 April 2020
Available online 22 April 2020

Keywords:
Hydrogen storage
Load uncertainty
Peer-to-peer home energy management
Solar generating unit

ABSTRACT

The peer-to-peer (P2P) energy management in the buildings is modeled and studied by this paper. In the proposed P2P home energy management, the buildings share their energy resources with each other to supply their demands. Three individual buildings are considered, two buildings are equipped with solar panels and the other building is equipped with hydrogen storage unit. The buildings are connected to each other by power lines for P2P operation. The uncertainty of loads and solar energy are incorporated and the model minimizes the cost of solar unit, power lines, fuel-cell, electrolyzer, and storage tank. The optimization problem finds optimal power of solar system, power lines, fuel-cell, electrolyzer; optimal capacity of hydrogen storage tank; and optimal operation pattern (charging-discharging regime) of hydrogen storage system. The results demonstrate that P2P operation helps the buildings to benefit from their energy resources.

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1. Introduction

The new energy management systems such as home energy management and microgrids [1] are the proper platforms to increase the integration of renewables [2]. In this regard, the P2P system is new paradigm that can be properly applied to increase the penetration of renewable energies [3]. In P2P, the users share the resources among each other without using the centralized servers and it has been developed as the proper substitute for client-server paradigm, where the individual users can only share their resources with the centralized server. The P2P system may be combined with client-server model to make a hybrid model. One of the well-known applications of P2P systems may be referred as Bitcoin that is P2P based digital cryptocurrencies [4].

The P2P energy dispatch is a new model of energy management systems, where the buildings (or the individuals) produce their own energy and share the energy with each other locally. The P2P energy dispatch schemes are not mature systems currently and they need more investigations to develop the business models, communication technologies, and control networks [5]. Several P2P energy trading projects have been developed over the last years. The Piclo is a project in UK and it enables the business consumers to buy their required energy from neighboring resources [6]. The Vandebron is an on-line project in Netherland and the users can directly purchase their required energy from the individual producers such as the mounted wind turbines in the local farms [5]. Some other P2P energy trading systems are Peer-Energy-Cloud, Sonnen-Community, Lichtblick-Swarm-Energy, and Smart-Watts in Germany [5]; Yeloha-Mosaic, Community-First-Village, Trans-Active-Grid, and Electron in USA [5].

Application of P2P energy management systems in microgrids demonstrate that P2P operation is more economical than independent operation of prosumers [7]. Such P2P operation needs proper business models to share energy [8]. In Ref. [7], the price-based demand response is presented to share energy among the photovoltaic prosumers. Since the P2P energy management systems can locally balance the generation and consumption of energy, they have a potential to increase renewable level in networks [8]. The P2P energy management systems in microgrids are often designed based on game theory [9].

The P2P energy management seems to be a proper option for home energy management systems (HEMS) [10,11]. The HEMS utilizes various energy generating units like solar [12], fuel-cell [13], and hydrogen [14]. The energy storages such as hydrogen systems and battery are the inseparable parts of HEMS [15,16].

This paper aims to present the P2P home energy management in which the buildings share their energy with each other to supply their demands. Three individual buildings are operated as an off-grid net zero energy system. Two buildings are equipped with

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https://doi.org/10.1016/j.renene.2020.04.090
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Nomenclature

Index and Set

i, I	Symbol and set of scenarios
j, J	Symbol and set of seasons
k, K	Symbol and set of time periods

Parameters

AIC	Annual investment cost ($/year)
ASV	Annual salvage value ($/year)
cf_h^e	conversion factor between electricity and hydrogen (kWh/kg)
dr	Discount rate (%)
EAC	Equivalent annual cost
ls	Lifespan of asset (year)
MC	Maintenance cost ($/day)
Mc_{sc}	Daily maintenance cost of solar panels ($/kW)
$Mc_{\ln}$	Daily maintenance cost of power lines ($/kW)
Mc_{fc}	Daily maintenance cost of fuelcell ($/kW)
Mc_{we}	Daily maintenance cost of electrolyzer ($/kW)
Mc_{ht}	Daily maintenance cost of hydrogen tank ($/kg)
Pr_{sc}	Price of solar panels ($/kW)
Pr_{ht}	Price of hydrogen tank ($/kg)
Pr_{fc}	Price of fuelcell ($/kW)
Pr_{we}	Price of electrolyzer ($/kW)
$\mathrm{Pr}_{\ln}$	Price of power lines ($/kW)
$P_{b1}^{i,j,k}$	Loading of building 1 (kW)
$P_{b2}^{i,j,k}$	Loading of building 2 (kW)
$P_{b3}^{i,j,k}$	Loading of building 3 (kW)
SV	Salvage value ($)
Sv_{sc}	Salvage value of solar panels ($/kW)
$Sv_{\ln}$	Salvage value of power lines ($/kW)
Sv_{fc}	Salvage value of fuelcell ($/kW)
Sv_{we}	Salvage value of electrolyzer ($/kW)
Sv_{ht}	Salvage value of hydrogen tank ($/kg)
TC	Total investment cost ($)
$\eta_{hs}^{i,j}$	Efficiency of hydrogen storage system (%)

Design Variables

$C_h^{i,j,k}$	Hydrogen consumption by fuel-cell (kg)
$G_h^{i,j,k}$	Hydrogen generation by electrolyzer (kg)
$H_s^{i,j,k}$	Stored hydrogen inside hydrogen tank (kg)
Pn_{s1}	Solar power in building 1 (kW)
Pn_{s2}	Solar power in building 2 (kW)
Pn_{fc}	Fuel-cell power (kW)
Pn_{we}	Electrolyzer power (kW)
Pn_{ht}	Capacity of hydrogen tank (kg)
Pl_{12}^m	Nominal power of power line between buildings 1 and 2 (kW)
Pl_{23}^m	Nominal power of power line between buildings 2 and 3 (kW)
Pl_{31}^m	Nominal power of power line between buildings 3 and 1 (kW)
$P_{12}^{i,j,k}$	Power from building 1 to 2 (kW)
$P_{13}^{i,j,k}$	Power from building 1 to 3 (kW)
$P_{31}^{i,j,k}$	Power from building 3 to 1 (kW)
$P_{32}^{i,j,k}$	Power from building 3 to 2 (kW)
$P_{23}^{i,j,k}$	Power from building 2 to 3 (kW)
$P_{21}^{i,j,k}$	Power from building 2 to 1 (kW)
$P_{s2}^{i,j,k}$	Power of solar system on building 2 (kW)
$P_{s1}^{i,j,k}$	Power of solar system on building 1 (kW)
$P_{we}^{i,j,k}$	Power of electrolyzer (kW)
$P_{fc}^{i,j,k}$	Power of fuelcell (kW)
Z_1	Annualized cost of solar systems ($/year)
Z_2	Annualized cost of power lines ($/year)
Z_3	Annualized cost of fuel-cell ($/year)
Z_4	Annualized cost of electrolyzer ($/year)
Z_5	Annualized cost of hydrogen tank ($/year)
Z_6	Final annualized cost of plan ($/year)

solar panels and the other building is equipped with hydrogen storage device. All three buildings can trade energy with each other as P2P. The cooperation of solar panels and hydrogen storage system is optimized to supply the demand of all buildings. The planning cost includes the investment, operational, and maintenance costs on solar systems, the power lines between the buildings, fuel-cell, electrolyzer, and storage tank. The optimization programing finds optimal power of solar systems, capacity of power lines between the buildings, optimal power of fuel-cell and electrolyzer, and optimal capacity of hydrogen tank.

1.1. Highlights of the proposed problem

The highlights of the proposed problem are listed as follows;

- An off-grid system including three individual buildings is modeled.
- The individual buildings are operated through P2P home energy management.
- All the buildings have bilateral energy trading with each other.
- The energy of buildings is supplied by association of solar panels and hydrogen storage.
- The plan obtains power of solar systems, capacity of power lines between the buildings, power of fuel-cell, power of water electrolyzer, capacity of hydrogen storage tank, and optimal operation of hydrogen storage.

2. The proposed model

2.1. P2P system

In the traditional systems, the clients are connected to the main server and they can share their resources with the server. There is not a direct connection between the clients. This system is shown in Fig. 1-A on the other hand, the P2P system enables the clients to share their resources directly with each other without the main server. The P2P system increases the flexibility of the system and the clients can locally balance their supply and demand.

2.2. Hydrogen storage system

The hydrogen storage device includes the water electrolyzer component, the hydrogen storage container, and the fuel-cell stocks as illustrated in Fig. 2. The input energy is reformed to hydrogen by chemical process through the water electrolyzer and it is stored inside the container. This process is the charging process. The hydrogen is fed into a fuel cell and converted to electricity and this process is the discharging process. The hydrogen tank stores the hydrogen and supports the charging-discharging process [17].

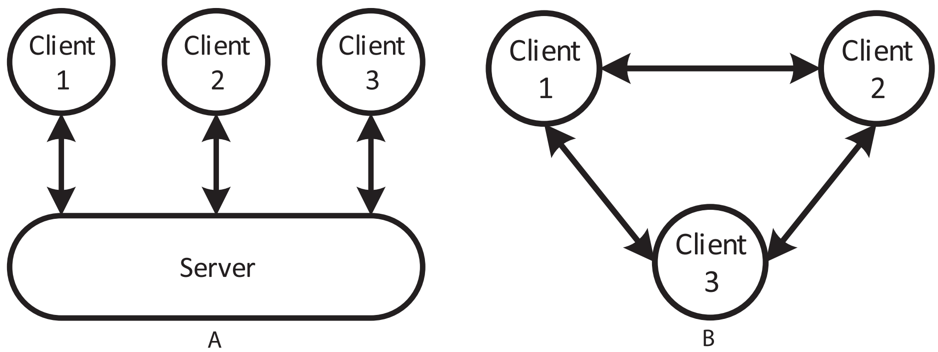

Fig. 1. P2P system against client-server system (**A**: client-server; **B**: P2P).

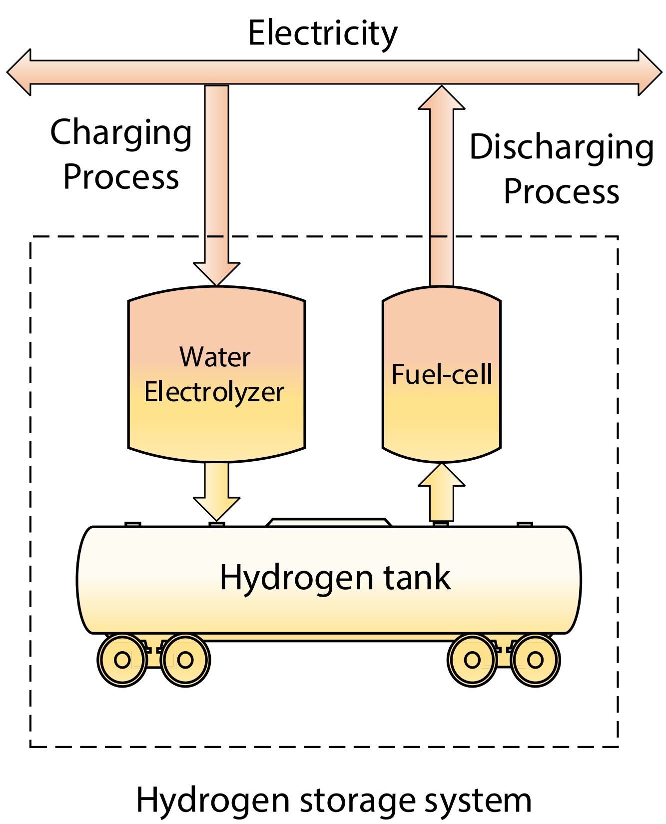

Fig. 2. Hydrogen storage system and charging-discharging process.

2.3. P2P buildings

Fig. 3 shows the P2P buildings with the solar panels and hydrogen storage system. The building 1 and 2 are equipped with solar panels and the building 3 is supplied by hydrogen storage device. The hydrogen storage device has already been introduced in subsection 2.2. All the buildings have different load demand profiles. The coordination of solar panels and hydrogen storage system enables the buildings to supply their demands under loading and solar uncertainty. The hydrogen storage system stores excess of solar energy as hydrogen form and it afterward supplies the loads when the solar energy is not available. The P2P operation of the buildings allows them to share their resources and energy capacities with each other. As a result, the buildings 1 and 2 that are equipped with solar panels benefit from the hydrogen storage system on building 3 and the building 3 also benefits from the solar energy on the building 1 and 2. The P2P operation reduces the investment cost of the buildings. Because they do not need to install new energy resources and they can share their available resources with each other. The P2P system can properly balance the generation and load at all buildings and efficiently supplies all the energy demands locally.

3. Formulation of P2P system

In this paper, the equivalent annual cost (EAC) is used to present all costs. The EAC assists to evaluate the cost effectiveness of two or more assets with dissimilar lifetimes and it is modeled by (1). The first item represents the investment cost, the second item is the salvage value, and the last item is the maintenance cost. The "*AIC*" and "*ASV*" are defined as (2) and (3).

$$EAC = TC \times AIC - SV \times ASV + MC \times 365 \tag{1}$$

$$AIC = \frac{\left(dr \times (1+dr)^{ls}\right)}{(1+dr)^{ls} - 1} \tag{2}$$

$$ASV = \frac{dr}{(1+dr)^{ls} - 1} \tag{3}$$

With respect to the above explanation about the equivalent annual cost, all the following costs are presented as equivalent annual cost. The solar cost is calculated by (4). The cost of power lines between the buildings is modeled as (5). The costs of fuel-cell and water electrolyzer are given as (6) and (7). The annualized cost of hydrogen storage tank is presented by (8). Eventually the final annualized cost is achieved as (9). The problem minimizes the cost given by (9) as the objective function of the programming.

$$Z_1 = (\mathrm{Pn}_{s1} + \mathrm{Pn}_{s2}) \times (\mathrm{Pr}_{sc} \times AIC - Sv_{sc} \times ASV + Mc_{sc} \times 365) \tag{4}$$

$$Z_2 = (Pl^m_{12} + Pl^m_{23} + Pl^m_{31}) \times (\mathrm{Pr}_{\mathrm{ln}} \times AIC - Sv_{\mathrm{ln}} \times ASV + Mc_{\mathrm{ln}} \times 365) \tag{5}$$

$$Z_3 = \left(Pn_{fc}\right) \times \left(\mathrm{Pr}_{fc} \times AIC - Sv_{fc} \times ASV + Mc_{fc} \times 365\right) \tag{6}$$

$$Z_4 = (Pn_{we}) \times (\mathrm{Pr}_{we} \times AIC - Sv_{we} \times ASV + Mc_{we} \times 365) \tag{7}$$

$$Z_5 = (Pn_{ht}) \times (\mathrm{Pr}_{ht} \times AIC - Sv_{ht} \times ASV + Mc_{ht} \times 365) \tag{8}$$

$$Z_6 = \mathrm{e} = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 \tag{9}$$

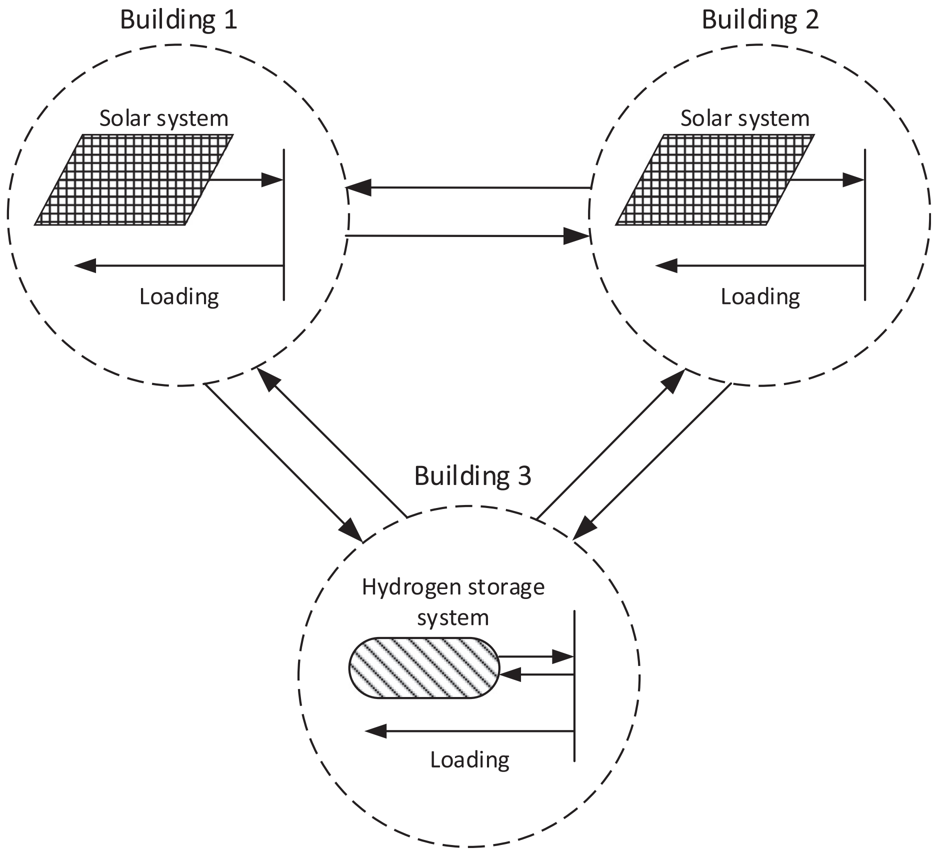

Fig. 3. P2P buildings with solar panels and hydrogen storage system.

The power balance in building 1 is given by (10). This building is equipped with solar system and solar power is defined by (11). The power balance in building 2 is also confirmed by (12) and solar power in building 2 is modeled by (13).

$$P_{b1}^{i,j,k} + P_{12}^{i,j,k} + P_{13}^{i,j,k} - P_{s1}^{i,j,k} = 0 \quad \forall i \in I, j \in J, k \in K \tag{10}$$

$$P_{s1}^{i,j,k} \le \mathrm{Pn}_{s1} \quad \forall i \in I, j \in J, k \in K \tag{11}$$

$$P_{b2}^{i,j,k} + P_{23}^{i,j,k} + P_{21}^{i,j,k} - P_{s2}^{i,j,k} = 0 \quad \forall i \in I, j \in J, k \in K \tag{12}$$

$$P_{s2}^{i,j,k} \le \mathrm{Pn}_{s2} \quad \forall i \in I, j \in J, k \in K \tag{13}$$

The third building is equipped with hydrogen storage device. The power balance in this building is defined as (14) and the electrolyzer and fuel-cell powers are modeled by (15) and (16).

$$P_{b3}^{i,j,k} + P_{31}^{i,j,k} + P_{32}^{i,j,k} + P_{we}^{i,j,k} - P_{fc}^{i,j,k} = 0 \quad \forall i \in I, j \in J, k \in K \tag{14}$$

$$P_{we}^{i,j,k} \le \mathrm{Pn}_{we} \quad \forall i \in I, j \in J, k \in K \tag{15}$$

$$P_{fc}^{i,j,k} \le \mathrm{Pn}_{fc} \quad \forall i \in I, j \in J, k \in K \tag{16}$$

The power lines connected among the buildings transfer the power between the buildings. The transferred power between the buildings is modeled through (17) to (19). The nominal capacity of the power lines is also defined through (20) to (22).

$$P_{12}^{i,j,k} + P_{21}^{i,j,k} = 0 \quad \forall i \in I, j \in J, k \in K \tag{17}$$

$$P_{23}^{i,j,k} + P_{32}^{i,j,k} = 0 \quad \forall i \in I, j \in J, k \in K \tag{18}$$

$$P_{31}^{i,j,k} + P_{13}^{i,j,k} = 0 \quad \forall i \in I, j \in J, k \in K \tag{19}$$

$$\left| P_{12}^{i,j,k} \right| \le Pl_{12}^{m} \quad \forall i \in I, j \in J, k \in K \tag{20}$$

$$\left| P_{23}^{i,j,k} \right| \le Pl_{23}^{m} \quad \forall i \in I, j \in J, k \in K \tag{21}$$

$$\left| P_{13}^{i,j,k} \right| \le Pl_{31}^{m} \quad \forall i \in I, j \in J, k \in K \tag{22}$$

Table 1
Seasonal loading profile in building 1.

Hour	Season 1 (%)	Season 2 (%)	Season 3 (%)	Season 4 (%)
1	25	30	25	15
2	20	30	22	15
3	20	30	22	20
4	15	25	10	25
5	20	25	10	25
6	25	30	15	30
7	30	40	20	45
8	30	45	20	65
9	35	45	25	90
10	45	50	30	85
11	55	55	40	80
12	75	80	55	80
13	90	95	70	85
14	85	90	75	90
15	70	60	65	90
16	60	60	55	100
17	70	65	80	95
18	85	100	100	100
19	100	100	90	75
20	100	100	100	50
21	95	100	90	25
22	90	95	80	20
23	75	85	70	20
24	50	55	60	15

Table 2
Seasonal loading profile in building 2.

Hour	Season 1 (%)	Season 2 (%)	Season 3 (%)	Season 4 (%)
1	15	25	10	25
2	20	25	10	25
3	25	30	25	15
4	20	30	22	15
5	20	30	22	20
6	25	30	15	30
7	30	40	20	45
8	75	80	55	80
9	90	95	70	85
10	85	90	75	90
11	70	60	65	90
12	60	60	55	100
13	70	65	80	95
14	85	100	100	100
15	30	45	20	65
16	35	45	25	90
17	45	50	30	85
18	55	55	40	80
19	100	100	90	75
20	100	100	100	50
21	95	100	90	25
22	90	95	80	20
23	75	85	70	20
24	50	55	60	15

The operation of hydrogen storage device is modeled through (23) to (27). At each timespan, the hydrogen storage system only works on hydrogen combustion by fuel cell (discharging process) or hydrogen generation by electrolyzer (charging process). This point is modeled by (23). It is clear that the system cannot work on both the charring and discharging states at the same time [17].

$$\begin{cases} if\ C_h^{i,j,k} > 0 \Rightarrow G_h^{i,j,k} = 0 \\ if\ G_h^{i,j,k} > 0 \Rightarrow C_h^{i,j,k} = 0 \\ \forall i \in I, j \in J, k \in K \end{cases} \tag{23}$$

The hydrogen combustion by fuel cell (discharging process) is presented as (24) and the hydrogen generation by electrolyzer (charging process) is defined as (25).

$$C_h^{i,j,k} = P_{fc}^{i,j,k} \times cf_h^e \quad \forall i \in I, j \in J, k \in K \tag{24}$$

$$G_h^{i,j,k} = P_{we}^{i,j,k} \times cf_h^e \quad \forall i \in I, j \in J, k \in K \tag{25}$$

The stored hydrogen inside the hydrogen container is shown in (26). The efficiency of hydrogen storage system is determined by (27) and the capacity of hydrogen container is limited by (28) [17].

$$H_s^{i,j,k} = H_s^{i,j,k-1} + G_h^{i,j,k} - C_h^{i,j,k} \quad \forall i \in I, j \in J, k \in K \tag{26}$$

$$\eta_{hs}^{i,j} = \frac{\sum_{k \in K} C_h^{i,j,k}}{\sum_{k \in K} G_h^{i,j,k}} \qquad \forall i \in I, j \in J \tag{27}$$

$$H_s^{i,j,k} \le Pn_{ht} \quad \forall i \in I, j \in J, k \in K \tag{28}$$

Table 3
Seasonal loading profile in building 3.

Hour	Season 1 (%)	Season 2 (%)	Season 3 (%)	Season 4 (%)
1	30	45	20	65
2	35	45	25	90
3	45	50	30	85
4	55	55	40	80
5	75	80	55	80
6	90	95	70	85
7	85	90	75	90
8	70	60	65	90
9	60	60	55	100
10	70	65	80	95
11	85	100	100	100
12	100	100	90	75
13	100	100	100	50
14	95	100	90	25
15	90	95	80	20
16	75	85	70	20
17	50	55	60	15
18	25	30	25	15
19	20	30	22	15
20	20	30	22	20
21	15	25	10	25
22	20	25	10	25
23	25	30	15	30
24	30	40	20	45

3.1. Optimization programming

The final optimization programming is modeled as below where the objective function (equation (1)) is minimized subject to all constraints (equation (2) to (28)).

Minimize Equation (1)Subject toEquations (2)–(28).

The above-mentioned optimization programming in realized in GAMS software and solved by CPLEX solver. The solver finds optimal value for all parameters while minimizes the objective function and satisfies all constraints.

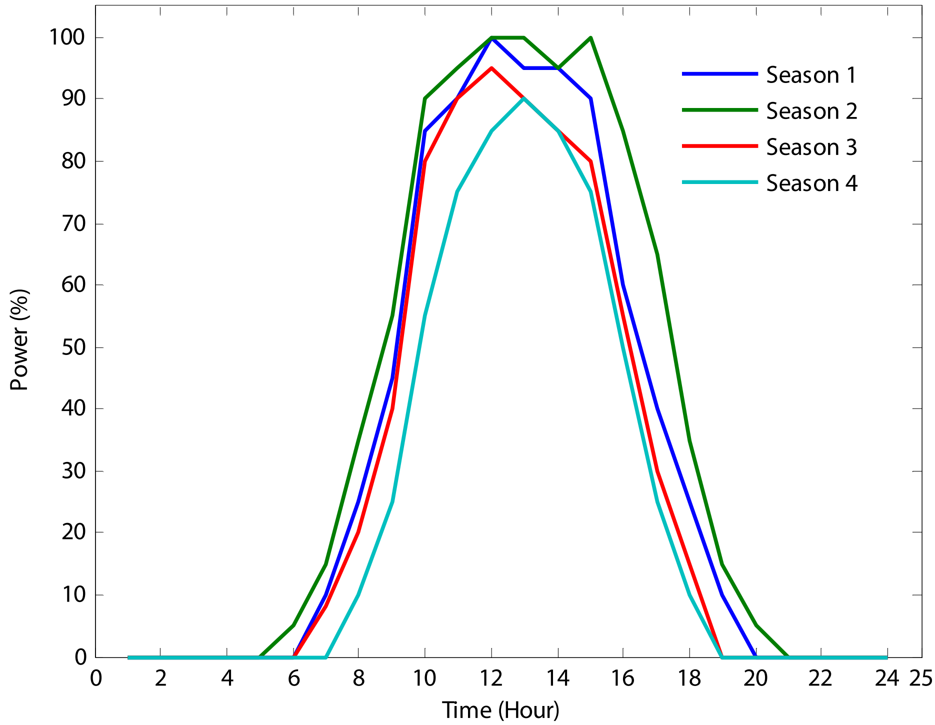

Fig. 4. Seasonal solar energy profile.

Table 4
Economic parameters of the system.

Item	level
Price of solar system ($/kW)	1200
Price of power lines ($/kW)	100
Price of fuelcell ($/kW)	100
Price of water electrolyzer ($/kW)	300
Price of hydrogen storage tank ($/kg)	300
Salvage value of solar system (%)	10
Salvage value of power lines (%)	30
Salvage value of fuelcell (%)	20
Salvage value of water electrolyzer (%)	20
Salvage value of hydrogen storage tank (%)	20
Daily maintenance cost of solar system ($/kW)	0.5
Daily maintenance cost of power lines ($/kW)	0.1
Daily maintenance cost of fuelcell ($/kW)	0.2
Daily maintenance cost of water electrolyzer ($/kW)	0.2
Daily maintenance cost of hydrogen storage tank ($/kg)	0.2

3.2. *Uncertainty management technique*

In the developed optimization programming, uncertainty is given to parameters and variables. This paper uses the conventional stochastic programming to handle the uncertainty in the model. In this method, the samples are randomly chosen from the total population. A subset of individuals is therefore created from the main population. If the subset of samples is very large including many samples, it can be reduced by sample reduction techniques such forward or backward scenario reduction methods. In the current research, the backward scenario reduction is applied on the subset to reach the preferred number of samples. The details of the used method (random sampling and stochastic programming) can be found in Refs. [1,3].

4. Data of the problem

The off-grid topology shown in Fig. 3 is adopted as test system. The system includes three buildings in which two buildings are equipped with solar panels and the next one is installed with hydrogen storage system. The buildings are connected to each other by power lines. The seasonal loading profiles in buildings 1 to 3 are listed in Tables 1–3, respectively [16]. The peak loads of buildings 1, 2, 3 are equal to 15, 12, 18 kW, respectively [10].

The seasonal solar energy profile is depicted in Fig. 4. Table 4 lists the economic parameters of the system including investment-maintenance costs and salvage values. The discount rate is 10%. The lifespan of the power lines, solar components, fuel-cell device, electrolyzer device, and hydrogen container are 15, 10, 5, 5, and 5 years. The efficiency of hydrogen storage device is 60%. The initial hydrogen of container is assumed equal to 8 kg and the conversion factor between electricity and hydrogen is 40 kWh to 1 kg hydrogen [18].

Table 5
Optimal level of annualized costs.

Item ($/year)	Optimal level
Solar unit cost	63315.32
Power lines cost	17160.56
Fuel-cell cost	4540.904
Electrolyzer cost	29778.659
Hydrogen container cost	4752.735
Final cost of scheme	**119548.178**

Table 6
Optimal power of technologies.

Item	Optimal level
Power of solar 1 (kW)	71
Power of solar 2 (kW)	100
Capacity of power lines (kW)	117.45
Power of fuel-cell (kW)	47.25
Power of electrolyzer (kW)	209.25
Capacity of hydrogen container (kg)	33.397

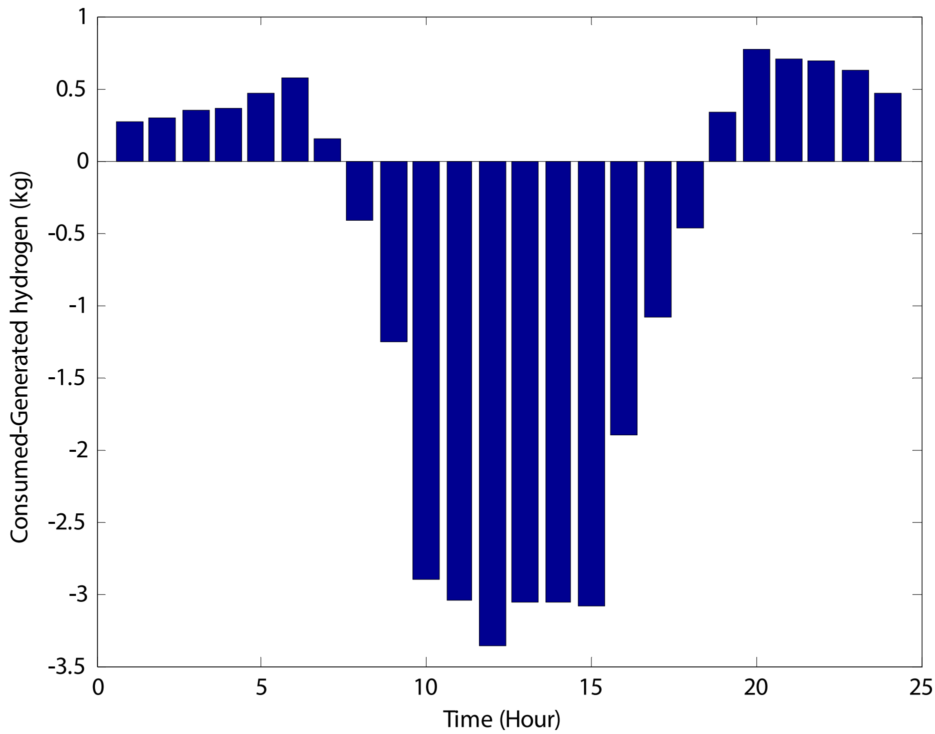

Fig. 5. Generated and consumed hydrogen at season 1 scenario 1.

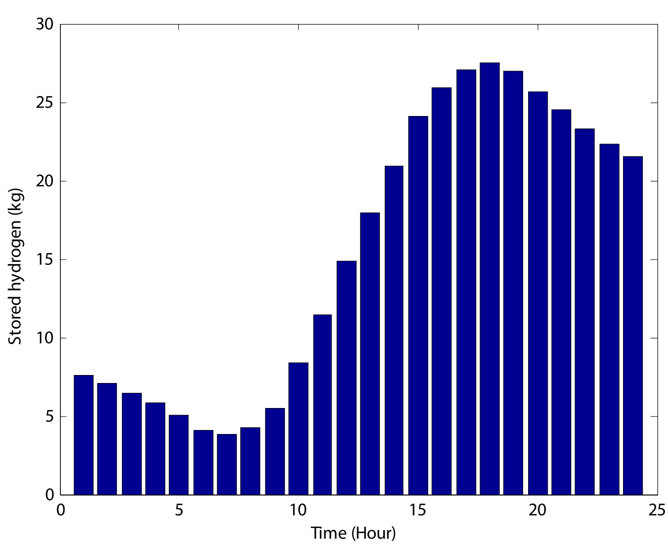

Fig. 6. Stored hydrogen at season 1 scenario 1.

5. Numerical results

Tables 5–6 demonstrate the optimal levels of the costs and powers achieved by the optimization programming. It is obvious that the programming finds optimal power for solar systems, power lines, fuel-cell, water electrolyzer, and optimal capacity for hydrogen storage tank. The final cost of the system is attained as 119548.178 ($/year). The solar systems 1 and 2 are related to the buildings 1 and 2, respectively. The most part of the planning costs (about 68%) is related to the solar systems. The optimal capacity of the power lines is also set to 117 kW. It confirms that the buildings need high capacity of power lines to share their energy resources.

Table 7
Traded power between the buildings.

Hour	Power from home 2 to 1 (kW)	Power from home 3 to 2 (kW)	Power from home 3 to 1 (kW)
1	3.75	5.55	0
2	3	5.4	0
3	3	6	0
4	2.25	4.65	0
5	3	5.4	0
6	3.75	6.75	0
7	−2.6	−9	0
8	−13.25	−29.25	0
9	90.75	56.55	−117.45
10	63.85	−10.95	−117.45
11	61.8	−19.8	−117.45
12	57.7	−35.1	−117.45
13	63.5	−23.1	−117.45
14	62.75	−22.05	−117.45
15	64.05	−22.35	−117.45
16	83.85	28.05	−117.45
17	99.55	64.95	−117.45
18	−5	−23.4	0
19	7.9	9.9	0
20	15	27	0
21	14.25	25.65	0
22	13.5	24.3	0
23	11.25	20.25	0
24	6.95	0.95	14.45

Fig. 5 presents the generated and consumed hydrogen by hydrogen storage system. The hydrogen is generated by electrolyzer and charged into the hydrogen storage tank (i.e., charging process). The hydrogen is afterward discharged from the hydrogen storage tank and consumed by fuelcell to produce electricity (i.e., discharging process). The charging-discharging process of hydrogen storage system shows that the surplus of solar energy is stored in hydrogen form at hours 8 to 18, when the solar energy is available. The hydrogen storage system then discharges the

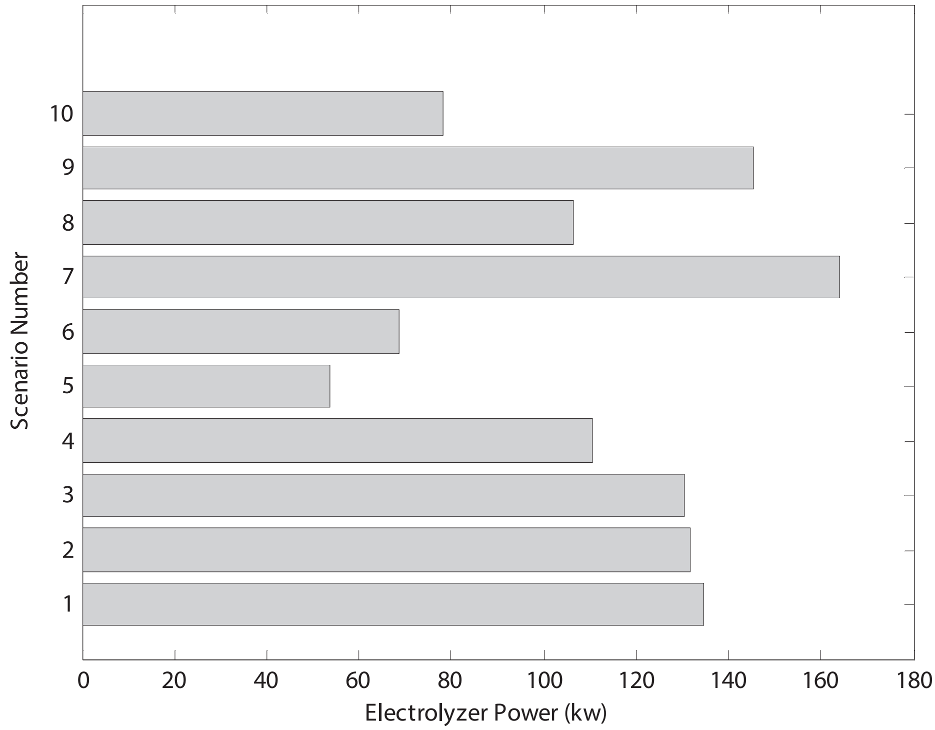

Fig. 7. Fuelcell power at season 1 h 20.

hydrogen and generates electricity once the solar power is not available at hours 1–17 and 19–24.

Fig. 6 shows the stored hydrogen inside the hydrogen storage tank. At beginning hours, the hydrogen storage system uses the initial hydrogen inside the hydrogen tank to produce the electricity. As a result, the hydrogen inside the hydrogen tank is reduced at these hours. After hour 7, the solar energy is available and it is used to generate hydrogen. As a result, the hydrogen inside the hydrogen tank is increased. The extra amount of hydrogen is transferred to the next day and it can be sold by the owner.

Table 7 lists the traded power between the buildings. The buildings show P2P energy exchange to supply the load demands.

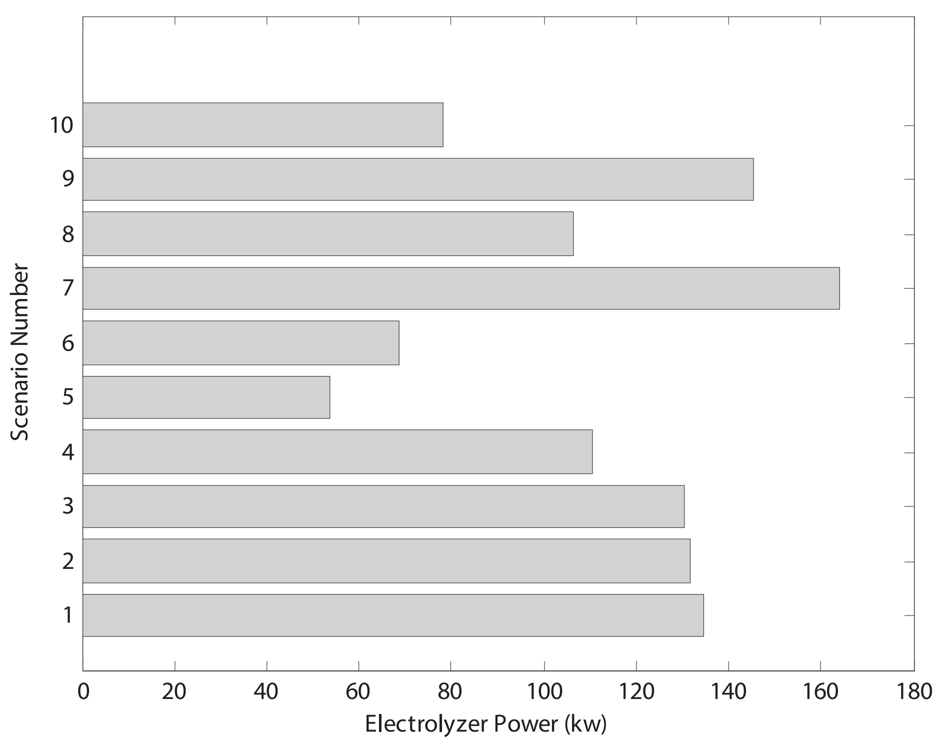

Fig. 8. Electrolyzer power at season 1 h 12.

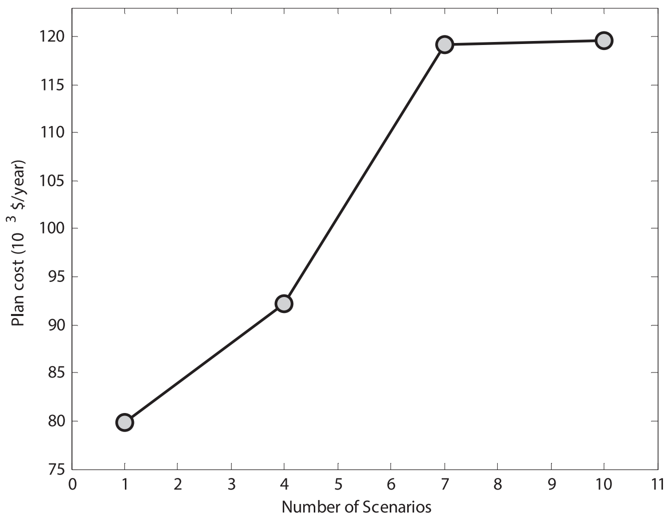

Fig. 9. Planning cost versus number of scenarios.

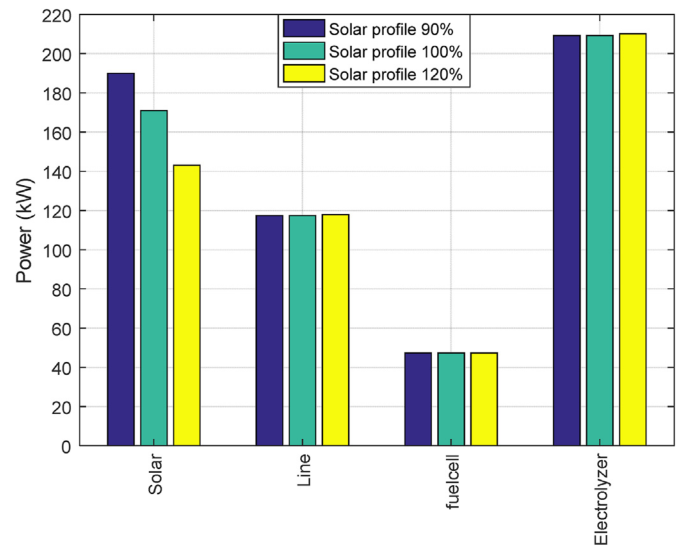

Fig. 11. Optimal powers under various solar energy profiles.

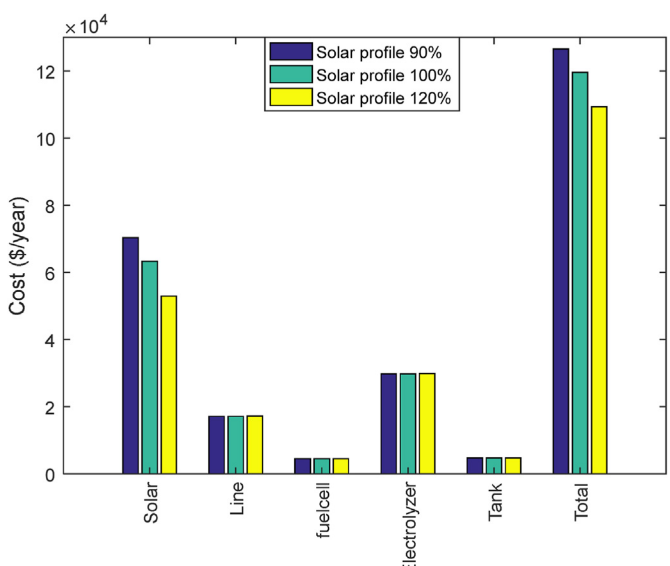

Fig. 10. Optimal costs under various solar energy profiles.

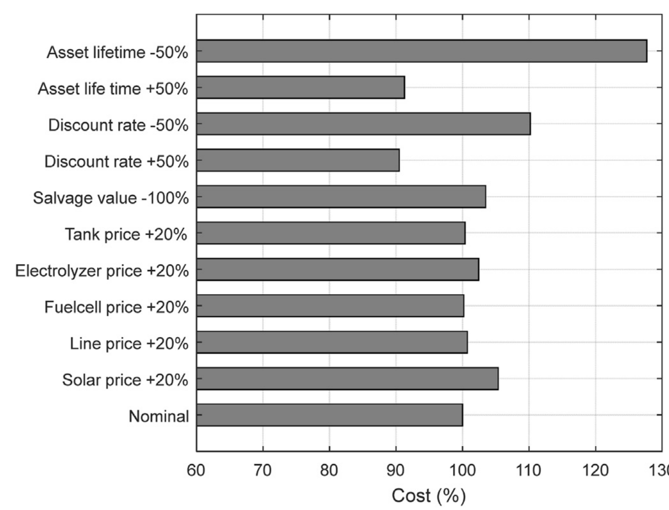

Fig. 12. Sensitivity analysis on parameters of the plan.

The buildings 1 and 2 are equipped with solar panels and building 3 is equipped with hydrogen storage device. At hours 1 to 7 when the solar power is not accessible, the hydrogen storage device produces electricity to deliver energy to the loads. The energy is sent from building 3 to 2 and then from 2 to 1. Such P2P operation supply the demands on buildings 1 and 2. For instance at hour 1, the loading on buildings 1, 2 and 3 is 3.75, 1.75, and 5.4 kW, respectively. The produced electricity by hydrogen storage system on building 3 is 10.95 kW. The produced energy on building 3 supplies 5.4 kW loading on building 3 and excess of energy (5.55 kW) is sent to building 2. About 1.8 kW is consumed in building 2 and the rest of energy (3.75 kW) is transferred to the building 1. At hours 9 to 17, the excess of solar energy is sent to building 3 to be stored by hydrogen storage system.

5.1. Scenarios of performance and uncertainty

The fuel-cell and electrolyzer change their operation under various scenarios to handle such uncertainty and balance the generation and consumption of energy in the system. Fig. 7 shows the fuelcell power under various scenarios of performance at hour 20. At hour 20, the fuelcell produces power to supply the loads while the electrolyzer is not working. Fig. 8 depicts the electrolyzer power under various scenarios of performance at hour 12. At this hour, the electrolyzer consumes power to produce hydrogen and the fuelcell is not working. It is clear that fuelcell and electrolyzer change their operation under various scenarios to deal with the loads and solar energy uncertainty.

The planning cost versus number of scenarios is shown in Fig. 9. The cost is increased alongside rising the scenarios. After 7 scenarios, the cost is almost constant. As a result, considering about 10 scenarios to model the uncertainty of the system is acceptable.

5.2. Influences of solar energy pattern

Solar energy profile is given in Fig. 4. The data in this figure are the nominal level of solar power profile. The solar power pattern changes from one geographic to another location which may make effects on the model. In order to studying the influence of solar system location on the model, the problem is solved under various solar energy profiles including 90, 100, 120%. 100% means the nominal level of solar energy profile given by Fig. 4 and in 90%, the data of Fig. 4 are reduced by 10%.

Problem is solved under defined solar energy profiles and results are summarized in Figs. 10 and 11. The outputs specify that the planning cost is a function of solar energy profile. The system needs larger solar system when the solar energy profile is low and vice-versa. Together with increasing the solar energy profile, the planning cost is significantly reduced. It is demonstrated that increasing solar energy profile reduces the required solar power about 28 kW (17%).

5.3. Error analysis

Fig. 12 presents error analysis on the key items. The results show that the solar system price is the most important economic item in the model and the fuelcell price is the least important economic item of the problem. The salvage value does not provide significant impacts on the outputs, but the discount rate shows significant influences on the model and it can change the costs about 9%. Eventually, the asset lifetime is very important and decreasing the assets life time by 50% increases the costs about 28%.

6. Conclusions

This paper addresses the P2P home energy management. Three individual buildings are modeled, two buildings are equipped with solar panels and one building is equipped with hydrogen storage device. The outcomes illustrate that the cost of the plan is equal to 119548.178 ($/year) and about 68% of cost is devoted to the solar systems. The excess of solar energy is stored in hydrogen form at hours 8 to 18 and the hydrogen is discharged at hours 1–17 and 19–24. At initial hours (hours 1 to 7), the hydrogen storage uses the initial hydrogen inside the hydrogen tank. The P2P operation of all buildings is verified in the model. At hours 9 to 17, the excess of solar energy is sent to building 3 to be stored by hydrogen storage system. It is demonstrated that the fuelcell and electrolyzer change their operations under various scenarios to handle the uncertainty and balance the generation and consumption of the energy. It is demonstrated that increasing solar energy profile reduces the required solar power about 17%. The sensitivity analysis on the parameters demonstrated that the solar system price is the most important economic item in the model.

Further to this work, it is suggested to compare the proposed hydrogen storage device with the other energy storage technologies like batteries. It is also suitable to consider accurate model for losses including loss of power generation and loss of power conversion.

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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