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Energy storage in renewable-based residential energy hubs

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Abstract: Energy storage systems are expected as a near-term solution for renewable energy application in the residential energy hubs. Within this context, this study investigates the feasibility of using storage systems in improving the technical and financial performance of the residential renewable-based energy hub. A new approach has been proposed in this study in which economic dispatch problem has been formulated for an energy hub including both electrical and heat storage system. The proposed approach determines the optimal supply of energy demand and storage system operation to minimise the total energy cost of the hub. The economic benefit of storage system due to energy cost saving and emission reduction has been determined and the investment payback of the storage system have also evaluated in the proposed approach. The proposed approach has been applied to 12 different residential energy hubs and the impact of energy tariff and storage size has been analysed. The obtained simulation results demonstrate the importance of correctly modelling the hub elements in evaluating the storage system benefit in residential energy hub.

Nomenclature

Variables

$\boldsymbol{P}$	energy hub input vector (kW)
v	dispatch factor
γ	combination factor
Q_i, Q_o	storage power input and output (kW)
E	the level of stored energy (kWh)
ESB	energy storage benefit
SIC	storage investment cost
SIP	storage investment payback

Parameters

$\boldsymbol{L}$	the energy hub output vector (kW)
EP	energy price (\$/kWh)
CE	carbon dioxide emission (g/kWh)
N_t	operation period
P_{pv}	output power of photovoltaic unit (kW)
P_{swh}	output of solar water heater (kW)
η_C	air conditioner efficiency
η_{AC}	absorption chiller efficiency
η_T	transformer efficiency
η_{GTe}	electrical efficiency of the CHP unit
η_{GTh}	thermal efficiency of the CHP unit
η_F	boiler efficiency
η_{ES}^{+}, η_{ES}^{-}	electrical charging, discharging efficiency
η_{HS}^{+}, η_{HS}^{-}	thermal charging, discharging efficiency
E^{stb}	loss of standby stored energy
$\bar{P}_T$	upper bounds of the transformer output (kW)
$\bar{P}_{\mathrm{CHP}}$	upper bounds of the CHP output (kW)
$\bar{P}_F$	upper bounds of boiler output (kW)
$\bar{P}_C$	upper bounds of air conditioner output (kW)
$\bar{P}_{AC}$	upper bounds of absorption chiller output (kW)
$\bar{Q}$, $\underline{Q}$	upper and lower bounds of storage power (kW)
$\bar{E}$, $\underline{E}$	upper and lower bounds of stored energy (kWh)

Sets

C	set of convertors
e	electricity
g	gas
h	heating
c	cooling
t	time (hour)

1 Introduction

Increasing application of renewable energy resources, energy storage systems, distributed generation units and combined heat and power generation (CHP) technologies [1–4] have brought into existence the interaction between different energy infrastructures. While the energy infrastructures have been yet independently planned and operated, new concepts, methods and tools are required to study the interaction between the energy infrastructures.

The concept of 'Energy Hub' has been introduced in [5, 6] to properly model the synergies among different forms of energy. Energy hub is defined as an interface between different energy infrastructures in which energy carriers can be stored, converted or transferred within it. Energy hub intakes various types of energy carrier at the input ports, connected to the energy infrastructures, to supply the energy demand at the output ports. Within the hub, the energy is converted and conditioned using energy conversion technologies. Recent researches have focused on technical and financial study of multi-carrier energy systems using the energy hub approach to evaluate efficacy of such a combined or integrated approach [4–11].

Evaluation and optimisation of the energy flow in the building has been well evaluated in the available research works [12, 13]. Bianchi *et al.* [12] have investigated decentralised CHP systems comprised of an innovative CHP unit, an auxiliary boiler and electric as well as thermal storage in the residential context.

Some recent research works have applied the energy hub concept to analyse the building energy flow [9, 14, 15]. A two-level hierarchical scheme has been proposed in [9] in which the household energy consumption has been optimised at the micro-hub level while the set of houses is controlled at the macro-hub level by the system operator. Optimal size of a combined cooling, heat and power (CCHP) system for a house has been determined in [14] using the energy hub concept.

Taking into account the concept of energy hub, the authors in [15] has tried to demonstrate the benefits of employing renewable-based DGs in the urban areas for procuring or supplying both electricity and heating demands of the consumers. Analysis of energy flow in the residential loads has been implemented in [16] by the concept of energy hub.

This paper is aimed to perform a comprehensive study on the effect of energy storage application on the optimal operation of residential energy hub. A new approach has been proposed in this paper in which the economic dispatch (ED) problem for the residential hub is formulated and solved to investigate the abilities of different storage systems in improving energy efficiency, reducing the energy cost and alleviating the emission cost. The ED of the hub is modelled as a non-linear programming optimisation problem. A residential area in Iran is considered and different case studies are introduced to show that how the presence of storage units can affect the technical and financial aspects of this system. Both of electrical and heat storages are considered in the hub to lend the operator a hand in more efficiently use of the available energy resources.

Major innovations in the paper are:

(i) Considers thermal and electrical storage simultaneously in energy hub.
(ii) Includes the emission cost in economic evaluation of storage system.
(iii) Evaluate the impact of hub elements on storage application benefit.

The rest of this paper is arranged as follows: Section 2 describes the basic concepts to model the home energy system as energy hub. Proposed residential hub model is described in Section 3. Application of the proposed approach has been explained in Section 4. Method comparison is discussed in Section 5. Sensitivity analysis results and concluding remarks have been presented in Sections 6 and 7, respectively.

2 Residential energy hub

2.1 Energy hub concept

An integrated system, in which the energy carriers can be converted, conditioned and stored, is referred to as the energy hub. Fig. 1 illustrates different levels of a general energy hub.

In an energy hub, different forms of energy are received at the input ports connected to the energy infrastructures and the energy services in form of electricity, heating, and cooling are delivered at the output ports [5]. Within an energy hub, different forms of energy are converted and conditioned using converter technologies such as transformers, air conditioner (A/C), CHP technology, heat exchangers and absorption chiller.

In an energy hub, the mapping of input energy carriers, P, to the loads at the output ports, L, is mathematically modelled through a matrix named the coupling matrix ($\boldsymbol{C}$) as shown.

$$\begin{bmatrix} L_\alpha \\ \vdots \\ L_\omega \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & \cdots & C_{\omega\alpha} \\ \vdots & \ddots & \vdots \\ C_{\alpha\omega} & \cdots & C_{\omega\omega} \end{bmatrix} \begin{bmatrix} P_\alpha \\ \vdots \\ P_\omega \end{bmatrix}. \quad (1)$$

Each element of the coupling matrix is called coupling factor which relates one input to a particular output. Coupling factor incorporates efficiency and dispatch factor associated with the converters used to convert the input energy into the output.

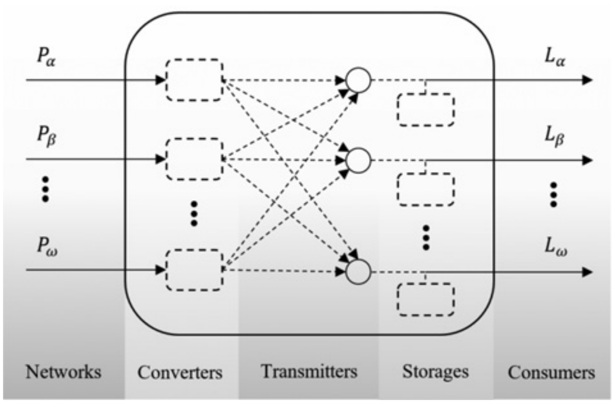

Fig. 1 *General model of an energy hub*

2.2 House energy model as an energy hub

In each house, there are many appliances which utilise different forms of energy to provide daily needs of the consumers.

The way to optimally manage the energy flows in a house is so called 'housing energy model'. Many works are available in which different methods have been proposed to systematically model the energy flow in a house including 'energy-services supply systems' [17], 'basic units' [18, 19], and so-called 'hybrid energy hubs' [20].

To develop the energy hub framework for a house, the energy carriers that are fed to the house via urban energy infrastructures should be determined, energy conversion technologies should be identified and, finally, the house load should be categorised based on the required energy.

Fig. 2 is an illustrative example depicts the energy flow model in a residential area based on the concept of energy hub. As shown in Fig. 2, the energy demands of the house are categorised into four different groups including non-replicable electricity, cooling needs, heating and hot water demand. The grid electricity, natural gas, photovoltaic generation and solar water heater are the forming the input carriers. Electrical output of the CHP unit is utilised to supply the electric need. Electricity can also be stored in the battery storage system.

The cooling demand is provided from the A/C or absorption chiller. The output of boiler, CHP unit or solar water heater can be employed to supply the heat demand or to be stored in heat storage for future uses. Fig. 2 is a comprehensive model that can be used to study and explain different operating modes of the residential energy hub, as discussed in Section 3.

3 ED problem

The objective of ED problem for residential energy hub is to minimise the cost of energy during the operation period of N_t without affecting the customer's comfort [21]. The total energy cost (TEC) of such a system can be formulated as follows

$$\mathrm{TEC} = \sum_{t=1}^{N_t} \left(EP_{\mathrm{e}}^t P_{\mathrm{e}}^t + EP_{\mathrm{g}}^t P_{\mathrm{g}}^t + OCF \times v^t \eta_{GTe} P_{\mathrm{g}}^t \right). \quad (2)$$

The TEC is sum of the imported electricity and gas cost as well as the operation cost of the CHP unit. In this equation, EP_{e}^t and EP_{g}^t, respectively, stand for electricity and gas price. It is assumed that the electricity cannot be sold to the electric grid. The objective function in (2) is calculated with and without use of storage system, as explained hereafter.

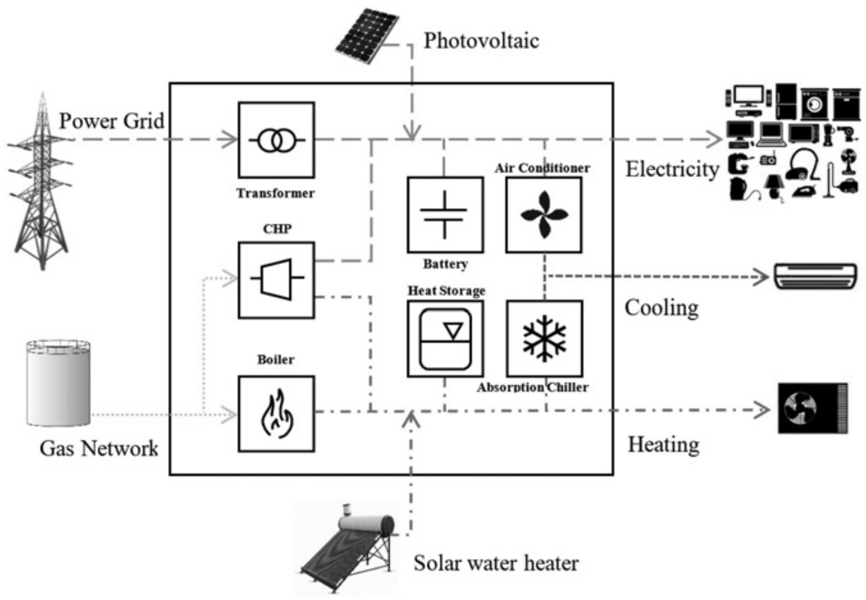

Fig. 2 *Energy hub model of a home*

3.1 No storage system

The energy hub supply electricity (L_e^t), heating (L_h^t) and cooling (L_c^t) loads at the output port. Without use of energy storage systems, the energy demand is supplied through the grid electricity (P_e^t), natural gas (P_g^t), photovoltaic system (P_{pv}^t) and solar water heating (P_{swh}^t). The converter technologies, namely, transformer, CHP, A/C and absorption chiller are used. The dispatch factor v^t represents the fraction of the natural gas that is devoted to CHP unit while the remaining goes to the boiler. Furthermore, the combination factor γ^t shows the fraction of the cooling load comes from chiller and the rest is supplied by A/C.

The balance of input–output power the system should be kept

$$\begin{bmatrix} L_e^t \\ L_h^t \end{bmatrix} + \begin{bmatrix} \dfrac{\gamma^t}{\eta_C} \\ \dfrac{(1-\gamma^t)}{\eta_{AC}} \end{bmatrix} [L_c^t] = \begin{bmatrix} \eta_T & v^t \eta_{GTe} \\ 0 & v^t \eta_{GTh} + (1-v^t)\eta_F \end{bmatrix} \times \begin{bmatrix} P_e^t \\ P_g^t \end{bmatrix} + \begin{bmatrix} P_{pv}^t \\ P_{swh}^t \end{bmatrix} \tag{3}$$

Limits on dispatch factor and combination factor value are the last inequality constraints of the problem

$$0 \le v^t \le 1. \tag{4}$$

$$0 \le \gamma^t \le 1. \tag{5}$$

Loading limit of the converter elements should also be considered as in (6)–(10).

$$P_e^t \le \bar{P}_T \tag{6}$$

$$v^t \eta_{GTe} P_g^t \le \bar{P}_{CHP} \tag{7}$$

$$(1-v^t)\eta_F P_g^t \le \bar{P}_F \tag{8}$$

$$\gamma^t L_c^t \le \bar{P}_C \tag{9}$$

$$(1-\gamma^t) L_c^t \le \bar{P}_{AC} \tag{10}$$

The objective function (2) along with the constraints in (3)–(10) forms a non-linear optimisation problem. Once solved, the optimal values of $\boldsymbol{Y}$ can be found

$$\boldsymbol{Y} = [v^t, P_{(.)}^t]. \tag{11}$$

Once the optimal values of $\boldsymbol{Y}$ is obtained, the TEC without storage, TEC^{NS} is calculated.

In addition, Based on (11) and Iran Energy Flow Diagram in [22], the cost of carbon emission (CCE) of the energy hub is obtained as follows.

$$\text{CCE} = \text{PCE} \times \sum_{t=1}^{N} \left[CE_{PG} P_e^t + CE_{CHP} v^t \eta_{GTe} P_g^t + CE_F (1-v^t)\eta_F P_g^t \right]. \tag{12}$$

Based on the optimal values of $\boldsymbol{Y}$, CCE without storage, CCE^{NS} is also calculated.

3.2 Storage benefit evaluation

When electrical and thermal energy storage systems are used, the storage systems contribute to both energy supply and demand of the hub, depending on being charged/discharged. The balance of input–output power of the system changes as follows (see (13) at the bottom of next page)

The variation in state of charge of the electrical and thermal storage systems is presented in the following equation

$$\begin{bmatrix} E_e^t \\ E_h^t \end{bmatrix} = \begin{bmatrix} (1-E_e^{\text{stb}})E_e^{t-1} \\ (1-E_h^{\text{stb}})E_h^{t-1} \end{bmatrix} + \begin{bmatrix} Q_{ie}^t \eta_{ES}^+ \\ Q_{ih}^t \eta_{HS}^+ \end{bmatrix} - \begin{bmatrix} Q_{oe}^t/\eta_{ES}^- \\ Q_{oh}^t/\eta_{HS}^- \end{bmatrix} \tag{14}$$

Limits on the charge and discharge rates and stored energy of the both electricity (e) and heat (h) storage units are also considered as follows

$$\underline{Q}_{i\alpha} \le Q_{i\alpha}^t \le \bar{Q}_{i\alpha} \quad \alpha \in e, h. \tag{15}$$

$$\underline{Q}_{o\alpha} \le Q_{o\alpha}^t \le \bar{Q}_{o\alpha} \quad \alpha \in e, h. \tag{16}$$

$$\underline{E}_{\alpha} \le E_{\alpha}^t \le \bar{E}_{\alpha} \quad \alpha \in e, h. \tag{17}$$

Table 1 Various case studies

Case	Trans.	CHP	Boiler	A/C	Chiller	PV	SWH
S1	✓		✓	✓			
S2	✓		✓	✓			✓
S3	✓		✓	✓		✓	
S4	✓		✓		✓		
S5	✓		✓		✓		✓
S6	✓		✓		✓	✓	
S7	✓	✓	✓	✓			
S8	✓	✓	✓	✓			✓
S9	✓	✓	✓	✓		✓	
S10	✓	✓	✓		✓		
S11	✓	✓	✓		✓		✓
S12	✓	✓	✓		✓	✓	

Aimed to reach sustainable storage utilisation, the energy stored in a storage unit at the end of study period should be equal to the initial value as in.

$$E_{\alpha}^{1} = E_{\alpha}^{24} \quad \alpha \in e, h. \tag{18}$$

An important issue regarding the dispatch problem is that the problem should be solved for the steady state condition. This means that the period for which the TEC is optimised should be repeatable and this requires that the storage level at the end of the operation period shall be equal to the level at the beginning of the period. That is why (18) has been considered in the paper.

The objective function (2) along with the constraints in (4)–(10) and (13)–(18) forms a non-linear optimisation problem. Once solved, the optimal values of $\boldsymbol{Y}^{s}$ can be found.

$$\boldsymbol{Y}^{s} = \left[v^{t}, P_{(.)}^{t}, Q_{i(.)}^{t}, Q_{o(.)}^{t}\right]. \tag{19}$$

Once the optimal values of $\boldsymbol{Y}^{s}$ is obtained, the TEC and CEE with storage system, TEC^{S} and CCE^{S} are calculated. Change in TEC and CEE due to the application of storage system are calculated as

$$\Delta\text{CEE} = \text{CCE}^{NS} - \text{CCE}^{\text{S}}. \tag{20}$$

$$\Delta\text{TEC} = \text{TEC}^{NS} - \text{TEC}^{\text{S}}. \tag{21}$$

The energy storage benefit (ESB) is then obtained as follows

$$\text{ESB} = \Delta\text{CEE} + \Delta\text{TEC}. \tag{22}$$

As an economic performance index for storage system application, storage investment payback (SIP) is defined as follows

$$\text{SIP} = \frac{\text{SIC}}{\text{ESB}}. \tag{23}$$

In which storage investment cost (SIC) includes the capital cost associated with the deployed energy storage systems.

SIP represents the number of operation periods required to payback the initial investment of the storage system. Any judgment on the feasibility of storage system application should be based on a cost-benefit analysis. SIP can be used as an index to evaluate the economic attractiveness of storage application. Smaller SIP means that storage system application is more profitable.

Table 2 Energy hub parameters [23, 24]

Device	Variable	Value	Unit
transformer	$\bar{P}_T$	5	kW
	η_T	0.98	–
CHP	$\bar{P}_{\text{CHP}}$	1	kW
	η_{GTe}	0.35	–
	η_{GTh}	0.4	–
	OCF	0.006	$/kWh
	CE_{CHP}	230	g/kWh
boiler	$\bar{P}_F$	6	kW
	η_F	0.9	–
	CE_F	250	g/kWh
air conditioner	$\bar{P}_{\text{C}}$	2	kW
	η_{C}	0.6	–
absorption chiller	$\bar{P}_{\text{AC}}$	2	kW
	COP	1.5	–
electricity storage	$\bar{E}_{\text{e}}$	1.8	kWh
	$\bar{Q}_{\text{ie}}$	0.3	kW
	$\bar{Q}_{\text{oe}}$	0.6	kW
	$E_{\text{e}}^{\text{stb}}$	0.5	%/h
	$\eta_{\text{ES}}^{+}, \eta_{\text{ES}}^{-}$	0.95	–
heat storage	$\bar{E}_{\text{h}}$	10	kWh
	$\bar{Q}_{\text{ih}}$	3	kW
	$\bar{Q}_{\text{oh}}$	5	kW
	$E_{\text{h}}^{\text{stb}}$	0.8	%/h
	$\eta_{HS}^{+}, \eta_{HS}^{-}$	0.9	–

4 Method application

4.1 Study data

To investigate the role of different elements in optimal operating strategy of a residential energy hub, 12 case studies have been defined as itemised in Table 1.

Each of the case studies represents a possible structure for energy conversion devices available in a home. For each case, both heat and electricity storage systems are considered. Unit cost of electrical and thermal energy storage systems are considered 10 and 3 $/kWh, respectively. SIC for the storage systems in the study cases is, so, equal to 15 $. Parameters of the energy hub elements related to a sample home in Tehran are listed in Table 2. These components parameters are collected from their catalogue.

Efficiency of absorption chiller and A/C is calculated as follows.

$$\eta_{\text{AC}} = \frac{\text{COP}}{1 + \text{COP}}. \tag{24}$$

Study home energy demand profiles during the summer and the winter have been presented in Figs. 3*a* and *b*, respectively, based on the home energy demand in Tehran [23].

Price of carbon emission is considered as 20 $ per ton of carbon dioxide [25]. Electricity and natural gas tariff for purchasing from the network during the summer and the winter have been shown in Fig. 4*a*, according to [26, 27]. As can be seen in Fig. 4*a*, the tariff of natural gas is fixed during the day, while the electricity tariff follows a time-of-use trend for low (2.3 cent/kWh), medium (3.3 cent/kWh) and peak (4 cent/kWh) load periods.

Daily output profile for PV system with 4 m^2 panel and SWH system with 4 m^2 flat plate collector during the summer and the winter have been shown in Fig. 4*b*, based on calculations made for Tehran [28].

It has been assumed that extra SWH output will be passed to the heat dump radiator.

$$\begin{bmatrix} L_{\text{e}}^{t} \\ L_{\text{h}}^{t} \end{bmatrix} + \begin{bmatrix} \dfrac{\gamma^{t}}{\eta_{\text{C}}} \\ \dfrac{(1-\gamma^{t})}{\eta_{\text{AC}}} \end{bmatrix} \left[L_{c}^{t}\right] = \begin{bmatrix} \eta_T & v^{t}\eta_{GTe} \\ 0 & v^{t}\eta_{GTh} + (1-v^{t})\eta_F \end{bmatrix} \begin{bmatrix} P_{\text{e}}^{t} \\ P_{\text{g}}^{t} \end{bmatrix} + \begin{bmatrix} P_{\text{pv}}^{t} \\ P_{\text{swh}}^{t} \end{bmatrix} - \begin{bmatrix} Q_{i\text{e}}^{t} \\ Q_{i\text{h}}^{t} \end{bmatrix} + \begin{bmatrix} Q_{\text{oe}}^{t} \\ Q_{\text{oh}}^{t} \end{bmatrix} \tag{13}$$

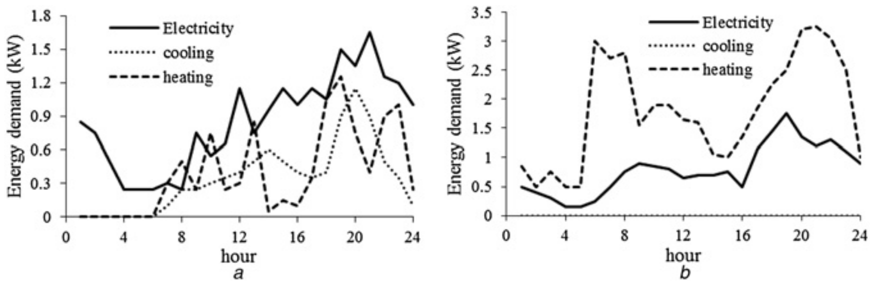

Fig. 3 *Study home energy demands*

a In summer
b In winter

4.2 Results and discussion

The case studies have been analysed using the proposed method for the study period of one year. The optimisation problem has been solved using BARON solver in GAMS platform [29] on a Dell Laptop, 1.7 GHz Intel CPU with 2 GB of RAM.

The calculated TES with and without energy storage as well as ESB and SIP for all the 12 cases have been presented in Table 3.

It can be seen in Table 3 that the smallest TEC is obtained for case S12 in both with and without storage. However, different values for ESB and SIP have been obtained for the different case. In particular, SIP varies between 0.88 year for case S11 to 2.77 year for case S1, showing that storage application benefit depends highly on the elements used in the hub. However, for all cases, SIP is quite small, meaning that storage application is economically justified.

It can be seen in Table 3 that the largest ESB is obtained for case S11 in which the electricity demand can be supplied through the CHP or the grid. CHP generation is also used in case S11 to charge the battery for selling back at peak load price.

Fig. 5*a* represents the electricity demand supply for S11 in a summer day: the electricity is stored in period of 5:00 a.m. to 13:00 and is discharged between 19:00 to 22:00. During the winter, the electrical energy is stored in period of 4:00 to 11:00 and is discharged in the interval 17:00 to 21:00. Due to the electrical storage application, the electricity supply from the grid in summer and winter decrease from 0.6 to 0.2 kW and 0.75 to 0.3 kW, respectively.

Fig. 5*b* shows the home thermal load supply during the winter. It can be seen in Fig. 5*b* that, during the winter, a little extra heat is produced during 13:00 to 15:00 which is stored for being consumed during 16:00 to 19:00. During the summer, however, extra CHP heat production in the period of 1:00 to 6:00 is stored for consumption during 7:00 to 10:00. Likewise, extra output energy of solar water heater is stored and is used in the period of 18:00 to 23:00.

5 Method comparison

The proposed approach to minimise home energy cost has been compared with two other methods to minimise the home energy cost:

- Method I: determine the optimal use of electrical energy storage system, as in [30], to minimise TEC.
- Method II: based on the method presented in [31], uses thermal energy storage system to minimise TEC.

The 12 case studies have been analysed using Method I and Method II based on the study input data. For each case, TEC and CCE have been determined with and without storage systems using the proposed approach, Method I and Method II and the storage impact has been calculated. Results have been presented in Table 4.

It can be seen in Table 4 that the TEC and CCE reduction obtained with Method I is larger than those obtained by Method II in the cases S7–S11 which include CHP unit. As Method I is just based on the electricity storage, it can be concluded that the electricity storage is more beneficial when CHP is applied.

Regarding the results obtained for Method II, it can be seen that for both of cases S2 and S11, energy storage is more beneficial than in other cases. As Method II considers the thermal storage, it can be concluded that application of solar water heater or CHP with chiller (CCHP) will increase the benefit of thermal energy storage.

However, for all cases, it can be seen in Table 4 that the benefit obtained using the proposed approach is larger of those obtained using Method I or Method II. This happens, in particular in S7 to S11 where both storage systems are contributing to supply hub energy demand.

It can also be seen in Table 4 that, for some cases, such as S1, S3, S4 and S6, the results obtained by the proposed method is equal to those obtained by either Method I or Method II. This shows that in those cases, just one of the electrical or thermal storage systems is working and the other one is not beneficial. Hence, one may claim that the proposed approach is not useful in such cases.

However, the applicability of either of the storage systems cannot be determined a priori. Even the hub element cannot merely be used to determine which storage system is beneficial. For example, S2 has all elements of S1 with an extra solar water heater. However, while the thermal storage is of no use for S1, it has contributed to hub energy system in S2.

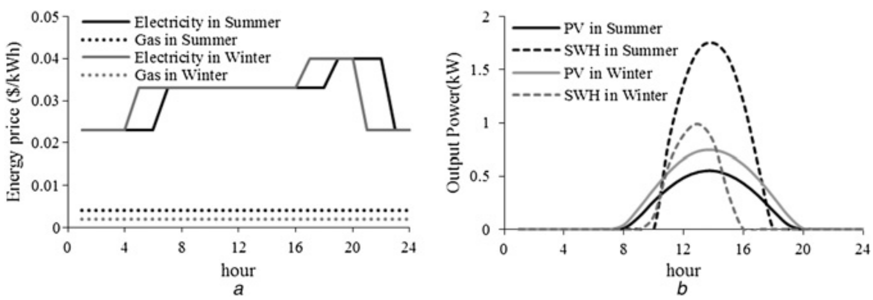

Fig. 4 *Study input data*

a Electricity and natural gas price
b Output of renewable-based devices

Table 3 Optimal results for case studies

Case	TEC ($) With storage	TEC ($) without storage	ESB ($/y)	SIP (y)
S1	349.55	354.95	5.40	2.77
S2	342.00	351.76	9.76	1.53
S3	290.74	297.35	6.61	2.27
S4	269.43	274.84	5.41	2.77
S5	260.96	267.74	6.78	2.22
S6	210.63	217.24	6.61	2.27
S7	250.87	261.60	10.73	1.38
S8	249.50	260.45	10.95	1.36
S9	211.14	221.14	10.00	1.49
S10	164.81	180.10	15.29	0.98
S11	161.34	178.22	16.88	0.88
S12	133.48	147.29	13.81	1.08

Table 4 Total benefit calculation comparison

Case	Proposed approach		Method I (elec. storage)		Method II (thermal storage)	
	ΔTEC	ΔCCE	ΔTEC	ΔCCE	ΔTEC	ΔCCE
S1	5.40	0.00	5.40	0.00	0.00	0.00
S2	9.76	4.90	5.40	0.00	4.35	4.90
S3	6.61	0.00	6.61	0.00	0.00	0.00
S4	5.41	0.00	5.40	0.00	0.00	0.00
S5	6.78	1.55	5.40	0.00	1.38	1.55
S6	6.61	0.00	6.61	0.00	0.00	0.00
S7	10.73	4.40	10.64	4.30	0.09	0.10
S8	10.95	5.30	10.55	4.52	0.39	0.78
S9	10.00	4.43	9.91	4.33	0.09	0.10
S10	15.29	8.48	12.03	5.56	2.60	2.92
S11	16.88	12.41	11.63	5.44	5.89	6.97
S12	13.81	8.66	11.92	6.49	1.93	2.17

Hence, as do the proposed approach, both storage systems should be considered simultaneously to evaluate the storage system benefit. This shows that the proposed approach has the advantage of obtaining the largest profit as it simultaneously considers thermal and electrical storage.

Another issue in Table 4 is that CCE reduction in S7 to S12 is comparable with TEC reduction and a good share of SIB achieved for cases S7 to S12 is due to the emission reduction. In the other words, if CCE reduction is not considered in ESB calculation, the results presented in Table 3 would change drastically and the economic performance of storage system application could be negligible for some cases. Hence, the emission reduction benefit has an important role in economic justification of storage system application and should be clearly considered.

6 Sensitivity analysis

6.1 Energy price

Fig. 6*a* shows the variation in the ESB of the case studies against change in the electricity tariff in which a multiplication factor has been applied to the tariff presented in Fig. 6*a*. A multiplication factor greater than unity shows an increase in the electricity tariff from those presented in Fig. 6*a*. The obtained results showed that as long as the electricity tariff increases, more benefit can be experienced by the application of energy storage. Better improvement can be observed in Fig. 6*a* for the cases S7–S12 in which CHP electricity generation is used to charge the electricity storage unit for selling back in the peak hours.

The graph shown in Fig. 6*b* represents the impact of gas price on the storage benefit. It can be seen in Fig. 6*b* that, for cases S2 and S11, ESB has been decreased once the gas price has increase from those presented in Fig. 6*b* and it has been well increased according to the increase in the gas price. However, if the gas price increases 1.5 times of the base case, 50% energy cost can be seen in the cases 2 and 11. The cases 5, 7, 8 and 9 also experience a light increasing trend. For cases of 10 and 12 which have CCHP system, it can be seen that the heat storage has the highest improvement.

The impact of CHP size on the storage benefit for cases S7–S12 has been analysed and the results have been presented in Fig. 6*c*. It can be seen in Fig. 6*c* that, for cases S7–S12, the benefit has been decreased with increase in the CHP size. This is due to the reason that the increased CHP generation cannot be anymore stored in the electricity storage unit and the economic attractiveness of the storage system will be decreased. In the cases which photovoltaic and CHP have been deployed simultaneously (S9 and S11), for the conditions with smaller CHP size, the system tends to store all the excess photovoltaic output, resulting to increase in the storage benefit. For the other cases, however, storage benefit has been decreased once CHP size reduced.

The electricity sell to the electric grid has been considered and the electricity sale price is considered as a fraction of the EP. The impact of variation in the electricity purchase price on ESB has been evaluated. Results have been presented in Fig. 6*d*. It can be traced in Fig. 6*d* that as long as the electricity purchase price rises, the benefit of electricity storage decreases. In particular, if the electricity sale price is equal to the grid electricity price, the storage unit is of no help to improve the cost of energy hub as the surplus electricity is sold to the grid directly.

6.2 Uncertainty impact

Sensitivity analysis has also been performed to investigate the impact of uncertainties associated with the electricity demand and PV output.

The impact of 10% variation in the hub electricity demand on SEB has been presented in Fig. 7*a*.

It can be seen in Fig. 7*a* that, in cases S1, S2, S4 and S5 where neither PV nor CHP is used, SEB does not depend on the

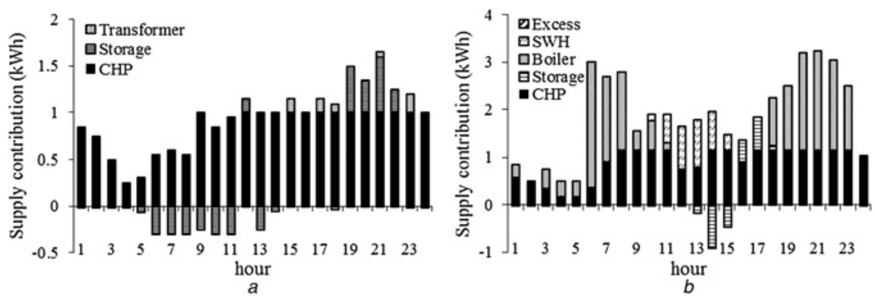

Fig. 5 *Demand supply for S11 in a summer day*

a Electrical demand
b Heating demand

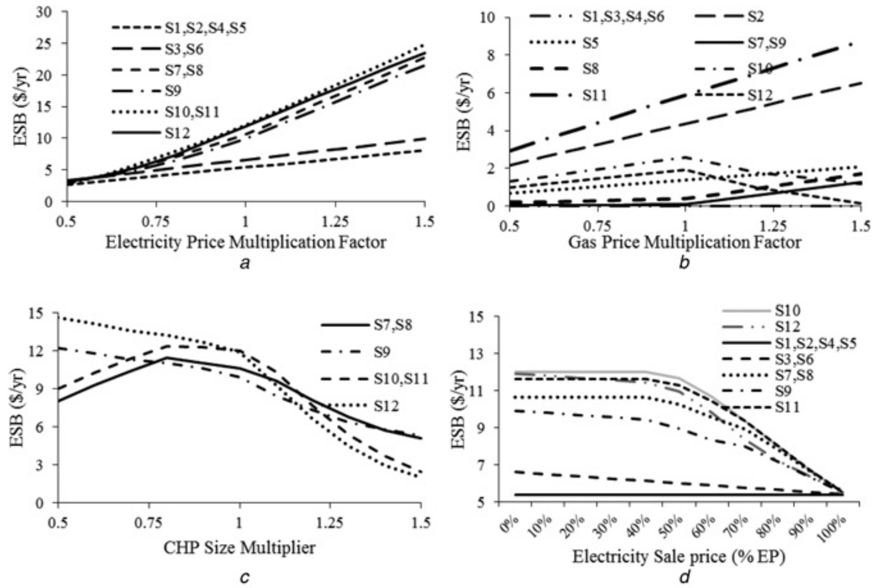

Fig. 6 *Sensitivity analysis on energy prices and CHP size*

a Storage benefit against the electricity tariff change
b Thermal storage benefit against the gas tariff changes
c Storage benefit against the changes in CHP size
d Electrical storage benefit against the changes in power price

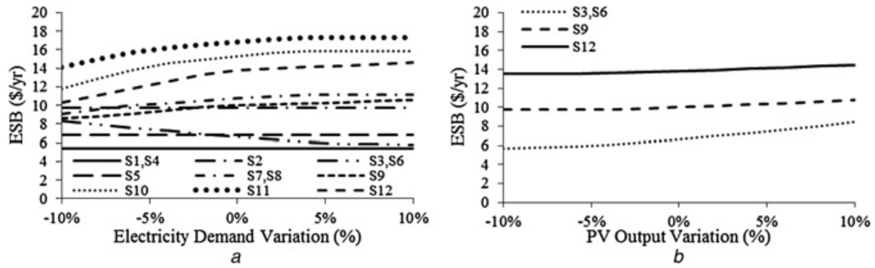

Fig. 7 *Impact of uncertainty on storage benefit*

a Electricity demand uncertainty
b PV generation uncertainty

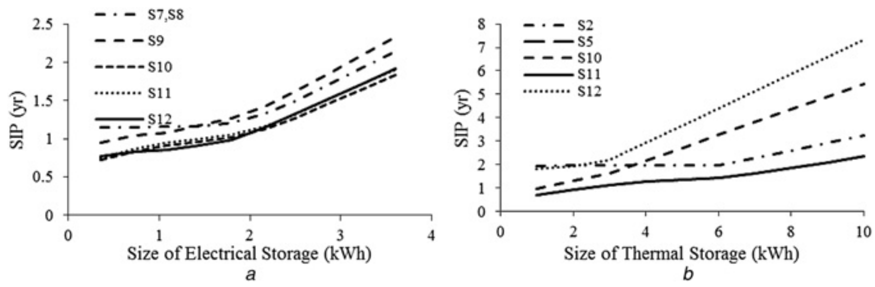

Fig. 8 *Impact of storage size on the economic performance of the storage system*

a Electrical storage capacity variation
b Thermal storage capacity variation

electricity demand. In S3 and S6 which just use just, SEB has decreased with increase in the demand. However, in other cases which use CHP, SEB has increased with increase in the hub electricity demand. This shows that the impact of uncertainty in the hub demand on ESB depends mainly on the hub elements. In particular, CHP application results to increase the sensitivity of ESB to variation in the hub electricity demand.

The impact of 10% variation in PV generation on ESB associated with the cases that use PV has been studied and the results depicted in Fig. 7*b*. As can be traced in Fig. 7*b*, the variation in SEB associated with the cases are not the same: in cases S3 and S6 which do not use CHP, SEB highly depends on PV generation. However, for cases S9 and S12 where both CHP and PV are used, SEB does not change significantly with variation in PV output. This shows that CHP application in energy hub helps to reduce the sensitivity of ESB to the uncertainty in renewable generation.

However, load and generation uncertainty is an important issue in energy hub. The authors are working on an advanced technique to fully include the uncertainty in energy hub dispatch problem.

6.3 Storage size

The impact of storage size on the economic performance of the storage system has been evaluated. Fig. 8*a* shows the variation in SIP against change in the electrical storage size.

As presented in Fig. 8*a*, SIP increases as the size of storage system increases. This shows that, with increased storage size, the economic attractiveness of storage system application reduces.

Variation in SIP associated with thermal storage with change in the size is presented in Fig. 8*b*. It can be seen in Fig. 8*b* that SIP variation is different for the study cases: for S10 and S12, SIP increases quickly with storage size. However, for S2, SIP variation in negligible as the capacity increases to 6 kWh. This shows that for S2, the thermal storage capacity can be increased to 6 kWh without losing the economic attractiveness.

Hence, the elements of energy hub directly affect the suitable storage capacity. Suitable models and methods should be used to determine the optimal size of storage system according to the hub elements.

7 Conclusions

This paper has presented an approach to investigate the impact of electrical and thermal storage systems in improving technical and financial performance of a residential energy hub. Modelling the energy flow of a home as an energy hub, the formulation of ED problem in the home has been extracted. The benefit and investment payback of storage system application in various study cases have been analysed. Results showed that the hub elements affects directly the benefit and payback of storage systems. It was also observed that a great share of storage benefit is due to the reduction in carbon emission and the storage benefits generally increase with increase in the energy tariff. However, selling the electricity to the grid can reduce the storage benefit. CHP size generally have positive impact on the storage benefit while in some cases it might has negative impact on the storage benefit. The impact of variation in the electricity demand and PV generation on the storage benefit can be positive, negative or negligible, depending on the elements of the hub. In particular, CHP application in the hub results to protect the storage benefit against the variation in PV generation.

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