Optimal operation of hybrid electrical and thermal energy storage systems under uncertain loading condition

Mehrjerdi, Hasan; Rakhshani, Elyas

DOI
10.1016/j.applthermaleng.2019.114094

Publication date
2019

Document Version
Final published version

Published in
Applied Thermal Engineering

Applied Thermal Engineering 160 (2019) 114094

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Optimal operation of hybrid electrical and thermal energy storage systems under uncertain loading condition

Hasan Mehrjerdi[a,*], Elyas Rakhshani[b]

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

ARTICLE INFO

Keywords:
Electrical energy storage system
Hybrid storage
Load uncertainty
Stochastic programming
Thermal energy storage system

ABSTRACT

This paper presents a hybrid model of an energy storage system including thermal and electrical energy storage systems in the building with thermal and electrical loads. Building receives its energy from electrical grid and purpose is to reduce the daily energy cost by optimal operation of hybrid energy storage system. Load forecast error is included as uncertainty and both thermal and electrical loads are modeled by Gaussian probability distribution function. The proposed problem for optimal cooperation of hybrid thermal-electrical storage systems is mathematically expressed as mixed integer binary linear programming. The scenario-based stochastic modelling is also included to deal with uncertainty in loading. The expressed stochastic optimization programming minimizes the daily energy cost in building and determines the optimal charging-discharging pattern for both thermal and electrical storage systems at the same time. The results demonstrate that electrical energy storage system reduces the cost about 15%, the thermal energy storage system decreases the cost about 17%, and coordinated thermal-electrical energy storage system reduces the cost about 34%. As a result, the best operation is achieved by the coordinated thermal-electrical energy storage system.

1. Introduction

The energy storage systems (ESSs) are the technologies can store energy during off-peak or low-cost time intervals and then send the energy back to the system when the energy price is high or during on-peak time periods [1]. The energy may be stored in different forms [2]. The mechanical ESS stores the energy in the mechanical form. The most common mechanical ESS may be the pumped-storage hydroelectricity (PSH). In the PSH, the water is pumped into a reservoir at times of peak demand and then it is released through hydro-turbine to generate electricity during on-peak loading [3]. The other main types of mechanical ESSs may be referred as compressed air ESS and flywheel ESS. The compressed air is proper for long-term, high-capacity, and low-speed operations and the flywheel is useful for short-term, low-capacity, fast-speed operations [4].

The electrochemical ESSs store energy in the form of electrochemical process. The common electrochemical ESSs are batteries such as lead-acid battery, nickel–cadmium battery, lithium-ion battery, and flow battery [5]. The supercapacitor is also one of the main methods to store energy in the form of electrochemical process [6].

The chemical storage methods often store energy in the form of chemical gases such as hydrogen, nitrogen, or methane [7]. The process to convert energy to gas is known as power to gas (P2G) [8]. In this method, the electricity is converted to hydrogen through water electrolyzer and it is stored as hydrogen form in hydrogen storage systems. The hydrogen can be combined with carbon dioxide to produce the methane [9]. ESSs often store energy in the form of the electrical field (e.g., capacitors) or magnetic field (e.g., Superconducting magnetics) [10].

Thermal ESSs are also one of the useful technologies to store energy in the form of heat [11] or cold [12]. The molten-salt technology is one of the most common methods that is used in solar power plants [13]. The heat storage in tanks and hot rocks are the other types that store thermal energy in the form of heat. One of the recent technologies is the electric thermal storage heaters that are proper for home energy management [14]. It can supply the heating energy of the home during on-peak time intervals for bill saving [15]. The pumped-heat electricity storage may also be used for home energy management [16]. The cold storage systems such as ice-based technology are often applied for cooling the system during on-peak time intervals for bill saving [17].

Together with the development of different ESSs, the hybrid storage methods are also developed and designed. In the hybrid ESS, often two different ESSs are applied; one slow-speed and high-capacity ESS to deal with energy issues such as energy shifting, and one high-speed and

* Corresponding author.
E-mail addresses: Hasan.mehrjerdi@qu.edu.qa (H. Mehrjerdi), E.rakhshani@tudelft.nl (E. Rakhshani).

https://doi.org/10.1016/j.applthermaleng.2019.114094
Received 1 March 2019; Received in revised form 31 May 2019; Accepted 6 July 2019
Available online 08 July 2019

Nomenclature

Variables and parameters Definition

C_d	daily operational cost ($/day)
C_{egy}^t	cost of electricity ($/kWh)
D_{ti}^t	duration of time interval (Hour)
E_{ts}^t	energy of thermal storage (BTU-hour)
E_{ts}^r	rated capacity of thermal storage (BTU-hour)
E_{es}^t	energy of electrical storage (kWh)
E_{es}^r	rated capacity of electrical storage (kWh)
K_{te}	coefficient for converting electrical energy to thermal energy
$P_{net}^{s,t}$	total received power from grid (kW)
$P_{net1}^{s,t}$	received power from grid for electrical demand (kW)
$P_{net2}^{s,t}$	received power from grid for thermal demand (kW)
$P_{de}^{s,t}$	electrical demand (kW)
Pc_{es}^t	charged power to electrical storage (kW)
Pd_{es}^t	discharged power from electrical storage (kW)
$P_{nett}^{s,t}$	thermal energy produced by electrical energy (BTU)
$P_{dt}^{s,t}$	thermal demand (BTU)
Pc_{ts}^t	charged power to thermal storage (BTU)
Pd_{ts}^t	discharged power from thermal storage (BTU)
P_{net}^r	limit of power between system and grid (kW)
P_{ts}^r	rated power of thermal storage (BTU)
P_{es}^r	rated power of electrical storage (kW)
R_r^s	probability of scenario
s, S	index of scenarios, set of scenarios
t, T	index of time intervals, set of time intervals
Uc_{ts}^t	binary variable showing charging state for thermal storage
Ud_{ts}^t	binary variable showing discharging state for thermal storage
Uc_{es}^t	binary variable showing charging state for electrical storage
Ud_{es}^t	binary variable showing discharging state for electrical storage
η_{ts}, η_{es}	efficiency of thermal and electrical storages (%)

low-capacity ESS to deal with power issues such as power quality [18]. The different combinations of hybrid ESSs have been developed such as battery-capacitor, superconducting magnet-battery, compressed air-capacitor, and battery-flywheel [19]. The three-level hybrid storage method is also presented to shift energy over the months [20].

ESSs have different applications in the buildings [21] and electrical grids [22]. In the electrical network, the ESSs can be applied for a variety of applications ranging from short to long term functions such as voltage control, reliability improvement, loss reduction, cost saving, making profit, congestion relief, or renewable energy smoothing [23]. In the buildings, ESSs are used through a home energy management system (HEMS) [24]. The HEMS is an optimization tool that optimizes energy consumption in buildings considering different purposes such as cost, reliability, technical constraint, resiliency, self-healing, contingency, renewable energies, and ESSs [25]. ESSs are one of the useful technologies in the HEMS and they make significant positive impacts on the energy management tools [26].

This paper models hybrid ESS including thermal-electrical storage in a building. The hybrid storage is optimally operated to manage energy in building. The uncertainties of the thermal and electrical loads are modeled through Gaussian probability distribution function. The results demonstrate that the proposed methodology can properly utilize the hybrid thermal-electrical ESS to minimize the operational cost of the building.

The main contributions of the paper are highlighted as follows:

- The hybrid ESS including thermal-electrical storages is utilized in the building to reduce the energy cost (bill saving) during 24-h.
- The building is connected to the electrical grid and electrical-thermal loads are modeled.
- The uncertainty in the loading is modeled by Gaussian probability distribution function and scenario-based stochastic modelling is included to deal with the uncertainty.
- The stochastic programming minimizes the daily energy cost in the

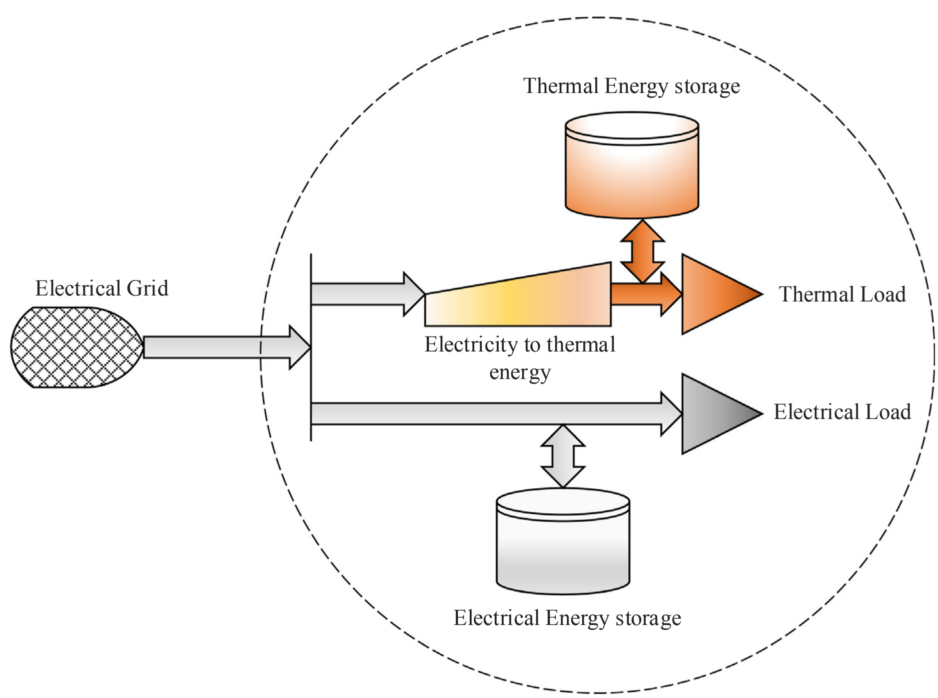

Fig. 1. The proposed model for including electrical and thermal storages.

building and determines the optimal charging-discharging pattern for both the thermal and electrical ESSs.
- Coordinated operation of thermal and electrical storage systems is optimized.

2. Case study model

The schematic of the proposed model is given in the Fig. 1. In the model, electrical and thermal loads are supplied by the electrical grid. The electrical load is directly connected to the grid, but the electrical ESS is operated in associated with the electrical load. The electrical ESS stores electrical energy during off-peak loading and the electrical load can get its energy from the electrical ESS when the energy price is high. The thermal load is also supplied through an interfacing device for converting the electrical energy to the thermal energy. The thermal ESS is also operated together with thermal load. Thermal ESS can supply thermal energy of load during on-peak time intervals. The operation patterns of both electrical and thermal ESSs are optimized by the proposed planning and the energy cost is minimized.

Electrical and thermal loads are uncertain parameters in the system and their uncertainty is modeled by Gaussian probability distribution function. The Gaussian function is the most common function to model the uncertainty of the loads. This function has been widely and successfully applied to model uncertainty related to the loads [20,27].

2.1. Numerical data of the model

In the proposed model, the initial energy of both the thermal and electrical ESSs is set to zero and the efficiency for both of them is set to 85% [28]. The daily time is divided into 24 time periods and each time interval is equal to one hour. The electrical and thermal loading profiles are listed in Table 1 [26]. The peak of electrical loading is 5 kW and thermal loading is 17,060 BTU. Each kWh is equal to 3412 BTU. The rated power of thermal ESS is 27,296 BTU and its rated capacity is 170,600 BTU-hour. The rated power of electrical ESS is 5 kW and its rated capacity is 50 kWh. The electricity price is listed in Table 1 [24].

The rating of ESS is often selected based on the system requirements and depended on system loading. ESS is assumed to supply peak loading and as a result, the best selection for rating of ESS is equal to the peak-loading. In this paper, the peak of electrical loading is 5 kW and the rating of ESS is therefore taken as 5 kW to deal with peak loading.

3. Mathematical modelling

The proposed model for coordination of electrical and thermal ESSs is expressed through an optimization programming. The optimization problem aims to minimize the daily energy cost of the system as shown by (1). The cost of the received power from the grid is minimized in (1). The received power from the grid is divided into two terms as specified by (2), the first term for supplying the electrical demand and the second term supplying the thermal demand. All the mentioned variables are positive as modeled through (3)–(5).

$$C_d = \sum_{s\in S}\sum_{t\in T}\{(P_{net}^{s,t} \times C_{egy}^{t}) \times R_r^s\} \tag{1}$$

$$P_{net}^{s,t} = P_{net1}^{s,t} + P_{net2}^{s,t} \quad \forall\, s\in S,\, t\in T \tag{2}$$

$$P_{net}^{s,t} \geqslant 0 \quad \forall\, s\in S,\, t\in T \tag{3}$$

$$P_{net2}^{s,t} \geqslant 0 \quad \forall\, s\in S,\, t\in T \tag{4}$$

$$P_{net1}^{s,t} \geqslant 0 \quad \forall\, s\in S,\, t\in T \tag{5}$$

The received power from the grid to supply electrical demand is modeled by (6). It includes the charged and discharged power of electrical ESS. The variables are positive as shown by (7) and (8).

$$P_{net1}^{s,t} = P_{de}^{s,t} + Pc_{es}^{t} - Pd_{es}^{t} \quad \forall\, s\in S,\, t\in T \tag{6}$$

$$Pc_{es}^{t} \geqslant 0 \quad \forall\, t\in T \tag{7}$$

$$Pd_{es}^{t} \geqslant 0 \quad \forall\, t\in T \tag{8}$$

The received power from the grid to supply thermal demand is converted to thermal energy as modeled by (9) and the thermal energy balance in the system is explained by (10). The charged and discharged power of thermal ESS are modeled in (10). The variables are positive as indicated through (11)–(13). The traded power between system and electrical grid may also be limited by line capacity as shown in (14).

$$P_{net2}^{s,t} = P_{nett}^{s,t} \times K_{te} \quad \forall\, s\in S,\, t\in T \tag{9}$$

$$P_{nett}^{s,t} = P_{dt}^{s,t} + Pc_{ts}^{t} - Pd_{ts}^{t} \quad \forall\, s\in S,\, t\in T \tag{10}$$

$$P_{nett}^{s,t} \geqslant 0 \quad \forall\, s\in S,\, t\in T \tag{11}$$

$$Pc_{ts}^{t} \geqslant 0 \quad \forall\, t\in T \tag{12}$$

$$Pd_{ts}^{t} \geqslant 0 \quad \forall\, t\in T \tag{13}$$

$$0 \leqslant |P_{net}^{s,t}| \leqslant P_{net}^{r} \quad \forall\, s\in S,\, t\in T \tag{14}$$

3.1. Thermal energy storage modelling

The thermal ESS is modeled through (15)–(22). The thermal ESS charges and discharges the thermal energy. Both the charged and discharged powers are limited by rated power of thermal ESS as shown by (15) and (16).

$$Pc_{ts}^{t} \leqslant P_{ts}^{r} \quad \forall\, t\in T \tag{15}$$

$$Pd_{ts}^{t} \leqslant P_{ts}^{r} \quad \forall\, t\in T \tag{16}$$

The thermal ESS can only operate on one of the charging or discharging states at each time period as modeled through (17)–(19).

$$Uc_{ts}^{t} + Ud_{ts}^{t} \leqslant 1 \quad \forall\, t\in T \tag{17}$$

$$if\ Uc_{ts}^{t} = 1 \Rightarrow \begin{cases} Pc_{ts}^{t} \leqslant P_{ts}^{r} \\ Pd_{ts}^{t} = 0 \end{cases} \quad \forall\, t\in T \tag{18}$$

Table 1
Electrical-thermal load profiles and electricity price.

Hour	Electrical load profile (%)	Thermal load profile (%)	Electricity price ($/kWh)
1	0.25	0.45	0.08
2	0.2	0.35	0.08
3	0.2	0.25	0.08
4	0.15	0.25	0.08
5	0.2	0.35	0.08
6	0.25	0.45	0.08
7	0.3	0.6	0.08
8	0.3	0.6	0.08
9	0.35	0.65	0.16
10	0.45	0.7	0.16
11	0.55	0.7	0.16
12	0.75	0.6	0.16
13	0.9	0.6	0.16
14	0.85	0.5	0.16
15	0.7	0.55	0.16
16	0.6	0.6	0.16
17	0.7	0.75	0.24
18	0.85	0.7	0.24
19	1	0.8	0.24
20	1	0.85	0.24
21	0.95	1	0.24
22	0.9	0.9	0.24
23	0.75	0.85	0.24
24	0.5	0.65	0.24

Table 2
Daily operational cost with energy storage systems.

Case	Daily operational cost ($/day)
Thermal-Electrical ESS	17.71
Thermal ESS	21.81
Electrical ESS	22.16
No ESS	26.26

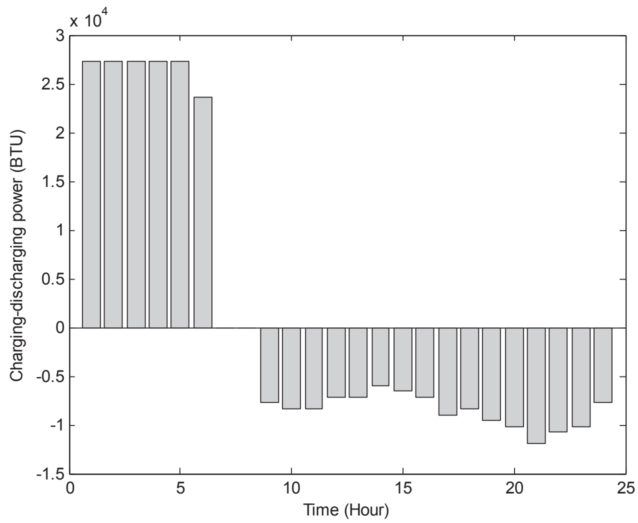

Fig. 2. Charging-discharging pattern of thermal storage system.

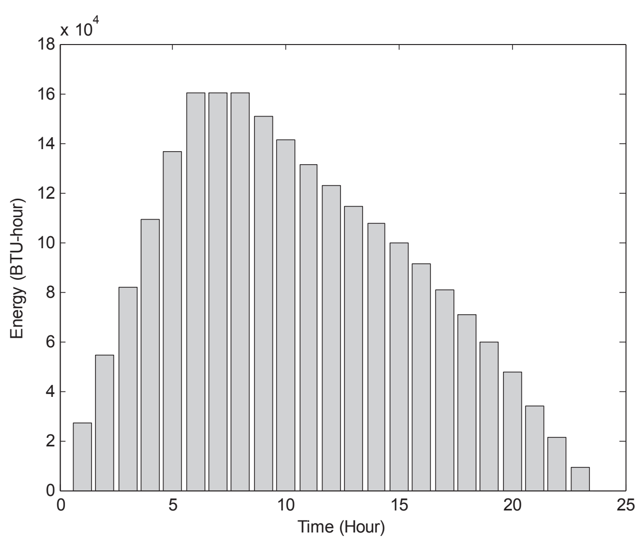

Fig. 3. Energy of thermal storage system.

$$if\ Ud_{ts}^{t} = 1 \Rightarrow \begin{cases} Pd_{ts}^{t} \leqslant P_{ts}^{r} \\ Pc_{ts}^{t} = 0 \end{cases} \quad \forall\ t \in T \tag{19}$$

The thermal ESS stores thermal energy as modeled by (20) and its capacity to store energy is limited by (21). The efficiency of the thermal ESS is defined by (22).

$$E_{ts}^{t} = E_{ts}^{t-1} + (Pc_{ts}^{t} - Pd_{ts}^{t}) \times D_{ti}^{t} \quad \forall\ t \in T \tag{20}$$

$$E_{ts}^{t} \leqslant E_{ts}^{r} \quad \forall\ t \in T \tag{21}$$

$$\eta_{ts} = \frac{\sum_{t \in T} Pd_{ts}^{t}}{\sum_{t \in T} Pc_{ts}^{t}} \tag{22}$$

3.2. Electrical energy storage modelling

The electric ESS has a model same as thermal ESS. The charged and discharged powers of electrical ESS must be less than the rated power as shown in (23) and (24). The storage system can only operate on one of the charging or discharging states at each time period as shown through (25)–(27). The efficiency and energy of storage system are defined through (28)–(30).

$$Pc_{es}^{t} \leqslant P_{es}^{r} \quad \forall\ t \in T \tag{23}$$

$$Pd_{es}^{t} \leqslant P_{es}^{r} \quad \forall\ t \in T \tag{24}$$

$$Uc_{es}^{t} + Ud_{es}^{t} \leqslant 1 \quad \forall\ t \in T \tag{25}$$

$$if\ Uc_{es}^{t} = 1 \Rightarrow \begin{cases} Pc_{es}^{t} \leqslant P_{es}^{r} \\ Pd_{es}^{t} = 0 \end{cases} \quad \forall\ t \in T \tag{26}$$

$$if\ Ud_{es}^{t} = 1 \Rightarrow \begin{cases} Pd_{es}^{t} \leqslant P_{es}^{r} \\ Pc_{es}^{t} = 0 \end{cases} \quad \forall\ t \in T \tag{27}$$

$$\eta_{es} = \frac{\sum_{t \in T} Pd_{es}^{t}}{\sum_{t \in t \in TT} Pc_{es}^{t}} \tag{28}$$

$$E_{es}^{t} = E_{es}^{t-1} + (Pc_{es}^{t} - Pd_{es}^{t}) \times D_{ti}^{t} \quad \forall\ t \in T \tag{29}$$

$$E_{es}^{t} \leqslant E_{es}^{r} \quad \forall\ t \in T \tag{30}$$

4. Simulation results and discussions

The proposed method is simulated on the given model and the results are listed in Table 2. In order to demonstrate the impacts of both electrical and thermal ESSs, four cases are simulated in Table 2. The daily operational cost ($/day) in the system without storages is 26.26 ($/day) and installing the electrical storage reduces the cost about 15%. The thermal ESS decreases the cost about 17%, and installing both the thermal-electrical storages results about 34% cost reduction. It is obvious that the hybrid electrical-thermal ESS is more efficient than the individual ESSs. The proposed optimal coordinated plan on the hybrid electrical-thermal ESS reduces the cost more than the individual operation of the ESSs. When the hybrid ESS utilizes the electrical and thermal ESSs together, the building faces more options to utilize the ESSs and the flexibility of the model is increased. The building, therefore, can set its operation on the low cost operating conditions resulting in more cost saving.

The proposed model determines the optimal charging-discharging pattern for both electric and thermal storage systems. The charging-discharging pattern of thermal ESS is shown in Fig. 2. It is obvious that the thermal ESS stores thermal energy during hours 1–6 when the electricity price is 0.08 ($/kWh) and it discharges the energy at hours 9–24 when the electricity price is high. Such energy arbitraging reduces the daily energy cost by about 34% (as it was discussed in Table 2). The energy of thermal storage is depicted in Fig. 3. It is clear that the energy is stored at initial hours and restored at the next hours. The energy at the final time interval is zero.

The charging-discharging regime of electrical ESS is presented in Fig. 4. It charges electrical energy during hours 1–9 and discharges the energy when the electricity price is higher. This optimal operation properly reduces the daily energy cost. The energy of electrical ESS is also depicted in Fig. 5. The maximum capacity required for electrical ESS is about 40 kWh. In this paper, the ESS shifts energy from low-cost off-peak hours to the high-cost on-peak hours. The ESS often charges energy in the initial 8 h of the day and discharges energy in the next 16 h. These operations are shown in Figs. 2 and 4. The backup time to charge energy in the thermal storage system is 6 h as shown in Fig. 2

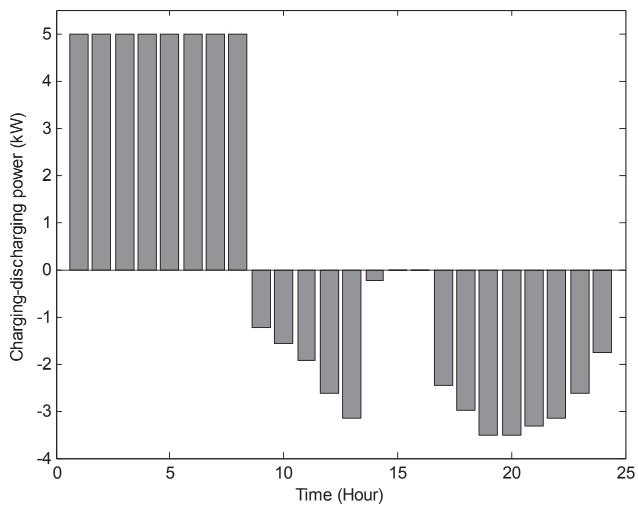

Fig. 4. Charging-discharging regime of electrical storage system.

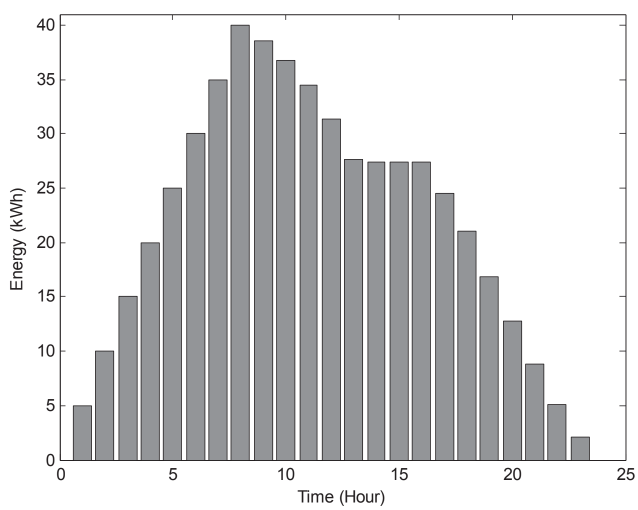

Fig. 5. Energy of electrical storage system.

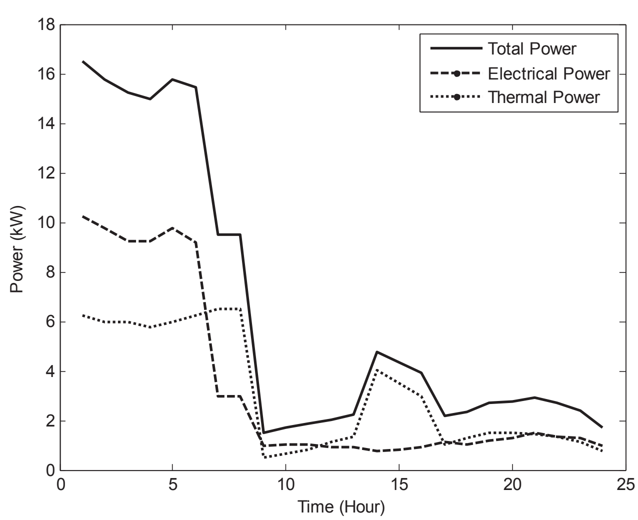

Fig. 6. Received power form the grid including electrical, thermal, and total power.

and it is 8 h as shown in Fig. 4.

Fig. 6 shows the received power from the grid including electrical, thermal, and total power. The total power is the sum of electrical power and thermal. It is seen that the received power from the grid is increased at the initial hours (hours 1–9) and it is decreased during the next hours. This process is because of energy shifting by ESSs. ESSs shift energy from on-peak hours (hours 9–14) to the off-peak hours (hours 1–8). As a result, the peak of loading is shifted to the initial hours as shown in the figure.

Fig. 7 shows the power of loads under on-peak loading (Hour 19). It is clear that 70% of power is supplied by ESSs and 30% is taken from the grid. This procedure reduces the energy cost under high-cost hours.

4.1. *Error in load forecasting*

Thermal and electrical loads are modeled by Gaussian distribution to reflect the error in the load forecasting. In order to analysis the influence of such modeling, two cases including the loads without uncertainty and with uncertainty are modeled, simulated, and compared as listed in Table 3. The results show that the uncertainty increases the cost about 2 ($/day). However, the thermal-electrical ESSs can properly reduce the cost under both loadings with and without uncertainty.

4.2. *Efficiency of energy storage systems*

In order to analyze the effects of ESS efficiency on the model, the efficiency of ESSs is changed and the results are listed in Table 4. It is clear that increasing the efficiency results in less operational cost because of less energy losses. On the other hand, ESSs with low efficiency are not used by the planning. Furthermore, costs under 40% efficiency are similar to the case when no ESS is utilized. The results reveal that the high-efficiency ESSs are required to make the model practical and economic.

4.3. *Sensitivity analysis*

Table 5 presents the sensitivity analysis on the economic parameters and costs. The trends of the outputs emphasize the accuracy of the simulations. The operational cost is increased along with growing the costs and vice-versa. It is also demonstrated that the electricity price is a dominant factor in the model and it makes significant effects on the model.

5. Conclusions

This paper presented a model for energy management by coordinated electrical and thermal ESSs. The results demonstrated that the electrical ESS reduces the cost about 15%, the thermal ESS decreases the cost by about 17%, and coordinated thermal-electrical ESS reduces the cost by about 34%. As a result, the best operation is achieved by coordinating thermal-electrical storages. The charging-discharging pattern for both the electric and thermal ESS is also optimized by the planning. The outputs illustrate that both the ESSs store energy during initial hours when the electricity price is 0.08 ($/kWh) and they discharge the energy at hours 9–24 when the electricity price is high. Such energy shifting reduces the daily energy cost about 34%. The received power from the grid is increased at initial hours (hours 1–9) and decreased during the next hours because of such energy shifting. Under on-peak hours, about 70% of load demand is supplied by ESSs and 30% is taken from the grid. The results indicate that the uncertainty in load modeling increases the cost about 2 ($/day). The ESS efficiency is also studied and discussed. The results show that the ESSs with low efficiency are not used by the planning because of losses.

Acknowledgement

This publication was made possible by NPRP Grant no. 11S-1125-170027 from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility

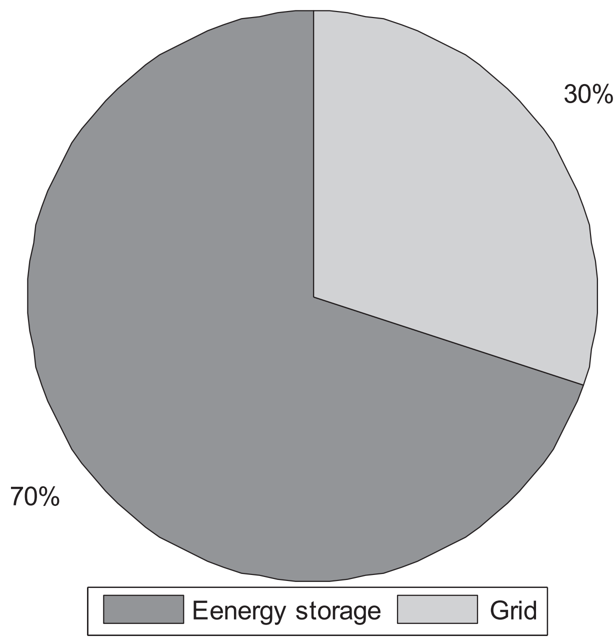

Fig. 7. Power of loads under on-peak loading (Hour 19).

Table 3
Daily operational cost with and without uncertainty in loads.

	Daily operational cost ($/day)	
	with uncertainty in loads	without uncertainty in loads
Thermal-Electrical ESS	17.71	15.58
Thermal ESS	21.81	20.48
Electrical ESS	22.16	20.98
No ESS	26.26	25.88

Table 4
Impacts of ESS efficiency on the model.

		Daily operational cost ($/day)	
	Efficiency 40%	Efficiency 85%	Efficiency 100%
Thermal-Electrical ESS	26.26	17.71	16.19
Thermal ESS	26.26	21.81	21.25
Electrical ESS	26.26	22.16	21.20
No ESS	26.26	26.26	26.26

Table 5
Sensitivity analysis of the economic parameters and costs.

	Daily operational cost ($/day)
Nominal case	17.71
Increasing thermal load by 10%	18.68
Decreasing thermal load by 10%	16.83
Increasing electrical load by 10%	18.83
Decreasing electrical load by 10%	16.60
Increasing electricity price by 10%	19.48
Decreasing electricity price by 10%	15.94

of the authors.

References

[1] H. Mehrjerdi, R. Hemmati, E. Farrokhi, Nonlinear stochastic modelling for optimal dispatch of distributed energy resources in active distribution grids including reactive power, Simul. Model. Pract. Theory 94 (2019) 1–13.

[2] H. Saboori, R. Hemmati, S.M.S. Ghiasi, S. Dehghan, Energy storage planning in electric power distribution networks–a state-of-the-art review, Renew. Sustain. Energy Rev. 79 (2017) 1108–1121.

[3] M.A. Hozouri, A. Abbaspour, M. Fotuhi-Firuzabad, M. Moeini-Aghtaie, On the use of pumped storage for wind energy maximization in transmission-constrained power systems, IEEE Trans. Power Syst. 30 (2) (2015) 1017–1025.

[4] A.H. Alami, Experimental assessment of compressed air energy storage (CAES) system and buoyancy work energy storage (BWES) as cellular wind energy storage options, J. Storage Mater. 1 (2015) 38–43.

[5] R. Hemmati, H. Saboori, M.A. Jirdehi, Stochastic planning and scheduling of energy storage systems for congestion management in electric power systems including renewable energy resources, Energy 133 (2017) 380–387.

[6] R. Amirante, E. Cassone, E. Distaso, P. Tamburrano, Overview on recent developments in energy storage: mechanical, electrochemical and hydrogen technologies, Energy Convers. Manage. 132 (2017) 372–387.

[7] H. Mehrjerdi, Off-grid solar powered charging station for electric and hydrogen vehicles including fuel cell and hydrogen storage, Int. J. Hydrogen Energy 44 (23) (2019) 11574–11583.

[8] H. Mehrjerdi, Optimal correlation of non-renewable and renewable generating systems for producing hydrogen and methane by power to gas process, Int. J. Hydrogen Energy 44 (18) (2019) 9210–9219.

[9] M. Bailera, P. Lisbona, L.M. Romeo, S. Espatolero, Power to Gas projects review: lab, pilot and demo plants for storing renewable energy and CO2, Renew. Sustain. Energy Rev. 69 (2017) 292–312.

[10] B. Zakeri, S. Syri, Electrical energy storage systems: a comparative life cycle cost analysis, Renew. Sustain. Energy Rev. 42 (2015) 569–596.

[11] S. Seddegh, S.S.M. Tehrani, X. Wang, F. Cao, R.A. Taylor, Comparison of heat transfer between cylindrical and conical vertical shell-and-tube latent heat thermal energy storage systems, Appl. Therm. Eng. 130 (2018) 1349–1362.

[12] C. Veerakumar, A. Sreekumar, 'Phase change material based cold thermal energy storage: materials, techniques and applications–a review', Int. J. Refrig. 67 (2016) 271–289.

[13] H. Mehrjerdi, E. Rakhshani, Vehicle-to-grid technology for cost reduction and uncertainty management integrated with solar power, J. Cleaner Prod. 229 (2019) 463–469.

[14] H. Mehrjerdi, Multilevel home energy management integrated with renewable energies and storage technologies considering contingency operation, J. Renew. Sustain. Energy 11 (2) (2019) 025101–25109.

[15] R. Hemmati, H. Saboori, Stochastic optimal battery storage sizing and scheduling in home energy management systems equipped with solar photovoltaic panels, Energy Build. 152 (2017) 290–300.

[16] V. Bianco, F. Scarpa, L.A. Tagliafico, Estimation of primary energy savings by using heat pumps for heating purposes in the residential sector, Appl. Therm. Eng. 114 (2017) 938–947.

[17] A. Sciacovelli, A. Vecchi, Y. Ding, Liquid air energy storage (LAES) with packed bed cold thermal storage–from component to system level performance through dynamic modelling, Appl. Energy 190 (2017) 84–98.

[18] R. Hemmati, H. Saboori, Emergence of hybrid energy storage systems in renewable energy and transport applications–a review, Renew. Sustain. Energy Rev. 65 (2016) 11–23.

[19] P. Zhao, M. Wang, J. Wang, Y. Dai, A preliminary dynamic behaviors analysis of a hybrid energy storage system based on adiabatic compressed air energy storage and flywheel energy storage system for wind power application, Energy 84 (2015) 825–839.

[20] R. Hemmati, M. Shafie-Khah, J.P.S. Catalão, Three-level hybrid energy storage planning under uncertainty, IEEE Trans. Ind. Electron. 66 (3) (2019) 2174–2184.

[21] H. Mehrjerdi, M. Bornapour, R. Hemmati, S.M.S. Ghiasi, Unified energy management and load control in building equipped with wind-solar-battery incorporating electric and hydrogen vehicles under both connected to the grid and islanding modes, Energy 168 (2019) 919–930.

[22] R. Hemmati, H. Saboori, P. Siano, Coordinated short-term scheduling and long-term expansion planning in microgrids incorporating renewable energy resources and energy storage systems, Energy 134 (2017) 699–708.

[23] X. Luo, J. Wang, M. Dooner, J. Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, Appl. Energy 137 (2015) 511–536.

[24] R. Hemmati, Optimal design and operation of energy storage systems and generators in the network installed with wind turbines considering practical characteristics of storage units as design variable, J. Cleaner Prod. 185 (2018) 680–693.

[25] B. Zhou, W. Li, K.W. Chan, Y. Cao, Y. Kuang, X. Liu, et al., Smart home energy management systems: concept, configurations, and scheduling strategies, Renew. Sustain. Energy Rev. 61 (2016) 30–40.

[26] R. Hemmati, Technical and economic analysis of home energy management system incorporating small-scale wind turbine and battery energy storage system, J. Cleaner Prod. 159 (2017) 106–118.

[27] P. Firouzmakan, R.-A. Hooshmand, M. Bornapour, A. Khodabakhshian, A comprehensive stochastic energy management system of micro-CHP units, renewable energy sources and storage systems in microgrids considering demand response programs, Renew. Sustain. Energy Rev. 108 (2019) 355–368.

[28] A. Poullikkas, A comparative overview of large-scale battery systems for electricity storage, Renew. Sustain. Energy Rev. 27 (2013) 778–788.