Economical operation of energy hub by using energy storage systems focusing on resilience and energy security indices

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The combination of various energy carriers is an essential factor in power systems to increase endurance and resistance against high-impact events to supply network loads. In this article, a model is presented that deals with the optimal economic operation of the energy hub by increasing the system load resiliency and energy security at the lowest cost. To achieve these goals, energy storage devices and types of energy carriers are used. Furthermore, the loads are categorized as critical and noncritical loads and the highest priority in this article is to supply critical loads. In addition, four scenarios are considered, and each scenario is scrutinized in four steps. Critical load resilience index and energy security indices have been studied in this article, HHI and diversity indices are energy security indices. The operating horizon is 24 hours. In this article, there is a challenge between increasing load resilience and energy security and minimizing costs in the energy hub. In this study, mixed integer nonlinear programming [MINLP] is applied to formulate this optimization problem, which is implemented and solved by GAMS software. The results show that costs rise as critical load resilience increases.

Keywords: *Critical /Non-Critical Load, Diversity Index, Energy Hub, Energy Security, Energy Storage, HHI Index, Resilience.*

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Nomenclature

Indices

c	Cooling
e	Electricity
t	Time
g	Gas
h	Heating
i	Equipment
K	A set of output energy {e/h/c}
N	Number of the input carrier
Ns	Scenario number
S	Scenario
X	Set of input carries{e/g/h}

Scalars

lo_S^e	Electrical storage losses
lo_S^h	Heating storage losses
lo_S^c	Cooling storage losses
W_S	Probability of the S^{th} scenario
μ_B	Boiler efficiency
μ_CCHP^e	CCHP electrical efficiency
μ_CCHP^h	CCHP heating efficiency
μ_CCHP^c	CHP cooling efficiency
μ_CHP^e	CHP electrical efficiency
μ_CHP^h	CHP heating efficiency
μ_H	Heater efficiency
μ_S^e	Electrical storage efficiency
μ_S^h	Heating storage efficiency
μ_S^c	Cooling storage efficiency
μ_Tr	Transformer efficiency

Parameters

DF_{max}	Maximum diversity index
DF_S	Diversity index of S^{th} scenario
DF_Norm	Normalized diversity index
ES_{max}_c	Maximum capacity of cooling storage
ES_{max}_e	Maximum capacity of electrical storage
ES_{max}_h	Maximum capacity of heating storage
ES_{min}_c	Minimum capacity of cooling storage
ES_{min}_e	Minimum capacity of electrical storage
ES_{min}_h	Minimum capacity of heating storage
HHI_S	Herfindahl–Hirschman index of S^{th} scenario
L_t^c	Total cooling load
L_t^e	Total electrical load
L_t^h	Total heating load
P_{max}_B	The highest capacity of a boiler
P_{max}_CCHP	The highest capacity of CCHP
P_{max}_CHP	The highest capacity of CHP
P_{max}_Tr	The highest capacity of transformer

P_{min}_B	The lowest capacity of a boiler
P_{min}_CCHP	The lowest capacity of CCHP
P_{min}_CHP	The lowest capacity of CHP
P_{min}_Tr	The lowest capacity of transformer
Pen_t^e	Electrical load penalty which is not supplied
Pen_t^h	Heating load penalty which is not supplied
Pen_t^c	Cooling load penalty which is not supplied
S_{max}_c	The highest input to cooling storage
S_{max}_h	The highest input to heating storage
S_{min}_c	The lowest input to cooling storage
S_{min}_h	The lowest input to heating storage
So_{max}_c	The highest output of cooling storage
So_{max}_h	The highest output from heating storage
So_{min}_c	The lowest output from cooling storage
So_{min}_h	The lowest output from heating storage
$THHI$	Total Herfindahl–Hirschman index
$\$\_e_t$	Input electricity price
$\$\_g_t$	Input gas price
$\$\_h_t$	Input heat price
$\$\_S_{i.t}^c$	Price of i^{th} cooling storage
$\$\_S_{i.t}^e$	Price of i^{th} electrical storage
$\$\_S_{i.t}^h$	Price of i^{th} heating storage

Binary Variable

I_B_i	i^{th} Boiler status (in service=1,else=0)
I_CCHP_i	i^{th} CCHP status (in service=1,else=0)
I_CHP_i	i^{th} CHP status (in service=1,else=0)
$I\_ES\_c_i$	i^{th} Cooling storage status (in service=1,else=0)
$I\_ES\_e_i$	i^{th} Electrical storage status (in service=1,else=0)
$I\_ES\_h_i$	i^{th} Heating storage status (in service=1,else=0)
I_H_i	i^{th} Heater status (in service=1,else=0)
I_Tr_i	i^{th} Transformer status (in service=1,else=0)

Variable

CL_t^e	Electrical critical load
CL_t^h	Heating critical load
ES_e	Energy stored in electrical storage
ES_h	Energy stored in heating storage
ES_c	Energy stored in cooling storage
IC_s	Total input cost of S^{th} scenario
$NCL\_NS_t^e$	Not-supplied non-critical electrical load
$NCL\_NS_t^h$	Not-supplied non-critical heating load
$NCL\_S_t^e$	Supplied non-critical electrical load
$NCL\_S_t^h$	Supplied non-critical heating load
OC	Total operation cost
S_{max}_e	The highest input to electrical storage
S_{min}_e	The lowest input to electrical storage
So_{max}_e	The highest output from electrical storage
So_{min}_e	The lowest output from electrical storage
S_c	The input energy to cooling storage
So_h	The output energy from heating storage
STC_s	Energy storage cost of S^{th} scenario
$PenC_s$	Penalty cost for not supplying a non-critical load of S^{th} scenario
P_{max}_H	The highest capacity of the heater
P_{min}_H	The lowest capacity of the heater
Pin^e	Total input electrical energy
Pin^g	Total input gas
Pin^h	Total input heat
P_B_i	The energy of i^{th} boiler
P_CCHP_i	The energy of i^{th} CCHP
P_CHP	The energy of i^{th} CHP
P_H_i	The energy of i^{th} heater
P_Tr_i	The energy of the i^{th} transformer
PO_B_i	Output Heating energy of i^{th} boiler
$PO\_CCHP_i^c$	Output cooling energy of i^{th} CCHP
$PO\_CCHP_i^e$	Output Electrical energy of i^{th} CCHP
$PO\_CCHP_i^h$	Output Heating energy of i^{th} CCHP
$PO\_CHP_i^e$	Output Electrical energy of i^{th} CHP
$PO\_CHP_i^h$	Output Heating energy of i^{th} CHP
PO_H_i	Output Heating energy of i^{th} heater
PO_Tr_i	Output Electrical energy of i^{th} transformer

Abbreviations

CL_t^c	Cooling critical load
$CNCL$	Critical and non-critical loads
$CNCL^c$	Critical and non-critical cooling loads
$CNCL^e$	Critical and non-critical electrical loads
$CNCL^h$	Critical and non-critical heating loads
g_{CCHP}	Share of input gas to CCHP
g_{CHP}	Share of input gas to CHP
M_{yz}	Coupling matrix
$MECS$	Multi-energy-carrier system
NCL_NS	Non-critical loads which are not supplied
$NCL\_NS_t^c$	Not-Supplied non-critical heating load
NCL_S	Non-critical loads which are supplied
$NCL\_S_t^c$	Supplied non-critical cooling load
R_t^k	Resiliency index
S_e	The input energy to electrical storage
S_h	The input energy to heating storage
SO_e	The output energy from electrical storage

1. Introduction

1.1. Motivation

With the growth of industries in countries and the importance of economic matters, load supply is the main issue that network operators are faced, that, not providing the loads leads to consumer dissatisfaction. In this regard, in recent years, a general structure has been suggested that combines different energy carriers and supplies the needed load by conversion and storage, which is called an energy hub concept. [1]. On the other hand, the study of the energy carriers' security in the energy hub from various aspects such as political, social, and economic issues, etc. is a new concept that is called energy security [2]. Improving the security of infrastructure systems such as power grids against the occurrence of low-impact and high-probability events has been applied by designers and operators for a long time ago [3]. However, the performance of the system in the face of severe events that has a high impact with low probability and lead to severe damage to the system has been less investigated; this approach is recognized as a new characteristic called system resilience [4]. Endurance, damage rate, and reversibility are the main parts of the resilience concept that are addressed in severe events, and operators use storage devices to increase resilience [5]. Therefore, in this article, energy security and resilience are studied with an economic approach in the energy hub using storage devices.

1.2. Literature review

A review of current research on network resilience is illustrated that examines severe weather events and their severe impact on power systems. In addition, it describes several methods of evaluating network resilience and some quantitative indicators [6]. The energy hub is integrated with renewable energy and is examined. Energy hub flexibility is obtained according to photovoltaic, wind power outputs, and load curves in various seasons, Also, two sets of flexibility indices are presented [7]. Scheduling of energy hub systems has been investigated considering the uncertainty of renewable energies, and game theory has been used to solve the problem [8]. A stochastic-robust coordinated pattern for CCHP considering multi-energy carriers has been addressed; moreover, the uncertainty of clearing price as stochastic scenarios in the real-time and day-ahead market has been described [nine]. The demand response program has been studied in the day-ahead market of the energy hub; furthermore, the effects of ice storage as one of the storage devices have been specially investigated [10]. Water has been considered one of the hub's energy loads along with heat and electricity. The scheduling of the energy hub has been proposed based on the maximum profit in the day-ahead market and with the market-clearing price [11]. The operation of coordinated electricity and gas distribution grids by using interconnected energy hubs has been proposed. Moreover, the model has been illustrated as a two-step scenario model aiming to minimize operational costs considering electrical load, wind power, and electricity price uncertainties [12]. Energy hub systems are modeled using a distributed multi-periodic multi-energy operational model. An energy hub acts as a distributed decision-maker in this model that investigates the synergistic interactions between natural gas, heating, and electrical energy networks [13]. An optimal coordinated energy dispatch technique in both island and grid-connected states for a multi-energy microgrid is presented. The demonstrated microgrid includes multiple energy carriers covering the uncontrollable and controllable generation units [14]. Energy security indicators and the Shannon-Wiener diversity index are used to investigate the relationship between energy security and diversity in an energy system [15]. A sustainable structure for the optimal design of an energy hub, which aims to specify the optimal capacity of the candidate distributed energy resources, is presented by providing a modeling framework to consider the social and environmental effects of an energy hub [16]. Uncertainty of solar energy and flexibility of heating, cooling, and electric load demand are considered in the microgrid, where a p-efficient point method is used to calculate photovoltaic power at different assurance levels based on historical data. A stochastic photovoltaic power is converted into a deterministic power to be incorporated into the optimization model by using this method [17]. To participate in the carbon trading market in the energy hub, a power-to-gas converter has been introduced based on the feature of carbon recycling. One of the advantages of this process is the reduction of costs in the energy hub [18]. The effect of uncertainties is modeled in the scenario-based structure as stochastic programming in the microgrid. In the represented calculation, the operator schedules its energy resources considering the demand response program and resiliency of the microgrid to islanding and uncertainties in load, generation of renewable energy resources, and the market price at a minimum cost [19]. To quantify the degradation in microgrid performance, the applied framework uses both fragility curves for overhead distribution branches and windstorm profiles. In addition, a collection of metrics is defined which determines a comparable tool for evaluating resilience in different operating conditions [20]. Based on energy security indicators, the Baltic States have been investigated. The proposed indicators take into account the economic, technical, sociopolitical, and geopolitical aspects of energy security. The indicators are applied using statistical data for the Baltic State, which enables the assessment of the level of energy security [21]. A multi-carrier energy system has been addressed in the presence of a wind farm, storage system; demand response program, also thermal and electricity market, which has been considered uncertainties such as wind speed, market prices, and demands [22]. A new energy hub model has been proposed for areas where cold and heat demand is created due to environmental temperature changes in various periods of the year [23]. A stochastic unit commitment model is presented to evaluate the effect of wind uncertainty on energy storage systems (ESSs) and the scheduling of generating units in the problem. The ESSs have been modeled based on technical specifications considering various levels of wind penetration and forecasting accuracies [24]. A novel standard categorization of uncertainty modeling techniques for the decision-making process is represented. These structures are compared and their strengths and weaknesses are illustrated. [25]. A complete overview of uncertainty modeling methods for power system studies is presented, which addresses the strengths and weaknesses of these methods that help to choose the most suitable method for each application [26]. A novel method illustrated by optimal responsive load analyses the energy hub schedule and prices [27]. A method is introduced to assess the security of the energy supply of a country using various indicators of energy dependence and energy diversity, which are appointed as the two principal paradigms of energy supply security [28]. A model proposed in the reliability criterion is applied in addition to the well-established technical constraints for an energy hub. In this methodology, the reliability evaluation is added as a novel constraint to the model [29]. A load dispatch model has been presented for a community energy hub, which targets to decrease the total cost of the energy hub (CO2 emission and operation costs). The uncertainties of future electricity prices have been modeled by the robust optimization approach; also, the modeling of electric vehicle uncertainties has been executed by Monte Carlo simulation [30]. An index has been proposed to increase resilience in the microgrid network against a hurricane, which is the sum of electricity and heat storage. The increase in this index has led to a decrease in load shedding [31]. The Information Gap Decision Theory (IGDT) technique has been employed to simulate the uncertainty of power outages in the optimal operation of a system. By utilizing the IGDT method, a distribution network operator can implement a suitable approach to achieve a robust optimal point [32]. An stochastic model based on probability distribution functions for load and generation (photovoltaic and wind) is proposed that energy scheduling of an energy hub is analyzed [33].Increasing resilience while minimizing the operation cost has been introduced in the energy hub, where electricity, cooling and heating loads are divided into two critical and non-critical categories [34]. One of the main benefits of the energy hub systems is their ability to maintain the acceptable level of flexibility within power systems [35]. Furthermore, In order to exploit the maximum available flexibility within the power system, the resource-specific constraints with less than one-hour characteristics were characterized in an hourly-based security-constraint unit commitment [36].

1.3. Contribution

A review of other articles is tried to investigate the research gaps in energy security and resilience in hub energy. The important goal of this article is to enhance the resilience and energy security of the energy hub, which must be achieved at a minimum cost.

Improving the energy security of the hub system coupled with increasing resilience has not been addressed in other articles. Furthermore, the supply of critical loads is an important issue that should be provided by storage devices in the worst conditions, which has been less studied in other articles. In addition, considering storage losses and storage costs is an issue that has been less illustrated in other articles. Above all, the compromise between increasing energy security and critical load resiliency and reducing the operating cost of the energy hub is examined in this paper. Table 1. Demonstrates an overview of previous articles and their shortcomings. In most of the studies related to load supply, the separation of critical loads such as hospitals and sensitive security centers compared to industrial and residential loads has not been considered. In this article, to study this research gap, the provision of these loads at the time of severe events is included. In addition, the simultaneous increase of resilience and security indices of incoming carriers by including HHI and Shanon-Winer (diversity) indices has not been investigated in previous studies.

The followings are the contributions and novelty of this article compared to the reviewed articles:

- Increasing the resilience of critical loads and energy security of the energy hub with an economic approach

✓ Enhancing energy security of the energy hub using HHI and SHANON-Winer indices

✓ Determining the index for the resilience of critical loads

✓ Determining the share of energy hub input carriers and storage devices to supply critical and non-critical loads

✓ Simultaneous consideration of storage device losses and their efficiency

Table 1. Review of previous papers compared to this study

Ref.	Case study	Problem Type	Objective	Input data	Storages Loss	Energy security index	Storage	Load Type	Resilience index
[4]	Integrated 18-bus, 54-bus	MINLP	Minimizing cost	Electricity, Gas	×	×	×	Normal	✓
[5]	A distribution network	MINLP	Minimizing cost	Electricity	×	×	✓	Normal	✓
[7]	Hub	MIP	Minimizing cost	Electricity, PV, Wind,	✓	×	✓	Normal	×
[8]	Multi hubs	MINLP	Minimizing cost	Electricity, Gas, Wind	×	×	✓	Normal	×
[9]	CCHP micro-grid	LP	Minimizing cost	Electricity, Wind, Gas	×	×	✓	Normal	×
[10]	Hub	MINLP	Minimizing cost	Electricity, Wind, Gas	✓	×	✓	Normal	×
[11]	Hub	MILP	Maximizing profit	Electricity, Gas, Water	✓	×	✓	Normal	×
[12]	Hub	MINLP	Minimizing cost	Electricity, Gas	×	×	✓	Normal	×
[13]	Multi hubs	MINLP	Minimizing cost	Electricity, Wind, Gas	×	×	✓	Normal	×
[14]	Microgrids	MILP	Minimizing cost	Electricity, Water, Wind, Solar	×	✓	✓	Normal	×
[15]	Energy systems	NLP	Maximizing security energy	Electricity, Thermal, Nuclear	×	✓	×	Normal	×
[17]	Microgrids	MILP	Minimizing cost	Electricity, Gas, Solar	×	×	✓	Normal	×
[18]	Hub	MILP	Minimizing cost	Electricity, Wind, Heat	×	×	✓	Normal	×
[19]	Microgrids	MINLP	Minimizing cost	Electricity, Wind	×	×	✓	Normal	×
[20]	Microgrids	MINLP	Maximizing resilience	Electricity, Wind, Solar	×	×	✓	Critical, Non-Critical load	✓
[21]	Baltic States	NLP	Maximizing resilience	Electricity, Gas	×	✓	×	Normal	✓
[22]	Hub	MILP	Minimizing costs	Gas, Electricity, Wind, Heat	✓	×	✓	Normal	×
[23]	Hub	MINLP	Minimizing cost	Electricity, Gas	×	×	✓	Normal	×
[27]	Hub	MINLP	Minimizing costs	Electricity, Gas, Heat	✓	×	✓	Normal	×
[28]	Distribution network in Korea	NLP	Maximizing security energy	Electricity, Fossil fuels	×	✓	×	Normal	×
[29]	Hub	MINLP	Minimizing cost	Electricity,	✓	×	✓	Normal	×

Ref.	Case study	Problem Type	Objective	Input data	Storages Loss	Energy security index	Storage	Load Type	Resilience index
				Gas, Heat					
This paper	Hub	MINLP	Minimizing cost Maximizing Resiliency and power security	Electricity, Gas, Heat	✓	✓	✓	Critical NC-S, NC-NS	✓

1.4. Article structure

The motivation, literature review, contribution, and article structure have been included in the introduction. The second part, which is related to methodology and has three sections: 1-Expression of energy hub concepts using storage devices. 2-Determination of HHI and diversity indicators to evaluate the energy security of the hub system. 3-Definition of critical load resilience index in energy hub. 4- Solve the economic load dispatch of the energy hub based on the constraints and the indicators of energy security and resiliency.

The third part is the results section, which has two sub-section. The first sub-section investigates the case study and introduces the assumptions and types of scenarios. The second sub-section represents the simulation results and analyzes them in different scenarios. The fourth part is the conclusion section, in which the findings and future work are stated.

The model Multi-Input-Multi-Output (MIMO) of multi energy carriers is applied, where an energy hub system has three carriers in input (electricity, gas, and heat) and the output includes electrical, heating and cooling load. In additional, Transformers, CHPs, Boiler, Heater, and CCHPs plays vital role as converters.

GAMS software is used to model the operation of the energy hub, and the BARON (Branch and Reduce Optimization Navigator) solver is utilized.

2. Methodology

2.1. Concept of energy Hub

The energy hub has multiple inputs, storage elements, converters, and multiple outputs. The overview of the energy hub is depicted in Fig. 1.Furthermore, Eq. (1) shows the relationship between inputs and outputs. The energy hub has three inputs: electricity, gas, and heat. There are also storage elements for electricity, heat, and cooling. In addition, converters include transformers, boilers, CHPs, CCHPs, and heaters. The outputs are also electrical, heating, and cooling loads

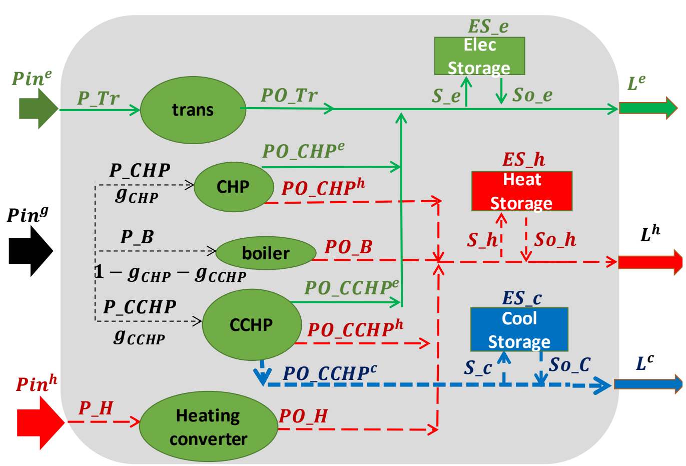

Fig. 1. The general structure of the energy hub

$$\begin{bmatrix} L^e \\ L^h \\ L^c \end{bmatrix} = \begin{bmatrix} \mu\_Tr & g_{CHP}\times\mu\_CHP^e + g_{CCHP}\times\mu\_CCHP^e & 0 \\ 0 & g_{CHP}\times\mu\_CHP^h + g_{CCHP}\times\mu\_CCHP^h + (1-g_{CHP}-g_{CCHP})\times\mu\_B & \mu\_H \\ 0 & \mu\_CCHP^c & 0 \end{bmatrix} \times \begin{bmatrix} Pin^e \\ Pin^g \\ Pin^h \end{bmatrix} + \begin{bmatrix} SO\_e - S\_e \\ SO\_h - S\_h \\ SO\_c - S\_c \end{bmatrix} \quad (1)$$

2.2. HHI and diversity indicators modelling whit uncertainty

Energy security has been studied in various dimensions, including political, economic, environmental, social, and technical in recent years. The IEA defines energy security as the uninterrupted availability of energy resources at a proper price. In this article, Hirschman-Herfindahl (HHI) and Shannon Weiner indices are used as appropriate criteria to evaluate energy availability. On the other hand, with increasing availability, energy security improves. The HHI_S index is defined as the sum of the squares of each input to the total input carriers to the hub for each scenario. If the value of this index is equal to one, the energy hub has only one input, and if the value of this index is close to zero, the share of each input to supply the output loads is equal and we have maximum availability. This index is modeled in Eq. (2) in this article, and the total index in all scenarios with different probabilities is shown in Eq. (3). In addition, Shannon Weiner's energy security index, which determines the diversity of energy supply, is presented in Eq. (4), the maximum value of this index is proportional to the number of inputs and is shown in Eq. (5). Moreover, the normalized Shannon Weiner index is modeled as Eq. (6) in this paper, if the value of this index is equal to one, the maximum diversity is available, and if it is close to zero, there is a minimum amount of diversity in the energy hub [2,34].

$$HHI_S = \sum_X \left(\frac{\sum_t Pin_{t.s}^X}{\sum_t \sum_X Pin_{t.s}^X} \right)^2 \qquad X\,\epsilon\{e.g.h\} \quad (2)$$

$$THHI = \sum_{s=1}^{Ns} \left(W_S \times \frac{\sum_t Pin_{t.s}^X}{\sum_X \sum_t Pin_{t.s}^X} \right) \quad (3)$$

$$DF_S = -\sum_X \hat{P}in_S^X \times LN(\hat{P}in_S^X) \quad (4)$$

$$DF_{Max} = LN(A) \quad (5)$$

$$DF\_Norm = \frac{1}{DF_{Max}} \sum_{S=1}^{Ns} W_S \times DF_S \quad (6)$$

2.3. Critical load resiliency index

The ability to stand against severe events (low-frequency and high-impact) and the capability to recover and restore within a short time frame is called resiliency. Resilience includes three main themes: 1- prediction and preparation, 2-resistance 3-recovery. The output load of the energy hub at typical and severe event conditions is represented in Fig. 2. Fig. 3 demonstrates the total output load, which includes the three categories: 1-critical load. 2-Non-critical loads that have been supplied (NCL_S). 3-Non-critical loads that have been not supplied (NCL_NS). The $R_{t.s}^k$ index is considered the resiliency index in this article according to Eq. (7). On the other hand, the main purpose is supplying the critical load and maximizing the non-critical load.

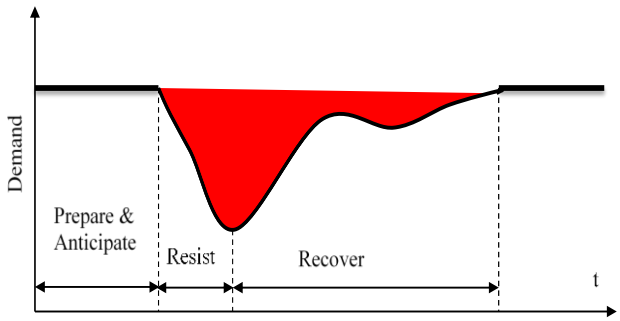

Fig. 2. The resilience concept model

$$R_{t.s}^{k} = \frac{\int_t CL_s^k \times dt}{\int_t L_s^k \times dt} \tag{7}$$

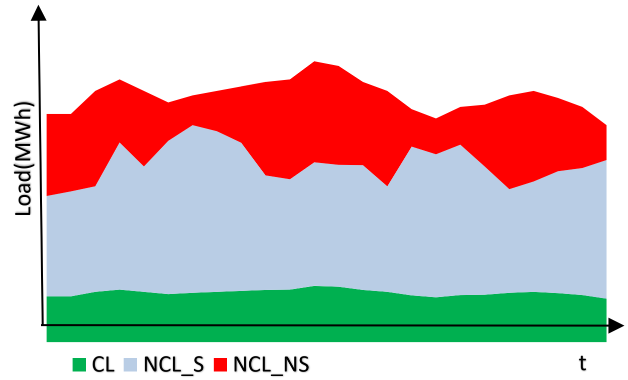

Fig. 3. The loads classification based on operation

2.4. Economic dispatch

Eq. (8) is defined as the objective function that minimizes the total cost over a time horizon.

$$OC = minimizing \sum_{s=1}^{Ns} w_s \times (IC_s + STC_s + PenC_s) \tag{8}$$

The objective function has three parts. IC is input carriers' cost. STC is the energy storage cost. The $PenC$ is the penalty cost.

The input cost obtained by multiplying the amount of inputs and their corresponding price is shown in Eq. (9)

$$IC_S = \sum_{t=1}^{24} (Pin_{t.s}^{e} \times \$\_e_t) + (Pin_{t.s}^{g} \times \$\_g_t) + (Pin_{t.s}^{h} \times \$\_h_t) \tag{9}$$

The storage cost is also achieved from Eq. (10). The STC is obtained from the total input/output energy at the price of energy storage.

$$STC_s = \sum_i \sum_t \$\_S_{i.t}^{K} \times (S\_K_{i.t.s} + So\_K_{i.t.s}) \tag{10}$$

PenC in Eq. (11) is the penalty cost for the NCL_NS, it is clear that PenC should be minimized, so to achieve this aim, the value of NCL_S should be maximized. This cost is obtained by multiplying the value of NCL_NS and the penalty factor for different types of load.

$$PenC_s = \sum_K \sum_t NCL\_NS_{t.s}^{K} \times Pen_t^K \tag{11}$$

The formulation of the constraints in this paper is described as follows :

Equilibrium constraint of the electrical input to transformers is based on Eq. (12)

$$Pin_{t.s}^{e} = \sum_i P\_Tr_{i.t.s} \tag{12}$$

Equilibrium constraint of gas input to Boilers/CHPs/CCHPs is based on Eq. (13)

$$Pin_{t.s}^{g} = \sum_i (P\_CHP_{i.t.s} + P\_CCHP_{i.t.s} + P\_B_{i.t.s}) \tag{13}$$

Equilibrium constraint of heat input to heaters converter is based on Eq. (14)

$$Pin_{t.s}^{h} = \sum_i P\_H_{i.t.s} \tag{14}$$

The equilibrium constraints of energy converters are demonstrated in Eqs. (15-19) [18, 22].

$$I\_Tr_{i.t.s} \times P_{min}\_Tr \le P\_Tr_{i.t.s} \le I\_Tr_{i.t.s} \times P_{max}\_Tr \tag{15}$$

$$II\_H_{i.t.s} \times P_{min}\_H \le P\_H_{i.t.s} \le I\_H_{i.t.s} \times P_{max}\_H \tag{16}$$

$$I\_CHP_{i.t.s} \times P_{min}\_CHP \le P\_CHP_{i.t.s} \le I\_CHP_{i.t.s} \times P_{max}\_CHP \tag{17}$$

$$I\_CCHP_{i.t.s} \times P_{min}\_CCHP \le P\_CCHP_{i.t.s} \le I\_CCHP_{i.t.s} \times P_{max}\_CCHP \tag{18}$$

$$I\_B_{i.t.s} \times P_{min}\_B \le P\_B_{i.t.s} \le I\_B_{i.t.s} \times P_{max}\_B \tag{19}$$

Equilibrium constraints of energy converters output are shown in Eqs. (20-24). It should be noted that efficiency affects the output energy of each converter. Each converter has specified outputs, for example, the output of CCHP consists of electrical, cooling, and heating energy.

$$PO\_Tr_{i.t.s} = P\_Tr_{i.t.s} \times \mu\_Tr_i \tag{20}$$

$$PO\_CHP_{i.t.s}^{K} = P\_CHP_{i.t.s} \times \mu\_CHP_i^K \tag{21}$$

$$PO\_CCHP_{i.t}^{K} = P\_CCHP_{i.t.s} \times \mu\_CCHP_i^K \tag{22}$$

$$PO\_B_{i.t.s} = P\_B_{j.t.s} \times \mu\_B_i \tag{23}$$

$$PO\_H_{i.t.s} = P\_H_{j.t.s} \times \mu\_H_i \tag{24}$$

The constraint of storage capacity is illustrated in Eq. (25), also, constraints of input/output energy to/of storage systems are represented in Eqs. (26-27).

$$I\_ES\_K_{i.t.s} \times ES_{min}\_K \le ES\_K_{i.t.s} \le I\_ES\_K_{i.t.s} \times ES_{max}\_K \tag{25}$$

$$I\_ES\_K_{i.t.s} \times S_{min}\_K \le S\_K_{i.t.s} \le I\_ES\_K_{i.t.s} \times S_{max}\_K \tag{26}$$

$$I\_ES\_K_{i.t.s} \times SO_{min}\_K \le SO\_K_{i.t.s} \le I\_ES\_K_{i.t.s} \times SO_{max}\_K \tag{27}$$

Equilibrium constraint of storage is shown in Eq. (28). It is worth mentioning loss and efficiency of storage systems are considered simultaneously

$$ES\_K_{i.t.s} = (\mu\_S_i^K \times S\_K_{i.t.s}) - SO\_K_{i.t.s} + ES\_K_{i.t-1.s} \times (1 - lo\_S_i^K) \tag{28}$$

Equilibrium constraints of different loads are illustrated in Eq. (29-

31).

$$CL_{t.s}^{e} + NCL\_S_{t.s}^{e} = \sum_{i} (PO\_Tr_{i.t.s} + PO\_CHP_{i.t.s}^{e} + PO\_CCHP_{i.t.s}^{e} + SO\_e_{i.t.s} - S\_e_{i.t.s}) \quad (29)$$

$$CL_{t.s}^{h} + NCL\_S_{t.s}^{h} = \sum_{j} (PO\_H_{i.t.s} + PO\_B_{i.t.s} + PO\_CHP_{i.t.s}^{h} + PO\_CCHP_{i.t.s}^{h} + SO\_h_{i.t.s} - S\_h_{i.t.s}) \quad (30)$$

$$CL_{t.s}^{c} + NCL\_S_{t.s}^{c} = \sum_{i} (PO\_CCHP_{i.t.s}^{c} + SO\_c_{i.t.s} - S\_c_{i.t.s}) \quad (31)$$

In addition, the balance should be equal for output loads. Eq. (32) represents this matter.

$$CL_{t.s}^{K} + NCL\_S_{t.s}^{K} + NCL\_NS_{t.s}^{K} = L_{t}^{K} \quad (32)$$

The flowchart of modeling is shown in Fig.4

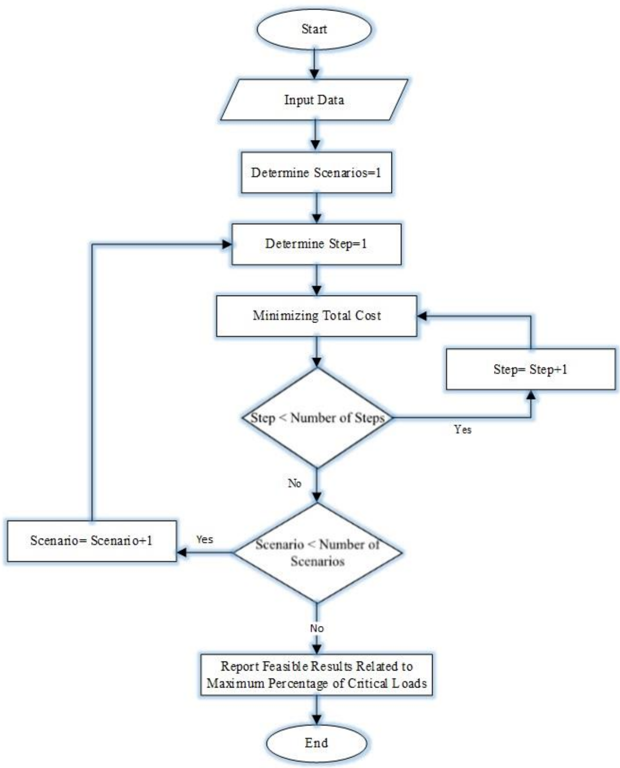

Fig. 4. The flowchart of modeling

3. Results

3.1. Case Study

A comprehensive energy hub is used in the test system, in which inputs contain electricity, gas, and heat. also, the outputs have three loads (electrical, heating, and cooling) which are supplied by input carriers. The operating horizon is examined for a period of 24 hours. Also, the value of energy is considered in per-unit. And the base amount is equal to 1MW, furthermore, prices are illustrated in $ / MWh. The number of energy hub equipment for storage and converters is equal to 5. The input carriers' prices are demonstrated in Fig.5. As well as the trend of output loads during operation time is represented in Fig.6. The technical specifications of converters and storage devices are addressed in Table 2. and Table 3. Furthermore, penalty costs of the NCL_NS and charging/discharging cost are shown in Table 4. The electrical, heating, and cooling storage begin with an initial storage of 1 MWh, 1 MWh, and 0.5 MWh, respectively. In all cases, the critical load equals 10% of the total load. Data of [18], [22] and [29] are used.

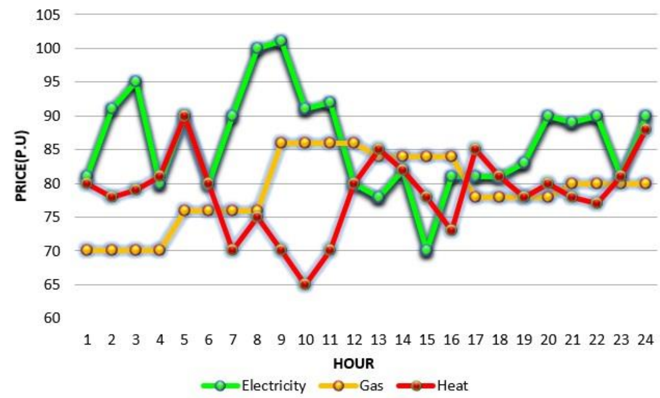

Fig. 5. The input carriers'prices

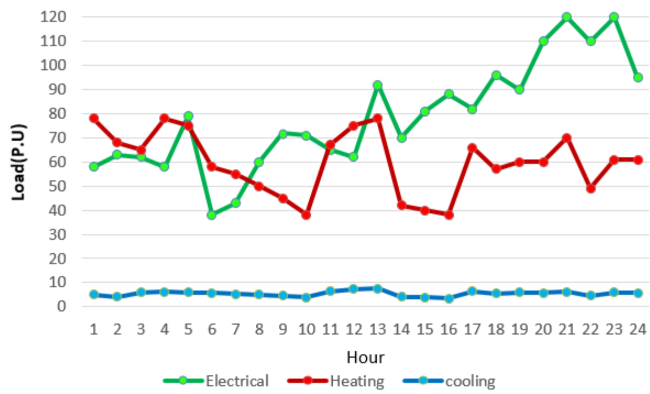

Fig. 6. The trend of output loads

Table 2. The storage devices data

Hub equipment	μ_S^e	μ_S^h	μ_S^C	ES_{max}_k	ES_{min}_k	S_{min}_k	S_{max}_k	SO_{min}_k	SO_{max}_k	lo_S^e	lo_S^h	lo_S^C
e	0.95			20	0	0	5	0	5	0.01		
h		0.94		10	0	0	5	0	5		0.03	
c			0.93	3	0	0	1	0	1			0.04

Table 3. The converter data

Elements	The highest capacity	The lowest capacity	Efficiency (μ)		
Trans	$P_{max}\_Tr = 30$	0	0.97	–	–
CHP	$P_{max_{CHP}} = 13$	$P_{min}\_CHP = 0.1$	$CHP^e = 0.42$	$CHP^h = 0.23$	–
CCHP	$P_{max}\_CCHP = 18$	$P_{min}\_CCHP = 0.2$	$CCHP^e = 0.42$	$CCHP^h = 0.15$	$CHP^C = 0.18$
Boiler	$P_{max}\_B = 4$	$P_{min}\_B = 0.1$	–	$B = 0.78$	–
Heater	$P_{max}\_H = 6$	$P_{min}\_H = 0.1$	–	$H = 0.92$	–

Table 4. The Penalty and charging/discharging cost

	$\frac{\$}{MWh}$
Pen_t^e	600
Pen_t^h	550
Pen_t^c	480
$\$\_S_{i.t}^e$	40
$\$\_S_{i.t}^h$	35
$\$\_S_{i.t}^c$	36

3.2. Scenarios

The problem is studied in two parts: in the first part, with the certainty of the event time, and in the second part with the uncertainty of the event time.

3.2.1 Certainty of Events Time

In this part: four scenarios are included and each scenario is examined in four steps, which are explained as follows:

- ○ Scenario1: no events have occurred
- ○ Scenario2: Only the electricity input will be interrupted from 14:00
- ○ Scenario3: Electricity input will be interrupted from 14:00, also gas input will be interrupted from 19:00
- ○ Scenario4: Electricity input will be interrupted from 14:00, also gas input will be interrupted from 19:00, and heat input will be interrupted from 21:00

- Step 1: The energy hub has no constraint for load supply
- Step 2: At least 10% of the critical load must be supplied
- Step 3: Not only must 10% of the critical load be supplied but also the HHI index must be less than 40%.
- Step 4: Not only must 10% of the critical load be supplied but also the diversity index must be more than 92%.

Fig. 7. represents the chronological chain of events

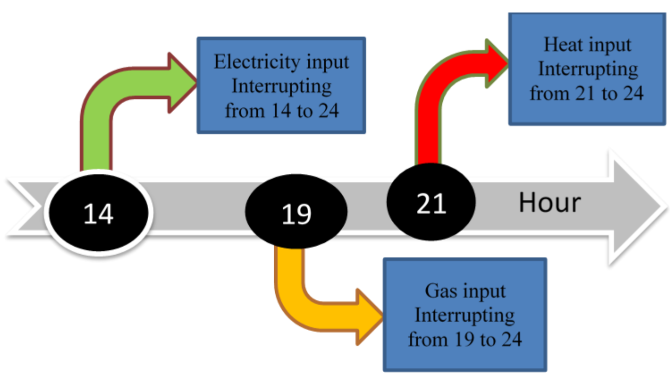

Fig. 7. Time steps of events

3.2.2 Uncertainty of events time

Given that the uncertainty of events is very probable, so we have tried to investigate the performance of the energy hub with the uncertainty of the timing of events, so the different scenarios are described below:

Scenario 1: Electricity input will be cut off from 13:00 with a 30% probability, in addition, gas input will be cut off from 18:00 with a 30% probability

Scenario 2: Electricity input will be cut off from 13:00 with a 30% probability, and the gas input will be also cut off from 19:00 with a 40% probability

Scenario 3: Electricity input will be cut off from 13:00 with a 30% probability and the gas input will be also cut off from 20:00 with a 30% probability

Scenario 4: Electricity input will be cut off from 14:00 with a 60% probability, and the gas input will be also cut off from 18:00 with a 30% probability

Scenario 5: Electricity input will be cut off from 14:00 with a 60% probability, and the gas input will be also cut off from 19:00 with a 40% probability

Scenario 6: Electricity input will be cut off from 14:00 with a 60% probability, and the gas input will be also cut off from 20:00 with a 30% probability

Scenario 7: Electricity input will be cut off from 15:00 with a 10% probability, and the gas input will be also cut off from 18:00 with a 30% probability

Scenario 8: Electricity input will be cut off from 15:00 with a 10% probability, and the gas input will be also cut off from 19:00 with a 40% probability

Scenario 9: Electricity input will be cut off from 15:00 with a 10% probability, and the gas input will be also cut off from 20:00 with a 30% probability

3.3 Analysis of uncertainty/certainty results

In the first scenario, the total cost, which includes is input carriers' cost, penalty costs, and storage costs, is shown separately for four different steps in Fig. 8.

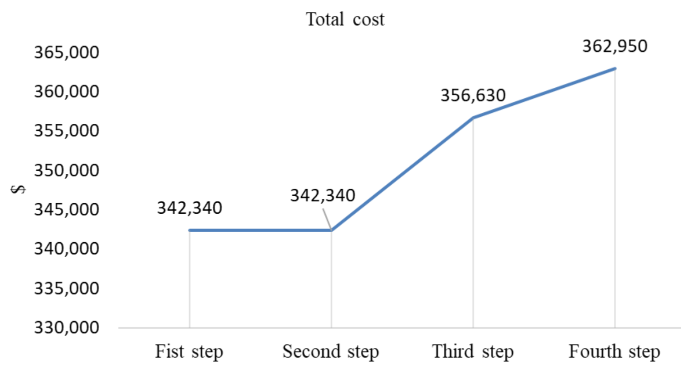

Fig. 8. Total cost in first scenario

In the first step of this scenario, as can be seen, the total cost is 342,340 $, and in the second step, where 10% of the critical load should be provided, the total cost does not change because the inputs are not interrupted.

In the third step, which should supply 10% of the critical load and also the HHI index should be less than 40%, the total cost has increased by 4.17% compared to the previous case (14,290 $).

In the fourth step, which should supply 10% of the critical load and also the diversity index should be more than 92%, the total cost has increased by 6.02% compared to the previous case (20,610 $).

Moreover, Fig. 9 is demonstrated the process of using the storage for the first scenario in the second step, which due to the increase in electricity prices at t=8,9 the electrical storage is discharged, Additionally, since the price of heat input at t=9 to 11 is the lowest, the highest charge occurs during these times. As well as, the cooling storage is charged at t=1 to 4, due to the low price of gas within these times.

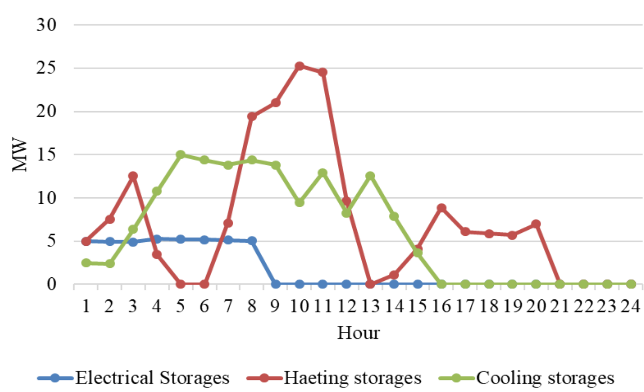

Fig. 9. Trend of charges/discharges storage devices in first scenario

In the second scenario, all costs for the four different steps are depicted in Fig. 10.

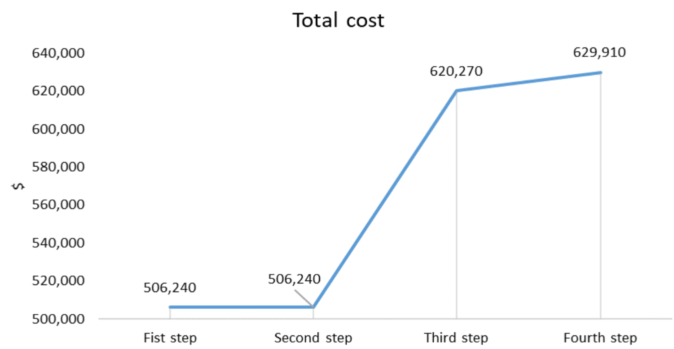

Fig. 10. Total cost in second scenario

In the first step of this scenario, the total cost is 506,240 $, and in the second step, where 10% of the critical load should be supplied, the total cost is not changed. That is why CHP and CCHP and electrical storage units are used in the latter.

In the third step, which should supply 10% of the critical load and also the HHI index should be less than 40%, the total cost has increased by 22.5% compared to the previous case (114,030 $). In the fourth step, which should supply 10% of the critical load and also the diversity index should be more than 92%, the total cost has increased by 6.02% compared to the previous case (123,670 $).

Fig. 11 is depicted the process of using the storage for the second step of the second scenario, since due to an electricity outage at t=14, the highest capacity of electrical storage is at t=13, and at this hour storage device is discharged. As well as, since the input heat price has the lowest value at t=9 to 11, the highest charge has occurred at these times.

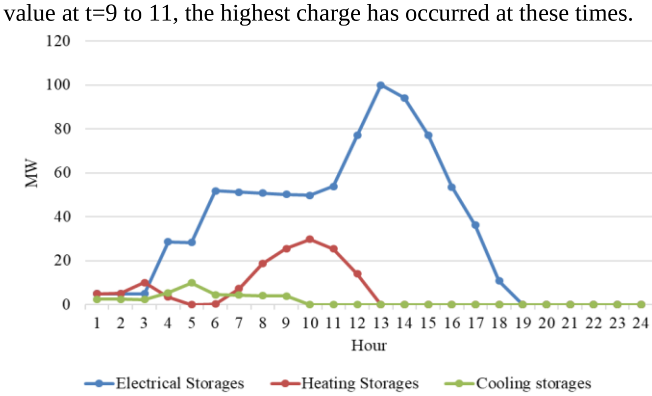

Fig. 11. Trend of charges/discharges storage devices in second scenario

On the other hand, from t=13 onwards, due to the use of CHP and CCHP for electricity supply, there is no heating storage. The cooling storage is charged from t=1 to 4, due to the low price of gas within these times.In the third scenario, the costs for the four different steps are shown in Fig. 12:

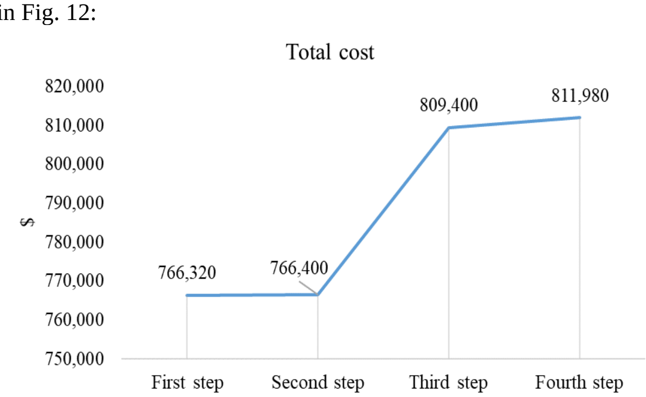

Fig. 12. Total cost in third scenario

In the first step of this scenario, the total cost is 766,320 $, also, in the second step, the cost changes by 0.01% compared to the previous case the previous case (43,000 $). In the fourth step, the total cost has increased by 5.94% compared to the previous case (45,580 $).

In the third step, the total cost has increased by 5.61% compared to

Fig. 13 is demonstrated the process of using the storage for the second step of the third scenario, since due to electricity/gas outage from t=14, t=19, the highest capacity of electrical/heating storages device are at t=13 and t=18 respectively, and at this hour storage units are discharged.

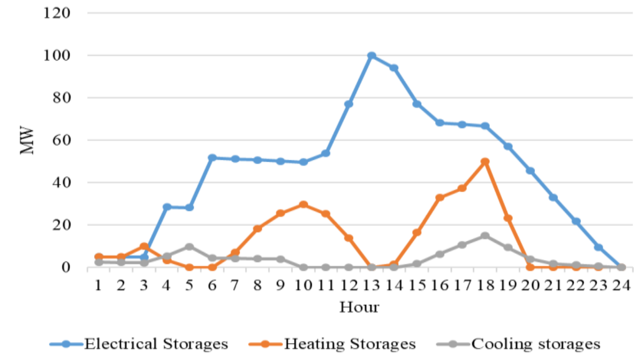

Fig. 13. Trend of charges/discharges storage devices in third scenario

In the fourth scenario, all costs for the four different steps are depicted in Fig. 14, in the first step of this scenario, the total cost is 815,850 $, also, in the second step, the cost changes by 0.31% compared to the previous case (2,580 $).

In the third step, the total cost has increased by 6.37% compared to the previous case (52,200$). In the fourth step, the total cost has increased by 6.76% compared to the previous case (55,370 $).

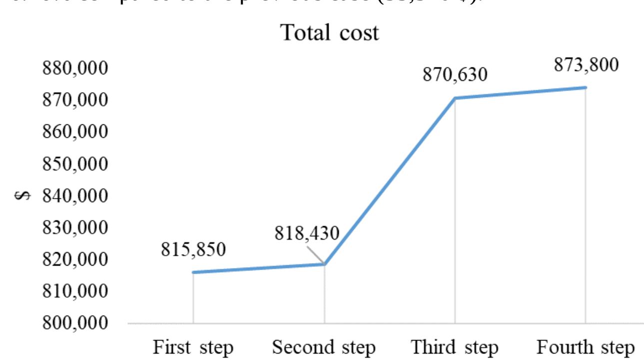

Fig. 14. Total cost in fourth scenario

Fig. 15. is represented the process of using the storage for the second step of the fourth scenario since due to electricity/gas/heat outage from t=14, t=19, the highest capacity of electrical/heating/cooling storage existed at t=13 and t=18 t=20

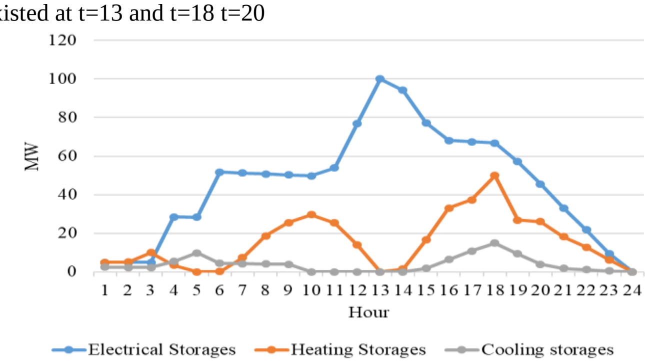

Fig. 15. Trend of charges/discharges storage devices in fourth scenario

All costs in uncertainty conditions are compared to a similar case without uncertainty in Fig. 16. with investigating the uncertainty, it was found that $ 3855 has increased the total cost of the entire system.

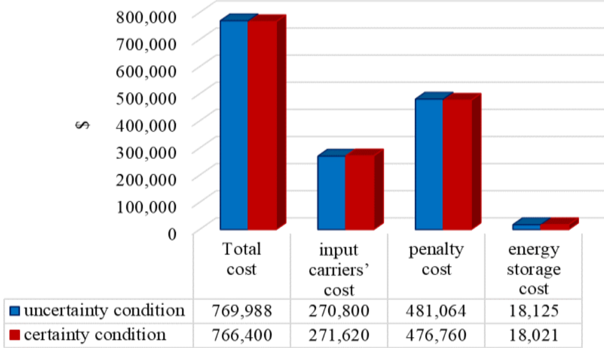

Fig. 16. Compare cost in uncertainty/certainty conditions

3.1. Analysis of energy security results

In the second step of the second scenario, the effect of increasing the HHI index on the total cost is shown in Fig. 17. In the first case, where the HHI index is equal to 0.43, the results show that the total cost is equal to 342,070 $, while in the second case when the HHI index is less than 0.4, the total cost is equal to 356,630$ (for a 1% improvement of the index, the cost has increased by $ 7,280). In the third case, where the HHI index is less than 0.39, the total cost is 363,920 $ (for 1% improvement of the index, the cost has increased by 7,290 $). in the fourth case, where the HHI index is less than 0.37 The total cost is equal to 386,970 $ (for 1% improvement of the index, the cost has increased by 11,525 $) and in the last case, where the HHI index is less than 0.35, the total cost is equal to 611,370 $ (for 1% improvement of the index, the cost has increased by 112,200 $).

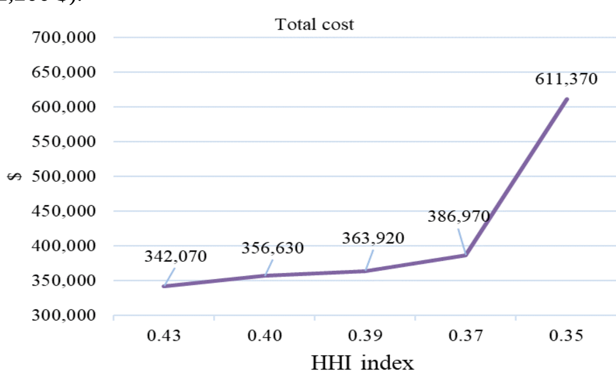

Fig. 17. The effect of HHI index

Moreover, Fig.18. Shows the percentage of input power based on the diversity index.

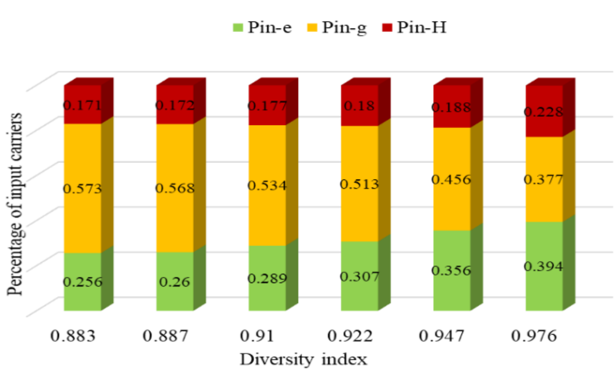

Fig. 18. The effect of diversity index on energy security

As the results indicate, when the diversity index rises, one can come to the following observations:

The share of input powers becomes closer to each other, as shown in Fig. 18.

The total cost is increased, which its trend is shown in Fig. 19.

Where the diversity index is equal to 0.91, the results show that the total cost has increased by 14,650 $ compared to where the diversity index is equal to 0.88. It is worth mentioning, Where the diversity index is equal to 0.98, the total cost has increased by 224,400 $ compared to where the diversity index is equal to 0.95. This demonstrates that as the diversity index rises, the extra cost will be significantly increased.

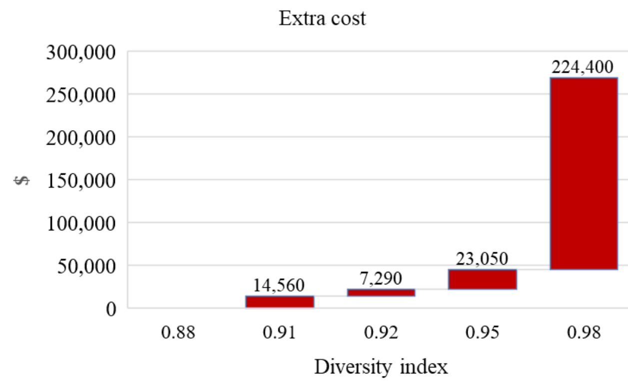

Fig. 19. The trend of extra cost regarding to diversity index

As the results indicate, when the diversity index rises, one can come to the following observations:

4. Conclusions

This article has tried to increase energy security and resilience at the lowest cost. For this purpose, resilience index and energy security indices have been used. Increasing the percentage of critical loads that should be supplied has led to an enhancement in energy hub costs.

On the other hand, with the increase of storage units, more critical loads are supplied; but the cost of the energy hub increases. Energy security was examined with the HHI and Diversity indices, and the results showed that the improvement in energy security has led to an increase in the cost of the energy hub so that with the improvement of the index from 0.37% to 0.35%, the cost has increased to 224,400

Observations summarized in this paper include the following:

1. The observations indicated that increasing the resilience of critical loads leads to an enhancement in costs. In the first scenario, the cost of the system has increased from 342,340 to 362,950, in the second scenario from 506,240 to 629,910, in the third scenario from 766,320 to 811,980, and in the fourth scenario from 815,580 to 873,800. As noted, the percentage of cost increase in each scenario considering the energy security indices (fourth step) in comparison with the base case (first step) is equal to 6.02%, 24.43%, 5.96% and 7.10% respectively

2. In the worst-case scenario, for each percent increase in critical load, the total cost is enhanced by 0.3%

3. The utilization of energy storages device helps to raise supplied critical load, Furthermore, Storage devices are increasingly used in intense events.

4. The results showed that with the reduction of the HHI index, the total cost increases sharply. (78% increase in cost for 18% improvement)

5. The simulations showed that the maximum storage capacity is when input carriers have a low price.

6. With the increase of the diversity index for each percent, the total cost has increased by 7.15 %

7. The observations showed, that limitations of input carriers increase the total cost of the energy hub.

In future studies, resilience optimization in multi-hubs would be investigated. In addition, the operation of the energy hub under resiliency conditions with the presence of renewable units and their uncertainty will be studied. Furthermore, the optimal capacity of storage devices in the energy hub is determined by the approach of increasing resilience and considering their investment costs. The resilience of the energy hub with various weights from different critical loads will be examined. Exploring the strategic interaction of different players in energy hubs system in the context of game theory model and reaching the optimal solution will be investigated in future works. The inclusion of load management and financial incentives in the condition of severe events will be fully investigated in future research efforts.

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