Chapter 8
Supply Side Management in Renewable Energy Hubs

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8.1 Introduction

Energy as the most vital issue in the current century can be discussed from various viewpoints like efficiency, economy, reliability, etc. As an appropriate option for such mentioned goals, hub energy system can be used in power systems. Hub energy systems including integrated renewable [1, 2] and non-renewable generation units [3–5] can be employed to efficiently supply energy demands [6, 7] along with satisfying economic and environmental goals [6, 8].

8.1.1 Literature Review

Previously, hub energy systems have been studied and their summaries are briefly presented in the following:

In order to solve power flow problem of hub energy system in [9], heuristic based optimization algorithm called time varying acceleration coefficient-gravitational search algorithm is employed. With the aim of minimizing total operation cost of hub energy system, robust based optimization approach is used in [10]. Using energy hub concept, steady-states in microgrids have been studied in [11]. Multi-carrier energy system has been optimally planned and scheduled in the presence of renewable generation units in [12]. With the aim of improving energy efficiency, energy hub concept including various local generation units has been implemented

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in [13]. Optimal economic operation of energy hub system has been evaluated in [14]. Energy hub concept has been implemented in [15] to create a decentralized and integrated energy system in neighborhoods. Using stochastic programming in [16], optimum performance of energy hub system under uncertainties has been evaluated. Economic dispatch problem of multi-carrier energy system has been studied using coefficient-gravitational search algorithm in [17]. Energy hub system has been investigated form viewpoint of reliability in [18, 19]. Techniques used for analyzing hub energy systems have been reviewed in [20]. Optimum operation of energy hub system has been evaluated with respect to energy balance limitation in [21]. Similar problem has been studied considering dynamic and time-of-use pricing in [22]. Optimum performance of multi-carrier energy system has been evaluated in the presence of demand response and thermal storage in [23]. Optimum operation of energy hub system embedded in a smart home has been investigated in [24, 25]. Optimum impact of heating networks on the operation of energy hub system has been investigated in [26].

Supply side management tools have been also interesting topics for various researchers. Different options can be employed as the supply side management tool in generation systems and one of them is energy storage system. Energy storage systems are various. From viewpoint of discharging time, storage systems are categorized into two groups: storage systems with short discharging time up to a few hours like batteries, flywheels, super magnetic energy storage, and super capacitors and the second group is the systems with long discharging time up to a day like compressed air energy storage system (CAES) and pumped hydro storage system. So, it can be concluded that CAES and pumped hydro are the only available mature energy storage systems with large-scale storage capacity. Using energy in off-peak time periods, CAES compresses air and later in peak time periods, stored compressed air is used to produce electric power. It should be mentioned that due to large scale size of storage capacity in CAES, this storage system is a suitable option for economic goals [27, 28].

In this chapter, a multi-objective model has been proposed for eco-emission operation of renewable-based hub energy system in the presence of CAES and DRP. Compressed air energy storage system (CAES) has been used as a supply side management tool to handle severe uncertainties created by renewable generation units in the hub energy system. In addition to CAES, demand response program has been employed to improve economic and environmental operation of renewable-based hub energy system.

8.1.2 Novelty and Contributions of This Research

Summarizing mentioned explanations above, novelty and contributions of this chapter can be expressed as follows:

- Optimum eco-emission operation of renewable-based hub energy system.
- Implementation of CAES as a supply side management for further improvement of economic and environmental performance of renewable-based hub energy system.
- Implementation of DRP for total cost and emission reduction of renewable-based hub energy system.

8.2 Problem Formulation

In this section, eco-emission performance of hub renewable-based energy system has been investigated in which compressed air storage system has been employed as a supply side management tool to handle uncertainties of renewable units. Proposed optimum eco-emission performance of renewable-based energy hub system in the presence of compressed air energy storage system and demand response program has been mathematically investigated in the following sections.

8.2.1 Objective Functions

In the proposed scheme, there are two confliction objective functions to be minimized which are total operation cost and emission of renewable-based hub energy system. Total operation cost of renewable-based energy hub system in the presence of DRP and CAES is presented through Eqs. (8.1)–(8.10).

$$\text{Min } \Phi_1 = \text{Total cost} = C_{\text{net}} + C_{\text{Wind}} + C_{\text{BS}} + C_{\text{DR}} + C_{\text{Ex}} + C_{\text{TS}} + C_{\text{Bo}} + C_{\text{CHP}} + C_{\text{Wa}} \quad (8.1)$$

$$C_{\text{net}} = \sum_{t=1}^{H} \left(\lambda_t^e \times p_t^e\right) \quad (8.2)$$

$$C_{\text{Wind}} = \sum_{t=1}^{H} \left(\lambda^{\text{wi}} \times p_t^{\text{wi}}\right) \quad (8.3)$$

$$C_{\text{BS}} = \sum_{t=1}^{H} \left(\lambda_s^b \times \left(p_t^{\text{ch,BS}} + p_t^{\text{dis,BS}}\right)\right) \quad (8.4)$$

$$\mathrm{C}_{\mathrm{TS}} = \sum_{t=1}^{H} \left(\lambda_s^h \times \left(p_t^{\mathrm{ch},h} + p_t^{\mathrm{dis},h}\right)\right) \tag{8.5}$$

$$\mathrm{C}_{\mathrm{DR}} = \sum_{t=1}^{H} \left(\lambda^{\mathrm{DR}} \times \left(p_t^{e,\mathrm{shdo}} + p_t^{e,\mathrm{shup}}\right)\right) \tag{8.6}$$

$$\mathrm{C}_{\mathrm{CHP}} = \sum_{t=1}^{H} \left(\lambda^g \times g_t^{\mathrm{CHP}}\right) \tag{8.7}$$

$$\mathrm{C}_{\mathrm{Bo}} = \sum_{t=1}^{H} \left(\lambda^g \times g_t^B\right) \tag{8.8}$$

$$\mathrm{C}_{\mathrm{Wa}} = \sum_{t=1}^{H} \left(\lambda^{\mathrm{wa}} \times \mathrm{wa}_t\right) \tag{8.9}$$

$$\mathrm{C}_{\mathrm{Ex}} = \sum_{t=1}^{H} \left(\lambda_t^e \times \left(p_t^{\mathrm{ch},e} - p_t^{\mathrm{dis},e}\right)\right) \tag{8.10}$$

Cost of purchased power from upstream network (8.2) plus the cost of wind-turbine generation (8.3) plus the operation cost of battery and thermal storage systems including charge/discharge costs (8.4) and (8.5) plus the cost of DRP (8.6) plus the operation cost of CHP and boiler (8.7) and (8.8) plus the cost of purchased water (8.9) and cost/revenue of exchanged power (8.10) result the total operation cost of renewable-based hub energy system to be minimized (8.1).

Due to utilization of CHP system and boiler in hub energy system as well as due to gas consumption in residential section and also because of burning fossil fuels in power plants which power is later transferred to the hub system, this system emits three types of pollutants, namely CO_2, SO_2, and NO_x. In order to satisfy environmental concerns, these emissions should be minimized. The objective function related to environmental operation of renewable-based energy hub system is presented in detail through Eqs. (8.11)–(8.15).

$$\mathrm{Min}\ \ \Phi_2 = \mathrm{Em} = \left(\mathrm{Em}^{\mathrm{CHP}} + \mathrm{Em}^B + \mathrm{Em}^L + \mathrm{Em}^{\mathrm{NET}}\right) \tag{8.11}$$

$$\mathrm{Em}^{\mathrm{CHP}} = \left(\mathrm{EF}_{\mathrm{CO}}^{\mathrm{CHP}} \times g_t^{\mathrm{CHP}}\right) + \left(\mathrm{EF}_{\mathrm{SO}}^{\mathrm{CHP}} \times g_t^{\mathrm{CHP}}\right) + \left(\mathrm{EF}_{\mathrm{NO}}^{\mathrm{CHP}} \times g_t^{\mathrm{CHP}}\right) \tag{8.12}$$

$$\mathrm{Em}^B = \left(\mathrm{EF}_{\mathrm{CO}}^B \times g_t^B\right) + \left(\mathrm{EF}_{\mathrm{SO}}^B \times g_t^B\right) + \left(\mathrm{EF}_{\mathrm{NO}}^B \times g_t^B\right) \tag{8.13}$$

$$\mathrm{Em}^{L}=\left(\mathrm{EF}_{\mathrm{CO}}^{L}\times g_t^{L}\right)+\left(\mathrm{EF}_{\mathrm{SO}}^{L}\times g_t^{L}\right)+\left(\mathrm{EF}_{\mathrm{NO}}^{L}\times g_t^{L}\right) \tag{8.14}$$

$$\mathrm{Em}^{\mathrm{NET}}=\left(\mathrm{EF}_{\mathrm{CO}}^{\mathrm{NET}}\times p_t^{e}\right)+\left(\mathrm{EF}_{\mathrm{SO}}^{\mathrm{NET}}\times p_t^{e}\right)+\left(\mathrm{EF}_{\mathrm{NO}}^{\mathrm{NET}}\times p_t^{e}\right) \tag{8.15}$$

8.2.2 Electrical Model

One of the energy demands due to be supplied by renewable-based hub energy system is electrical demand. Electrical demand which is capable of participating in DRP should be satisfied through generation of wind-turbine, CHP system, purchased power from upstream network and discharged power of battery and compressed air energy storage systems (8.16).

$$\begin{aligned}\left(p_t^{l}+p_t^{\mathrm{shup}}-p_t^{\mathrm{shdo}}+P_t^{c,p}\right)&=\left(A^{\mathrm{NET}}\times\eta_{\mathrm{ee}}^{T}\times p_t^{e}\right)+\left(A^{\mathrm{WIND}}\times\eta_{\mathrm{ee}}^{\mathrm{CON}}\times p_t^{\mathrm{wi}}\right)\\&+\left(A^{\mathrm{CHP}}\times\eta_{\mathrm{ge}}^{\mathrm{CHP}}\times g_t^{\mathrm{CHP}}\right)+\left(p_t^{\mathrm{dis,BS}}-p_t^{\mathrm{ch,BS}}\right)+\left(P_t^{c,s}\right)\end{aligned} \tag{8.16}$$

8.2.2.1 Model of Upstream Network

Each transmission system has its own components with their specific technical characteristics for power transmission which should be taken into account. Imported power from upstream network should be within the nominal capacity of transformer connecting renewable-based hub system to the upstream network (8.17).

$$\eta_{\mathrm{ee}}^{T}\times p_t^{e}\le p_c^{T} \tag{8.17}$$

8.2.2.2 Model of Renewable Energy Sources

In order to generate clean energy and reduce total cost and emission of energy hub system, wind-turbine has been used as a renewable generation unit to satisfy both economic and environmental objectives. Generation pattern according to which wind-turbine produces electrical power is presented in Eq. (8.18)

$$p_t^{\mathrm{wi}}=\begin{cases}0 & w<w_{\mathrm{ci}}\\ p_r\left(z-y\cdot w(t)+x\cdot w^2(t)\right) & w_{\mathrm{ci}}\le w<w_r\\ p_r & w_r\le w<w_{\mathrm{co}}\\ 0 & w\ge w_{\mathrm{co}}\end{cases} \tag{8.18}$$

8.2.2.3 Model of Battery Storage

Two types of electrical storage systems with specific characteristics have been employed in renewable-based energy hub system to handle uncertainties of generation. In this section, limitations of battery storage system have been presented through (8.19)–(8.24).

$$C_t^{\mathrm{st},e} = C_{t-1}^{\mathrm{st},e} + p_t^{\mathrm{ch},e} \times \eta_{\mathrm{ch}}^e - p_t^{\mathrm{dis},e} / \eta_{\mathrm{dis}}^e - p_t^{\mathrm{loss},e} \tag{8.19}$$

$$\alpha_{\min}^e \times C_c^{\mathrm{st},e} \le C_t^{\mathrm{st},e} \le \alpha_{\max}^e \times C_c^{\mathrm{st},e} \tag{8.20}$$

$$\frac{\alpha_{\min}^e \times C_c^{\mathrm{st},e} \times I_t^{\mathrm{ch},e}}{\eta_{\mathrm{ch}}^e} \le p_t^{\mathrm{ch},e} \le \frac{\alpha_{\max}^e \times C_c^{\mathrm{st},e} \times I_t^{\mathrm{ch},e}}{\eta_{\mathrm{ch}}^e} \tag{8.21}$$

$$\alpha_{\min}^e \times C_c^{\mathrm{st},e} \times I_t^{\mathrm{dis},e} \times \eta_{\mathrm{dis}}^e \le p_t^{\mathrm{dis},e} \le \alpha_{\max}^e \times C_c^{\mathrm{st},e} \times I_t^{\mathrm{dis},e} \times \eta_{\mathrm{dis}}^e \tag{8.22}$$

$$p_t^{\mathrm{loss},e} = \alpha_{\mathrm{loss}}^e \times C_t^{\mathrm{st},e} \tag{8.23}$$

$$I_t^{\mathrm{ch},e} + I_t^{\mathrm{dis},e} \le 1 \tag{8.24}$$

Available stored energy level of battery storage is presented by (8.19). Limitations of available energy, charge and discharge power of battery storage are presented through Eqs. (8.20), (8.21), and (8.22), respectively. Battery storage energy loss is presented by Eq. (8.23). Finally, simultaneous charge and discharge of battery is restricted by Eq. (8.24).

8.2.3 Thermal Model

Heating is another type of energy demands due to be supplied by renewable-based energy hub system. Using generated heat by boiler and CHP system as well as released heat from thermal storage system, heating demand is satisfied (8.25).

$$p_t^h = \left[\eta_{\mathrm{gh}}^B \times g_t^B\right] + \left[A^{\mathrm{CHP}} \times \eta_{\mathrm{gh}}^{\mathrm{CHP}} \times g_t^{\mathrm{CHP}}\right] + \left(p_t^{\mathrm{dis},h} - p_t^{\mathrm{ch},h}\right) \tag{8.25}$$

8.2.3.1 Model of Thermal Storage

Besides battery and compressed air energy storage systems which have been embedded in electrical section, thermal energy storage system has been used in thermal section to handle excess generated heat by CHP system and boiler. Limitations of employed thermal storage are presented through Eqs. (8.26)–(8.31).

$$C_t^{\text{st},h} = C_{t-1}^{\text{st},h} + p_t^{\text{ch},h} \times \eta_{\text{ch}}^h - p_t^{\text{dis},h} / \eta_{\text{dis}}^h - p_t^{\text{loss},h} \tag{8.26}$$

$$\alpha_{\min}^h \times C_c^{\text{st},h} \le C_t^{\text{st},h} \le \alpha_{\max}^h \times C_c^{\text{st},h} \tag{8.27}$$

$$\frac{\alpha_{\min}^h \times C_c^{\text{st},h} \times I_t^{\text{ch},h}}{\eta_{\text{ch}}^h} \le p_t^{\text{ch},h} \le \frac{\alpha_{\max}^h \times C_c^{\text{st},h} \times I_t^{\text{ch},h}}{\eta_{\text{ch}}^h} \tag{8.28}$$

$$\alpha_{\min}^h \times C_c^{\text{st},h} \times I_t^{\text{dis},h} \times \eta_{\text{dis}}^h \le p_t^{\text{dis},h} \le \alpha_{\max}^h \times C_c^{\text{st},h} \times I_t^{\text{dis},h} \times \eta_{\text{dis}}^h \tag{8.29}$$

$$p_t^{\text{loss},h} = \alpha_{\text{loss}}^h \times C_t^{\text{st},h} \tag{8.30}$$

$$I_t^{\text{ch},h} + I_t^{\text{dis},h} \le 1 \tag{8.31}$$

Stored energy level of thermal energy storage system is expressed by Eq. (8.26). Limitation of available heat and input as well as released heat of thermal storage system is expressed through Eqs. (8.27)–(8.29). Loss of heat inside the thermal energy storage system is expressed by Eq. (8.30). Heat injection and discharge to/from thermal energy storage system cannot occur at the same time which is expressed by (8.31).

8.2.3.2 Model of Gas network

The need for gas in CHP and boiler plus the gas demand in consumption side necessitates gas import from gas network. Imported gas is divided into three parts for various applications mentioned above (8.32). It should be that imported gas should be within the nominal capacity which has been set for gas network (8.33).

$$g_t^{\text{net}} = g_t^B + g_t^{\text{CHP}} + g_t^l \tag{8.31}$$

$$g_{\min}^{\text{net}} \le g_t^{\text{net}} \le g_{\max}^{\text{net}} \tag{8.32}$$

8.2.3.3 Model of CHP system

As a common rule in each generation unit, total produced energy by each generating system should be under the systems nominal capacity. According to this definition, total generated electric power by CHP system should be less than its nominal capacity (8.33). It should be noted that since heat generation of CHP system is a function of its electrical generation, therefore by satisfying Eq. (8.33), heat generation by CHP system will be kept under nominal heat generation capacity of CHP.

$$\eta_{\mathrm{ge}}^{\mathrm{CHP}} \times g_t^{\mathrm{CHP}} \leq p_c^{\mathrm{CHP}} \tag{8.33}$$

8.2.3.4 Model of Boiler

Boiler is the only energy resource in thermal section which responsibility is only heat generation. Produced heat by this unit is constrained through Eq. (8.34).

$$\eta_{\mathrm{gh}}^{B} \times g_t^{B} \leq p_c^{B} \tag{8.34}$$

8.2.4 Compressed Air Energy Storage System Model

In this section, model of employed CAES is presented. The air injected to the CAES is presented by Eq. (8.35). Generated electric power by CAES is presented by (8.36). Stored air in the CAES which is later pumped to the combustion chamber is mathematically modeled by (8.37) and (8.38), respectively. In order to limit operation mode of CAES which is either pumping mode or storage mode, Eq. (8.39) is employed. Available air in the CEAS is expressed and limited by Eqs. (8.40) and (8.41), respectively.

$$V_t^{\mathrm{inj}} = \kappa^{\mathrm{inj}} \times P_t^{c,p} \tag{8.35}$$

$$P_t^{c,s} = \kappa^{p} \times V_t^{p} \tag{8.36}$$

$$V_{\mathrm{min}}^{\mathrm{inj}} \times u^{\mathrm{inj}} \leq V_t^{\mathrm{inj}} \leq V_{\mathrm{max}}^{\mathrm{inj}} \times u^{\mathrm{inj}} \tag{8.37}$$

$$V_{\mathrm{min}}^{p} \times u^{p} \leq V_t^{p} \leq V_{\mathrm{max}}^{p} \times u^{p} \tag{8.38}$$

$$u^{\mathrm{inj}} + u^{p} \leq 1 \tag{8.39}$$

$$A_t = A_{t-1} + V_t^{\text{inj}} - V_t^p \tag{8.40}$$

$$A_t^{\min} \le A_t \le A_t^{\max} \tag{8.41}$$

8.2.5 Demand Response Program

As *n* new concept in energy markets, electrical consumers can participate in demand response programs to reduce their costs. By participating in these programs, consumers undertake to shift their energy demand from peak time periods to off-peak time periods. One of the common programs included in DRP is time-of-use rates (TOU) of DRP has been implemented [5, 29–31]. According to TOU, new electrical load is equal to the primary load plus the variable load. These variables can be either positive or negative meaning decrease or increase of load. The amount of increase or decrease of load which is percentage of load participation in DRP should be under a predefined limitation. Also, simultaneous increase and decrease of load is not allowed.

Summary of explanations given above is mathematically presented through Eqs. (8.42)–(8.45).

$$p_t^{\text{el,DRP}} = p_t^{\text{el}} + p_t^{\text{shup},e} - p_t^{\text{shdo},e} \tag{8.42}$$

$$0 \le p_t^{\text{shup},e} \le \text{LPF}^{\text{shup},e} \times p_t^l \times I_t^{\text{shup},e} \tag{8.43}$$

$$0 \le p_t^{\text{shdo},e} \le \text{LPF}^{\text{shdo},e} \times p_t^l \times I_t^{\text{shdo},e} \tag{8.44}$$

$$I_t^{\text{shup},e} + I_t^{\text{shdo},e} \le 1 \tag{8.45}$$

8.2.6 Model of Water Network

As the last type of energy demand, water consumer in demand side is provided through the imported water from water network which is expressed by Eq. (8.46) and limited by Eq. (8.47).

$$\text{wa}_t^l = \text{wa}_t^{\text{net}} \tag{8.46}$$

$$\text{wa}_{\min} \le \text{wa}_t^{\text{net}} \le \text{wa}_{\max} \tag{8.47}$$

8.3 Case Study

8.3.1 Input Data

Studied renewable energy hub system is composed of wind generation unit, combined heat and power system, boiler and various types of energy storage systems. Schematic diagram of mentioned system is shown in Fig. 8.1.

As illustrated in this figure, four types of energy demands should be supplied by multi-carrier renewable-based energy hub system. Three types of energy storage systems, namely, batter storage system, compressed air energy storage system, and thermal storage systems have been employed to manage excess generated energy in the hub energy system. It should be noted that since battery storage system is not

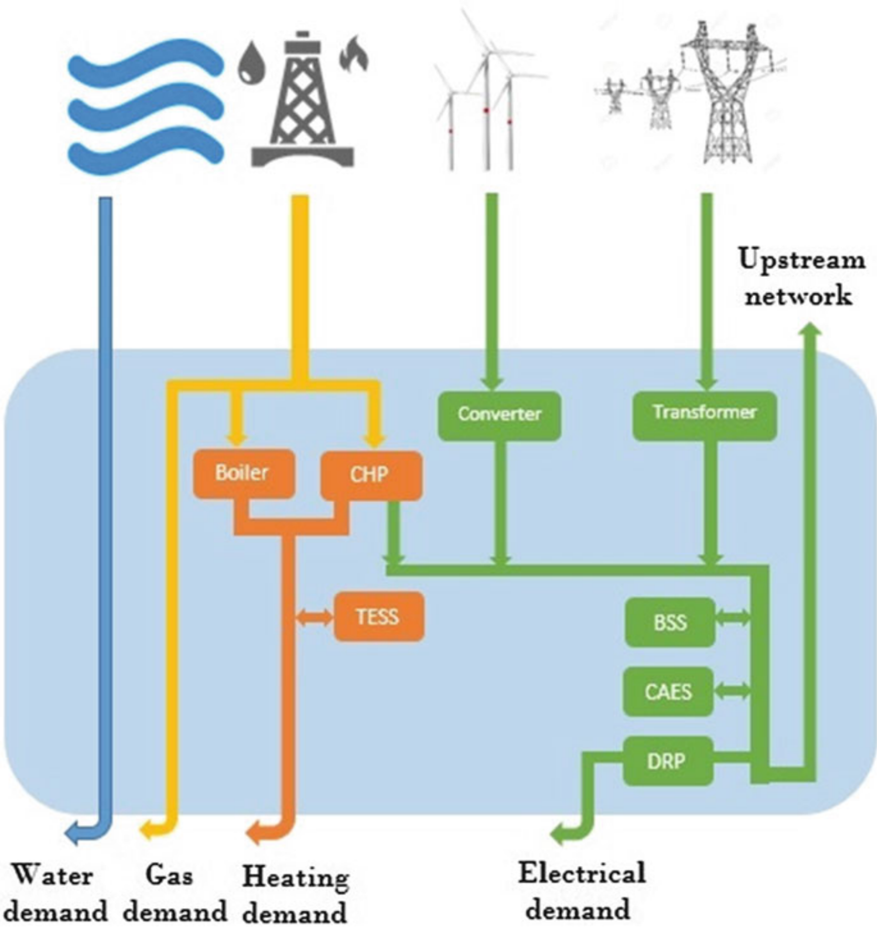

Fig. 8.1 Renewable-based hub energy system

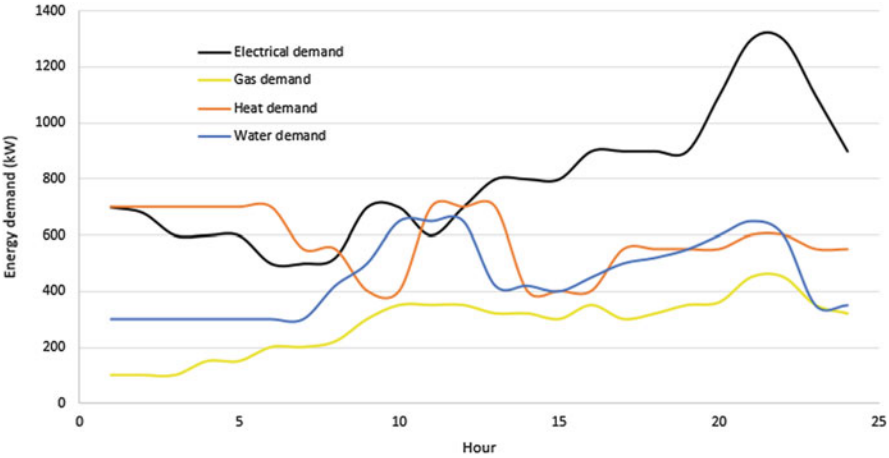

Fig. 8.2 Energy demands of renewable-based hub energy system

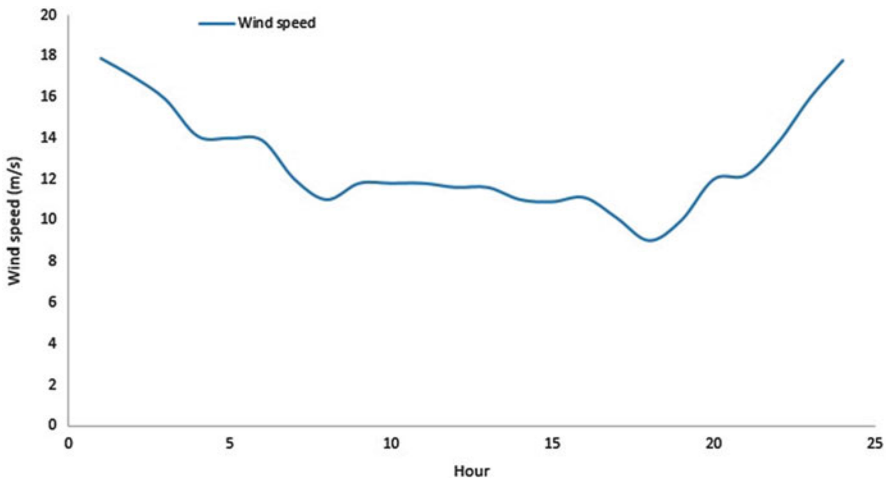

Fig. 8.3 Wind hourly speed

able to manage large quantities of uncertainty provided by wind generation and also because of that compressed air energy storage system is approximately operated at low operation cost, CAES has been used to control possible severe uncertainties caused by wind generation.

In order to model and simulate eco-emission operation of renewable-based hub energy system in the presence of CAES and DRP, the following data and info are used.

All four types of energy demands to be supplied by renewable-based hub energy system are illustrated in Fig. 8.2.

Wind speed is illustrated in Fig. 8.3.

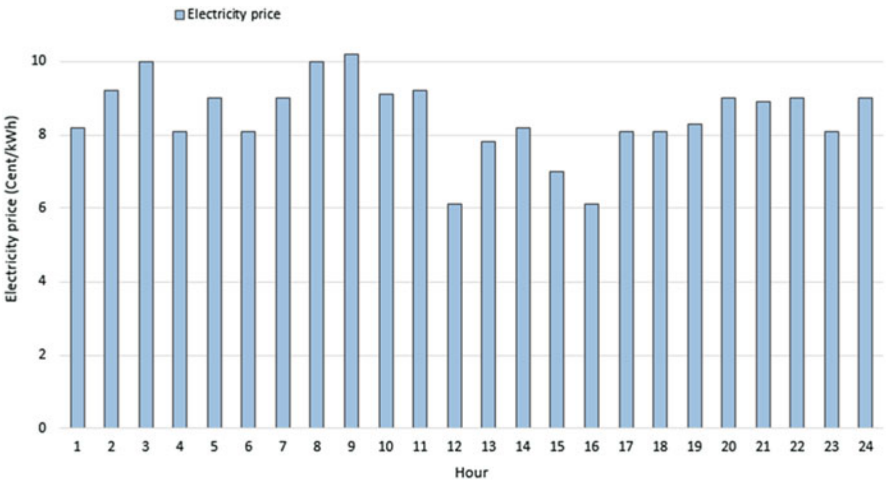

Fig. 8.4 Upper grid power price

Table 8.1 Generation unit's info

#	Unit	Value	#	Unit	Value
CHP parameter [32]			Boiler parameter [32]		
η_{ge}^{CHP}	%	40	η_{gh}^{B}	%	85
η_{gh}^{CHP}	%	35	p_c^B	kW	800
A^{CHP}	–	0.96	–	–	–
p_c^{CHP}	kW	800	–	–	–
Boiler emission [33]			CHP emission [33]		
#	Unit	Value	#	Unit	Value
#	Unit	Value	#	Unit	Value
EF_{CO}^{B}	kg/kWh	0.37	EF_{CO}^{CHP}	kg/kWh	0.37
EF_{SO}^{B}	kg/kWh	0.000003	EF_{SO}^{CHP}	kg/kWh	0.000003

Price of power provided by upper network is illustrated in Fig. 8.4.

Simulation data and info about storage systems are presented in Tables 8.1, 8.2, 8.3, 8.4, and 8.5.

Also, technical and environmental info of CHP system and boiler are presented in Table 8.1.

Simulation data and info about storage systems are presented in Table 8.2.

Operation cost and prices of various generation units and other sections are presented in Table 8.3.

Technical and environmental info of upper grid is presented in Table 8.4.

Finally, parameters necessary for modeling wind generation are presented in Table 8.5.

It should be mentioned that maximum capacity of gas and water networks are considered to be 1800 kW and 1000 kW, respectively. The whole simulations are carried out by CPLEX solver of GAMS under a mixed-integer linear programming [35].

Table 8.2 Storage systems data

Battery storage parameter [32]			CAES parameter [27]			Thermal storage parameter [32]		
#	Unit	Value	#	Unit	Value	#	Unit	Value
α^e_{min}	–	0.05	κ^{inj}	%	0.95	α^h_{min}	–	0.05
α^e_{max}	–	0.9	κ^p	%	0.95	α^h_{max}	–	0.9
α^e_{loss}	–	0.2	$V^{\text{inj}}_{\text{min}}$	kWh	5	α^h_{loss}	–	0.2
η^e_{ch}	%	90	$V^{\text{inj}}_{\text{max}}$	kWh	50	η^h_{ch}	%	90
η^e_{dis}	%	90	V^p_{min}	kWh	5	η^h_{dis}	%	90
$C^{\text{st},e}_c$	kW	300	V^p_{max}	kWh	50	$C^{\text{st},h}_c$	kW	200
–	–	–	A^{min}	kWh	50	–	–	–
–	–	–	A^{max}	kWh	500	–	–	–

Table 8.3 Operation costs and prices of various sections

Parameter [32]	Value	Unit
λ^g	6	Cent/kWh
λ^{wa}	4	Cent/kWh
λ^{wi}	0	Cent/kWh
λ^e_s	2	Cent/kWh
λ^h_s	2	Cent/kWh
λ^{DR}	2	Cent/kWh

Table 8.4 Upper grid info

Upstream network parameter [32]			Upstream network emission [34]		
#	Unit	Value	#	Unit	Value
A^{NET}	–	0.99	$\text{EF}^{\text{Net}}_{\text{CO}}$	kg/kWh	0.368
p^e_{max}	kW	1000	$\text{EF}^{\text{Net}}_{\text{SO}}$	kg/kWh	0.0002
p^e_{min}	kW	0	$\text{EF}^{\text{Net}}_{\text{NO}}$	kg/kWh	0.0008
p^T_c	kW	800	–	–	–

Table 8.5 Wind generation info

Parameters	Unit	Value
A^{WIND}	–	0.96
x,y,z	–	0.07, 0.01, 0.03
w_r	m/s	10
w_{ci}	m/s	4
w_{co}	m/s	22
p_r	kW	400

In order to evaluate effectiveness of CAES as the supply side management tool and also to investigate positive impacts of DRP, 4 simulation cases have been created as follows:

Case 1: Eco-environmental operation of renewable-based hub energy system without DRP and without CAES

Case 2: Eco-environmental operation of renewable-based hub energy system with DRP and without CAES
Case 3: Eco-environmental operation of renewable-based hub energy system without DRP and with CAES
Case 4: Eco-environmental operation of renewable-based hub energy system with DRP and with CAES

8.3.2 *Results*

Simulation results are presented in this section to validate effectiveness of employed techniques.

8.3.2.1 Pareto Fronts

Solving proposed eco-emission model for renewable-based hub energy system in the presence of CAES and DRP, Pareto solutions in four cases are obtained which are illustrated in Fig. 8.5.

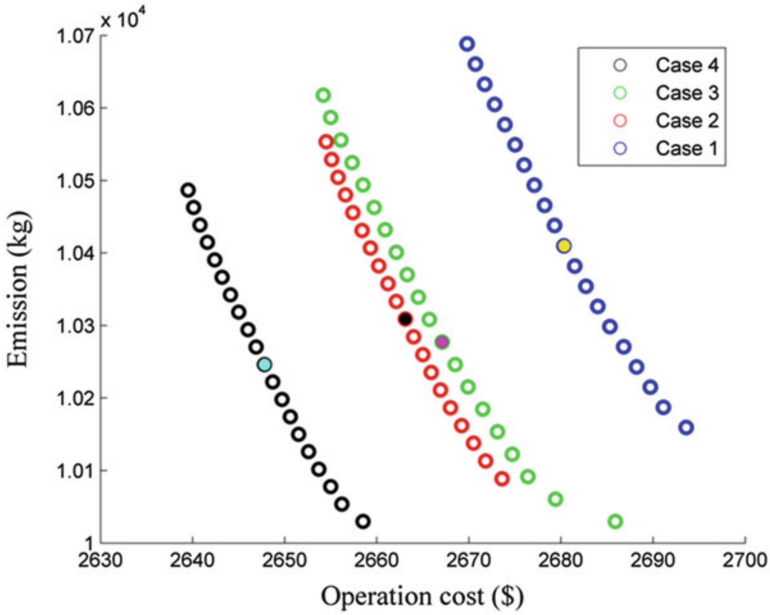

Fig. 8.5 Pareto front in four cases

It is clear from the above figure that by using CAES and DRP, Pareto front is shifted from areas with higher emission and cost to the areas with less emission and operation cost.

According to the selected solutions in each case study, total operation cost and emission of renewable-based hub energy system in case 1 are 2680.34$ and 10,410.04 kg, respectively. These values in case 2 with DRP are 2663.08$ and 10,308.98 kg, respectively. Total operation cost and emission of hub system in the presence of CAES in case 3 are 2667.09$ and 10,277.38 kg, respectively. By employing both CAES and DRP in case 4, total operation cost and emission of renewable-based hub energy system are 2647.81$ and 10,246.38 kg, respectively. Comparing the obtained results, it can be found that due to implementation of CAES and DRP in case 4, total operation cost of renewable-based hub energy system in comparison with case 1, 2, and 3 is decreased 1.24%, 0.57%, and 0.72%, respectively. Also, total generated emission of renewable-based hub energy system in case 4 is reduced 1.57%, 0.60%, and 0.30% in comparison with cases 1, 2, and 3, respectively. It can be understood from the obtained results above that both economic and environmental concerns of renewable-based hub energy system can be satisfied through utilization of CAES and DRP.

8.3.2.2 Other Results

Electrical energy demand in four cases has been illustrated in Fig. 8.6. It can be understood that in the cases 2 and 4, because of DRP implementation, electrical demand has been mostly transferred from peak periods to off-peak periods which leads to less energy procurement in peak periods and therefore more economic benefits for renewable-based hub energy system can be obtained.

As a result of DRP implementation in cases 2 and 4, total provided power by upper grid in these cases has been shifted to off-peak periods which is expressed by Fig. 8.7. Also, due to utilization of CAES, wind-turbine has been optimally used to support electrical demand which his illustrated in Fig. 8.7.

As an economic result owing to utilization of CEAS and DRP, total purchased gas has been considerably reduced in cases 2, 3, and 4. Gas import pattern is illustrated in Fig. 8.8.

By using CAES and DRP, generation of renewable units has had optimal share in supplying electrical demand. So, the role of CHP unit as one of electrical generation units has been decreased and therefore less gas has been consumed and then electrical and heat generation of this unit have been reduced. Figures 8.9, 8.10, and 8.11 illustrate the results related to CHP unit.

Since used gas by CHP unit has been changed, gas procurement pattern for boiler unit is appropriately changed and boiler has attempted to generate heat in a new pattern. Gas consumption and heat generation pattern of boiler are illustrated in Figs. 8.12 and 8.13, respectively.

Generated and consumed air by compressed air energy storage system is illustrated in Fig. 8.14. It can be seen from this figure that due to implementation of DRP,

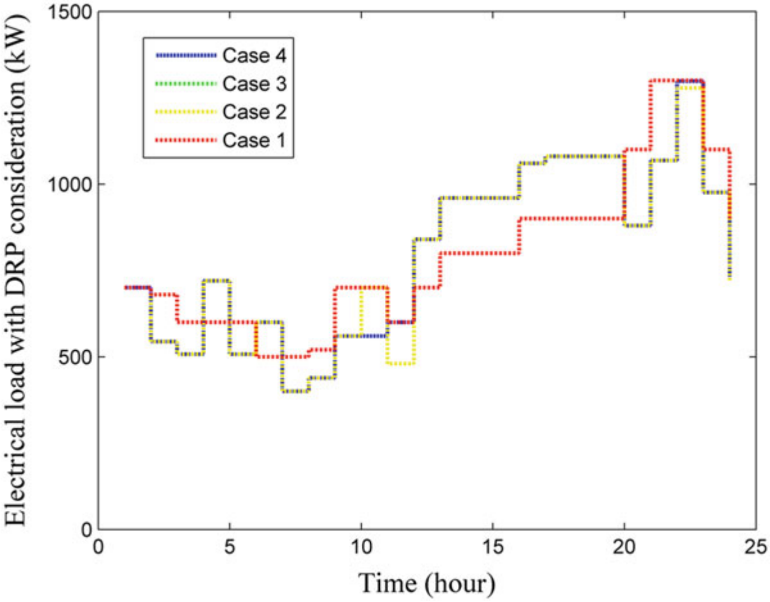

Fig. 8.6 Electrical energy demand in cases 1, 2, 3, and 4.

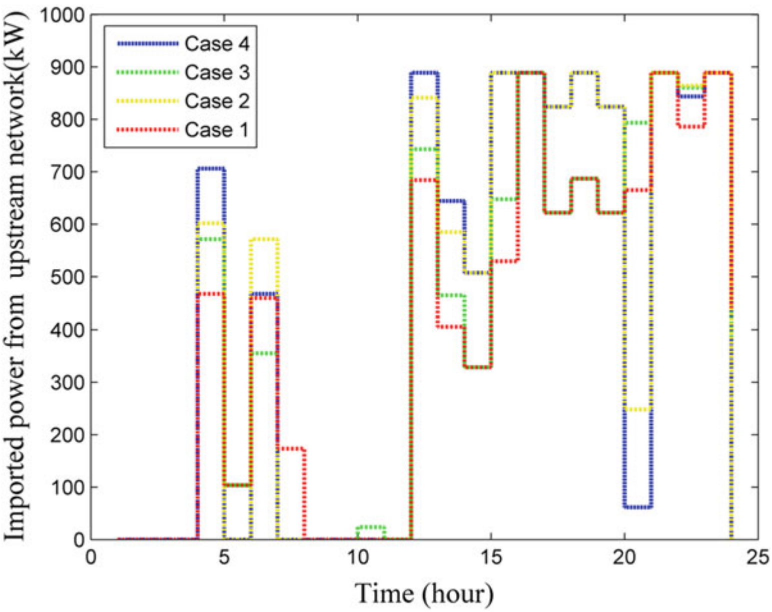

Fig. 8.7 Imported power from upper network

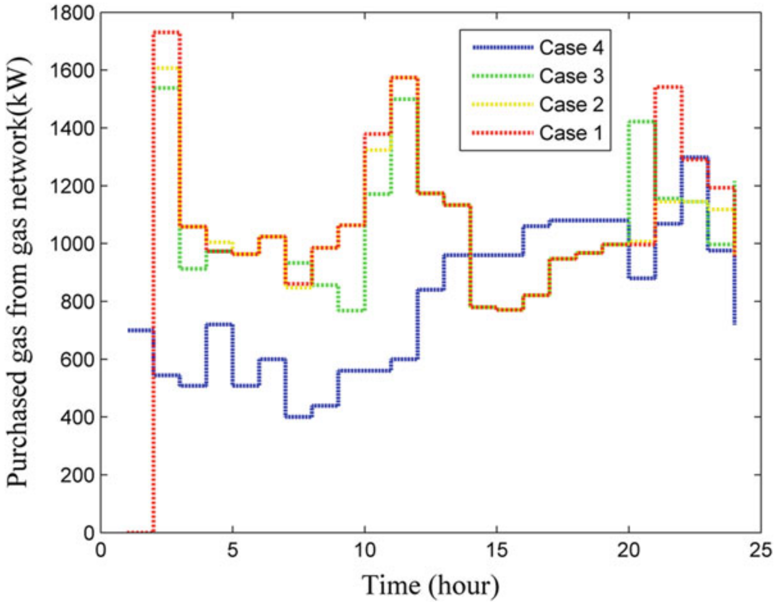

Fig. 8.8 Gas import

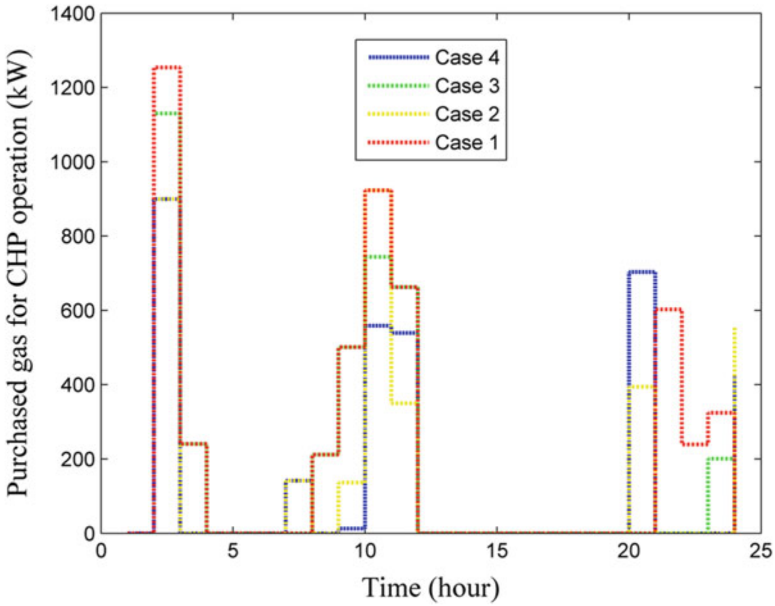

Fig. 8.9 Used gas by CHP unit

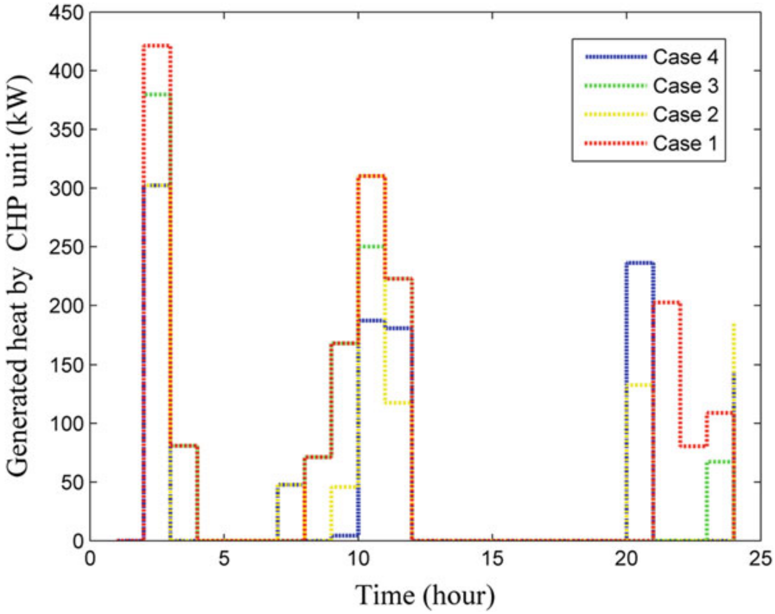

Fig. 8.10 Heat generated by CHP unit

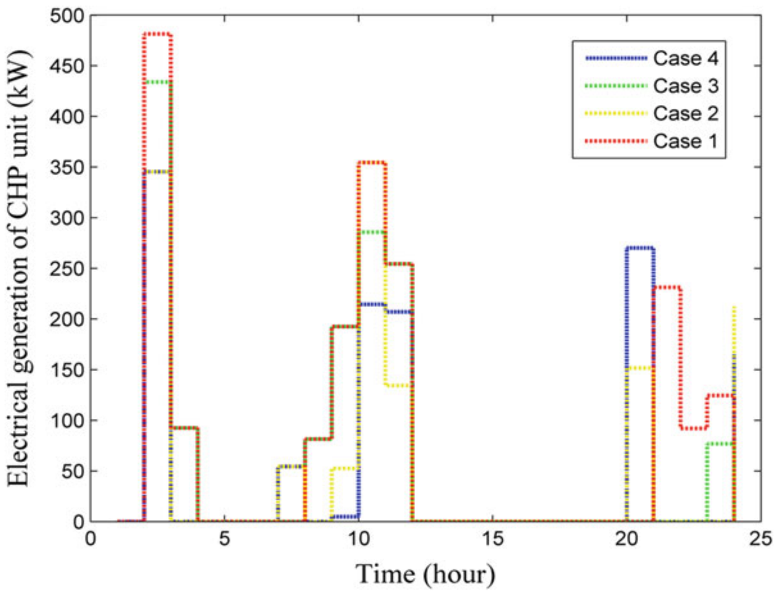

Fig. 8.11 Electrical power generated by CHP unit

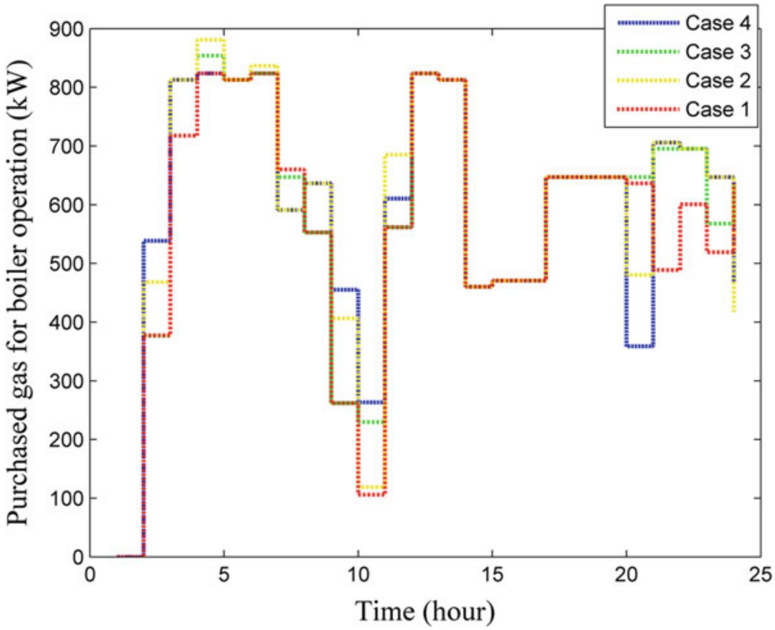

Fig. 8.12 Gas consumption of boiler

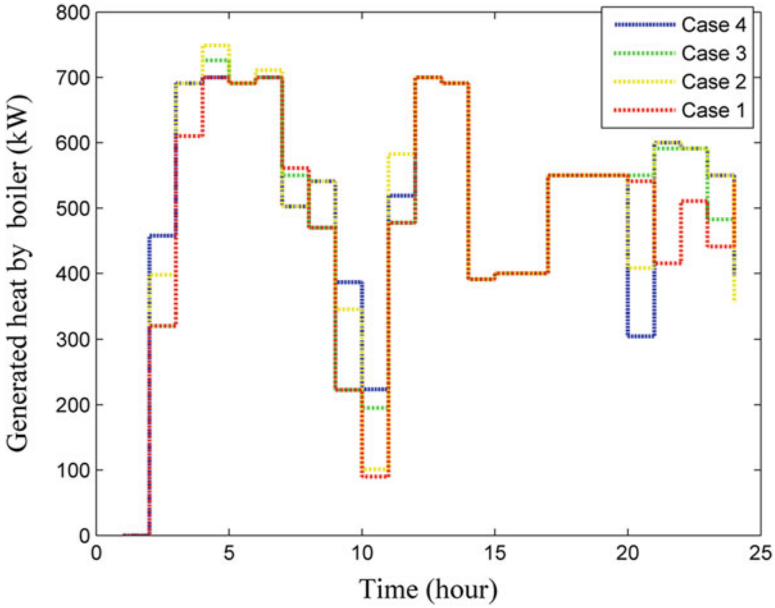

Fig. 8.13 Generated heat by boiler

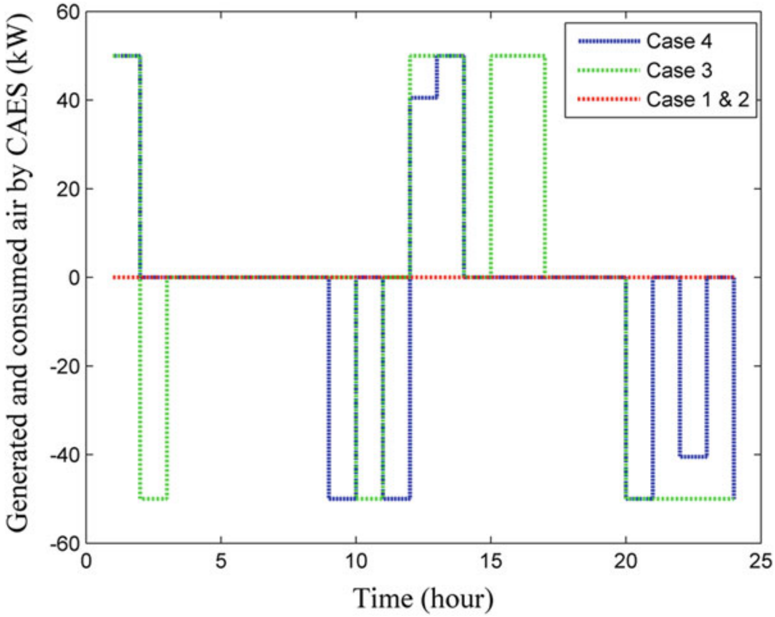

Fig. 8.14 Generated and consumed air by CAES

generation of air in CAES is increased and, on the other hand, consumption of power in CAES is reduced. Since power generation/consumption of CAES is proportional with its air generation/consumption, therefore power generation/consumption of CAES is changed with DRP which is illustrated in Fig. 8.15.

8.4 Conclusion

In this chapter, application of compressed air energy storage system as a supply side management tool has been investigated. A renewable-based hub energy system has been studied from economic and environmental viewpoints in the presence of CAES and DRP. Studied renewable-based hub system is composed of CHP system, boiler, and wind-turbine and storage systems. Since renewable generation units like wind-turbine have severe uncertainties in their outputs, CAES has been used to manage these uncertainties in the hub energy system. In simple words, CAES stores excess generation of such units and uses the saved energy in peak time periods to satisfy electrical energy demand. Optimal eco-emission operation of renewable-based hub energy system has been modeled through a mixed-integer linear programming and solved using GAMS software. Comparing the obtained results from simulations of various case studies, it can be found that due to implementation of CAES and DRP in case 4, total operation cost of renewable-based hub energy system in comparison with case 1, 2, and 3 is decreased 1.24%, 0.57%, and 0.72%, respectively. Also, total generated emission of renewable-based hub energy system in case 4 is reduced 1.57%, 0.60%, and 0.30% in comparison with cases 1, 2, and 3, respectively.

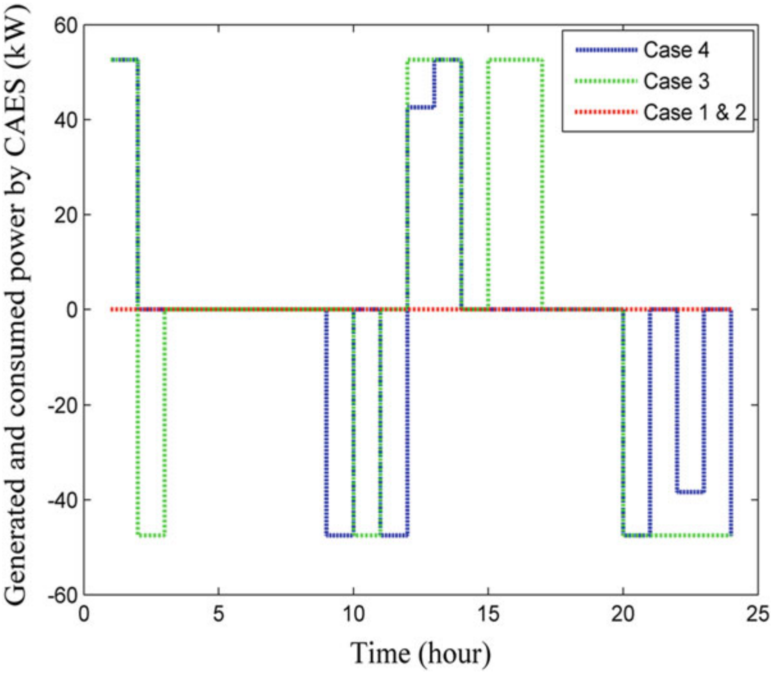

Fig. 8.15 Generated and consumed power by CAES

It can be understood from the obtained results above that both economic and environmental concerns of renewable-based hub energy system can be satisfied through utilization of CAES and DRP.

Nomenclature

Indices

t Time period index

Parameters

η_{ee}^{T} Efficiency of transformer

$\eta_{\text{ge}}^{\text{CHP}}$ Gas to electricity efficiency of CHP unit

$\eta_{\text{ee}}^{\text{CON}}$ Efficiency of converter unit

η_{ch}^{e} Charging efficiency of electrical storage system

η_{dis}^{e} Discharging efficiency of electrical storage system

η_{ch}^{h} Charging efficiency of heat storage system

η_{dis}^{h}	Discharging efficiency of heat storage system
α_{min}^{e}	Minimum limit coefficient of electrical storage system
α_{max}^{e}	Maximum limit coefficient of electrical storage system
α_{loss}^{e}	Loss of power coefficient for electrical storage system
α_{min}^{h}	Minimum limit coefficient of heat storage system
α_{max}^{h}	Maximum limit coefficient of heat storage system
α_{loss}^{h}	Loss of heat coefficient for electrical storage system
λ_{t}^{e}	Price of upstream network price
λ^{wi}	Wind turbine generation cost
λ^{g}	Gas price
λ^{wa}	Water price
λ_{s}^{e}	Electrical storage system operation cost
λ_{s}^{h}	Heat storage system operation cost
A^{NET}	Upstream network availability
A^{CHP}	CHP unit availability
A^{WIND}	Wind turbine availability
$C_{c}^{st,e}$	Rated capacity of electrical storage system
$C_{c}^{st,h}$	Rated capacity of heat storage system
EF_{CO}^{CHP}	CO_2 emission factor for CHP unit
EF_{SO}^{CHP}	SO_2 emission factor for CHP unit
EF_{NO}^{CHP}	NO_x emission factor for CHP unit
EF_{CO}^{B}	CO_2 emission factor for boiler
EF_{SO}^{B}	SO_2 emission factor for boiler
EF_{NO}^{B}	NO_x emission factor for boiler
EF_{CO}^{L}	CO_2 emission factor for residential gas consumption
EF_{SO}^{L}	SO_2 emission factor for residential gas consumption
EF_{NO}^{L}	NO_x emission factor for residential gas consumption
EF_{CO}^{Net}	CO_2 emission factor for upstream network
EF_{SO}^{Net}	SO_2 emission factor for upstream network
EF_{NO}^{Net}	NO_x emission factor for upstream network
g_{min}^{net}	Minimum nominal capacity of gas network
g_{max}^{net}	Maximum nominal capacity of gas network
g_{t}^{l}	Gas demand in residential section at time t
p_{min}^{e}	Minimum nominal capacity of upstream network
p_{max}^{e}	Maximum nominal capacity of upstream network

p_c^T	Nominal capacity of transformer
p_c^{CHP}	Rated capacity of CHP unit
p_c^B	Rated capacity of boiler unit
p_r	Rated power of wind turbine
p_t^{el}	Electrical demand at time t
p_t^h	Heat demand at time t
wa_t^l	Water demand at time t
$\mathrm{wa}_{\min}$	Minimum nominal capacity of water network
$\mathrm{wa}_{\max}$	Maximum nominal capacity of water network
$w_{\mathrm{ci}}, w_{\mathrm{co}}, w_r$	Cut-in, cut-out, and rated speeds of wind turbine
$w(t)$	Wind speed at time t
x,y,z	Indexes for modeling generation of wind turbine

Variables

Cost	Total operation cost of hub energy system
C_{BS}	Operation cost of battery storage
C_{DR}	Cost of DRP
C_{Ex}	Cost/revenue of exchanged power
C_{net}	Cost of purchased power from upstream network
$C_t^{\mathrm{st},e}$	Energy level of electrical storage system
$C_t^{\mathrm{st},h}$	Heat level of electrical storage system
C_{TS}	Operation cost of thermal storage
C_{Wind}	Operation cost of wind turbine
C_{Bo}	Operation cost of boiler
g_t^{CHP}	Consumed gas by CHP unit
g_t^B	Consumed gas by boiler unit
g_t^{net}	Total imported gas from gas network at time t
$I_t^{\mathrm{ch},e}$	Binary variable for modeling charging state of electrical storage system
$I_t^{\mathrm{dis},e}$	Binary variable for modeling discharging state of electrical storage system
$I_t^{\mathrm{ch},h}$	Binary variable for modeling charging state of heat storage system
$I_t^{\mathrm{dis},h}$	Binary variable for modeling discharging state of heat storage system
p_t^e	Imported power from upstream network at time t
$p_t^{\mathrm{ch},e}, p_t^{\mathrm{dis},e}$	Charging and discharging power of electrical storage system
$p_t^{\mathrm{ch},h}, p_t^{\mathrm{dis},h}$	Charging and discharging heat of electrical storage system
$p_t^{\mathrm{loss},e}$	Loss of power in electrical storage system

$p_t^{\mathrm{loss},h}$ Loss of heat in heat storage system
p_t^{wi} Electrical generation of wind turbine at time t
$\mathrm{wa}_t^{\mathrm{net}}$ Imported water at time t

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