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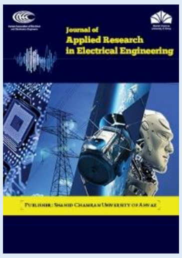

Research Article

Optimal Day-Ahead Scheduling of a CHP and Renewable Resources-Based Energy Hub with the Aim of Improving Resiliency During Input Energy Carriers' Outage

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Abstract: This paper proposes a novel day-ahead energy hub scheduling framework aimed at improving resiliency. Accordingly, an energy hub including combined heat and power (CHP), boiler, electric-heat pump (EHP), absorption and electric chillers, energy storages and renewable sources is considered. This energy hub is equipped with smart grid (SG) infrastructures, making it possible to implement demand response (DR) programs and optimally operate energy storages. The hub is connected to the electricity and natural gas networks. Outage of input energy carriers causes failure of devices in the energy hub, loss of electrical loads, failure in cooling and heating and thus reduced resiliency. Maintaining the security of the hub consumers' power supply system in the event of such severe disturbances is essential. Therefore, a new strategy based on the use of backup electric energy storages (EES) and DR program is proposed in this paper to improve resiliency. In addition, a numerical index is used to accurately calculate and evaluate resiliency. Numerical studies show that the proposed strategy improves resiliency during the outage of power and gas networks by 12.02% and 14.23% respectively when backup energy storages and DR program are implemented simultaneously.

Keywords: Energy hub, renewable energy sources, energy storage, demand response (DR), resiliency.

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NOMENCLATURE

Acronyms

AC	Absorption chiller
CES	Cooling energy storage
CHP	Combined heat and power
DER	Distributed energy resources
DR	Demand Response
EC	Electric chiller
EDS	Electric distribution system
EES	Electric energy storage
EH	Energy hub
EHP	Electric heat pump
HES	Heat energy storage
MINLP	Mixed-Integer Non-Linear Programming
NGDS	Natural gas distribution system
PV	Photo Voltaic
ST	Solar thermal energy
WT	Wind Turbine

Indices

t	Index for time periods
X	Type of storage in terms of energy stored (EES/ HES/ CES)
Y	Original or backup storage (O/B)

Parameters

γ_t^{GE} , γ_t^{NG}	Grid electricity and Natural gas

	prices in time t [$/MWh]
γ^{PV}, γ^{WT}, γ^{ST}	PV, WT and ST operation cost [$/MWh]
γ^{EHP}, γ^{EC}, γ^{AC}	EHP, EC and AC operation cost [$/MWh]
γ^{E}	Electrical DR program cost [$/MWh]
$\gamma^{X,Y}$	Deterioration cost of energy storages [$/MWh]
P_t^D, H_t^D, C_t^D	Electrical, heating and cooling demands at time t [MW]
a, b, c, d, e, f	Coefficients of fuel consumption of CHP unit [1/MWh, -, 1/MWh, -, 1/MWh, MWh]
$(E/H)_{(A/B/C/D)}^{CHP}$	Junction points of feasible operation region of CHP [MW]
M	Large and small enough constants for linearization of feasible operation region of CHP [MW]
η^{Boiler}	Efficiency of boiler [-]
$H_{\max}^{Boiler}$, $H_{\min}^{Boiler}$	Maximum and minimum output heat of boiler [MW]
COP_{cool}^{EC}	Coefficient of performance of electric chiller [-]
C_{max}^{EC}, $C_{\min}^{EC}$	Maximum and minimum output cooling of electric chiller [MW]
COP_{cool}^{AC}	Coefficient of performance of absorption chiller [-]
$C_{\max}^{AC}$, $C_{\min}^{AC}$	Maximum and minimum output cooling of absorption chiller [MW]
COP_{cool}^{EHP}	Coefficients of performance of EHP in cooling mode [-]
$C_{\max}^{EHP}$, $C_{\min}^{EHP}$	Maximum and minimum output cooling of EHP [MW]
$E_{max}^{X,Y,ch}$, $E_{max}^{X,Y,dch}$	Maximum charge and discharge rates of each X and Y [MW]
$E_{\max}^{X,Y}$, $E_{\min}^{X,Y}$, $E_0^{X,Y}$	Maximum, minimum and initial charge levels of each X and Y [MW]
$\eta^{X,Y,ch}$, $\eta^{X,Y,dch}$	Efficiencies of charge and discharge of each X and Y [-]
$par^{low,DR}$	Maximum ratio of shifted low electrical load by DR [%]
$par^{high,DR}$	Maximum ratio of shifted high electrical load by DR [%]
$E_{\max}^{EDS}$, $E_{\min}^{EDS}$	Maximum and minimum interacting power with EDS [MW]
F_{max}^{NGDS}	Maximum received power from natural gas distribution system [MW]

Continuous decision variables	
E_t^{PV}, E_t^{WT}, H_t^{ST}	Output power of PV, WT and ST in time t [MW]
F_t^{CHP}, E_t^{CHP}, H_t^{CHP}	Fuel consumption, output power and output heat of CHP unit in time t [MW]
H_t^{Boiler}, F_t^{Boiler}	Output heat and fuel consumption of boilers in time t [MW]
C_t^{EC}, E_t^{EC}	Output cooling and input electricity of electric chiller in time t [MW]
C_t^{AC}, H_t^{AC}	Output cooling and input heat of absorption chiller in time t [MW]
C_t^{EHP}, E_t^{EHP}	Output cooling and input electricity of EHP unit in time t [MW]
$E_t^{X,Y,ch}$, $E_t^{X,Y,dch}$, $E_t^{X,Y}$	Electricity/Heating/Cooling charge and discharge rates and the charge level of each X and Y in time t [MWh, MWh, MWh]
E_t^{LNS}, H_t^{LNS}, C_t^{LNS}	Load not supplied at time t [MW]
$P_t^{low,DR}$, $P_t^{high,DR}$	Shifted low and shifted high electrical power by DR at time t [MW]
E_t^{EDS}	Electricity purchased from (+) and sold to (-) EDS in time t [MW]
F_t^{NGDS}	Purchased natural gas from natural gas distribution system in time t [MW]
Binary decision variables	
V_t^{CHP}	If CHP unit is on in time t, V_t^{CHP} =1, otherwise 0.
$u_t^{X,Y}$	Binary variable to prevent simultaneous charging and discharging of energy storage
I_t^{low}, I_t^{high}	A binary variable representing shifting high and shifting low condition of electrical load by DR at time t

1. INTRODUCTION

1.1. Aim

Outage of the input electricity or gas of the energy hubs can create disruption in the supply of consumer demand. Therefore, it is necessary to study the behavior of the system subjected to such disturbances and to consider the required preparations in order to maintain resiliency. Resiliency is, in fact, the ability to resist, adapt, and quickly return to normal operation of a system after a severe disturbance [1]. In energy hubs, proper use of energy storage systems with the ability of quick restoration of critical loads can reduce the damage caused by long-term outages and thus improve network resiliency. Moreover, DR programs seem to be one of the efficient tools for proper load shifting and optimal scheduling of energy hub, leading to increased system resiliency. The objective of this paper is to investigate the effect of the participation of backup energy storages and DR programs on the resiliency improvement during the outage of electrical or natural gas networks using an energy hub day-ahead scheduling framework.

1.2. Literature Review

As a new concept in recent years, energy hub has attracted the attention of many researchers in the field of power system scheduling and management. It is a comprehensive and smart framework that provides the load required by the consumer side by combining, converting and storing various energy carriers. Optimal operation of the energy hub makes it possible to securely supply the required loads. In Ref. [2] the structure of a micro energy grid (MEG) based on energy hub including electrical, heating and cooling sub-hubs with renewable energy sources and energy storages has been presented. Also, a day-ahead dynamic optimal operation model has been formulated by considering DR in order to minimize the daily operation cost [2]. In Ref. [3] a model for scheduling an energy hub including CHP, gas boiler, absorption and electric chillers and electrical, heating and cooling energy storages has been proposed. The on/off switch of controllable equipment has been managed and DR programs have been implemented in this paper [3]. In Ref. [4] a combined energy system (CES) with the concept of energy hub including renewable energy sources such as wind and solar energy, electrical, heating and cooling energy storages, voltage conversion units and pressure and temperature control for storages, in the presence of the DR programs has been proposed. The aim of this system is to maximize the benefits of the energy hub [4]. In Ref. [5], an energy hub with three components of CHP, transformer and boiler, connected to electricity and natural gas networks, has been modeled to study the security of the system during natural gas flow outage.

Natural disasters and destructive actions are among the unpredictable events with low probability that can apply severe damage to the distribution system. Hence, around the world, the need to pay attention to higher network resiliency and energy continuity is felt more than ever due to the various consequences of energy outages at different levels. In general, the concept of resiliency is the capacity of an energy system to tolerate disturbances and continue the process of energy delivery to consumers [1]. In [6], a natural gas replacement scheme with electricity has been provided to improve service resilience at the time of earthquake and the creation of a problem for the gas network. In the project, household gas appliances have been replaced with ordinary and advanced electrical appliances so that consumers provide all their needs through the electricity grid. In this paper, the cost of replacing electrical appliances and also considering that power grid lines are more at risk than gas grid lines, potential problems for the power grid have not been considered [6]. Therefore, in the event of a problem for the power grid during the earthquake, replacing gas appliances with electrical appliances does not help increase service resilience.

The use of DR programs, renewable resources and storages can improve the resiliency of the power system. In [7] a distribution service restoration (DSR) framework using a multi-stage dynamic optimization model has been proposed to achieve a resilient distribution network in the presence of a DR program. In this paper, despite the use of electricity storage in the microgrids, the effect of storage on the improvement of resiliency has not been investigated [7]. In [8], a risk-constrained stochastic framework has been presented for joint energy and reserve scheduling of a resilient microgrid considering demand side management. In this article, the sensitivity of the microgrid profit, reliability indices, and the operator decision making in cases with and without the participation of customers to price-based DR programs have been studied by implementing a security-constrained power flow method in the scheduling process that can guarantee reliable operation of the microgrid under uncertainty, especially in islanding periods. In [9], an energy management strategy for daily networked microgrid scheduling called nested EMS has been proposed to increase system resiliency. In this method, if a microgrid is disconnected from the power grid and enters the island mode, the resiliency of the system through subgroups as well as the battery energy storage system will increase.

In [10], a process of resiliency analysis in networked microgrids in the presence of renewable energy sources along with an EES has been proposed. The EES has been scheduled to control fluctuations in the generation of renewable sources in both rainy and sunny days [10]. Moreover, the EES has been used to support the power distribution system during outage. However, in this paper, the power outage is considered to be a short interval of 3 hours and the solution adopted may not be suitable for long intervals. In [11] a process of resiliency analysis in microgrids along with distributed energy storage (DES) support for load restoration has been presented. In the case of power outage, DESs supply the required electricity by changing to the discharge mode. DESs are charged only through the power grid, which may not be able to restore the load in the event of a power outage and long-term lack of access to the grid, as well as in the event of consecutive outages.

In [12] energy resiliency modeling for a smart home (which is mainly powered by solar energy) with a local EES unit has been presented. Moreover, the effect of different EES operation strategies on resiliency for different generation and consumption patterns have been analyzed in this paper. In this paper, demand response programs are not used to improve resiliency that, better results will be obtained if this issue is considered. Using the idea of different strategies for using smart home batteries to improve the resiliency of the energy hub is useful due to the presence of converters such as CHP, boilers, chillers, etc. Also, the presence of heating and cooling energy carriers, the use of heating and cooling energy storages in addition to electrical energy storage can create more effective results. As mentioned earlier, in the energy hub, despite the smart grid infrastructure, the necessary ground is provided for the use of demand response programs. Therefore, the effect of demand response programs along with the idea of different battery operation strategies on improving resiliency can be examined. Therefore, examining the issue of resiliency and calculating the degree of resiliency using the metric in the energy hub can be a significant issue that has not been considered based on the knowledge of the authors.

1.3. Contributions

This paper proposes a day-ahead scheduling framework for a CHP-based energy hub and renewables aimed at improving resiliency. The energy hub includes CHP, boiler, absorption chiller, electric chiller, electric heating pump (EHP) and electrical, heating and cooling energy storages. Renewable sources such as wind turbines (WT), photovoltaic panels (PV) and solar-thermal panels (ST) have also been used to meet part of the electricity and heating demand. The hub energy supplies the required energy, gas and part of its required electricity through gas and electricity networks. Any outage or disruption in the electricity or natural gas network will cause heavy damage to the energy hub. Improving hub resiliency can reduce outage damage. Therefore, in this paper, the increase of resiliency and continuity of hub energy during power or gas outages has been addressed. Moreover, in order to improve resiliency, the DR program for electrical load as well as backup battery strategies for all three electrical, heating and cooling loads have been employed. The scope of models in the technical literature and the contribution of this article are summarized in Table 1 (in the appendix). Compared to the existing studies, the main contributions of this article can be summarized as follows.

1. An optimization framework for energy scheduling of a resilient energy hub with DR programs and backup storage has been provided. In the proposed model, the operation has been performed in two modes: normal mode (connected to the grid) and outage mode of energy carriers.

2. The sensitivity of operating costs, load shedding of different loads during outages of input energy carriers and energy hub resiliency in cases with and without the participation of customers to price-based DR programs and the impact of energy backup storage have been studied in the scheduling process that can guarantee resilient operation of the energy hub, especially in outages of input energy carriers periods.

3. The most important devices in the energy hub (CHP and Boiler), which provide the highest amount of energy, consume gas fuel. Also, in areas which their thermal demands depend on natural gas, during the gas lines contingency face with thermal load shedding disaster. Therefore, the study of energy hub resilience during gas network outage is one of the important issues studied in this paper. Also, resiliency has been calculated for all consumer demands (electricity, heating and cooling) using a practical and accurate index.

1.4. Paper Organization

The rest of this paper has been organized as follows: in section 2, the architecture of the energy hub is delineated. In section 3, problem formulation is proposed. Case studies and numerical results are illustrated in section 4. Finally, some related conclusions are derived in section 5.

2. Architecture of the Proposed Energy Hub

The energy hub is a new evolutionary trend for the traditional distribution network, which integrates natural gas, electricity, heating, cooling, etc. Fig. 1 shows the proposed energy hub architecture, in which electricity and gas are considered as input energy carriers. On the other hand, WTs, PVs and STs as renewable energy sources are the sources of electricity and heating, supplying a part of the demands of the energy hub at different hours. Electricity, heating and cooling are also identified as energy hub outputs. CHP, boiler, absorption chiller, electric chiller, EHP as energy converters along with electrical, heating and cooling energy storages form the desired energy hub architecture.

One of the essential aspects of energy management is to ensure system security and increase network resiliency during disturbances [5]. Therefore, the resiliency of the system during power or gas outages is studied in this paper. Accordingly, in order to manage storages in the multi-carrier space of the energy hub, as well as to improve energy efficiency and minimize operating costs and calculate resiliency a new scheduling framework has been presented in this paper as shown in Fig. 2 (in the appendix). The energy hub is equipped with an energy management system (EMS) to schedule its local resources and to trade energy with the main grid. In this scheme, the customers are equipped with house energy management controllers and are able to respond to the electricity prices by adjusting their demand to reduce their consumption costs.

The operation of the energy hub is decomposed into normal and resilient operations. At the normal operation, energy hub is connected to the main grid, thus the EMS schedules the local DERs. However, when a severe disturbance event occurs in the main grid, energy hub can switch into resilient operation (i.e., outage mode). In this mode, EMS schedules available local resources to supply local loads with the lowest mandatory load shedding. Due to the presence of several different energy carriers in the hub, the priority of load supply during outage is considered based on the type of output energy carriers. The first priority is related to electricity load supply. The reason for this is that a summer day is studied in this article and in summer the demand for cooling is high and most of the cooling energy is supplied by the electric chiller and EHP, with electricity consumption. Although cooling energy supply is very

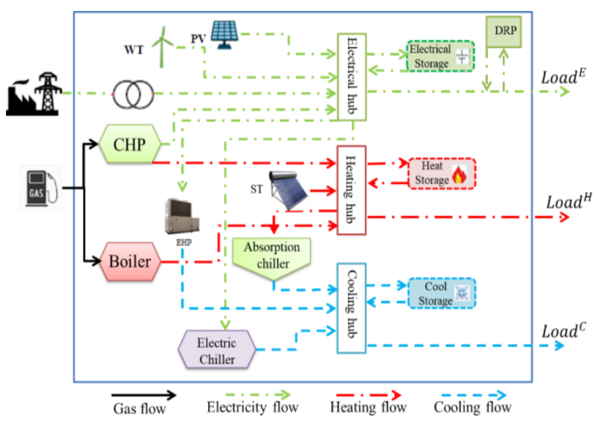


Fig. 1: The energy hub architecture.

important in summer, but the second priority is to provide heating load, which is due to the supply of some cooling energy by the absorption chiller with heating consumption. The electrical, heating and cooling energy storages in the energy hub can reduce the damage caused by long-term outages, and thus improve resiliency by restoring critical loads. Moreover, three more backup batteries have been provided in this paper to reduce the load shedding during the outage hours of energy carriers. In addition to storage devices, the DR program has been designed and implemented to change the pattern of electricity consumption with the aim of further adapting demand with generation hence, reducing load shedding and increasing resiliency at the outage hours of input energy carriers.

It should be noted that the cost of purchasing electricity from the electricity network, during the outage of the gas network, is considered higher than normal. The reason for this is more purchases from the electricity network during the gas network outage. This cost is defined as a step based on the comparison of the purchase of electricity from the electricity network in the normal state and the definite state of the gas network. Also in this model, demand response programs operate during the power network outage, based on the price set by the system operator. The price set by the operator is based on the percentage rate of load in the outage state compared to the normal state.

3. Mathematical Formulation

The general formula for the energy hub has been considered with respect to the effect of DR implementation and backup storage on system resiliency by creating different scenarios. This section includes objective function formulas, energy converters, and problem constraints. The formulation of energy converters has been presented to determine the relationship between the devices used in the energy hub.

3.1. The Objective Function

The objective function (1a) is to minimize the total cost of the energy hub across the scheduling horizon, i.e., overnight. The cost of an energy hub consists of two terms. The first term, defined in (1b), Refers to the cost of the energy hub in the conditions connected to the network. The second term, defined in (1c), Refers to the cost of the energy hub during the outage of the input energy carriers (electricity or gas networks). and include several costs that are defined separately. Term, defined in (1d), refers to the cost of fuel (natural gas) CHP and boiler. Term, defined in (1e), refers to the cost of buying/selling electricity from/to the grid. Term, defined in (1f), refers to the cost of photovoltaic panels and wind turbines. Term, defined in (1g), refers to the costs of generating cooling and heating energy by EHP, electric and absorption chillers, and solar-thermal panels. Term, defined in (1h), Refers to the cost of energy storage by the original storage in the energy hub. Term, defined in (1i), Refers to the cost of energy storage by the backup storage in the energy hub. Term, defined in (1j), refers to the cost of DR.

$$Min\ TotalCost = CostNormal + CostOutage \tag{1a}$$

$$\begin{aligned} CostNormal &= CostNG + CostGE + CostE + \\ &CostC\&H + CostOStorage + CostDR \end{aligned} \tag{1b}$$

$$CostOutage = \begin{cases} CostNG + CostE + CostC\&H + CostOStorage + \\ CostBStorage + CostDR & \text{Outage=Network Power} \\ \\ CostGE + CostE + CostC\&H + CostOStorage + \\ CostBStorage + CostDR & \text{Outage=Network Gas} \end{cases} \tag{1c}$$

$$CostNG = F_t^{CHP} + \left(F_t^{Boiler} \times \gamma_t^{NGDS}\right) \tag{1d}$$

$$CostGE = \sum_t \gamma_t^{GE} \times E_t^{EDS} \tag{1e}$$

$$CostE = \sum_t \gamma^{PV} \times E_t^{PV} + \sum_t \gamma^{WT} \times E_t^{WT} \tag{1f}$$

$$\begin{aligned} CostC\&H &= \sum_t \gamma^{EHP} \times C_t^{EHP} + \sum_t \gamma^{EC} \\ &\times C_t^{EC} + \sum_t \gamma^{AC} \times C_t^{AC} + \sum_t \gamma^{ST} \times H_t^{ST} \end{aligned} \tag{1g}$$

$$CostOStorage = \sum_{t,X} \gamma^{X,O} \times \left(E_t^{X,O,ch} + E_t^{X,O,dch}\right) \tag{1h}$$

$$CostBStorage = \sum_{t,X} \gamma^{X,B} \times \left(E_t^{X,B,ch} + E_t^{X,B,dch}\right) \tag{1i}$$

$$CostDR = \sum_t \gamma^{E} \times \left(P_t^{low,DR} + P_t^{high,DR}\right) \tag{1j}$$

3.2. CHP Modeling

CHP units receive gas as input energy and generate electricity and heating simultaneously. Therefore, CHP plays a key role in the energy hub by connecting the three energy carriers. It should be noted that the electricity and heating generation of CHP units are interdependent and cannot be controlled separately [13]. In other words, the electricity and heating are generated by each CHP unit overlap. This means that the electricity generated by the CHP limits its heating output and vice versa [3]. Each CHP unit has a practical operation area, which shows the interdependence of electricity and heating generation. The operating cost of CHP units is a function of electricity and heating generated defined as (2a):

$$F_t^{CHP} = a \times E_t^{CHP} + b \times \left(E_t^{CHP}\right)^2 + c + d \times H_t^{CHP} + e \times \left(H_t^{CHP}\right)^2 + f \times H_t^{CHP} E_t^{CHP} \quad (2a)$$

$$E_t^{CHP} - E_A^{CHP} - \frac{E_A^{CHP} - E_B^{CHP}}{H_A^{CHP} - H_B^{CHP}} \times \left(H_t^{CHP} - H_A^{CHP}\right) \le 0 \;\; \forall t \quad (2b)$$

$$E_t^{CHP} - E_B^{CHP} - \frac{E_B^{CHP} - E_C^{CHP}}{H_B^{CHP} - H_C^{CHP}} \times \left(H_t^{CHP} - H_B^{CHP}\right) \ge -\left(1 - V_t^{CHP}\right) \times M \quad \forall t \quad (2c)$$

$$E_t^{CHP} - E_C^{CHP} - \frac{E_C^{CHP} - E_D^{CHP}}{H_C^{CHP} - H_D^{CHP}} \times \left(H_t^{CHP} - H_C^{CHP}\right) \ge -\left(1 - V_t^{CHP}\right) \times M \quad \forall t \quad (2d)$$

$$E_C^{CHP} \le E_t^{CHP} \le E_A^{CHP} \times V_t^{CHP} \quad \forall t \quad (2e)$$

$$0 \le H_t^{CHP} \le H_B^{CHP} \times V_t^{CHP} \quad \forall t \quad (2f)$$

The feasible operation region for the CHP units studied in this paper has been shown in Fig. 3. This region is modelled by (2b) - (2d). Equation (2b) models the area below the line AB and (2c) models the area above the BC line. Also, the area above the CD line has been modeled using (2d). In these equations, M represents a very large number, and indices A, B, C and D represent the four margin points of the feasible operation region for CHP. And E_A^{CHP}, E_B^{CHP}, E_C^{CHP} and E_D^{CHP} are the electrical power and H_A^{CHP}, H_B^{CHP}, H_C^{CHP} and H_D^{CHP} are the thermal power points of the CHP areas. In (2c) and (2d), if the binary variable V_t^{CHP} is zero, the CHP output power and heating will be zero. Equations (2e) and (2f) express the power and heating generation constraints of CHP units.

3.3. Boiler Modeling

The boilers receive natural gas, F_t^{Boiler}, as their input energy source and convert the consumed gas to heat, H_t^{Boiler}, with the conversion efficiency of η^{Boiler} in (3a). The heating energy generated by the boilers is limited using (3b).

$$F_t^{Boiler} = \eta^{Boiler} \times H_t^{Boiler} \quad \forall t \quad (3a)$$

$$H_{min}^{Boiler} \le H_t^{Boiler} \le H_{max}^{Boiler} \quad \forall t \quad (3b)$$

3.4. Electric Chiller Modelling

The electric chiller uses electricity E_t^{EC} to generate cooling energy C_t^{EC}, where the amount of electricity consumed and the cooling generated are related by the chiller's coefficient of performance, COP_{cool}^{AC}; this relationship has been defined in (4a). Also, the cooling energy generated by the chiller is limited in (4b).

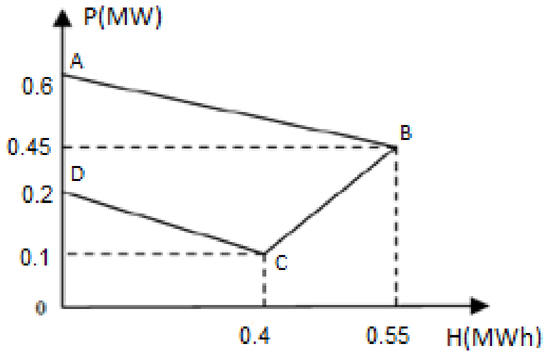


Fig. 3: Heat-power feasible operation region for the CHP.

$$C_t^{EC} = E_t^{EC} \times COP_{cool}^{EC} \quad \forall t \quad (4a)$$

$$C_{min}^{EC} \le C_t^{EC} \le C_{max}^{EC} \quad \forall t \quad (4b)$$

3.5. Absorption Chiller Modeling

The main difference between an absorption chiller and an electric chiller is that the input energy of the absorption chiller is heat, while the input energy of the electric chiller is electricity. The relationship between consumed heating, H_t^{AC}, and generated cooling of the absorption chiller, C_t^{AC}, as well as the constraint related to the generated cooling of the absorption chiller have been defined in (5a) and (5b), respectively.

$$C_t^{AC} = H_t^{AC} \times COP_{cool}^{AC} \quad \forall t \quad (5a)$$

$$C_{min}^{AC} \le C_t^{AC} \le C_{max}^{AC} \quad \forall t \quad (5b)$$

3.6. EHP Modeling

EHPs are of the most widely used equipment in the design of energy hubs, which work with electrical energy. These systems use heating stored in air, water and land to generate heating or cooling [14-16]. The electricity consumed in these systems is used to extract the stored heating and not to generate it. In these systems, several units of heating are usually extracted from the environment for the consumption of one unit of electrical energy [17]. EHPs are employed only for heating generation in winter and cooling generation in summer [3]. Given that this paper examines a summer day, EHP is used only to generate cooling. As demonstrated in (6a), power consumption, E_t^{EHP}, and generated cooling, C_t^{EHP}, are interconnected by the EHP coefficient of performance, COP_{cool}^{EHP}. Also, the cooling energy generated by EHP is limited by on (6b).

$$C_t^{EHP} = E_t^{EHP} \times COP_{cool}^{EHP} \quad \forall t \quad (6a)$$

$$C_{min}^{EHP} \le C_t^{EHP} \le C_{max}^{EHP} \quad \forall t \quad (6b)$$

3.7. Storage's Modeling

Energy storage devices are essential components for energy hubs, which have the ability to transfer energy in time dimensions. Storage devices store excessive energy or low-cost energy, and use it in times of energy shortages or high-priced hours [18]. The process of charging and discharging energy is similar for all the electrical, heating and cooling energy storages, which depends on the charge/discharge constraints, storage capacity and technical constraints [19]. The amount of energy stored is expressed in (7a) for scheduling horizon periods, and the constraints on the amount of energy stored are defined in (7b). The constraints on the amount of charge and discharge of energy have been defined in (7c) and (7d), respectively. Notably, the storage cannot charge and discharge energy simultaneously and, the binary variable $u_t^{X,Y}$ has been used to prevent simultaneous charging and discharging. Equation (7e) ensures that the initial charge level of the storage is equal to the end of the scheduling horizon.

$$E_t^{X,Y} = E_{t-1}^{X,Y} + \eta^{X,Y,ch} \times E_t^{X,Y,ch} - E_t^{X,Y,dch} \quad \forall X, \forall Y, \forall t \tag{7a}$$

$$E_{min}^{X,Y} \le E_t^{X,Y} \le E_{max}^{X,Y} \quad \forall X, \forall Y, \forall t \tag{7b}$$

$$0 \le E_t^{X,Y,ch} \le u_t^{X,Y} \times E_{max}^{X,Y,ch} \quad \forall X, \forall Y, \forall t \tag{7c}$$

$$0 \le E_t^{X,Y,dch} \le \left(1 - u_t^{X,Y}\right) \times E_{max}^{X,Y,dch} \quad \forall X, \forall Y, \forall t \tag{7d}$$

$$E_{24}^{X,Y} = E_0^{X,Y} \quad \forall X, \forall Y \tag{7e}$$

Superscript X indicates the type of storage in terms of energy stored in it, which is electrical energy storage (EES), heating energy storage (HES) and cooling energy storage (CES), whereas the superscript Y indicates the type of storage, i.e., original (O) or backup (B). $E_t^{X,Y}$ is the energy stored after charging/discharging energy, while $E_{t-1}^{X,Y}$ is the energy stored before charging/discharging energy at time t. $E_t^{X,Y,ch}$ is the charge rate and $E_t^{X,Y,dch}$ is the discharge rate at time t.

3.8. DR Program Modeling

DR program is an efficient tool for transferring load from peak to off-peak hours in order to optimally manage the energy hub [20], reduce electricity and natural gas consumption, as well as energy hub costs [21]. In this paper, in addition to the aforementioned applications, the DR program has been used as a tool to reduce the load shedding during the outage of energy carriers and increase resiliency. The following equations show the formulation of DR program constraints.

Equation (8a) show the balance between shifted high and low of electrical load. Or, in other words, the load shifting from high price time, $P_t^{high,DR}$, had to be done equally at a lower price time, $P_t^{low,DR}$. Equation (8b) express the limits allowed for the shifted high load at the low-price time with respect to the percentage of participation in the DR. The allowable limits for the shifted low load at the high price time and with respect to the percentage of participation in DR is expressed by (8c). Equation (8d) also states a constraint to prevent simultaneous load changes during high price hours and low-price hours, for which the binary values I_t^{low} and I_t^{high} have been used.

$$\sum_{t=1}^{24} P_t^{high,DR} = \sum_{t=1}^{24} P_t^{low,DR} \quad \forall t \tag{8a}$$

$$0 \le P_t^{high,DR} \le par^{high,DR} P_t^D I_t^{high} \quad \forall t \tag{8b}$$

$$0 \le P_t^{low,DR} \le par^{low,DR} P_t^D I_t^{low} \quad \forall t \tag{8c}$$

$$0 \le I_t^{high} + I_t^{low} \le 1 \quad \forall t \tag{8d}$$

3.9. Constraints of Connection Lines

The amount of electricity exchanged with the power grid, E_t^{EDS}, and the gas exchanged with the gas network, F_t^{NGDS}, should not exceed the maximum connection line between the energy hub and the electricity and natural gas network, where the constraints have been defined in (9a) and (9b).

$$E_{min}^{EDS} \le E_t^{EDS} \le E_{max}^{EDS} \quad \forall t \tag{9a}$$

$$0 \le F_t^{NGDS} \le F_{max}^{NGDS} \quad \forall t \tag{9b}$$

3.10. Energy Balance

- Balance in the electrical sector

$$E_t^{EDS} + E_t^{EES,Y,dch} \times \eta^{EES,Y,dch} + E_t^{CHP} + E_t^{WT} + E_t^{PV} + P_t^{high,DR} = P_t^D + E_t^{EES,Y,ch} + E_t^{EC} + E_t^{EHP} + P_t^{low,DR} \quad \forall t \tag{10a}$$

- Balance in the heating sector

$$H_t^{CHP} + H_t^{Boiler} + E_t^{HES,Y,dch} \times \eta^{HES,Y,dch} + H_t^{ST} + H_t^{EHP} = H_t^D + E_t^{HES,Y,ch} + H_t^{AC} \quad \forall t \tag{10b}$$

- Balance in the cooling section

$$C_t^{EC} + C_t^{AC} + E_t^{CES,Y,dch} \times \eta^{CES,Y,dch} = C_t^D + E_t^{CES,Y,ch} \quad \forall t \tag{10c}$$

3.11. Resiliency Modeling

Resiliency is the ability of a system to tolerate the events with a low probability of occurrence and high destructive effects by minimizing outages and returning to normal operation of the power system [22]. In power systems, load shedding is widely known as a disturbance which directly affects the system restoration process [23]. In the proposed model, the gas or electricity networks outage has been considered for the energy hub, and the effect of the participation of the power DR program and the backup storage on the load shedding and resiliency of the system is investigated. From the point of view of the system resiliency index presented in Ref. [23], system performance is defined as the load supply at any time t as shown in Fig. 4. It should be noted that the lower the load shedding and the more resilient the system, the smaller the hatched area [23].

Then, the resiliency of the system can be determined as follows:

$$Resilience = \int_{t_0}^{t_1} \left[Q_0(t) - Q_1(t) \right] dt \tag{11}$$

This index is used to assess the overall resiliency of the system under a particular disturbance. $Q_0(t)$ represents the load supply in normal state. $Q_1(t)$ denotes the load shedding after a gas or power outage in the time interval $[t_0, t_1]$.

4. Numerical Studies

4.1. Data and Assumptions

As mentioned earlier, the sample energy hub has been connected to the electricity and natural gas networks, and supplies its natural gas and part of the electricity demand through the electricity and natural gas networks. The maximum amount of electricity and gas received from electricity and natural gas networks are 0.78 and 0.6 MW/h, respectively. This paper has studied the resiliency of an energy hub during a power or gas network outage for 9 consecutive hours during a day (a typical summer day). Electrical, heating and cooling demands on this summer day have been shown in Fig. 5. In the desired energy hub, wind and solar energy has been used to meet a part of consumer demand. The output power of wind turbine, photovoltaic panel and solar-thermal panel has been shown in Fig. 6. Also, the cost of electricity and natural gas has been presented in Fig. 7, and information about the parameters of the energy hub components is summarized in Table 2 (in the appendix). Changes in the cost of purchasing electricity from the electricity network during the gas network outage are shown in Table 3. Also, the price set by the operator for the utilization of load response programs during the power outage, based on the cost of the power grid in normal mode is shown in Table 4. It is noteworthy that the proposed design has been formulated as an MINLP problem and is solved by GAMS [24] software and SBB solver. The SBB solver is used in GAMS software to solve MINLP models. The problem-solving method by this solver is usually based on a combination of standard branch and bound methods [25]. The average computation time on a core i5 PC, 2.6 MHz with 8 GB of RAM is less than a minute.

4.2. Case Studies

With the aim of analyzing the optimal operation of the energy hub and investigating the effect of DR program and backup storages on reducing load shedding and increasing system resiliency during the hours of gas or electricity networks outage, six different scenarios are examined (Table 5). In scenarios 1, 2 and 3, the energy hub resiliency is studied during the natural gas network outage. In scenario 1, no measures have been considered to increase the resiliency. In Scenario 2, backup storages, and in Scenario 3, backup

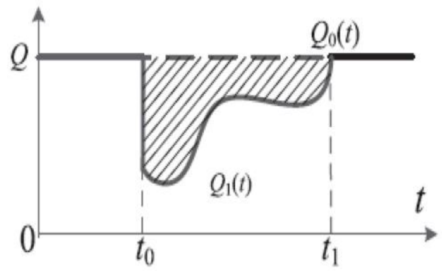


Fig. 4: Resiliency triangle.

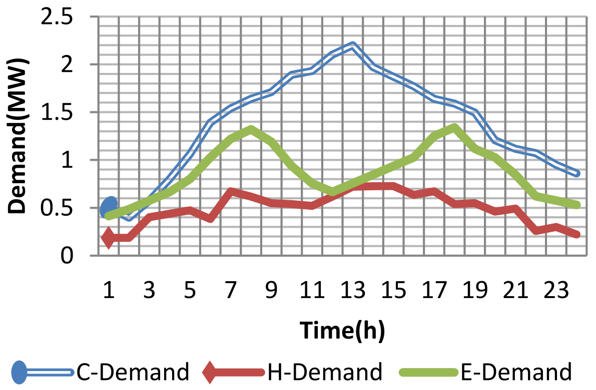


Fig. 5: The electrical, heating and cooling demand of the energy hub.

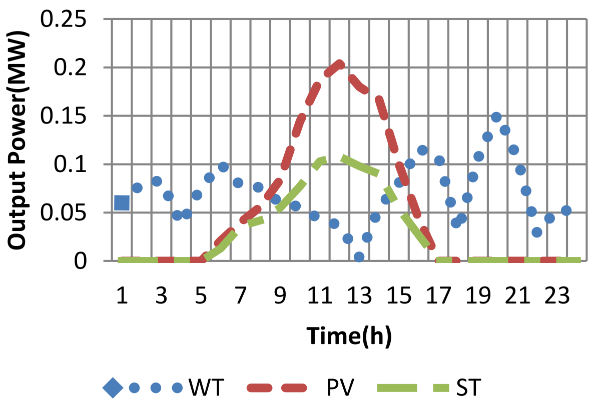


Fig. 6: Output power of WT, PV and ST.

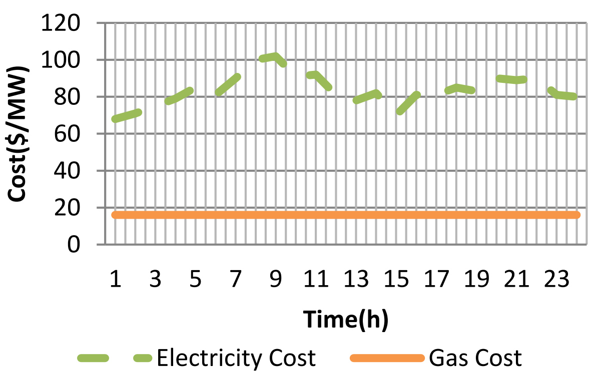


Fig. 7: The cost of electricity and gas.

Table 3: Changes in the cost of purchasing electricity from the grid during the outage network gas

The difference between buying electricity from the network in the normal state and the outage state of the gas network (MW)	Price($)
0	γ_t^{GE}
0.001-0.2	$1.05\gamma_t^{GE}$
0.201-0.4	$1.1\gamma_t^{GE}$
0.401-0.6	$1.15\gamma_t^{GE}$
0.601-0.8	$1.2\gamma_t^{GE}$

Table 4: The price set by the operator for the use of demand response programs during power network outage

The percentage of load in the outage state compared to the normal state	Price($)
0 – 20%	$1.2\gamma_t^{GE}$
21% - 40%	$1.15\gamma_t^{GE}$
41% - 60%	$1.1\gamma_t^{GE}$
61% - 80%	$1.05\gamma_t^{GE}$
81% - 100%	γ_t^{GE}

storages and DR program have been used simultaneously with the aim of enhancing resiliency in the energy hub. In Scenarios 4, 5 and 6, resiliency has been studied during the power outage. In Scenario 4, as in Scenario 1, no backup is provided to make the system resilient. In Scenario 5, only backup storages and in Scenario 6, in addition to backup storages, the DR program has been used to increase resiliency.

4.3. Simulation Results

4.3.1. Energy balance in scenarios related to gas network outages

- Electrical balance

The electrical balance for the first three scenarios, which are related to the gas network outage, has been shown in Fig. 8. In this figure, the upper bar charts show generation and the lower bar charts show consumption. CHP is one of the devices used to reduce energy purchases from the power grid, and consequently decrease operating costs in energy hubs. The CHP is switched off with gas network outage between 9- and 17-hours local time due to the gas fuel it uses. The CHP generates almost as much power as possible during all the hours it is in the circuit. This value shows the power generation corresponding to above point B in the

Table 5: Scenarios

Scenario	Outage of Gas network	Outage of Electricity network	Backup storage	DR program
1	❊	-	-	-
2	❊	-	❊	-
3	❊	-	❊	❊
4	-	❊	-	-
5	-	❊	❊	-
6	-	❊	❊	❊

operational area applicable to CHP in Fig. 3. According to Fig. 8, in all the first three scenarios, the purchase of electricity is less than EDS during the connection hours of the CHP. This is because the generation by CHP is cheaper than buying from EDS. However, during CHP outage, the amount of electricity purchased from the grid is at its maximum value of 0.78 MWh. Another efficient tool used in this energy hub to meet part of the electricity demand is renewable energy sources such as WT and PV. The maximum electricity generated by WT is 0.152 MW/h and the maximum generated electricity by PV is 0.204 MW/h, which reduces operating costs by generation. The original EES charge/discharge pattern is influenced by electricity tariffs.

In the first three scenarios, the original EES starts loading at low price hours and in case of excess electricity, the original of electricity stored in the original EES decreases at high price hours and if needed during CHP outage hours. As observed in Fig. 8, in the early hours of the day (1-3) and also sometimes in the middle hours of the day (11-14) when electricity costs are low, the original EES is charging. Also, in the hours 7-10 and 15-19 that the cost of electricity is high or there is a shortage of electricity, it is discharging energy. Therefore, the original EES system causes less energy to be purchased from the grid at high price hours and the cost of operating the energy hub is reduced. In scenarios 2 and 3, backup EES has also been used in addition to the original EES system. According to Fig. 8, in Scenario 1, which does not use backup EES and DR, the load shedding during the CHP outage hours is significant. But in Scenario 2, some of the load related to CHP outage hours is supplied by backup EES, and the load shedding is less than that in Scenario 1. In Scenario 3, a DR program has been also used in addition to the backup EES. With the participation of the DR program, some of the load related to the CHP outage hours has been transferred to the off-peak hours when the CHP is connected, and the load shedding has been reduced compared to scenarios 1 and 2.

- Cooling balance

The cooling balance for the first three scenarios has been shown in Fig. 10. In this figure, the upper bar charts show generation and the lower bar charts show consumption. Due to the fact that we have a summer day to study, the demand for cooling is high. Therefore, electric chiller, absorption chiller, EHP and CES have been used to

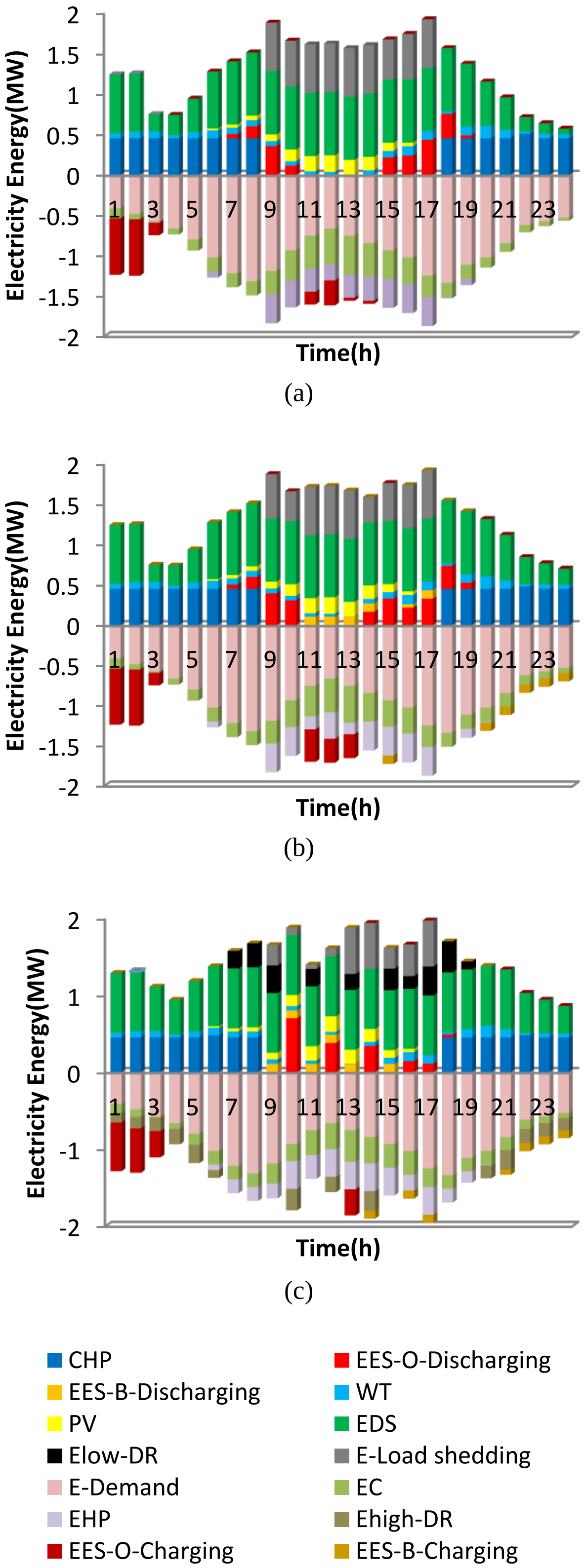


Fig. 8: Electrical balance in three scenarios related to gas network outages, (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

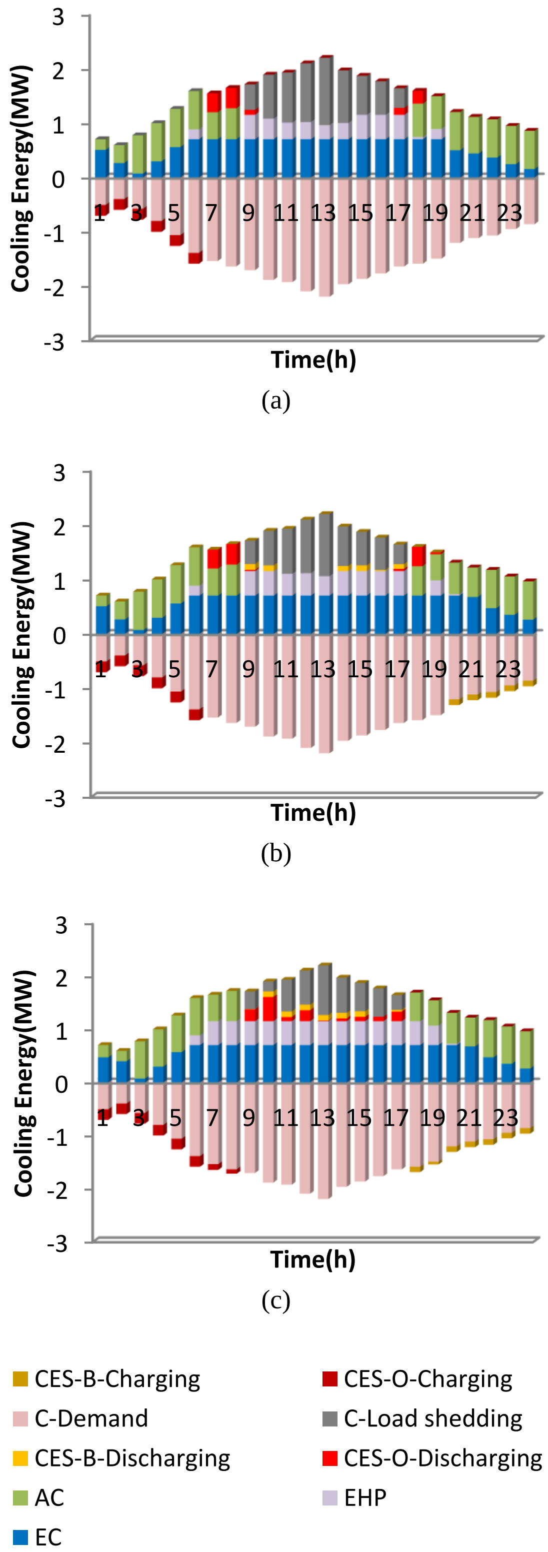


Fig. 9: Cooling balance in three scenarios related to gas network outage, (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

supply the cooling demand. In the early and last hours of the day, which are off-peak heating hours, most of the cooling demand is met by the absorption chiller. The reason for this is the use of heating energy by absorption chiller to generate cooling. After the absorption chiller, the electric chiller is more economical than EHP to generate cooling energy due to its higher coefficient of performance, as it uses less electricity to generate cooling energy. Absorption chiller generates cooling energy only at off-peak heating hours and electric chiller at almost all hours. EHP also helps generate cooling energy during peak cooling hours. Like the HES, the original CES stores excess cooling generation in the early hours of the day, which are off-peak cooling hours, and the original CES in the discharge mode during the outage hours of the gas network when there is a cooling load shedding and a lack of this energy. According to Fig. 9, the cooling load shedding is too high in Scenario 1 where there is no backup CES and DR program. But in Scenario 2, due to the use of backup CES and its help to supply a part of the cooling demand, the load shedding is less than that in Scenario 1. In Scenario 3, using backup CES and DR, the cooling load shedding compared to Scenario 2 has changed at different hours.

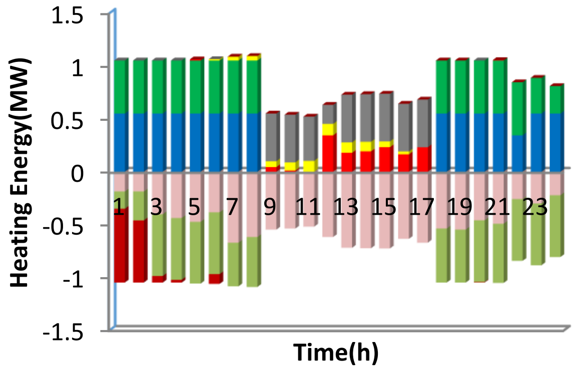
- Heating balance

The heating balance for the first three scenarios has been shown in Fig. 10. In this figure, the upper bar charts show generation and the lower bar charts show consumption. CHP also generates heating at the same time as generating electricity. The generated heat, like the electricity in all hours of the CHP ON state, is almost at the maximum possible value corresponding to point B in the CHP operating range. Therefore, for all hours, the CHP operating point changes with the AB line, where the electricity varies between 0.45 to 0.6 MWh, and the heating generated varies up to a maximum of 0.55 MWh. In addition to CHP, a boiler has been also used to generate heating energy in this energy hub. Boiler, like CHP, reduces the cost of operating an energy hub due to the use of natural gas as fuel. The boiler is also disconnected during the outage hours of the gas network. During all the hours that the boiler is in circuit, the heating output is very close to the maximum possible value. Due to the fact that there is no device for generating heating in the energy hub other than the boiler and CHP, the heating load shedding is significantly high. Since heating energy, in addition to meeting the demand for cooling generation is used to a large extent, the load shedding is also slightly reduced by using the backup HES. Moreover, since electricity load is not used in heating generation, DR has little effect on heating load shedding. According to Fig. 10, a small portion of the heating energy is supplied by ST, with a maximum output of 0.108 MWh. The original HES system helps to manage the hub energy to reduce operating costs. This system supplies the hub's energy demand by charging and discharging when needed. According to Fig. 9, the original HES is in the charging mode in the early hours of the day (1-6) when the boiler and CHP are in circuit and the heating energy is excess and, it helps to meet the demand by draining the heating in the outage hours of the gas network when there is a shortage of heating energy.

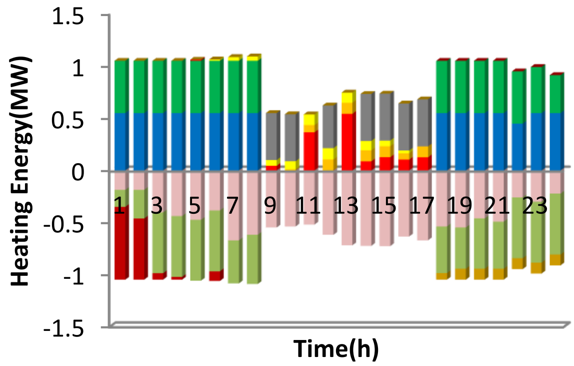
4.3.2. Energy balance in power outage scenarios

- Electrical balance

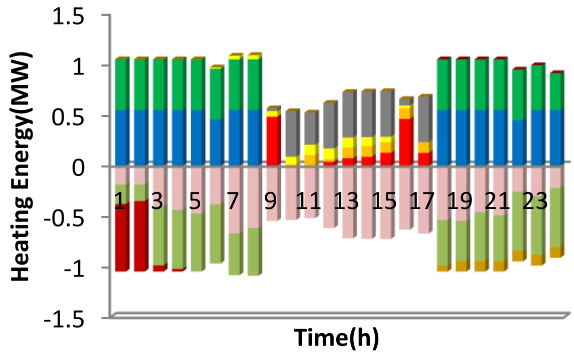
The electrical balance for the second three scenarios, which are related to the electrical network outage, has been shown in Fig. 11. In this figure, the upper diagrams show the electricity generation and the lower bar diagrams show the electricity consumption. Energy hubs supply a part of the electricity they need to supply the power for their through the electrical network. Disconnecting the energy hub from the electrical network for a few hours will cause much damage to the energy hub. According to Fig. 11, the connection of the electrical network with the energy hub has been terminated during 9-17 hours local time. During these



(a)



(b)



(c)

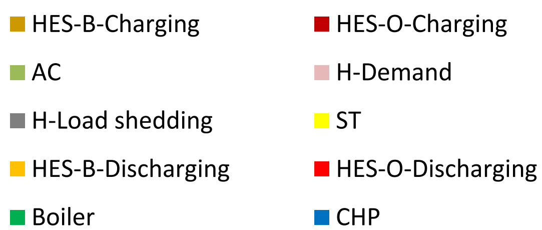


Fig. 10: Heating balance in three scenarios related to gas network outages, (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

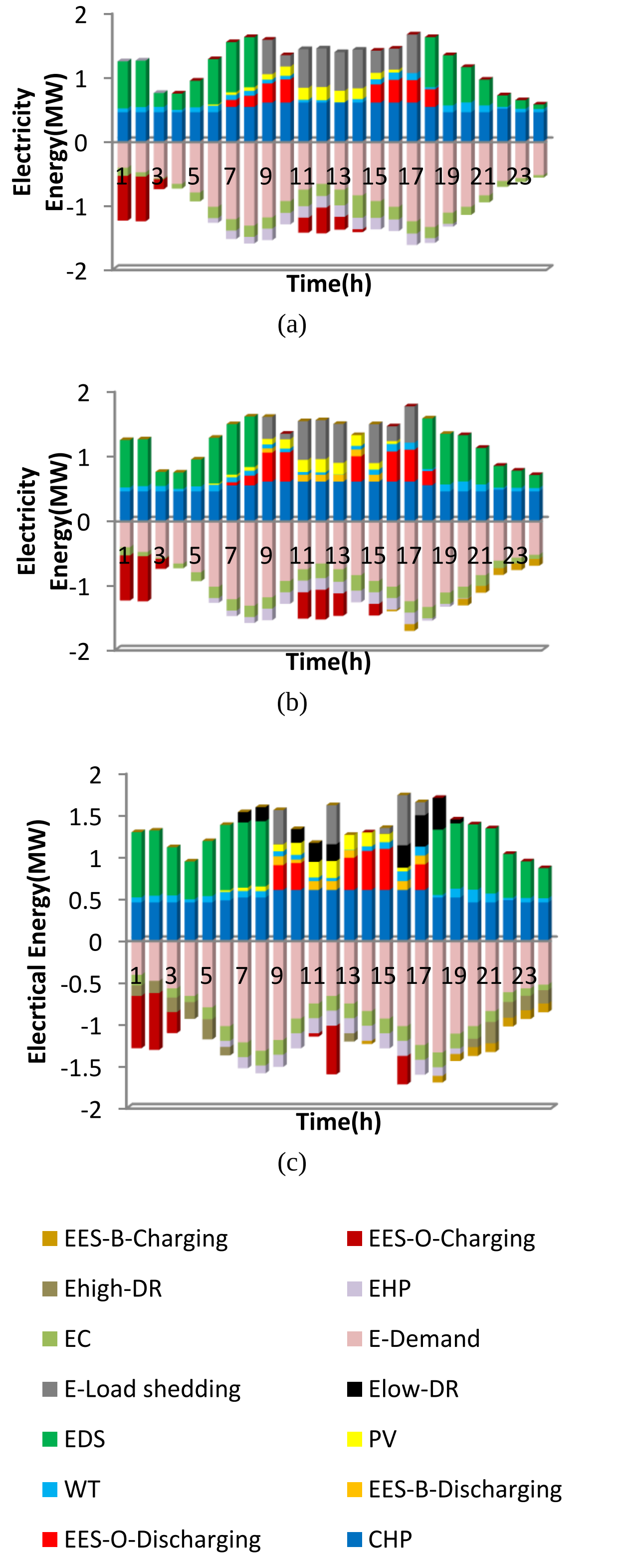


Fig. 11: Electrical balance in three scenarios related to electrical network outage, (a) Scenario 4, (b) Scenario 5, and (c) Scenario 6.

hours, the CHP generates maximum electricity to compensate for the outage of electrical network. In the second three scenarios, as in the first three scenarios, renewable sources such as PV and WT have been used to meet a part of the electricity demand. According to Fig. 11, in the second three scenarios, the charging/discharging pattern of the original EES is affected by electricity prices defined by the operator and begins to store energy in the early hours of the day due to low electricity prices. In addition, it is in discharging mode in high price hours and hours when there is a shortage of electricity. According to Table 2 (in the appendix), in Scenarios 5 and 6, backup EES is also used in addition to the original EES. In Scenario 4, which does not use backup EES and DR, the electrical load shedding is significantly high. In Scenario 5, which uses backup EES during a power outage, the load shedding is less than that in Scenario 4. Using DR along with the backup EES in Scenario 6, the electrical load shedding is significantly reduced compared to Scenarios 4 and 5.

- Heating balance

The heating balance for the second three scenarios has been shown in Fig. 12. In this figure, the upper bar graphs show heating generation and the lower bar graphs show heating consumption. According to Fig. 12, with the outage of electrical network, the heating load shedding does not occur and the CHP and the boiler meet all the heating demands being in the circuit. According to Fig. 12, the CHP and the boiler have their maximum generation at almost all hours in the second three scenarios. This is due to the replacement of heating energy for electricity for cooling generation, during the hours of the electricity network outage. In these three scenarios, a small part of the heating energy is provided by ST. In the second three scenarios, as in the first three scenarios, the original HES is in the charging mode during the hours when there is excess heating energy and during the hours of electrical network outage, when more heating is used to generate cooling. During the hours of lack of heat, the original HES is discharged to help meet heating demand.

- Cooling balance

The cooling balance has been demonstrated in Fig. 13 for the second three scenarios. In this figure, the upper bar diagrams show the cooling generation and the lower bar diagrams illustrate the cooling consumption. As can be seen in Fig. 13, the electrical network outage cause cooling load shedding, and since the boiler and CHP generate heating at all hours, most of the cooling demand is supplied by the absorption chiller. Like the first three scenarios after the absorption chiller, the electric chiller has the highest contribution in cooling energy generation. The EHP also helps meet demands for cooling during peak cooling hours, which is equivalent to off-peak electricity hours, due to the use of electricity to generate cooling. The original CES is also in charge mode during off-peak hours and in discharge mode during peak hours. According to Fig. 13, the cooling load shedding is too high in Scenario 1 where there is no backup CES and DR program. But in Scenario 2, due to the use of backup CES and its help to supply a part of the cooling demand, the load shedding is less than that in Scenario 1. In Scenario 3, using backup CES and DR, the cooling load shedding is reduced to zero.

4.3.3. *Scheduling the operation of backup storages and implementation of the DR program*

As shown in Table 5, backup storages have been used in

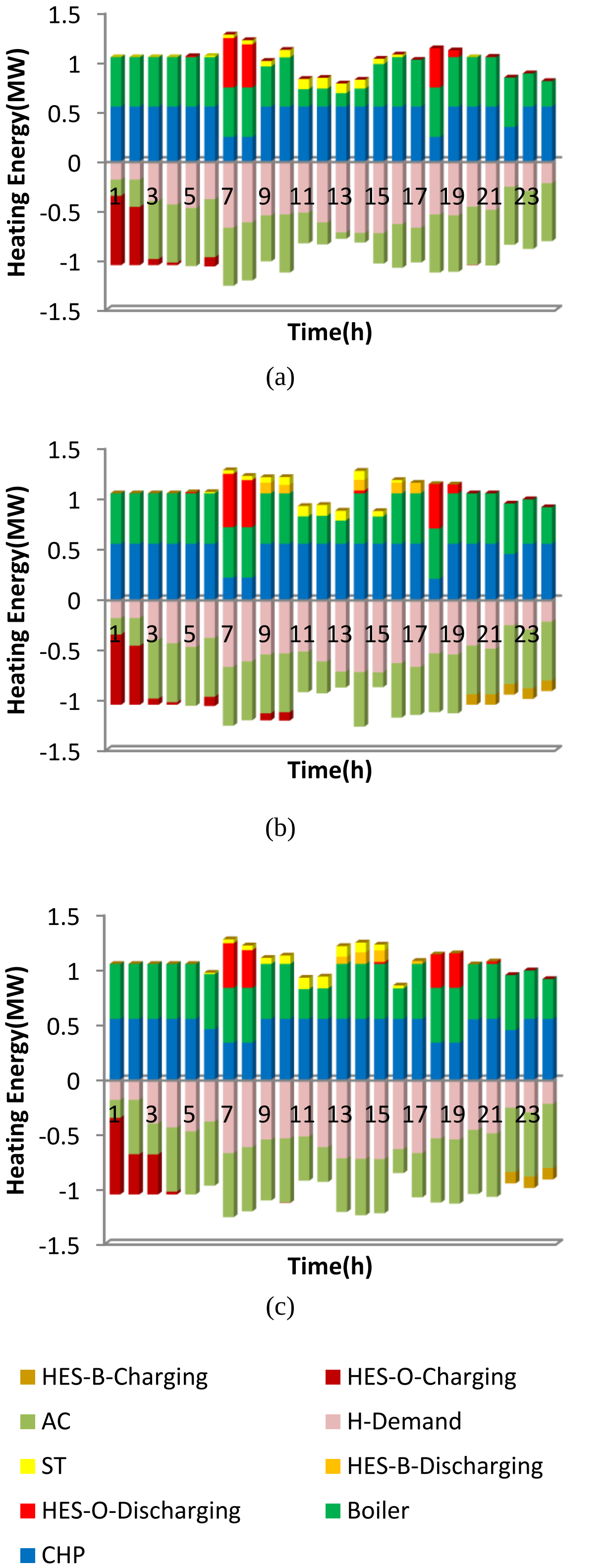


Fig. 12: Heating balance in three scenarios related to electrical network outage, (a) Scenario 4, (b) Scenario 5, and (c) Scenario 6.

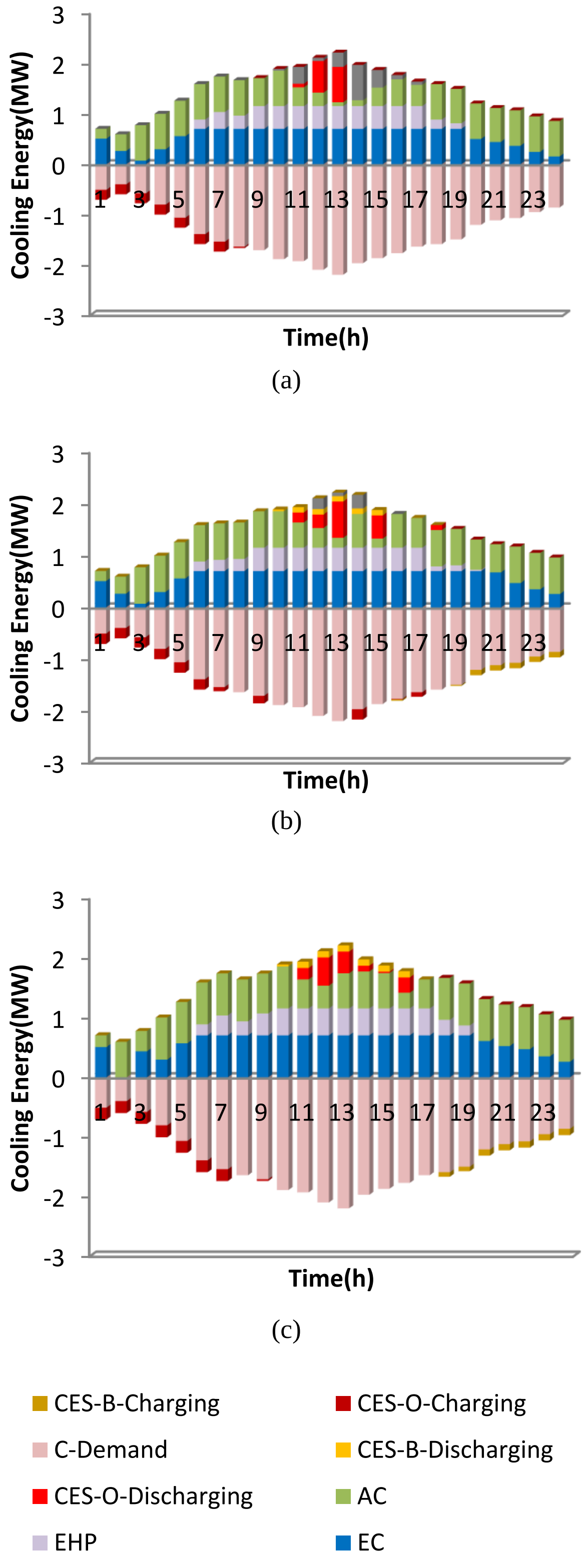


Fig. 13: Cooling balance in three scenarios related to electrical network outage, (a) Scenario 4, (b) Scenario 5, and (c) Scenario 6.

Scenarios 2, 3, 5, and 6. Fig. 14 shows the operation schedule of backup storages in 4 scenarios. In this figure, the upper bar diagrams show the battery discharge mode and the lower bar diagrams demonstrate the battery charge mode. Backup storages are in discharge mode in 4 scenarios during 9-17 hours local time, which are the outage hours of input energy carriers. And due to successive discharges, the level of energy stored in the backup storage devices decreases. Therefore, they are in charging mode in the last hours of the

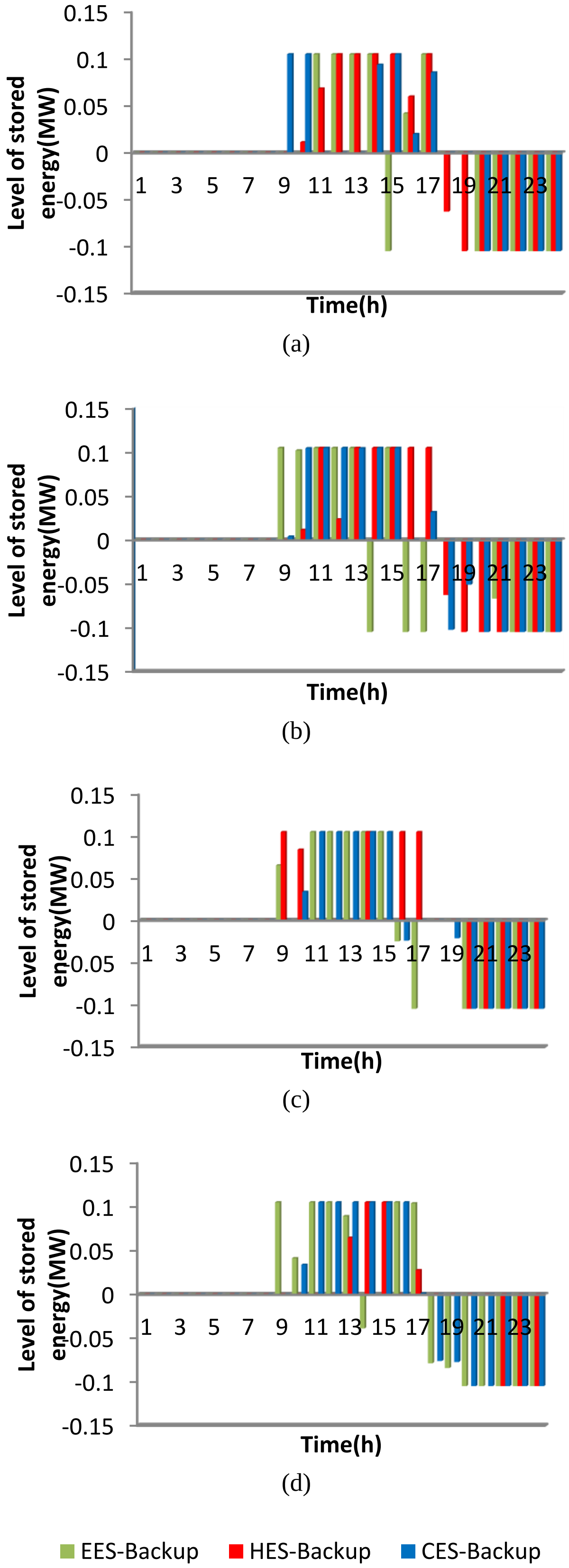


Fig. 14: Scheduling of backup storages operations, (a) Scenario 2, (b) Scenario 3, (c) Scenario 5, and (d) Scenario 6.

day to maximize their reserve amount to be ready to support any outages the day ahead. According to Fig. 14, in Scenario

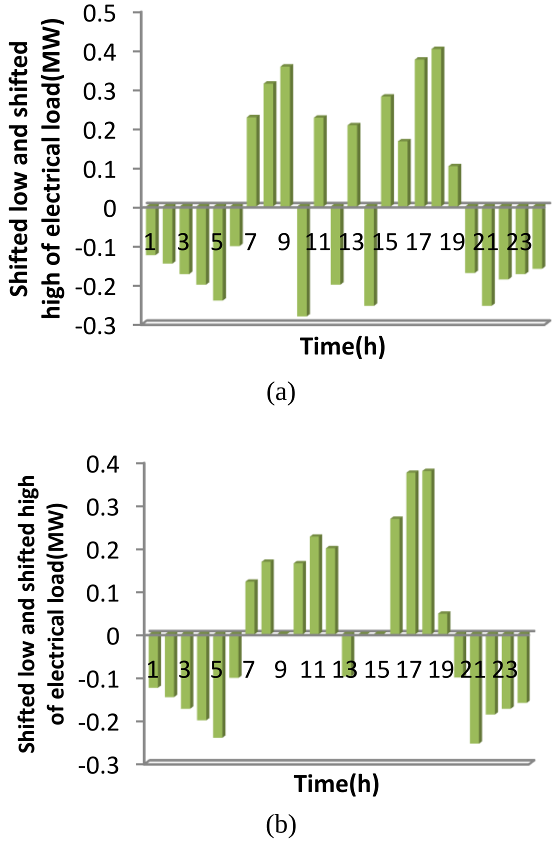


Fig. 15: Scheduling of DR program implementation, (a) Scenario 3, and (b) Scenario 6.

2, the battery works longer than in Scenario 3 in discharge mode, because of the effect of the DR program used in Scenario 3 on the displacement of the electrical load over time. Scenarios 5 and 6 are related to electrical network outages. As shown in the section on energy balance, the only results of electrical network outage is electrical and cooling loads shedding. However, diagrams in Scenarios 5 and 6 show that the backup heating battery are also charging/discharging. Moreover, since electricity is used to generate cooling and heating, the activity of heating and cooling backup batteries reduces the need for electricity, hence reducing electrical load shedding.

According to Table 5, the DR program has been used in two Scenarios 3 and 6 in order to flatten the demand curve. Fig. 15 shows the scheduling of load changes by executing a DR program for the two scenarios. According to Fig. 15, the electricity load has shifted from the hours of high electricity prices, to off-peak hours and low prices. Consequently, it has a great effect on reducing load shedding and improving resiliency in the outage hours of input energy carriers.

4.3.4. *Resiliency and economic analysis of energy hub*

According to Fig. 16 and the results obtained above, the effect of proper use of backup storages and participation of DR program in the optimal operation of the energy hub can be observed. In this paper, the resiliency of the energy hub has been calculated according to the total electrical, heating and cooling load shedding in the outage hours of natural gas or electricity network for the six scenarios, since there is a

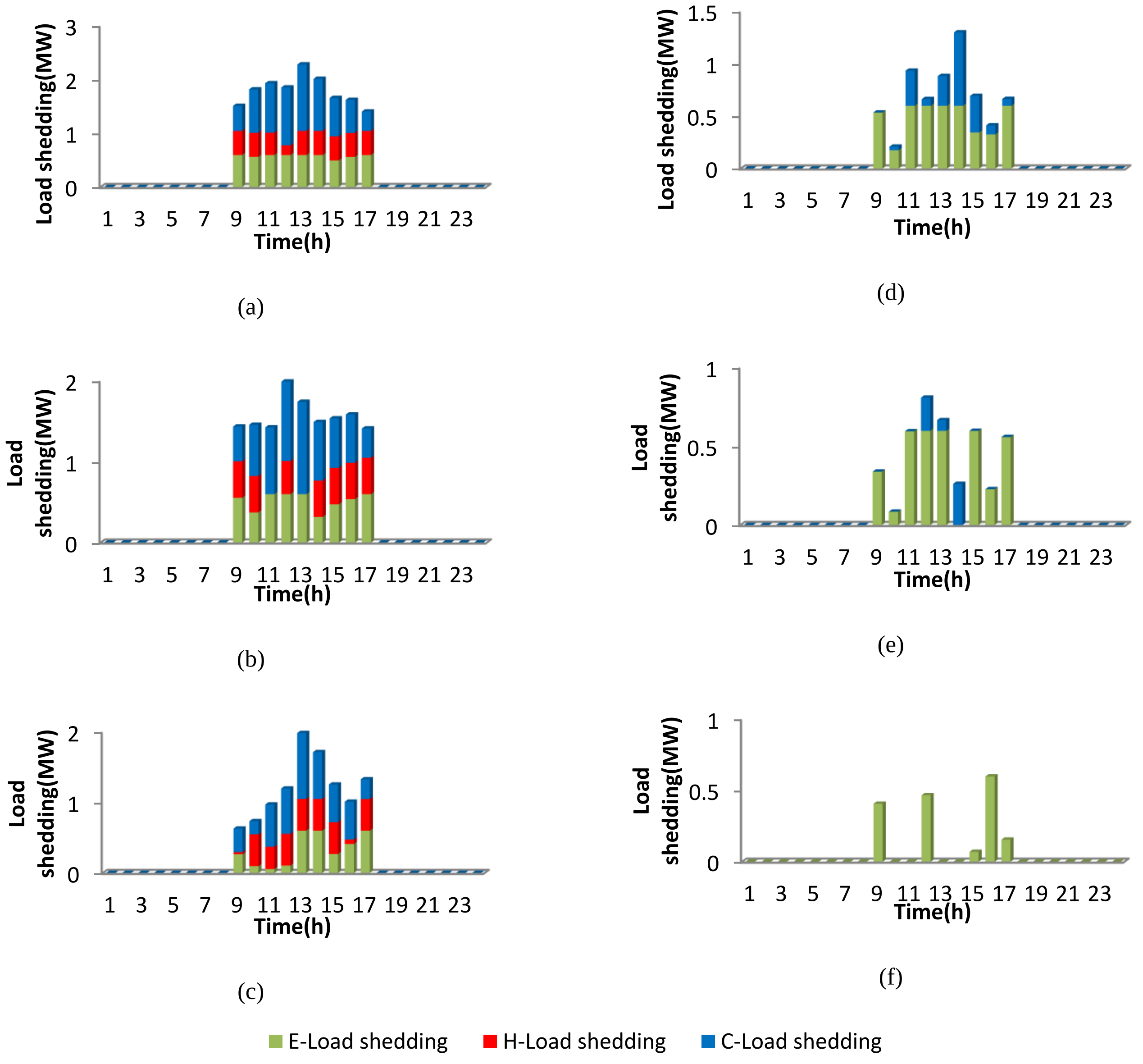


Fig. 16: Load shedding in six scenarios, a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, e) Scenario 5, and f) Scenario 6.

relationship between electricity, heating and cooling loads. Also, the cost of load penalties is not provided and the total cost for all six scenarios have been presented in Table 6 (in the appendix). The first three scenarios in Table 6 are associated with gas network outages. According to Table 6, the total cost in Scenario 1, where the backup storage and DR program is not used, is 5600.134$. Nonetheless, the total cost for Scenario 2 where only backup storage is used and for scenario 3, where the DR program has been used in addition to backup storage, has decreased to 5310.221$ and 4815.829$, respectively.

According to Table 6, the resilience of the whole system and the amount of load shedding at the hours of the natural gas network outage in the first three scenarios are equal to 21.764 – 23.182 - 27.335MWh and 16.148 - 15.024 - 10.826MWh, respectively. Also, the Percentage of resiliency of the whole system at the hours of the natural gas network outage in the first three scenarios is equal to 57.40%, 60.67% and 71.63%, respectively. These values indicate an increase in the resiliency of the energy hub through backup storage and DR during outage hours of the gas network. The second three scenarios in Table 3 are associated with power outages. According to Table 6, the total cost in Scenario 4, which lacks backup storage and DR, is 3448.813$, and the total cost for Scenario 5, where only backup storage has been used, and Scenario 6, where both backup storage and DR have been used, has decreased to 3085.937$ and 2808.270$, respectively. According to Table 6, the resilience of the whole system and the amount of load shedding at the hours of the power network outage in the second three scenarios are equal to 32.261 – 36.256 – 37.738MWh and 6.295 - 4.154 - 1.697MWh, respectively. Additionally, the resiliency of the system in the second three scenarios is 83.67%, 89.72% and 95.69%, respectively, which indicates an increase in resiliency in Scenarios 5 and 6 compared to Scenario 4.

5. Conclusion

In this study, we investigated the optimal energy hub scheduling based on CHP and renewable resources with the aim of minimizing costs and improving resiliency. Backup storages and DR program have been used in order to improve resiliency and reduce load shedding during power outages or natural gas. The proposed strategy has been evaluated by conducting extensive numerical studies in the form of multiple scenarios, and a numerical metric has been employed to accurately calculate resiliency. The results show that, in the event of a gas network outage, the use of backup storage alone will improve resiliency and reduce operating costs by 3.27% and 289.913$, respectively. Also, if DR programs are practiced alongside backup storage, the reduction in the resiliency improvements and operating costs will be 14.23% and 784.305$, respectively. In addition, during electrical network outage, the use of backup storage alone will improve resiliency and reduce operating costs by 6.05% and 362.876$, respectively. Also, in the case of the application of DR programs alongside backup storage, the resiliency improvements and operating costs decrease will be 12.02% and 640.543$, respectively. Therefore, the proposed strategy in the condition of the outage of input energy carriers can significantly improve the resiliency and reduce the operating cost of the hub.

CRediT Authorship Contribution Statement

Shabnam Rezaei: Data curation, Formal analysis, Investigation, Software, Validation, Roles/Writing - original draft, Writing - review & editing. **Ahmad Ghasemi:** Conceptualization**,** Methodology, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

Appendix

Table1: Summary of literature review and scope and contribution of this article

References		[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	This study
Operation mode	Grid-Connected	√	√	√	√	-	-	√	√	-	√	-	√
	Network outage	-	-	-	√	√	√	√	√	√	√	√	√
Power network outage		-	-	-	-	-	√	√	√	√	√	√	√
Gas network outage		-	-	-	√	√	-	-	-	-	-	-	√
Improves power load shedding during outages		-	-	-	-	-	√	√	√	√	√	√	√
Improves heating and cooling load shedding during outages		-	-	-	√	√	-	-	-	-	-	-	√
Calculate rates of resiliency by the index		-	-	-	-	√	-	-	-	-	-	-	√
CHP		√	√	√	√	-	-	√	-	-	-	-	√
Boiler		√	√	√	√	-	-	-	-	-	-	-	√
Chiller		√	√	√	-	-	-	-	-	-	-	-	√
EHP		-	√	-	-	√	-	-	-	-	-	-	√
Renewable energy		√	-	√	√	-	√	√	-	√	-	√	√
Energy storage		√	√	√	√	-	√	-	√	√	√	√	√
Study the impact of storage on resiliency		-	-	-	-	-	-	-	√	√	√	√	√
DR		√	√	√	-	-	√	√	-	-	-	-	√
Study the impact of DR on resiliency		-	-	-	-	-	√	√	-	-	-	-	√

Table2: Parameters of energy hub components

Renewable resource parameters				
$\gamma^{PV} = 151$	$\gamma^{WT} = 28$	$\gamma^{ST} = 126$		
CHP parameters				
$a = 0.1035$ $34.5\, b =$	$c = 26.5$	$d = 0.025$	$e = 2.203$	$f = 0.051$
$H_A^{CHP} = 0$	$H_B^{CHP} = 0.55$	$H_C^{CHP} = 0.4$	$H_D^{CHP} = 0$	
$E_A^{CHP} = 0.6$	$E_B^{CHP} = 0.45$	$E_C^{CHP} = 0.1$	$E_D^{CHP} = 0.2$	
Boiler parameters				
$H_{min}^{Boiler} = 0$	$H_{max}^{Boiler} = 0.5$	$\eta^{Boiler} = 0.95$		
Electric chiller parameters				
$C_{min}^{EC} = 0$	$C_{max}^{EC} = 0.7034$	$COP_{cool}^{EC} = 4$	$\gamma^{EC} = 2$	
Absorption chiller parameters				
$C_{min}^{AC} = 0$	$C_{max}^{AC} = 0.7034$	$COP_{cool}^{AC} = 1.2$	$\gamma^{AC} = 2$	
EHP parameters				
$C_{min}^{EHP} = 0$	$C_{max}^{EHP} = 0.45$	$COP_{cool}^{EHP} = 2.5$	$\gamma^{EHP} = 1$	
Original electrical energy storage parameters				
$E_{min}^{EES,O} = 0.4$	$E_{max}^{EES,O} = 1.8$	$E_{max}^{EES,o,ch} = 0.7$	$E_{max}^{EES,o,dch} = 0.7$	$\eta^{EES,o,ch} = 0.9$
$\eta^{EES,o,dch} = 0.9$	$E_0^{EES,O} = 0.4$	$\gamma^{EES,O} = 1$		
Power backup storage parameters				
$E_{min}^{EES,B} = 0.035$	$E_{max}^{EES,B} = 0.7$	$E_{max}^{EES,B,ch} = 0.105$	$E_{max}^{EES,B,dch} = 0.105$	$\eta^{EES,B,ch} = 0.9$
$\eta^{EES,B,dch} = 0.9$	$E_0^{EES,B} = 0.7$	$\gamma^{EES,B} = 1$		
Original heating energy storage parameters				
$E_{min}^{HES,O} = 0$	$E_{max}^{HES,O} = 1.8$	$E_{max}^{HES,o,ch} = 0.7$	$E_{max}^{HES,o,dch} = 0.7$	$\eta^{HES,o,ch} = 0.96$
$\eta^{HES,o,dch} = 0.96$	$E_0^{HES,O} = 0.4$	$\gamma^{HES,O} = 1$		
Heating backup storage parameters				
$E_{min}^{HES,B} = 0.035$	$E_{max}^{HES,B} = 0.7$	$E_{max}^{HES,B,ch} = 0.105$	$E_{max}^{HES,B,dch} = 0.105$	$\eta^{HES,B,ch} = 0.96$
$\eta^{HES,B,dch} = 0.9$	$E_0^{HES,B} = 0.7$	$\gamma^{HES,B} = 1$		
Original cooling energy storage parameters				
$E_{min}^{CES,O} = 0$	$E_{max}^{CES,O} = 1.8$	$E_{max}^{CES,o,ch} = 0.2$	$E_{max}^{CES,o,dch} = 0.7$	$\eta^{CES,o,ch} = 0.98$
$\eta^{CES,o,dch} = 0.98$	$E_0^{CES,O} = 0.4$	$\gamma^{CES,O} = 1$		
Cooling backup storage parameters				
$E_{min}^{CES,B} = 0.035$	$E_{max}^{CES,B} = 0.7$	$E_{max}^{CES,B,ch} = 0.105$	$E_{max}^{CES,B,dch} = 0.105$	$\eta^{CES,B,ch} = 0.98$
$\eta^{CES,B,dch} = 0.98$	$E_0^{CES,B} = 0.7$	$\gamma^{CES,B} = 1$		
Electricity DR parameters				
$par^{high,DR} = 30\%$	$par^{low,DR} = 30\ \%$	$\gamma^{E} = 1$		

Table 6: Results in various case studies

Scenario	Total cost($)	Load shedding (MWh)	Resiliency (MWh)	Resiliency(%)
1	5600.134	16.148	21.764	57.40%
2	5310.221	15.024	23.182	60.67%
3	4815.829	10.826	27.335	71.63%
4	3448.813	6.295	32.261	83.67%
5	3085.937	4.154	36.256	89.72%
6	2808.270	1.697	37.738	95.69%

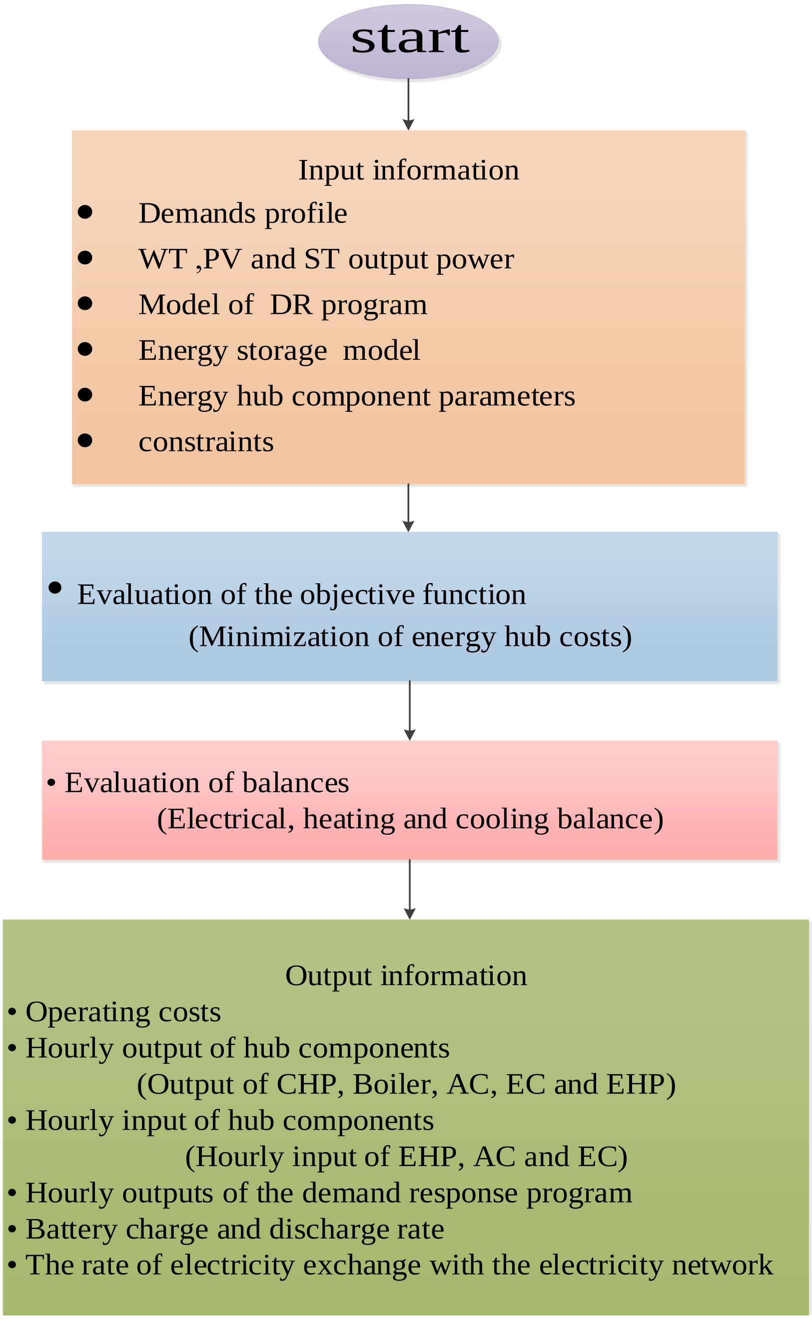


Fig. 2: The proposed scheduling framework.

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