Chapter 15

Energy hub: modeling, control, and optimization

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15.1 Introduction

Energy is the most important factor in the development of modern human societies. With the development of technology and automation in today's lifestyle, the use of energy is increasing very rapidly (Khan et al., 2019). Therefore countries need cheap, clean, safe, and sustainable energy for their development. Previously, fossil fuels were the main source of energy and generally converted into electrical energy by burning them at thermal power plants. This causes huge environmental concerns as they release hazardous gases into the atmosphere (Oruc & Dincer, 2019). Since, these thermal plants locate far away from the consumers, it results in high transmission and distribution losses which also increases its cost. To avoid these losses and increase energy efficiency, the concept of distributed generation (DG) has evolved (Kashyap, Mittal, & Kansal, 2019).

Instead of one far away centralized generation, DGs have gain popularity due to their numerous benefits over the conventional system. DGs or more generally distributed energy resources (DERs) have led to a more efficient power system and more competitive energy markets (Hou, Wang, & Luo, 2020). The idea of DER has led to the possibility of new power generators called prosumers (consumers who can generate their own electricity and can sell it back to the grid when needed) in the power grid. DGs have several advantages which include reduction in real power losses, emission reduction, grid stability enhancement, increased capacity of transmission lines and reduction in voltage deviation (Jalili & Taheri, 2020). So, with the active participation of the prosumers along with the demand response programs (DRPs), they are not only reducing their energy bills but also improving the grid reliability and stability.

The main source of DER is renewable energy resources (RERs), which can provide clean, economical, and sustainable energy. However, the intermittent nature of RERs limits their use, and to overcome this limitation, they are always accompanied with the energy storage systems (ESS). These storages can store excess amount of energy when generation is more than the load and provide stored energy back to the system in case of low RER generation or high demand. The maximum advantage of ESS can be obtained when used along with the demand side management (DSM) program. DSM program enables prosumers to interact with grid in a positive manner. By using DSM, prosumers reduce their demand when the grid in under stress by transferring their shift-able load to the off-peak hours. The DSM program also enables ESS to charge in off-peak hours and provide power back in peak hours or in times of need.

A significant amount of energy utilizes in heating and cooling of buildings either residential or commercial. Also, a lot of industrial processes requires heating and cooling for different purposes. Other than electrical energy, this heating and cooling can be obtained from different forms of energies. For example, gas can be directly used to heat up buildings in addition to the generation of electricity. Through the development of the devices that efficiently convert one form of energy to another form, it led the scientists to think of an intelligent hybrid system that can manage multiple energy sources. For this purpose, modeling, and optimization of a multienergy system (MES) is a required to increase the overall efficiency of the energy system. The inputs to the MES are electrical grid, gas grid, heating network, solar energy, wind energy, etc., and on the output side, it can provide electrical power, heating, cooling, gas, etc., simultaneously (Huang, Zhang, Yang, Wang, & Kang, 2017). The integration of MES can significantly improve the energy efficiency, increase renewable accommodation, and meet various types of energy demands.

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Energy hub is a new concept in which integration of different forms of energies, their conversion from one form to another, their storage, and consumptions are carried out at one place. This concept can be applied at different levels with different sizes of energy systems. For smaller energy systems, we use the term micro energy hub, such as residential, industrial, commercial, and agriculture micro hubs. These micro energy hubs can be combined to form macro energy hub. Macro energy hub is a group of several small micro hubs, which are integrated and control together in a coordinated way. Different kinds of micro energy hubs can be combined and controlled centrally by a centralized macro energy hub. In this way, large industrial area, huge residential complexes or even a whole city can be modeled as a macro energy hub. For the optimal operation of macro energy hub, it requires a lot of data communication between different micro energy hubs, such as weather forecasting data, price market information, and adjacent systems. The schematic representation of macro energy hub is shown in Fig. 15.1.

The depletion of fossil fuels for the generation of electrical energy and their adverse effect on the environment initiates the need of some clean and sustainable energy that can meet the ever-increasing demand of the world. The solution to this is the RERs that can provide clean and cheap energy which is also sustainable. So, the integration of RERs to the energy hub is a good idea but the uncertain behavior of renewable energy makes it difficult to accurately model them. This makes it difficult to solely depend upon them rather they can be useful for providing a portion of energy demand, which can reduce the overall cost of energy production and dependence upon fossil fuels. The integration of RERs to the energy hub greatly reduces the operational cost as it is not only clean but also very cheap compared to conventional energy resources.

The main types of RERs are wind energy, solar energy, biomass energy, geothermal energy, and hydroelectricity. Solar energy is the most rapidly growing type of renewable energy among all the others (Moriarty & Honnery, 2019). It has the potential to be the major shareholder of the global energy production. Wind energy is also gaining popularity as it can produce electricity even at night when the solar is not available. But its disadvantage is its intermittency as it stops generating electricity when the speed of wind falls below the threshold level. Biomass is a unique type of RER that resembles biofuels in a sense that it can be stored and used at the time of desire unlike solar and wind energies, which are obtainable only when sun or wind are present respectively. Major portion of electricity from biomass is generated by burning them which is less efficient and limits their use. Geothermal energy comes from interior heat of earth

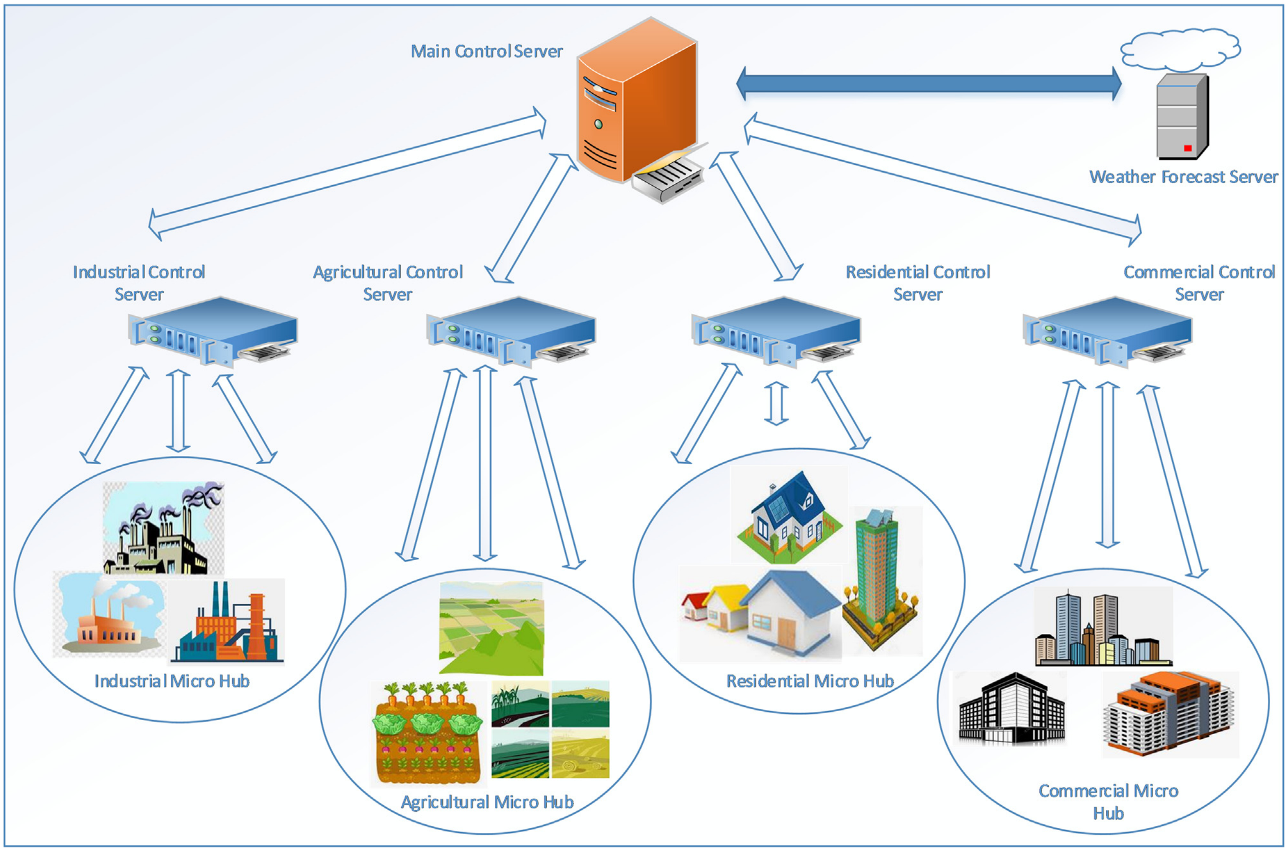

FIGURE 15.1 Schematic representation of macro energy hub.

or radioactive decay of different isotopes. Hydroelectricity is the production of electricity from running water and till now dominates the RERs' production despite advancements in solar and wind energy setups (Dudley, 2018).

RERs along with the storages can be used to meet demand in standalone or in a grid connected mode. This type of system is called hybrid renewable energy systems (HRES) (Rullo, Braccia, Luppi, Zumoffen, & Feroldi, 2019). The more the size of renewable energy and electrical storage (ES), the less will be the running operating cost of HRES, but for capital investment and system reliability, we need optimum sizing of RERs and ES. ES can store energy when renewable energy is in excess and can provide it back to the system when needed. The more the size of ES, more will be its capacity to store energy, but the capital cost of ES is high, and its life is relatively short. So, the proper sizing of ES is needed to optimize the system. HRES not only benefits consumers by reducing their energy bills but can also be helpful for the energy providers in a grid connected mode. For HRES to be connected and interacting with the grid, it needs to be smart enough for this purpose. For this, the term "Smart Grid" has repeatedly used in the literature.

Smart grid is a type of modern electrical grid that has the capability to accommodate and manage RERs, DGs, DRP, smart meters, smart appliances, storages, and communication modules and is considered as cyber secured. Smart grid is an umbrella term under which all features of futuristic modern grid come. For the grid to be smart it needs all components to communicate and respond with each other. In smart grid, consumers are well informed and responsive to the grid requirements. It can handle all types of DERs and storage options as well. It assesses condition of grid in real time, predicts behavior and also anticipates for any outages. With the inclusion of smart appliances, it can handle the stochastic demand by shifting less critical load in peak time. Thus we can get a lot of advantages by making our grid smart, but this would require great effort, new policies, a lot of money for research, and development.

This chapter focuses on the solution to the problem of optimization of energy hub. It includes the mathematical model of energy hub including different constraints associated with it. The mathematical models of electrical storage, heat storage (HS), and cold storage (CS) are also presented in this chapter. To make the energy hub more efficient, economical, and environment friendly, different types of renewable energies have been integrated to the energy hub. The problem of optimization of energy hub has been modeled as mixed integer linear programming (MILP) and solved in GAMS (General Algebraic Modeling System) software. Different case studies are analyzed to check the impact of storage capacities and RERs on the energy hub.

This chapter is divided into nine sections. Section 15.1 is an introductory part. Sections 15.2 and 15.3 describe the concepts of energy management systems and the energy hub, respectively. In Sections 15.4−15.6, mathematical modeling of energy hub, storage capacities, and RERs is presented. Section 15.7 deals with the system parameters whereas Section 15.8 is related to simulations, results, and discussion. Finally, the chapter is concluded in Section 15.9.

15.2 Energy management systems

Energy management has taken huge attention of researchers in the recent times due to increase in power demand by the growing population, which led to many problems, such as load shedding and power quality issues. A good energy management system can significantly reduce the energy requirements, thus leading to the cost savings and an additional advantage of environment protection. Energy management is equally important in distribution systems as well as in generation systems. In addition to these two systems, the applications of energy management are also required at different scales, that is, in industrial, commercial, and residential sectors to see the combined positive impact at national level. Fig. 15.2 shows the architecture of energy management system.

An efficient energy management system cannot be implemented without adopting energy management strategies. Following are the important points that should be considered while implementing energy management strategies.

1. Implementation of energy management strategies requires teamwork. An efficient team who knows the responsibilities can contribute to significant progress. This team should consist of energy manager, energy auditor, plant manager, maintenance experts, etc.
2. Energy management strategies should not be implemented in the same fashion across the plant. For example, a single plant may contain following systems to perform its operation (Kini, 2011):
   - **a.** Heating systems,
   - **b.** Boiler systems,
   - **c.** Power system/electricity,
   - **d.** Furnaces,
   - **e.** Uninterruptable power supply systems,
   - **f.** Temperature control systems,
   - **g.** Refrigeration systems,

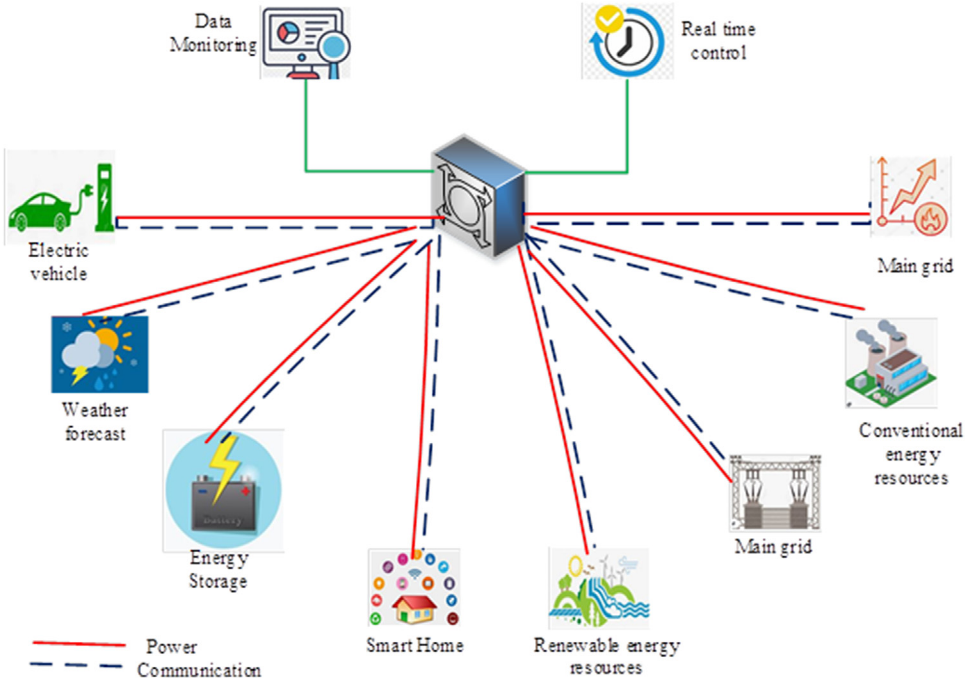

FIGURE 15.2 Energy management system architecture.

h. Illumination systems,
i. Ventilation systems,
j. Steam systems,
k. Motor systems,
l. Instrumentation systems,
m. Air-conditioning systems, and
n. Auxiliary systems, etc.

Different systems or sections of plant require different energy management strategies for effective savings.

3. All data of each system must be recorded for future planning. These data not only require defining the energy management strategies but also give the per unit cost of finished product.

15.2.1 Energy management information system

It is a performance management system that helps an individual or an organization in analyzing planning, and in decision-making regarding effective use of energy. It can also be considered as an IT-based unit that makes use of software applications to gather, record, and analyze energy data, which can also be used in future for planning purposes.

Data collection, processing, and analysis can be done on continuous basis by using the energy management information system. In modern industries, energy management systems are integrated along with the systems or subsystems of a plant. This helps in runtime monitoring of processes, which overall results in better control and management. As energy management information system processes all the critical and sensitive information, therefore it can be considered as the most important element of energy management systems. A good energy management information system should provide energy breakdown usage and product cost at different levels or processes. Main responsibilities of energy management information system include,

- Poor performance detection,
- Support in decision making,
- Performance reporting,
- Auditing,
- Justification of energy demand,
- Cost reduction, and
- Record management.

15.2.2 Energy management constraints

Energy management is related with planning, monitoring, and controlling energy-associated processes with the aim to preserve energy resources and energy cost savings and to protect environment. It is not so simple to manage energy as several constraints are associated with it. To apply energy management strategies on systems, it requires huge cost to bear at the start. Although it saves cost by managing energy, the capital cost of the system deployment cannot be ignored. The inclusion of many new devices and systems for energy management decreases the overall reliability of system because any device or system can malfunction at any time. The major part of energy management systems is renewables, but these renewables cannot be introduced beyond certain levels. Similarly, DRP for energy management cannot be used extensively because it will cause discomfort to the consumers. The balance between energy consumption and generation must be ensured all the time to avoid any disturbance. Reactive power in such systems must be within the range to ensure its stability. Energy management strategies requires huge amount of ESS for proper functioning, but their limited capacities make it difficult to apply properly for the energy management strategies. The summary of constraints associated with the energy management is shown in Fig. 15.3 (Alam & Arefifar, 2019).

15.3 Concept of energy hub

Energy hub can be considered as a multicarrier energy infrastructure that combines different types of DERs in which different forms of energies, such as electrical energy, gas energy, and renewables, are used as an input whereas the output of energy hub includes electrical demand, heating demand, and cooling demand. Integration of different types of energies at input side enhances the flexibility of continuous, cheap, and optimized energy provision. Energy hubs have the capability of receiving, sending, converting, and storing different kinds of energies. A combination of different types of energies can be integrated through the deployment of energy hub to optimally meet the demand (Fig. 15.4).

The main components of energy hub are,

1. Combined heat and power (CHP) unit,
2. Boiler,
3. Transformer,
4. Electric chiller,
5. Absorption chiller,
6. ES,
7. CS, and
8. HS.

CHP is the main part of energy hub that uses gas to produce electricity and heat. Its higher energy conversion efficiency makes it suitable to effectively couple the electrical and heating parts of energy hub (Wang, Zhang, Gu, & Li, 2017). Boiler on the other hand produces heat energy from gas to supply the heating load of energy hub. Transformer efficiently converts the high voltages from the grid to low voltages for the operation of electrical devices and appliances. Electric chiller converts electrical energy to cool energy for meeting the cooling demand. Absorption chiller uses

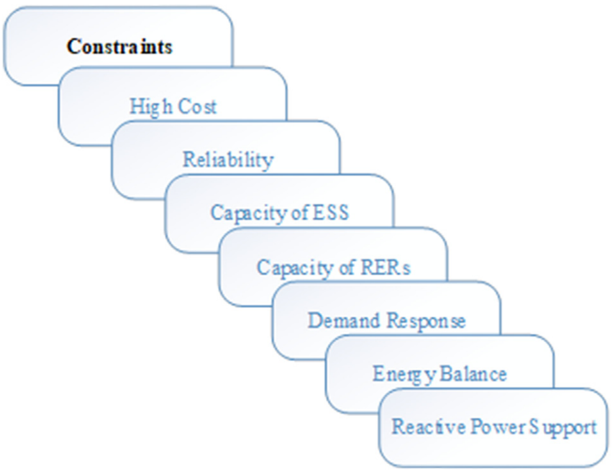

FIGURE 15.3 Constraints associated with energy management.

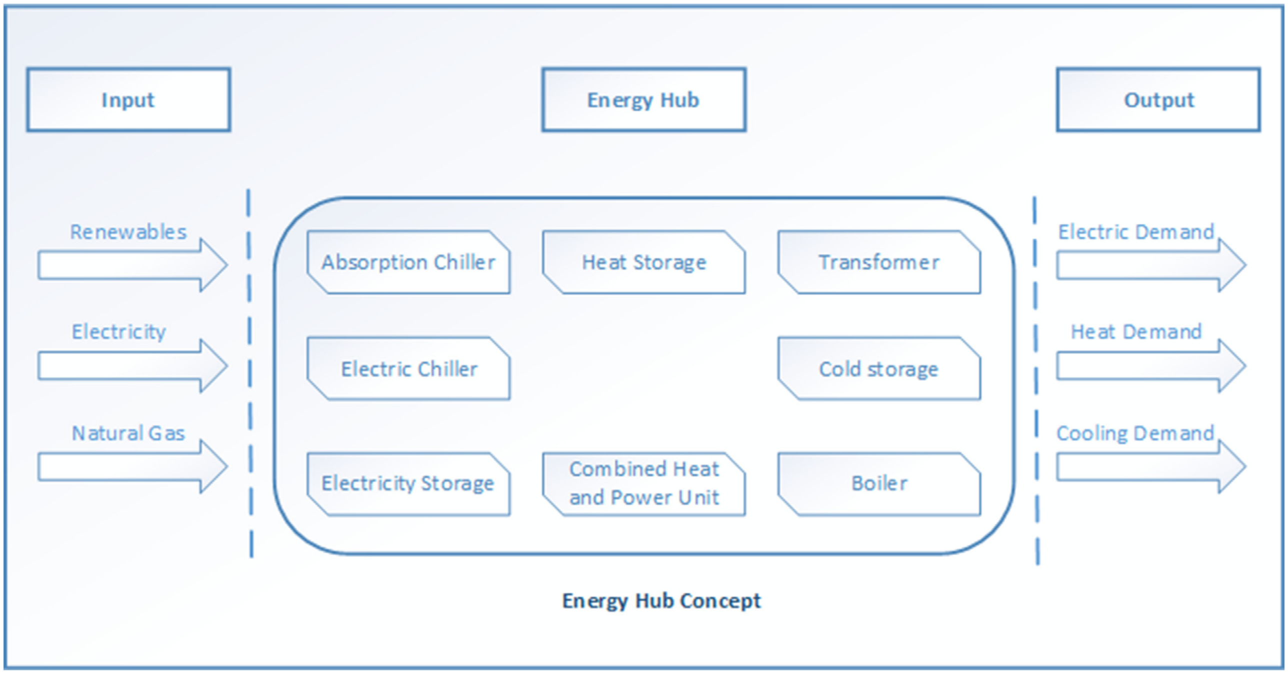

FIGURE 15.4 Energy hub concept.

the excess heat from the heating hub for the cooling process. Its combination with CHP makes it very cheap to run. The electrical storage, HS, and CS store excess amount of respective energies in them in case of less load demands. During the short supply, the same stored energy is given back from the storage to meet the demand. These storages can also be used for storing energies when the cost of purchasing energies is low and supply back when the cost is high. In this way a lot of cost can be saved.

15.3.1 Necessity of energy hub

The main disadvantage of conventional grid is that they mainly focus on electrical energy and consider only the electrical energy generation and demand. But the actual energy systems have multiple energy carriers, such as solar, wind, and natural gas, and multiple demands, such as electrical loads, heating loads, and cooling loads. Similarly, the concept of smart homes that focuses only on the controlling of electrical devices is incomplete without dealing with other types of devices. The sectors other than residential, such as industrial, commercial, and agriculture, also need various energy carriers to meet their demands. So, the conventional strategies that focus on single energy carrier need to be reviewed and a new model that can handle multiple energy carriers and different energy demands must be developed.

Recently, new developments on renewables have pushed the energy systems to increase their limits to accommodate the maximum amount of renewable energy. With our existing energy systems, it is not possible to penetrate renewable energy beyond certain limit. Therefore we need a system that can handle maximum RERs without compromising on the power quality and reliability. A lot of research has been done to maximize the usage of renewables in our energy systems. The dream of 100% renewable energy system is only possible by the smart integration of multi energy systems that combine in an intelligent framework (Connolly, Lund, & Mathiesen, 2016). The intelligent sustainable energy system to meet the future demand of world is only possible through the integration of different types of energy carriers.

15.3.2 Types of energy hub

The concept of energy hub can be applied at different levels and according to the consumption pattern of energy it can be classified into following four types.

1. Residential energy hub,
2. Commercial energy hub,
3. Industrial energy hub, and

4. Agricultural energy hub.

15.3.2.1 Residential energy hub

A significant amount of energy is consumed by the residential sector of any country. But the energy losses in this sector are significant due to poor distribution and transmission network, lack of responsive devices, and inefficient energy equipment. To make the consumption of energy efficient in residential sector, we need a smart and efficient multienergy management system. For this purpose, many countries have started using multiple energy resources, such as electricity and natural gas, to form residential energy hubs. A simple energy hub model for residential building has been proposed in Yuan et al. (2019), which includes RER and meets the electrical and heat demands of the building.

15.3.2.2 Commercial energy hub

Commercial buildings include offices, institutions, malls, hotels, etc., and are among the major consumers of energy through out the world. These buildings should be paid special attention for the efficient use of energy in their operation. Generally, commercial buildings purchase electricity from the grid for their electrical demand and depend upon gas for their heating load but with the increased prices of electricity and advancements in DER, the trend toward the onsite energy production has increased. The performance of combined cooling and heating power for commercial buildings and offices has been evaluated in Hanafizadeh, Eshraghi, Ahmadi, and Sattari (2016) and found very efficient in saving energy.

15.3.2.3 Industrial energy hubs

The development of any country can be measured by the strength of its industrial sector. By far the largest energy is consumed by this sector and is responsible for the major shareholder of greenhouse gas emission. So, the best way to save energy and reduce greenhouse gas emission is to make the consumption of our industrial sector more efficient. The prediction of industrial load is relatively easier and accurate as compared to commercial sector so it is easier to plan and integrate RERs in industry. Industrial energy hubs need to be optimally managed based upon several factors, such as cost minimization, profit maximization, and reduction in the consumption of energy (Paudyal, Cañizares, & Bhattacharya, 2014). For this purpose, multienergy systems with the integration of renewable energy along with the DSM program are required in industrial energy hub. The implementation of DSM programs in industrial energy hub is more difficult because it depends not only upon electricity and gas but also on other factors, such as water or raw material for their production (Alipour, Mohammadi-Ivatloo, & Zare, 2014). Also, some processes in industries are chain processes in which for the initiation of one process it needs completion of another process.

15.3.2.4 Agricultural energy hubs

Agriculture is the most important sector of any country, ensuring the food security and sustainability for it. Although the consumption of energy in agricultural sector is less than the other sectors, it is one of the fundamental factors for the profitability of agricultural products (Ball, Färe, Grosskopf, & Margaritis, 2015). Also, the consumption of energy in agricultural sector is increasing day by day due to the advancements in technology, use of automated machines, and need of more food across the world. Instead of expanding expensive transmission network, it is very beneficial to use RERs in agricultural sector as they are abundantly available on agricultural fields. Since the sun is readily available, solar energy can be used to generate not only electricity but also heating and drying agricultural crops. A large amount of agricultural waste can be used as a supply to biomass energy generation (Bilandzija et al., 2018). The wind energy in agricultural farms can be used for traditional grinding and water pumping and irrigation. Thus agricultural energy hub can be used to enhance the productivity of agriculture by efficiently utilizing the energy resources.

These micro energy hubs can be integrated together for their centralized control and operation, which makes the concept of macro energy hub (Walker, Labeodan, Maassen, & Zeiler, 2017). The integration of different micro energy hubs leads to increase in the overall efficiency of system and allows more penetration of RERs. The coordination between different micro energy hubs can efficiently handle the fluctuations in their individual demands and control the generation outages in a better way to increase the stability and reliability of macro energy hub.

15.4 Mathematical modeling of energy hub

The model presented here for energy hub includes two conventional energy sources, that is, electrical energy and natural gas. Two important forms of renewable energies, that is, solar and wind are also integrated in the proposed model.

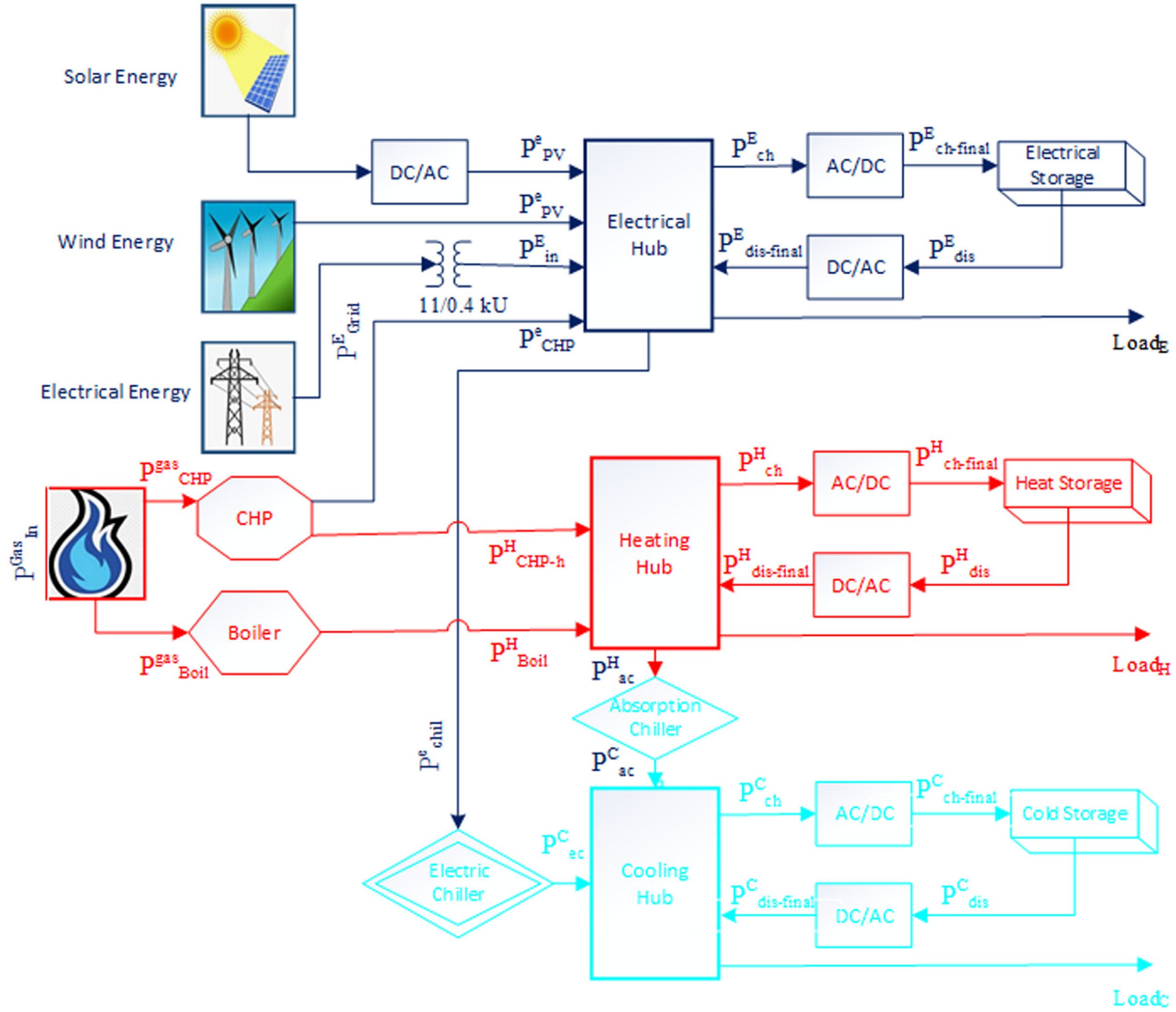

FIGURE 15.5 Proposed energy hub.

For simplicity energy hub model is divided into three subsections: electrical hub, heating hub, and cooling hub. The subenergy hubs are interconnected with each other for the conversion of one form of energy into another. The electrical hub includes solar energy, wind energy, electricity purchased from grid through transformer, electrical storage, and electrical load. The heating hub includes natural gas purchased from grid, CHP unit, boiler, HS, and heating load. The cooling hub contains electric chiller, absorption chiller, CS, and cooling loads. The electrical, heating, and cooling hubs are interconnected together to form a micro energy hub to meet the electrical, heating, and cooling demands efficiently. The proposed model of energy hub is shown in Fig. 15.5.

The proposed objective function to minimize the operational cost of energy hub during the 24 hours' time includes the cost of purchasing electricity from grid, cost of purchasing natural gas from grid, operational cost of wind turbine (WT), charging, discharging, and operational cost of electrical storage, HS, and CS and is given by Eq. (15.1).

$$\text{Cost} = \sum_{t=1}^{24}\Bigg\{\lambda_e(\text{t})P^E_{Grid}(\text{t}) + \lambda_g(\text{t})P^{GAS}_{in}(t) + \lambda_w P^e_{wind}(t)$$

$$+\left\{\lambda^E_{OC}\left(\frac{P^E_{ch-final}}{\eta^E_{\frac{AC}{DC}}}(t) + \frac{P^E_{dis-final}}{\eta^E_{\frac{DC}{AC}}}(t)\right) + \lambda_e(\text{t})\left(\frac{P^E_{ch-final}}{\eta^E_{\frac{AC}{DC}}}(t) - \frac{P^E_{dis-final}}{\eta^E_{\frac{DC}{AC}}}(t)\right)\right\}$$

$$+\left\{\lambda_{OC}^{H}\left(\frac{P_{ch-final}^{H}}{\eta_{Pr_{ch}^{H}}^{H}}(t)+\frac{P_{dis-final}^{H}}{\eta_{Pr_{dis}^{H}}^{H}}(t)\right)+\lambda_{g}(t)\left(\frac{P_{ch-final}^{H}}{\eta_{Pr_{ch}^{H}}^{H}}(t)-\frac{P_{dis-final}^{H}}{\eta_{Pr_{dis}^{H}}^{H}}(t)\right)\right\}$$

$$+\left\{\lambda_{OC}^{C}\left(\frac{P_{ch-final}^{C}}{\eta_{Pr_{ch}^{C}}^{C}}(t)+\frac{P_{dis-final}^{C}}{\eta_{Pr_{dis}^{C}}^{C}}(t)\right)+\left(0.5\lambda_{e}(t)+0.5\lambda_{g}(t)\right)\left(\frac{P_{ch-final}^{C}}{\eta_{Pr_{ch}^{C}}^{C}}(t)-\frac{P_{dis-final}^{C}}{\eta_{Pr_{dis}^{C}}^{C}}(t)\right)\right\}\Bigg\} \tag{15.1}$$

The objective function calculates the total operational cost of energy hub during the 24 hours, the breakup of overall operational cost includes cost of purchasing electrical energy from electrical grid, cost of purchasing gas from the gas grid, operating cost of WT for production of electrical energy, operating cost of electrical storages, cost of purchasing electrical energy for final charging of electrical storages, operating cost of HS, cost of purchasing gas for final charging of HS, operating cost of CS, and cost of purchasing of electrical and gas energy for final charging of CS. The rate of electrical energy is denoted by $\lambda_e(t)$ and electrical energy purchased from the grid is denoted by $P_{Grid}^{E}(t)$. The rate of gas for which it is purchased from the gas grid is denoted by $\lambda_g(t)$ and gas purchased from the grid is denoted by $P_{in}^{GAS}(t)$. The cost of operation of WT is denoted by λ_w and the electrical energy produced from turbine is denoted by $P_{wind}^{e}(t)$. The operating cost of electrical storage is denoted by λ_{OC}^{E}, the final charge and discharge are denoted by $P_{ch-final}^{E}$ and $P_{dis-final}^{E}$, respectively, converting efficiency from AC to DC is denoted by $\eta_{\frac{AC}{DC}}^{E}$, and converting efficiency form DC to AC is denoted by $\eta_{\frac{DC}{AC}}^{E}$. The operating cost of HS is denoted by λ_{OC}^{H}, the final charge and discharge are denoted by $P_{ch-final}^{H}$ and $P_{dis-final}^{H}$, respectively, and charging and discharging efficiencies of pressure and temperature control unit of HS are denoted by $\eta_{Pr_{ch}^{H}}^{H}$ and $\eta_{Pr_{dis}^{H}}^{H}$, respectively. The operating cost of CS is denoted by λ_{OC}^{C}, the final charge and discharge are denoted by $P_{ch-final}^{C}$ and $P_{dis-final}^{C}$, respectively, and charging and discharging efficiencies of pressure and temperature control unit of CS are denoted by $\eta_{Pr_{ch}^{C}}^{C}$ and $\eta_{Pr_{dis}^{C}}^{C}$, respectively. In our model, it is assumed that for charging of CS, 50% of electrical energy and 50% of gas energy are used.

For simplicity, the energy hub has been divided into three subparts, namely, electrical hub, heating hub, and cooling hub. The detailed mathematical modeling related to these subhubs is given below.

15.4.1 Modeling of electrical hub

The modeling of energy hub components, which deals mainly with electrical energy, is described in this section.

15.4.1.1 Electrical grid energy

The electrical energy purchased from the electrical grid is fed to the electrical hub by converting high voltage to low voltage through the transformer and is given by Eq. (15.2).

$$P_{in}^{E}(t)=\eta_{Trans}^{E}.P_{Grid}^{E}(t) \tag{15.2}$$

The efficiency of transformer is denoted by η_{Trans}^{E}.

15.4.1.2 Solar energy

The DC electrical energy generated from photovoltaic (PV) cells is converted into AC electrical energy and fed to the electrical hub and is given by Eq. (15.3).

$$P_{pv-final}^{e}(t)=\eta_{DC/AC}^{pv}.P_{pv}^{e}(t) \tag{15.3}$$

The DC electrical energy produced by PV cell is denoted by $P_{pv}^{e}(t)$, the efficiency of inverter that converts it into AC is denoted by $\eta_{DC/AC}^{pv}$, and the final AC electrical power that inputs to the energy hub by the solar is denoted by $P_{pv-final}^{e}(t)$.

15.4.1.3 Conversion of gas to electricity

The electrical energy produced from natural gas through CHP plant is given by Eq. (15.4).

$$P_{\mathrm{CHP}}^{e}(t)=\eta_{\mathrm{CHP}}^{e}\times P_{\mathrm{CHP}}^{gas}(t) \tag{15.4}$$

The gas input to the CHP from the grid is denoted by $P_{\mathrm{CHP}}^{gas}(t)$, the efficiency of CHP in converting gas energy into electrical energy is denoted by η_{CHP}^{e} and electrical power produced from the CHP is denoted by $P_{\mathrm{CHP}}^{e}(t)$.

15.4.1.4 Electrical load balance constraint

The electrical load and electrical generation through all means must be equal at each time interval, which is given by Eq. (15.5).

$$Load^E(t) + P^e_{chill}(t) + P^E_{ch}(t) = P^E_{in}(t) + P^e_{\mathrm{CHP}}(t) + P^e_{wind}(t) + P^e_{pv-final}(t) + P^E_{dis-final}(t) \tag{15.5}$$

The electrical demand of energy hub is denoted by $Load^E(t)$, the electrical power consumed by chiller to produce cool energy is denoted by $P^e_{chill}(t)$, the electrical energy consumed in charging of electrical storage is denoted by $P^E_{ch}(t)$, and the input electrical energy from transformer is denoted by $P^E_{in}(t)$.

15.4.1.5 Electrical grid constraint

The electrical energy purchased from the grid at any time interval must be within allowable grid limits, which is given by Eq. (15.6).

$$0 \le P^E_{Grid}(t) \le P^E_{Gridmax} \tag{15.6}$$

$P^E_{Grid}(t)$ denotes the electrical power purchased from the grid and $P^E_{Gridmax}$ denotes the maximum power that can be imported from the grid at any time interval.

15.4.1.6 Electric chiller constraint

The electric chiller must consume electrical power from the hub in allowable limits, which is given by Eq. (15.7).

$$0 \le P^e_{chill}(t) \le P^e_{chillmax} \tag{15.7}$$

$P^e_{chill}(t)$ denotes the electrical power consumed by the chiller and $P^e_{chillmax}$ denotes the maximum amount of power that can be consumed by the electric chiller at any time interval.

15.4.1.7 CHP constraint

The electrical power consumes by CHP must be within the allowable limits, which is given by Eq. (15.8).

$$0 \le P^e_{\mathrm{CHP}}(t) \le P^e_{CHPmax} \tag{15.8}$$

P^e_{CHP} denotes the electrical power consumed by the CHP and P^e_{CHPmax} denotes the maximum amount of power that can be consumed by the CHP at any time interval.

15.4.2 Modeling of heating hub

The modeling of heating hub components, which deals with the heat energy, is given in this section.

15.4.2.1 Gas balance constraints

The gas purchased from natural gas grid must be equal to the gas consumed by CHP and boiler at any instant of time and is given by Eq. (15.9).

$$P^{GAS}_{in}(t) = P^{gas}_{\mathrm{CHP}}(t) + P^{gas}_{Boil}(t) \tag{15.9}$$

15.4.2.2 CHP

The CHP takes input from the gas grid and converts it into heat power that is required by the heating hub. It is given by the Eq. (15.10).

$$P^H_{\mathrm{CHP}_h}(t) = \eta^H_{\mathrm{CHP}_h} \times P^{gas}_{\mathrm{CHP}}(t) \tag{15.10}$$

$\eta^H_{\mathrm{CHP}_h}$ denotes the heating efficiency of CHP, which shows that how efficiently it converts the gas power into heating power. $P^H_{\mathrm{CHP}_h}(t)$ denotes the heating power produced by the CHP unit at any time interval.

15.4.2.3 Boiler

The boiler converts gas energy into heat energy to meet a part of heating demand of energy hub and is given by Eq. (15.11).

$$P^H_{Boil}(t) = \eta^H_{Boil}.P^{gas}_{Boil}(t) \tag{15.11}$$

η^H_{Boil} denotes the heating efficiency of boiler, which shows that how efficiently it converts the gas power into heating power. $P^H_{Boil}(t)$ denotes the heating power produced by the boiler.

15.4.2.4 Heating load balance constraint

The heating generation and heating demand must be equal at each time interval and is given by Eq. (15.12).

$$Load^H(t) + P^H_{ac}(t) + P^H_{ch}(t) = P^H_{\mathrm{CHP}}(t) + P^H_{Boil}(t) + P^H_{dis-final}(t) \tag{15.12}$$

$Load^H(t)$ denotes the heating demand of the energy hub. $P^H_{ac}(t)$ denotes the heating power required by the absorption chiller. $P^H_{\mathrm{CHP}}(t)$ and $P^H_{Boil}(t)$ denote the heating power produced by CHP and boiler respectively. $P^H_{ch}(t)$ and $P^H_{dis-final}(t)$ denote the charging and discharging of heating power at any time interval respectively.

15.4.2.5 Gas grid constraint

The gas energy purchased from the grid at any time interval must be within the allowable grid limits and is given by Eq. (15.13).

$$0 \le P^{GAS}_{in}(t) \le P^{GAS}_{in\ max} \tag{15.13}$$

$P^{GAS}_{in\ max}$ is the maximum amount of gas that can be purchased from the gas grid at any time interval.

15.4.2.6 Boiler constraint

The boiler must take the input from gas grid in allowable limits and is given by Eq. (15.14).

$$0 \le P^H_{Boil}(t) \le P^H_{Boilmax} \tag{15.14}$$

$P^H_{Boilmax}$ is the maximum amount of power that boiler can produce at any time interval.

15.4.3 Modeling of cooling hub

The modeling of cooling hub components, which deals with the cool energy, is given in this section.

15.4.3.1 Absorption chiller

The conversion of heat energy into cool energy by the absorption chiller is given by Eq. (15.15).

$$P^C_{ac}(t) = \eta^C_{ac} \times P^H_{ac}(t) \tag{15.15}$$

$P^H_{ac}(t)$ is the heat power consumed by the absorption chiller to produce the cooling power $P^C_{ac}(t)$ at any time interval. η^C_{ac} is the conversion efficiency of absorption chiller.

15.4.3.2 Electric chiller

The conversion of electrical energy into cool energy by the electric chiller is given by Eq. (15.16).

$$P^C_{ec}(t) = \eta^C_{chill}.P^e_{chill}(t) \tag{15.16}$$

$P^e_{chill}(t)$ is the electrical power consumed by the electric chiller to produce the cooling power $P^C_{ec}(t)$ at any time interval. η^C_{chill} is the conversion efficiency of electric chiller.

15.4.3.3 Cooling load balance constraint

The cooling generation and cooling load must be equal at each time interval and is given by Eq. (15.17).

$$Load^C(t) + P^C_{ch}(t) = P^C_{ac}(t) + P^C_{ec}(t) + P^C_{dis-final}(t) \tag{15.17}$$

$Load^C(t)$ denotes the cooling demand of the energy hub. $P^C_{ch}(t)$ and $P^C_{dis-final}(t)$ denote the charging and discharging of cooling power at any time interval.

15.4.3.4 Absorption chiller constraint

The cooling power produced by absorption chiller must be in the allowable limits and is given by Eq. (15.18).

$$0 \le P^C_{ac}(t) \le P^C_{acmax} \tag{15.18}$$

P^C_{acmax} is the maximum amount of cooling power that can be produced by the absorption chiller.

15.5 Energy hub with storage capacities

The use of DER specifically RERs are increasing day by day, this shifts the paradigm from centralized power system to the distributed energy systems. The higher depletion rate of fossil fuel reserves and never-ending nature of RERs make it feasible to shift greatly toward renewables, but their intermittent and fluctuating nature limits their use. The production of energy from RERs mainly depends on the time and location which decreases the reliability of the power system (Mohammadi, Noorollahi, & Mohammadi-Ivatloo, 2018). The leading solution to the intermittency problem of RERs is the addition of ESS which store energy during the high production of renewables and provide the energy back to the system during low production. The additional advantage of ESS is that they can store energy in off-peak hours (low unit price) and provide energy back to the system in peak-hours (high unit price). The other advantages of ESS are less operational cost, less consumption of fossil fuels, less emissions and increased overall system efficiency (Barberis, Rivarolo, Traverso, & Massardo, 2016).

The three main types of ESS used in energy hub are (Rakipour & Barati, 2019),

1. ES,
2. HS, and
3. CS.

15.5.1 Mathematical modeling of ESS

The detailed modeling of ESS used in proposed energy hub is given in this section.

15.5.1.1 Electrical storages

The electrical power level in ES can be calculated by Eq. (15.19).

$$P_{es}(t) = P_{es}(t-1) + P^E_{ch-final}(t) - P^E_{dis}(t) - P^{loss}_{es}(t) \tag{15.19}$$

$P_{es}(t)$ and $P_{es}(t-1)$ are the current and previous power levels in ES, respectively. $P^E_{ch-final}(t)$ and $P^E_{dis}(t)$ are the charging and discharging powers of ES, respectively.

$P^{loss}_{es}(t)$ is the loss in electrical power stored in ES for any time interval and is given by Eq. (15.20).

$$P^{loss}_{es}(t) = \gamma^{loss}_e P_{es}(t) \tag{15.20}$$

γ^{loss}_e is the loss factor of ES that shows the loss of charge during storage.

The electrical charge must be stored within the specified limits and is given by Eq. (15.21).

$$\psi^e_{min} P^{cap^{max}}_{es} \le P_{es}(t) \le \psi^e_{max} P^{cap^{max}}_{es} \tag{15.21}$$

$P^{cap^{max}}_{es}$ denotes the maximum capacity of ES charge. ψ^e_{min} and ψ^e_{max} denote the allowable minimum and maximum limits of ES power level factors, respectively.

The allowable rate of charging of ES is given by Eq. (15.22).

$$\phi^e_{min} P^{cap^{max}}_{es} (1/\eta^E_{AC/DC}) I^e_{ch-final}(t) \le P^E_{ch-final}(t) \le \phi^e_{max} P^{cap^{max}}_{es} (1/\eta^E_{AC/DC}) I^e_{ch-final}(t) \tag{15.22}$$

ϕ^e_{min} and ϕ^e_{max} denote the minimum and maximum ES charge level factors, respectively. $\eta^E_{AC/DC}$ denotes the efficiency of rectifier.

The allowable rate of discharging of ES is given by Eq. (15.23).

$$\phi_{min}^{e} P_{es}^{cap^{max}} \eta_{DC/AC}^{E} I_{dis}^{e}(t) \le P_{dis}^{E}(t) \le \phi_{max}^{e} P_{es}^{cap^{max}} \eta_{DC/AC}^{E} I_{dis}^{e}(t) \tag{15.23}$$

$\eta_{DC/AC}^{E}$ denotes the efficiency of inverter.

To prevent the charge and discharge of ES simultaneously, Eq. (15.24) is used.

$$0 \le I_{ch-final}^{e}(t) + I_{dis}^{e}(t) \le 1 \tag{15.24}$$

$I_{ch-final}^{e}(t)$ and $I_{dis}^{e}(t)$ denote the binary variables for final charge and discharge of ES respectively.

15.5.1.2 Heat storages

The heat power level in HS can be calculated by using Eq. (15.25).

$$P_{hs}(t) = P_{hs}(t-1) + P_{ch-final}^{H}(t) - P_{dis}^{H}(t) - P_{hs}^{loss}(t) \tag{15.25}$$

$P_{hs}(t)$ and $P_{hs}(t-1)$ are the current and previous heat power levels in HS, respectively. $P_{ch-final}^{H}(t)$ and $P_{dis}^{H}(t)$ are the charging and discharging powers of HS, respectively.

$P_{hs}^{loss}(t)$ is the loss in heating power stored in HS for any time interval and is given by Eq. (15.26).

$$P_{hs}^{loss}(t) = \gamma_{h}^{loss} P_{hs}(t) \tag{15.26}$$

γ_{h}^{loss} is the loss factor of HS that indicates heat power dissipated during the storage.

The heat must be stored within the specified limits and is given by Eq. (15.27).

$$\psi_{min}^{h} P_{hs}^{cap^{max}} \le P_{hs}(t) \le \psi_{max}^{h} P_{hs}^{cap^{max}} \tag{15.27}$$

$P_{hs}^{cap^{max}}$ denotes the maximum capacity of HS. ψ_{min}^{h} and ψ_{max}^{h} denote the allowable minimum and maximum limits of HS power level factors, respectively.

The allowable rate of charging of HS is given by Eq. (15.28).

$$\phi_{min}^{h} P_{hs}^{cap^{max}} (1/\eta_{Pr_{ch}^{H}}^{H}) I_{ch-final}^{h}(t) \le P_{ch-final}^{H}(t) \le \phi_{max}^{h} P_{hs}^{cap^{max}} (1/\eta_{Pr_{ch}^{H}}^{H}) I_{ch-final}^{h}(t) \tag{15.28}$$

ϕ_{min}^{h} and ϕ_{max}^{h} denote the minimum and maximum HS charge level factors, respectively. $\eta_{Pr_{ch}^{H}}^{H}$ denotes the charging efficiency of pressure and temperature control unit of HS.

The allowable rate of discharging heat from HS is given by Eq. (15.29).

$$\phi_{min}^{h} P_{hs}^{cap^{max}} \eta_{Pr_{dis}^{H}}^{H} I_{dis}^{h}(t) \le P_{dis}^{H}(t) \le \phi_{max}^{h} P_{hs}^{cap^{max}} \eta_{Pr_{dis}^{H}}^{H} I_{dis}^{h}(t) \tag{15.29}$$

$\eta_{Pr_{dis}^{H}}^{H}$ denotes the discharge efficiency of pressure and temperature control unit of HS.

To prevent the charging and discharging of HS simultaneously, Eq. (15.30) is used.

$$0 \le I_{ch-final}^{h}(t) + I_{dis}^{h}(t) \le 1 \tag{15.30}$$

$I_{ch-final}^{h}(t)$ and $I_{dis}^{h}(t)$ denote the binary variables for final charge and discharge of HS, respectively.

15.5.1.3 Cold storages

The cooling power level in CS can be calculated by using Eq. (15.31).

$$P_{cs}(t) = P_{cs}(t-1) + P_{ch-final}^{C}(t) - P_{dis}^{C}(t) - P_{cs}^{loss}(t) \tag{15.31}$$

$P_{cs}(t)$ and $P_{cs}(t-1)$ are the current and previous cooling power levels in CS, respectively. $P_{ch-final}^{C}(t)$ and $P_{dis}^{C}(t)$ are the charging and discharging powers of CS, respectively.

$P_{cs}^{loss}(t)$ is the loss in cooling power stored in CS for any time interval and is given by Eq. (15.32).

$$P_{cs}^{loss}(t) = \gamma_{c}^{loss} P_{cs}(t) \tag{15.32}$$

γ_{c}^{loss} is the loss factor of CS that shows how much cooling power is dissipated during storage.

The cooling power must be stored within the specified limits and is given by Eq. (15.33).

$$\psi^{c}_{min}P^{cap^{max}}_{\mathrm{cs}} \le P_{\mathrm{cs}}(t) \le \psi^{c}_{max}P^{cap^{max}}_{\mathrm{cs}} \tag{15.33}$$

$P^{cap^{max}}_{\mathrm{cs}}$ denotes the maximum capacity of CS. ψ^{c}_{min} and ψ^{c}_{max} denote the allowable minimum and maximum limits of CS power level factors, respectively.

The allowable rate of charging of CS is given by Eq. (15.34).

$$\phi^{c}_{min}P^{cap^{max}}_{\mathrm{cs}}\left(1/\eta^{C}_{Pr^{C}_{ch}}\right)I^{c}_{ch-final}(t) \le P^{C}_{ch-final}(t) \le \phi^{c}_{max}P^{cap^{max}}_{\mathrm{cs}}\left(1/\eta^{C}_{Pr^{C}_{ch}}\right)I^{c}_{ch-final}(t) \tag{15.34}$$

ϕ^{c}_{min} and ϕ^{c}_{max} denote the minimum and maximum CS charge level factors, respectively. $\eta^{C}_{Pr^{C}_{ch}}$ denotes the charging efficiency of pressure and temperature control unit of CS.

The allowable rate of discharging cool energy from CS is given by Eq. (15.35).

$$\phi^{c}_{min}P^{cap^{max}}_{\mathrm{cs}}\eta^{C}_{Pr^{C}_{dis}}I^{c}_{dis}(t) \le P^{C}_{dis}(t) \le \phi^{c}_{max}P^{cap^{max}}_{\mathrm{cs}}\eta^{C}_{Pr^{C}_{dis}}I^{c}_{dis}(t) \tag{15.35}$$

$\eta^{C}_{Pr^{C}_{dis}}$ denotes the discharge efficiency of pressure and temperature control unit of CS.

To prevent the charging and discharging of CS simultaneously, Eq. (15.36) is used.

$$0 \le I^{c}_{ch-final}(t) + I^{c}_{dis}(t) \le 1 \tag{15.36}$$

$I^{c}_{ch-final}(t)$ and $I^{c}_{dis}(t)$ denote the binary variables for final charge and discharge of CS, respectively.

15.6 Integration of renewable resources to energy hub

Majority of energy suppliers produce electricity from the fossil fuels, which normally locates far away from the consumer side. Due to inefficient conversion of fossil fuels to electricity and transmission losses, a large amount of energy is being wasted; furthermore, long-distance transmission system decreases the overall reliability of the system. The easiest way to cater these issues is to use DER, more specifically RERs. Mathematical modeling of solar and wind energies is given in following sections.

15.6.1 Modeling of solar energy

PV cell produces electrical energy from the sunlight, which depends upon the solar irradiance. The solar irradiance further depends upon many factors, such as time of year, position of sun, cloud covering, intensity of sun, temperature, humidity, and de-rating factor of solar panel. The output from PV panels can be calculated by using Eq. (15.37) (Baneshi & Hadianfard, 2016; Gökçek, 2018).

$$P^{e}_{pv}(S_i(t)) = \mathrm{PV}^{array}df^{\mathrm{PV}}\left(\frac{S_i(t)}{S_{i,STC}}\right)\left[1+\alpha p\left(T_c - T_{c,STC}\right)\right] \tag{15.37}$$

P^{e}_{pv} is the electrical power produced by PV cell at solar irradiance $S_i(t)$. $S_{i,STC}$ denotes the solar irradiance at standard test conditions, df^{PV} is the de-rating factor of PV cell, αp is the temperature coefficient, PV^{array} is the rated capacity of solar panels, T_c is the temperature of PV cell, and $T_{c,STC}$ is the temperature of PV cell at standard test conditions.

15.6.2 Modeling of wind energy

Electrical power produced from the WT depends upon the wind speed. Eq. (15.38) is used for the production of electrical power from the wind (Shams, Shahabi, & Khodayar, 2018; Soroudi, Aien, & Ehsan, 2011).

$$P^{e}_{wind}(\omega(t)) = \begin{cases} P^{w}_{out};\ \omega^{w}_{r} \le \omega(t) \le \omega^{cut}_{o} \\ \dfrac{\omega(t)-\omega^{cut}_{i}}{\omega^{w}_{r}-\omega^{cut}_{i}}\left(P^{w}_{out}\right);\ \omega^{cut}_{i} \le \omega(t) \le \omega^{w}_{r} \\ 0;\ \omega(t) \le \omega^{cut}_{i} or\ \omega(t) \ge \omega^{cut}_{o} \end{cases} \tag{15.38}$$

P^{e}_{wind} is the electrical power produced from the WT, P^{w}_{out} is the rated capacity of WT. ω^{w}_{r}, ω^{cut}_{i}, and ω^{cut}_{o} are the rated, cut-in, and cut-out speed of WT, respectively.

15.7 Simulations

GAMS is high level optimization tool for modeling and solving complex engineering problems. It is widely used in literature for the optimization of linear, nonlinear, and mixed integer problems (AlRafea, Fowler, Elkamel, & Hajimiragha, 2016; Andrei, 2017; Ha, Zhang, Huang, & Thang, 2016; Ha, Zhang, Thang, & Huang, 2017; Soroudi, 2017). It includes several solvers to solve different kinds of mathematical problems. In this section, the proposed energy hub has been modeled in GAMS and solved as an optimization problem for reducing the operational cost of energy hub during 24 hours' time horizon. The inputs to the energy hub are electricity from the electrical grid, gas from the gas grid, and RERs (solar and wind). The outputs from the energy hub are electrical, heating, and cooling demands, which must be fulfilled. The optimization problem is further modeled as an MILP to run simulations in GAMS software. The simulation parameters for the optimization of energy hub are given in Table 15.1.

The price of electricity and gas purchased from the grid is shown in Fig. 15.6. Graph shows prices of electricity and gas in different time hours.

The electrical, heating, and cooling demands of energy hub are shown in Fig. 15.7. These demands must be fulfilled at any time interval. Due to change in demands all the time, it is possible to optimally select the low peak hour energy from the different inputs to minimize the overall cost.

The wind speed and solar irradiance used in the simulations are shown in Fig. 15.8.

Four case studies have been designed and performed as shown in Table 15.2, to check the effectiveness of storage capacities and RERs in energy hub.

15.8 Optimization of energy hub in GAMS

In the first case, the energy hub has been optimized without any storage capacities and RERs. The electricity and gas are purchased from the grid to meet the electrical, heating, and cooling demands. There is no storage available, so the

TABLE 15.1 Simulation parameters.

Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
λ_{OC}^{E}	2.5	Cent kWh^{-1}	η_{chill}^{C}	0.85	–	ψ_{max}^{c}	0.92	–
λ_{OC}^{H}	2.5	Cent kWh^{-1}	$P_{Gridmax}^{E}$	1200	kW	ϕ_{min}^{e}	0.05	–
λ_{OC}^{C}	2.5	Cent kWh^{-1}	$P_{in\ max}^{GAS}$	2000	kW	ϕ_{min}^{h}	0.05	–
λ_{w}	0.2	Cent kWh^{-1}	$P_{Boil\ max}^{H}$	800	kW	ϕ_{min}^{c}	0.05	–
$\eta_{\frac{AC}{DC}}^{E}$	0.92	–	$P_{CHP\ max}^{e}$	800	kW	ϕ_{max}^{e}	0.14	–
$\eta_{\frac{DC}{AC}}^{E}$	0.92	–	$P_{ac\ max}^{C}$	800	kW	ϕ_{max}^{h}	0.15	–
$\eta_{Pr_{ch}^{H}}^{H}$	0.92	–	$P_{CHP\ max}^{e}$	800	kW	ϕ_{max}^{c}	0.16	–
$\eta_{Pr_{dis}^{H}}^{H}$	0.92	–	γ_{e}^{loss}	0.02	–	P_{out}^{w}	300	kW
$\eta_{Pr_{ch}^{H}}^{H}$	0.92	–	$P_{es}^{cap^{max}}$	600	kW	ω_{r}^{w}	10	m s^{-1}
$\eta_{Pr_{dis}^{H}}^{H}$	0.92	–	$P_{hs}^{cap^{max}}$	600	kW	ω_{i}^{cut}	4	m s^{-1}
$\eta_{DC/AC}^{pv}$	0.95	–	$P_{cs}^{cap^{max}}$	600	kW	ω_{o}^{cut}	22	m s^{-1}
η_{Trans}^{E}	0.90	–	ψ_{min}^{e}	0.05	–	df^{PV}	80	%
η_{CHP}^{e}	0.40	–	ψ_{min}^{h}	0.05	–	$S_{i,STC}$	1	kW m^{-2}
$\eta_{CHP_h}^{H}$	0.35	–	ψ_{min}^{c}	0.05	–	αp	−0.5	% $degree^{-1}$
η_{Boil}^{H}	0.85	–	ψ_{max}^{e}	0.92	–	T_c	60	°C
η_{ac}^{C}	0.92	–	ψ_{max}^{h}	0.92	–	$T_{c,STC}$	25	°C

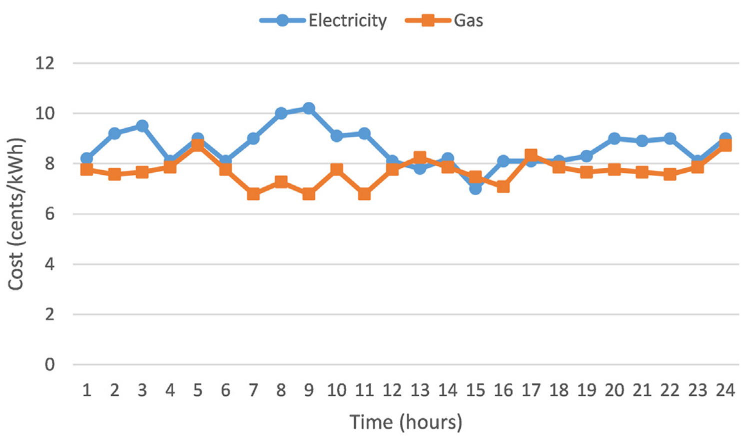

FIGURE 15.6 Cost of electricity and gas purchased from grid.

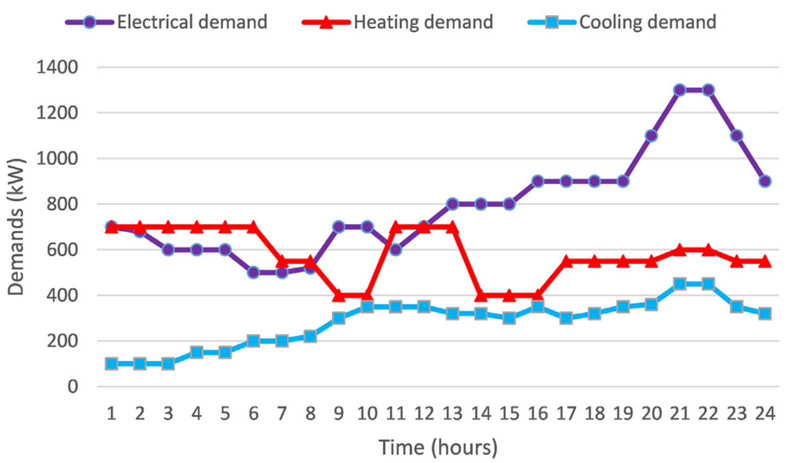

FIGURE 15.7 Electrical, heating, and cooling demands of energy hub.

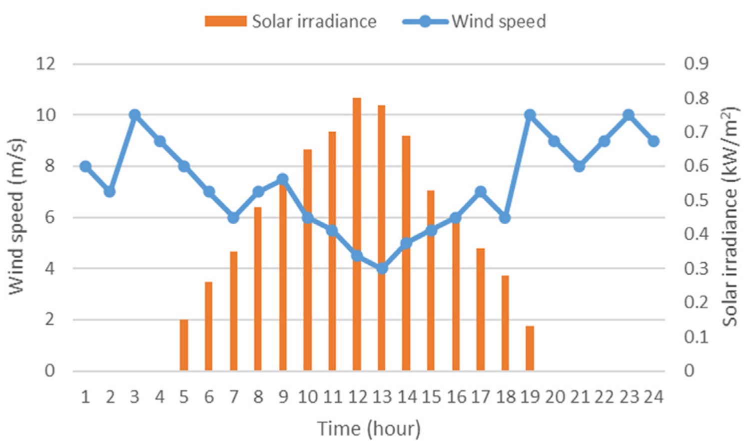

FIGURE 15.8 Wind speed and solar irradiance.

TABLE 15.2 Case studies.

Case studies	Demands	Storage capacities	Renewable energy resources
1	Electrical + heating + cooling	–	–
2	Electrical + heating + cooling	ES + HS + CS	–
3	Electrical + heating + cooling	–	Solar + wind
4	Electrical + heating + cooling	ES + HS + CS	Solar + wind

CS, cold storage; *HS*, heat storage.

electricity or gas must be purchased to meet the instantaneous demand, irrespective of the cost of electricity or gas. The total operational cost of energy hub for this case is 295,877.60$, which includes the cost of purchasing electricity and gas from the grid. In this case, no RERs are available, so no operational cost of renewables is included; similarly, the operational cost of storage capacities is also zero. The time in which the cost of electrical energy is high, dependency on gas increases due to its low price as shown in Fig. 15.9. Heat power generated by boiler is shown in Fig. 15.10. This gas is converted into electricity by CHP and more cooling power is produced by absorption chiller rather than electric chiller as shown in Fig. 15.11.

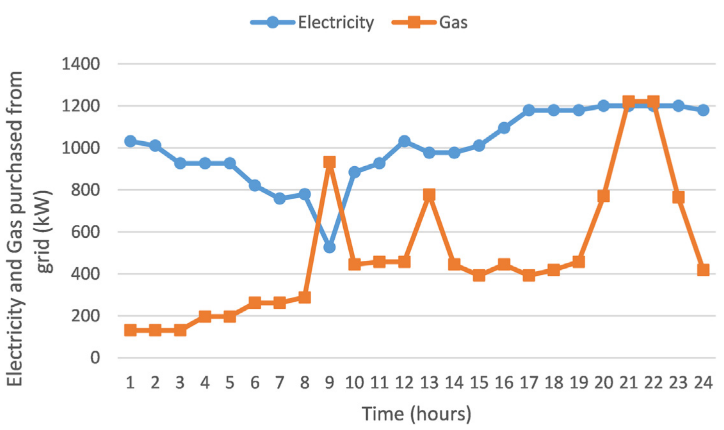

FIGURE 15.9 Electricity and gas purchased from grid in case 1.

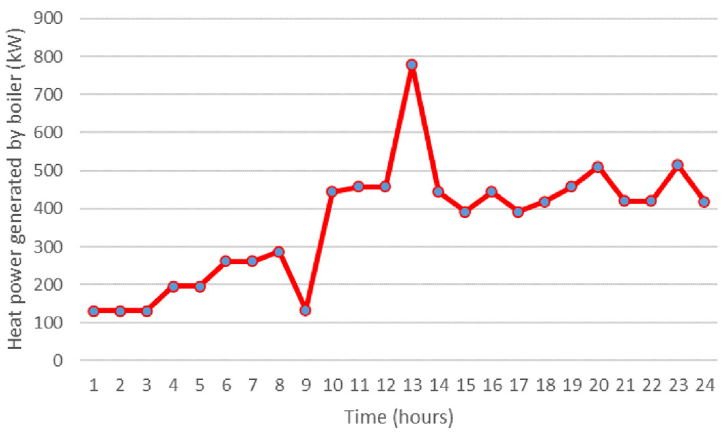

FIGURE 15.10 Heat power generated by the boiler in case 1.

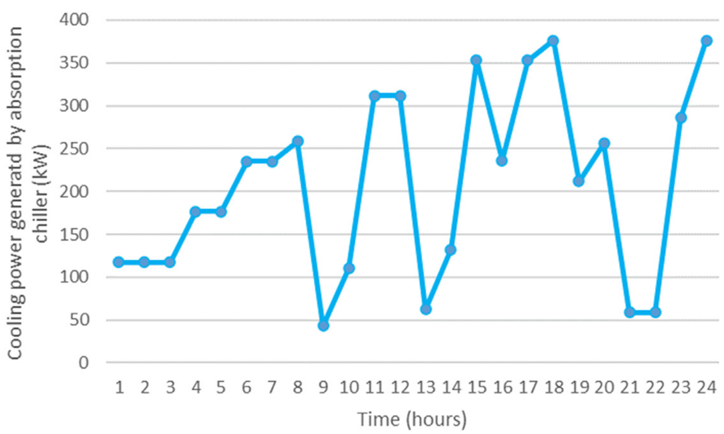

FIGURE 15.11 Electrical power generated by the absorption chiller in case 1.

15.8.1 Optimization of energy hub with storage capacities

In case 2, effect of storage capacities on the operational cost of energy hub has been analyzed whose function is to store energy when the energy cost is low and then provide the stored energy back to the hub when the energy cost is high. The total operational cost of energy hub in this case is 277,103.5$, which includes the cost of purchasing electricity and gas from the grid and operational cost of storage capacities. Although there is some operational cost of storage capacities, which is included in the overall operational cost of energy hub, this cost is far less than the savings done during the peak hours, in which either no or minimum energy is purchased from the commercial grid. The schedule of charge of the electrical storage, HS, and CS are shown in Fig. 15.12.

The electricity and gas purchased from the grid in case 2 is shown in Fig. 15.13.

The heat power generated by the boiler and cooling power generated by the absorption chiller in case 2 is shown in Figs. 15.14 and 15.15, respectively.

15.8.2 Optimization of energy hub with renewable energy resources

In case 3, energy hub has been optimized with the inclusion of RERs but without storage capacities. The cost of operation of energy hub in this case is 224,722.8$, which includes the cost of electricity and gas purchased from the grid and the operating cost of RERs. The operating cost of RERs is very less as compared to the cost of purchasing energy from the grid; this significantly reduces the overall operational cost of energy hub. Not only the inclusion of RERs decreases the quantity of purchased electricity but also the quantity of purchased gas due to coupling of different forms of energies in the energy hub. The additional electrical energy from the RERs is not only used to meet the electrical demand but also to convert it into the cooling power by the electric chiller. This reduces the burden on CHP, which allows it to

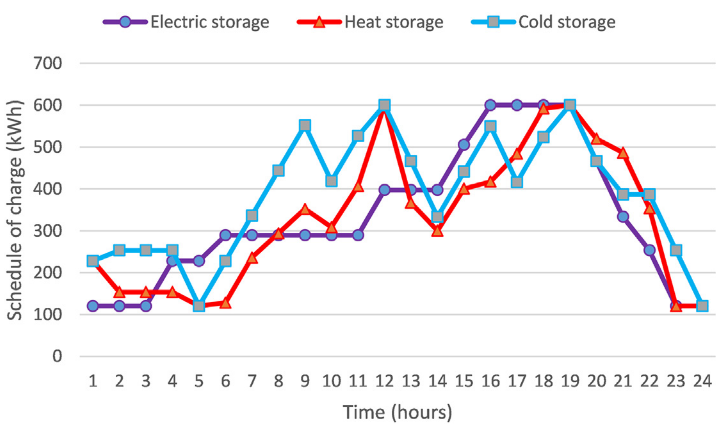

FIGURE 15.12 Schedule of charge for ES, heat storage, and cold storage in case 2.

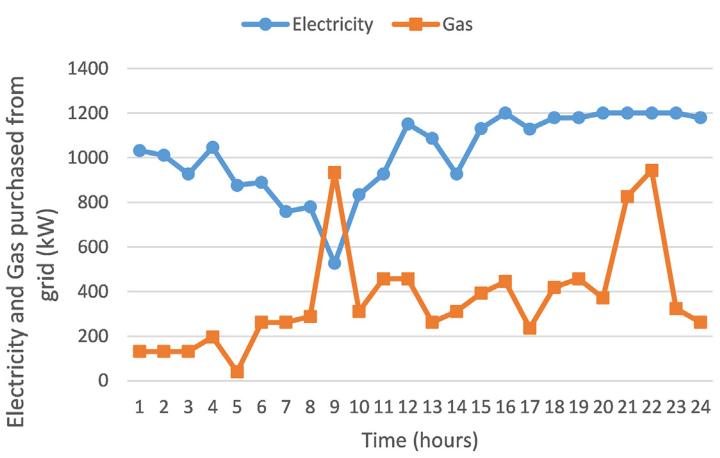

FIGURE 15.13 Electricity and gas purchased from the grid in case 2.

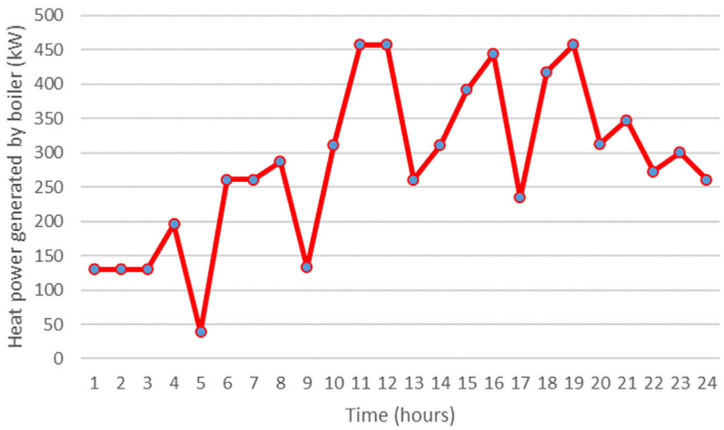

FIGURE 15.14 Heat power produced by the boiler in case 2.

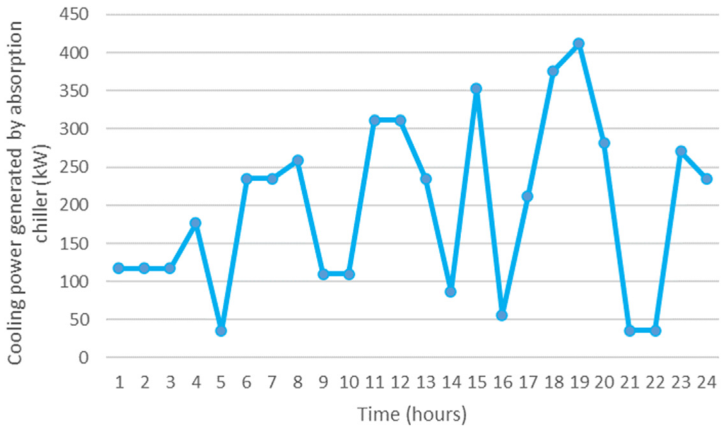

FIGURE 15.15 Cooling power generated by absorption chiller in case 2.

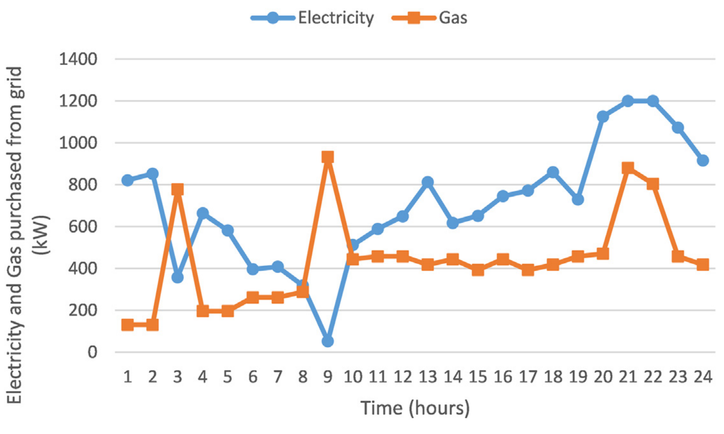

FIGURE 15.16 Electricity and gas purchased from the grid in case 3.

produce more heating power to meet the heating demand. The electricity and gas purchased from the grid in case 3 is shown in Fig. 15.16.

The heat power generated by the boiler and cooling power generated by the absorption chiller in case 3 is shown in Figs. 15.17 and 15.18, respectively.

15.8.3 Optimization of energy hub with storage capacities including renewable energy resources

In case 4, energy hub has been optimized with storage capacities including RERs. The total operational cost of energy hub in this case is 206,983.2$. The storage capacities enable the full utilization of RERs, which not only increases the

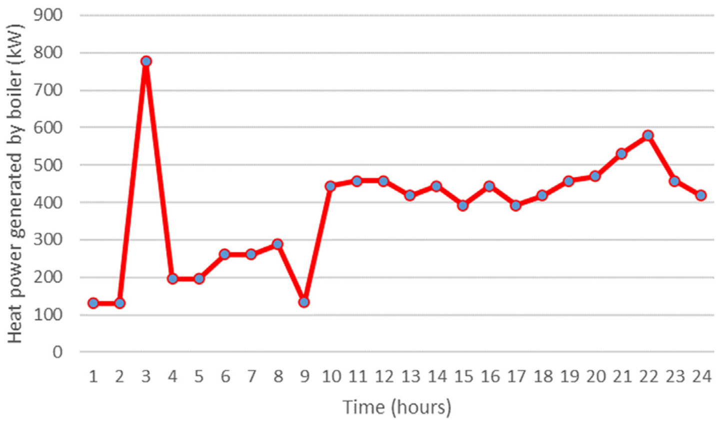

FIGURE 15.17 Heat power generated by the boiler in case 3.

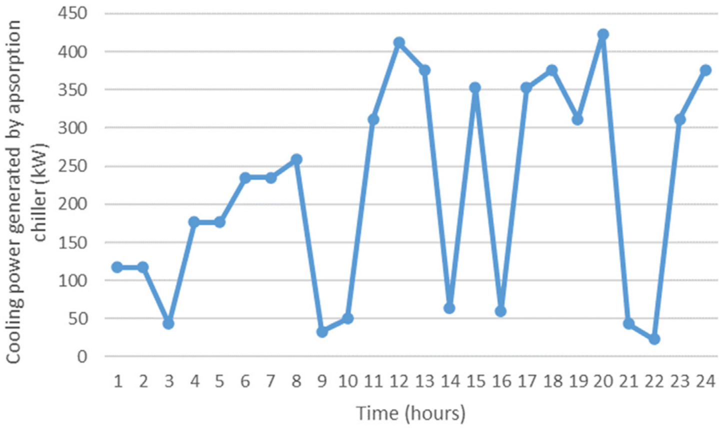

FIGURE 15.18 Cooling power generated by the absorption chiller in case 3.

reliability of the system but also reduces the operational cost of energy hub. The energy produced from the RERs is nondispatchable, which limits their use but with the storage capacities, their usage can be maximized. During the high energy production of RERs, the excess amount of energy is stored in storage capacities (which will not be utilized otherwise) to use at later time when generation is low or cost of purchasing electricity is very high. The electricity and gas purchased from the grid in case 4 is shown in Fig. 15.19. From the figure, it is clear that the purchased electricity and gas from the grid is significantly reduced as compared to the first three cases.

The schedule of charge for ES, HS, and CS in case 4 is shown in Fig. 15.20. The storage capacities charge when the excess energy is available (in case of low demands) or when the cost of purchasing gas or electricity is less. Similarly, when the generation is less, demand is high or the cost of purchasing gas or electricity is high, storage capacities discharge to meet the demand. The operating cost of storage capacities includes in this case. Also, some of the energy wastes in charging/discharging of storage capacities but this cost is much lower than the cost it saves by avoiding peak hour purchasing of gas and electricity.

The heating power generated by the boiler and cooling power generated by the absorption chiller in case 4 is shown in Figs. 15.21 and 15.22, respectively.

15.8.4 Discussion

In this chapter, energy hub model has been optimized under different scenarios to check the effectiveness of different components associated with energy hub. Four different cases are presented based on the combination of different inputs, which can be added to energy hub. In case 1, which is considered as the base case, the energy hub is connected with only conventional sources of energy, such as electricity and gas, as inputs. Some basic components, such as CHP, boiler, absorption chiller, and electric chiller, are used along with these energy sources to meet the electrical, heating, and cooling demands. The electrical demand is met by purchasing electrical energy from the grid or electrical energy

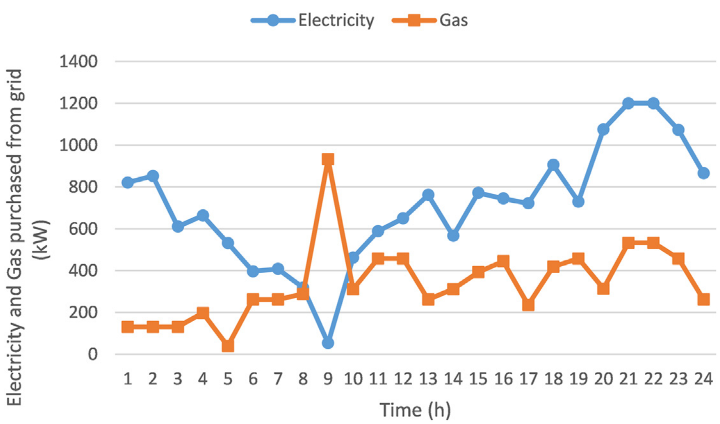

FIGURE 15.19 Electricity and gas purchased from the grid in case 4.

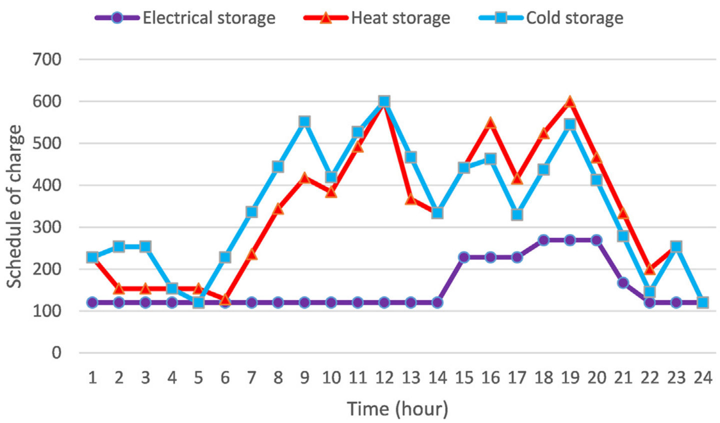

FIGURE 15.20 Schedule of charge for ES, heat storage, and cold storage in case 4.

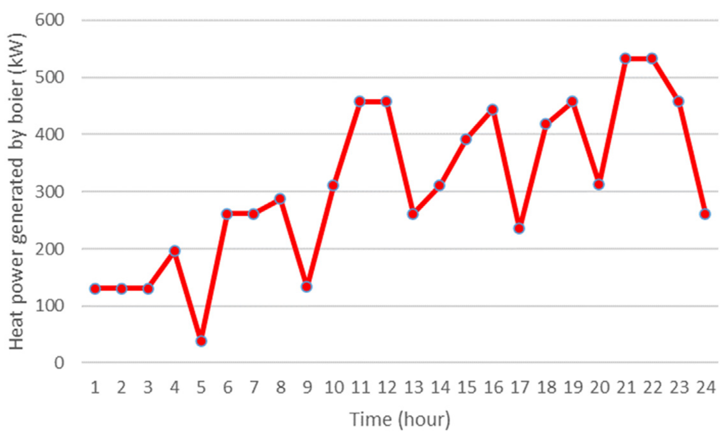

FIGURE 15.21 Heat power generated by the boiler in case 4.

produced by CHP. The gas consumed by the CHP is very high because it is cheaper to produce electrical energy from the CHP instead of purchasing electrical energy from the grid in peak hours as there are no alternatives available in case 1. To meet the cooling demand, the electric chiller and absorption chiller utilized the electrical energy and heat energy respectively. Similarly, heating demand is met by heat produced by the CHP unit and boiler; however, some part of heat produced is also consumed by absorption chiller to meet the cooling demand. The overall cost of operation of energy hub is higher as no cheap alternatives are available. In case 2, storages are added, which helped to store the energies during off-peak hours and this stored energy is supplied back to the energy hub in the peak hours for cost-saving purpose. However, this is not very simple to charge the batteries in off-peak hours and discharge in peak-hours as it includes the operating cost of charging/discharging and losses due to the conversion efficiencies. Despite this, in

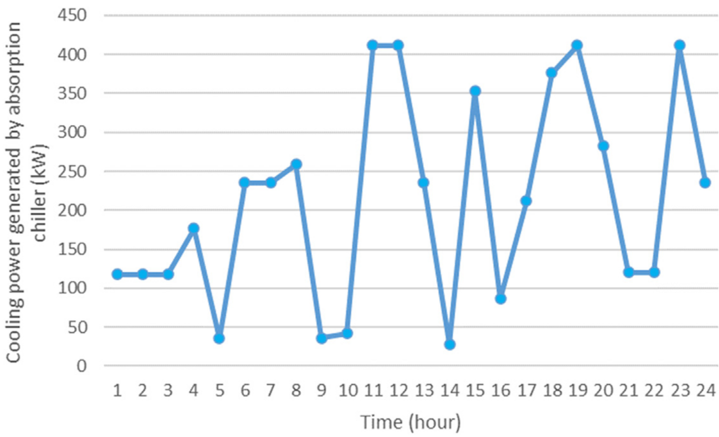

FIGURE 15.22 Cooling power generated by absorption chiller in case 4.

TABLE 15.3 Cost comparison of different cases of energy hub.

Cases	Energy hub	Total cost ($)	Percentage reduction in cost (%)
Case 1	Base case	295,877.6	–
Case 2	Base case + storages	277,103.5	6.34
Case 3	Base case + RERs	224,722.8	24.04
Case 4	Base case + storages + RERs	206,983.2	30.04

RERs, renewable energy resources.

some cases, it is more economical to charge the storages in off-peak time and discharge them in peak time. The inclusion of ESS capacities to energy hub makes it more economical by reducing 6.34% cost as compared to the base case. The percentage reduction in cost is not very promising since the operating cost of energy storages is significant due to charging/discharging. However, it can be useful in increasing the reliability of system upto some extent. In case 3, RERs are added to the base case of energy hub to check their impact on the operational cost of energy hub. The operating cost of RERs is very low as they depend upon wind and sun to produce electrical energy, which is freely available. The inclusion of RERs not only minimizes the dependency upon electrical grid (for purchasing electrical energy) but also decreases the dependency upon gas grid due to reduced consumption of gas by the CHP unit. In this case, most of the electrical energy demand is met by RERs, which reduces the burden on CHP to produce electrical energy, thus saving gas. The dependency upon absorption chiller is also decreased as major portion of cooling demand is now met by electric chiller. The overall operational cost of energy hub has been reduced by 24.04% as compared to the base case. In case 4, both RERs and storage capacities are included in the base case for the optimization of energy hub. Since the RERs are nondispatchable, their maximum benefit can be obtained by combining them with the ESS. The RERs depend upon the wind speed and solar irradiance for their production instead of demand profile—they produce electrical power when wind and solar irradiance are available irrespective required or not. So, if they produce more electrical power than the demand, it will be wasted but with the availability of storage capacities it can be stored for future use when required. The use of storage capacities with RERs increases the operational cost of storage capacities as they participate more in meeting the demands, but the overall operational cost of energy hub decreases significantly, that is, 30.04% compared to the base case. So, the best use of RERs is to use them with storage capacities to decrease the overall cost and increase the reliability of the system (Table 15.3).

15.9 Conclusion

In this chapter, the use and effect of RERs and storage capacities in energy hub are evaluated. The ever-increasing demand of energy with inadequate amount of fossil fuels and growing environmental concerns increases the need of optimal usage of energy sources and more penetration of renewables in existing system. The conventional inputs to the energy hub are electricity and gas from the grid supply, which are mainly from the fossil fuels so their utilization must be curtailed. The best way to do so is to maximize the penetration of renewables in existing system. But due to the unpredictable nature, their increased share can cause the imbalance between supply and demand, which effect the reliability of the system. This problem can be handled by using ESS, which stores the excess energy in case of low demand than the production. To check the effectiveness of RERs usage along with ESS, the energy hub is modeled in this chapter, which includes solar and wind energies as RERs and electrical storage, HS, and CS as ESS. The inclusion of RERs reduces the operational cost of energy hub, but its real advantage can be seen in combination with the ESS. So, the use of RERs in energy hub reduces the dependence on fossil fuels, which is further minimized by adding ESS with RERs. In future, some other kinds of renewables, that is, biogas, biomass, and hydrogen can be added to the energy hub model to make it even more optimal. RERs and load demands can be modeled stochastically to make the results more realistic. The evolving concept of electrical vehicles can be integrated to the energy hub model to charge vehicles when we have excess amount of energy. Similarly, these vehicles can be discharged in critical conditions to make the energy hub more economical, resilient, and reliable.

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