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Planning of Multiple Energy Hubs and Scheduling of Preventive Maintenance Equipment Under Uncertainty and Energy Storage

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Abstract *– Nowadays, the lack of energy regarding increasing population growth and increasing consumption to meet industries' needs is one of the major problems worldwide, especially in developing countries. This paper attempts to model multiple energy hubs to promptly meet customers' needs and prevent shortages and pay extra costs during peak periods by storing energy in regular periods. The system has several energy hubs with different equipment that will be used according to the customers' needs. Various maintenance policies have been defined to achieve the optimum conditions based on cost and capacity available by solving the model to increase the quality of service and the equipment's high efficiency. Due to uncertainties in customer demand and different maintenance policies, two-staged stochastic optimization has been used based on the scenario. Model solution results show that concerning the defined costs, each hub's interior equipment has better performance with a six-month maintenance policy and the hub input equipment has better performance with a monthly maintenance policy.*

Keywords*– Energy Hub, Maintenance Policies, Energy Response System, Energy Storage.*

I. INTRODUCTION

Until the industrial revolution, life was decentralized all over the world. The countries relied on resources available in their vicinity producers were consumers of agricultural products, and the surplus values were sent to the surrounding areas to compensate for shortages. At that time, most energy sources were renewable (such as wood, sunlight, wind turbines, and water mill), and humans had accepted the changes in renewable energy. For example, in order to use the maximum sunlight, things were delayed until daylight. Considering the benefits of scale economics, humans' life transformed by developing the system engines and the subsequent industrial revolution. The new giant industries born by steam turbines needed reliable and economical energy sources, which did not exist in renewable energy. Although renewable sources had advantages such as abundance and relative dispersed geographical distribution, problems such as limited access have introduced them as the most expensive energy sources. Limited access to energy sources such as sunlight and wind at various times indicated the need for auxiliary energy sources and the possibility of energy storage. In the absence of extra energy or storage, security and independence with renewable energies would not be possible. The importance of energy in various economic, social, environmental, and security aspects is clearly defined. Energy Security provides available, affordable, reliable, efficient, environmentally friendly, and socially acceptable energy

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services for end-users (Sovacool and Brown, 2010). Energy security provides the integrated concepts of national security, sustainable development, human security, and human rights (Winzer, 2012).

II. LITERATURE REVIEW

According to the descriptions in the introduction section, the need for continuous energy sources led to the use of fossil fuels, and the global supply of cheap and reliable fossil fuels has gradually driven renewable technologies out of the competition (Karimi and Khalilpour, 2019). With increasing energy consumption, especially in industrialized and developed countries, using fossil fuels to supply the desired energy and occurrence of problems such as increased CO_2 levels in the atmosphere exposed environmental factors to danger (Moghaddas-Tafreshi et al., 2019). Besides, the low efficiency of plants operating with fossil fuel encouraged researchers to use a new concept for renewable energies (Geidl and Andersson, 2007). These problems have shown that providing clean and sustainable energy is one of the most important concerns of environmental protection and energy security worldwide (Ma et al., 2017). Optimal utilization of energy systems is one of the main challenges in the economic debate, flexibility, and sustainable energy supply (Rakipour and Barati, 2019). The energy industry is based on sustainability and is transformed from a centralized and inflexible fossil fuel system into a decentralized and flexible system. As mentioned, in recent years, the economic crisis and environmental pollution have forced people to use different energy modes such as multiple energy systems (MES) to integrate different types of energy into each process and combined energy systems (CESs) in order to increase the efficiency and optimization of energy systems as well as the sustainable supply of energy to consumers (Krause et al., 2010, Rastegar et al., 2016). One of the practical terms extended because of the energy converters development is the term "hub". The hub means centrality. The first use of the hub in hub locating articles was made by O'kelly (1986) for the development of large-scale transport companies. These companies were keen to optimize their terminals to make maximum use of facilities and resources. The use of the hub in the energy sector is a new issue. The first energy hub was created in 1995 (Barylski, 1995). The point of conflict for energy carriers, equipment for the conversion, storage, and meeting energy demand is the energy hub. The energy hub is a new concept for the optimal management of multiple energy systems. These hubs have the significant potential to realize energy system models and move towards multiple sustainable energy systems (Mohammadi et al., 2018). In the hub, energy is the input carriers (electricity and natural gas), energy converters (transformers, CHPs, and furnaces), and the output loads (electricity, heat, and cold). In these systems, the electricity demand can be directly supplied by the electricity grid or by the CHP generation capacity (Malakoti-Moghadam et al., 2019). The use of energy hubs conduces to energy consumption reduction, simplicity, and high accuracy in analyzing and evaluating multiple energy systems, reliability improvement, and multidimensional analysis of the energy system (technical, economic, and environmental) (Sani et al., 2019). In energy hub systems, energy supply and demand balance are guaranteed by changing inputs' volume, focusing on system stability and economic performance, and coordinating traditional and renewable energy (Huang et al., 2019). The increasing influence of using combined heat and power (CHP) units indicates replacing different energy carriers. CHP can produce electricity and heat at the same time with fuel consumption (usually natural gas). For electricity generation, US natural gas consumption increased from 32 percent in 2007 to 39 percent in 2012. For the next decades, power generation capacity based on natural gas is considered the main fuel in this country. Therefore, due to the importance of natural gas in power generation, it is necessary to consider the natural gas network in planning (Bruno et al., 2017). The energy hub model study is generally divided into two categories: the connection matrix calculation model and optimal performance mode. Zhang and Liu (2019) proposed a multi-stage modeling approach that separates the EH model into several steps and adjusts the EH model by multiplying the connection matrix at each stage.

In (Sani et al., 2019), Energy hub equipment includes power and heat generation and water desalination equipment. The model uses its optimal capacity by using a genetic algorithm to supply demand, reduce costs, reduce pollution, and increase efficiency. The presented model in a cement factory shows that the total annual cost is reduced by about $ 37,000, the amount of produced CO_2 is reduced by around 21620 tons, and efficiency is increased by 36%. Researchers have focused especially on optimal scheduling of energy hub systems. One of these scheduling models is the mixed-integer linear programming model, which is used to solve the connection relationship between different energy sources

(Wang et al., 2018). Alipour et al. (2017) presented a probabilistic model for the optimal performance of an energy hub with respect to the demand response program. In this model, the storage of electrical, thermal energy, and hydrogen has been done; also the CHP is used to minimize the cost. Optimal scheduling of electric and heat hubs in economic and environmental conditions in the presence of peak load management with the minimum cost of energy hub and pollutant emissions can be found in (Nojavan et al., 2018). Several studies are focusing on the different aspects of an energy hub. Batić et al. (2016) presented the energy management approach using energy hub concept and demand system management. In (Kamyab and Bahrami, 2016), the strategic behavior of an energy hub was investigated in a competitive market of electricity. For this purpose, a distributed algorithm is used to obtain a competitive equilibrium in polynomial time. This paper presents a robust optimization approach due to economic and environmental limitations despite uncertainties in market price and multi-demand response programs. In a robust approach, low and high market prices are considered rather than forecasting the market price. Time-of-use (TOU) and real-time pricing (RTP) of demand response programs play an important role in flattening the load curve to reduce the total costs of operation and emission of CO_2. In (Majidi et al., 2017), a multi-objective optimization model is presented concerning environmental costs and in the presence of a demand response program. The weighted sum method is used to solve the multi-objective model, and the fuzzy satisfaction method is used to choose the best compromise solution. The load management programs transfer a percentage of the load from the peak period of consumption to a low-pressure period leading to a reduction in the total cost and pollutant emissions of the energy hub system. For the compatible model, integer linear programming and GAMS software have been used. In (Pazouki and Haghifam, 2016), a mathematical equation for optimal EH planning due to functional limitations is presented. In the objective function for definite and random conditions, wind power, electricity price, and electricity demand are provided. Input carriers are water, electricity, gas, and output demands are electricity, heat, water, and gas. In (Vahid-Pakdel et al., 2017), stochastic programming is performed for uncertainty modelings such as demand, market price, and wind speed. It is shown that adding a new source of heat energy to meet demand concerning the market mechanism changes the optimal point.

Shahmohammadi et al. (2014) took advantage of the integration options such as smart technology, storage systems, multi-generation systems, renewable energy sources, distributed energy sources, and demand-driven management by introducing the concept of smart energy hubs. In order to use zero-emission renewable sources in combined cycle power plants, Bahrami et al. (2017) presented a real-time energy hub timing issue with dynamic price conditions in the market. The interactive effect of an energy hub is used in a potential game to optimize gas and electricity payments. The results of this algorithm show an average increase in efficiency of up to 18.8%. This paper presents a combined energy system (CES) with the concept of energy hubs that include electric, heating, and cooling hubs with demand response programs (DRPs) for electricity, cold, and the use of renewable energy resources (RERs). In this model, uncertainty and different scenarios are considered for the electricity, heat and cold, wind speed, solar radiation demands, and the number of energy carriers. Different scenarios are produced for uncertainty using the Monte Carlo method. The model results show an increase in energy hub profits, a decrease in the cost of electricity purchased, and a reduction in operating costs. Due to the effect of uncertainty on energy demand and market price in power systems, these parameters play an important role in increasing computation volume in a scenario-based random programming approach. For this reason, stochastic or robust optimization methods have been studied by controlling forecast errors, wind turbine uncertainty, demand rate, and component availability (Dolatabadi et al., 2017).

Brahman et al. (2015) presented a residential energy hub model that includes solar radiation, natural gas, and electricity as input and produced cooling, heating, and electricity as output. The problem of hub energy system performance involving different energy carriers was investigated in (Skarvelis-Kazakos et al., 2016) using the multi-factor technique. This paper presents a residential energy hub model for a smart home concerning hot water pump heaters and coordinating pollutant emission sources. This article is examined in two dimensions. The first dimension optimizes the combined CHP system and dynamic pricing storage system. The second dimension is explored to fulfill the important issues of meeting household demand in a smart network and performing optimal load management. The combination of production and maintenance programs in recent years has been widely used in theory and practice. Production planning models seek to balance production costs and material maintenance costs, while maintenance models attempt to balance the costs and benefits of maintenance programs for the system's optimal performance (Amiri and Honarvar, 2018). Because of the expensive and advanced equipment, it is usually tried to take advantage of the maximum production time. Nevertheless, when an unexpected breakdown occurs in the production line and reduces the efficiency of the production system, there will be a long interruption in the system. This causes changes in product quality and service level. Therefore, integrated preventive activities are needed to reduce casualties (Aghezzaf and Najid, 2008).

Weinstein and Chung (1999) presented a three-part model to solve the contradictory goals of increasing reliability and profitability. First, a comprehensive production program is developed, and then a production schedule is prepared for the minimum weight deviation from the specified goals. Finally, the loading requirements at the work center are determined by scheduling capacity and used to simulate equipment failure over the planning horizon. The effective factors in selecting maintenance policies are the type of maintenance activity, number of maintenance times, the importance of failures, maintenance cost, and integrated production policies. Aghezzaf et al. (2003) presented a preventive maintenance and production planning model for a single-line production system and presented an integrated maintenance program, assuming a reduction in the production line capacity for maintenance activities. Kang and Subramaniam (2018) provide simultaneous control of dynamic maintenance and production in a system subject to failure. This policy includes corrective, preventive, and opportunistic maintenance. Opportunistic maintenance uses machine failures as a potential opportunity to apply maintenance on other machines. Costs used in this article include inventory, waste, and maintenance costs. This model is solved using an iterative approximation algorithm. Jamalzadeh et al. (2020) have proposed a hybrid interval-stochastic framework for robust planning based on the thermal energy market, heat and electrical demand response program, and energy flexible management to reduce operating costs. This two-objective model includes the cost of deviation and the average cost and is solved by the weighted sum method. The results show that with a smooth increase in the average cost, the deviation cost decreases significantly. A normal distribution is used to obtain the uncertain heat and electricity demands, and for wind speed, Weibull distribution is used. Zhu et al. (2020) proposed a mathematical model of energy hub structure by responding to integrated demand. The energy hub flexible demand is obtained according to the wind power output and load curves on different season days. The purpose of this model is to reduce annual expenditure, including economic costs, the cost of insufficient system flexibility fines and the cost of environmental protection. Flexibility constraints help decision making to optimize benefits while meeting system flexibility needs. Heidari et al. (2020) examined the effect of ice storage as a new storage device on the performance and efficiency of energy hub costs. Stochastic and definite behavior of ice storage was also compared. This article uses clean, green, and renewable energy sources such as wind turbines and solar panels. The results show a 22% reduction in operating costs with the new hub structure. Heidari et al. (2020) used game theory for optimal bidding strategy in a competitive and balanced market in the field of energy hub pricing. The high flexibility of the energy hub helps to benefit from participation in the energy market. Price uncertainty has been achieved with the Monte Carlo simulation model, and stochastic bi-level programming has been used to solve the model. Luo et al. (2020) presented a three-level energy planning for multi-level integrated energy system (IES) based on hierarchical Stackelberg game approach. The high level includes electricity and natural gas companies, the middle level includes energy hubs, and the third level includes consumers. The simulation results show that increasing the number of energy hubs decreases energy prices and increases energy demand. A summary of the literature review is shown in Table I. In this table, an attempt has been made to make a comparison between the various articles and our article so that the research innovations can be clearly identified.

Based on the literature review and previous studies, the application of different maintenance policies on multiple energy hub systems with response scheduling and meeting demand for customers and the storage system is a new model presented in an integrated model for the first time in this paper.

III. MULTIPLE ENERGY HUB DEMAND PLANNING AND SCHEDULING MODELING

Multiple energy hub demand planning and scheduling model includes two significant issues: maintenance scheduling and multiple energy hub response programs. In this problem, we try to increase the reliability of acceptable responses to customers and reduce the total cost of the system. The equipment uses electricity and natural gas as a primary fuel for activities, and after meeting the needs, part of the energy production is stored in special storage tanks to be used in peak periods to prevent shortages. Tables II and III present the parameters and variables used in the problem.

The information on the energy hub equipment is described in Table IV. As shown in Table II, each equipment has unique features and generates the power to provide the required energy. The use of new technologies such as Combined Heat and Power (CHP) and Absorption Chiller (Ab.chiller) provides energy streams from complementary systems; this equipment intensifies system connectivity at the same time and leads to Increasing the efficiency and complexity of optimal system planning (Huang et al., 2019).

Table I. A summary of the literature review

Authors	*Year of publish*	*Article subjects*			*Objective*		*Energy carrier*						*Uncertainty*				*Storage system*	*Environmental issues*	*Solving technique*
		single	*multiple*	*maintenance*	*Min Cost*	*Max reliability*	*natural gas*	*renewable energy*	*water*	*cooling*	*thermal*	*electrical*	*demand*	*equipment*	*price*	*energy*			
Aghezzaf & Najid	2008				✓														A lagrangian-based heuristic
Alipour et.al.	2017	✓			✓		✓				✓	✓			✓	✓			Monte carlo simulation
Amiri & Honarvar	2018	✓		✓	✓	✓	✓			✓	✓	✓	✓						Two-stage stochastic programming approach/ ε -constraint method
Bahrami et.al.	2017	✓			✓		✓					✓	✓		✓				Potential game approach
Batic et.al.	2016	✓			✓			✓		✓	✓	✓				✓		✓	Rule-based heuristic
Brahman et.al.	2015	✓			✓		✓	✓				✓				✓		✓	GAMES
Heidari et.al.	2020	✓			✓			✓		✓	✓	✓				✓	✓	✓	Stochastic programming
Huang et.al.	2019		✓		✓		✓	✓		✓	✓	✓				✓			Game theory
Jamalzade et.al.	2020	✓			✓		✓				✓	✓			✓				Robust programming
Kamyab & Bahrami	2016	✓			✓		✓	✓			✓	✓			✓		✓		Game theory
Luo et.al.	2020		✓		✓		✓				✓	✓							Stackelberg game approach
Ma et.al.	2017		✓		✓			✓		✓	✓	✓				✓	✓		Generic modeling method
Majidi et.al.	2017	✓			✓		✓	✓	✓		✓	✓				✓		✓	Fuzzy satisfying technique
Malakoti-Moghadam et.al.	2019	✓			✓		✓				✓	✓							Genetic algorithm
Moghaddas-Tafreshi et.al.	2019	✓			✓		✓	✓				✓				✓			Gap decision theory
Nojavan et.al.	2018	✓			✓		✓	✓	✓		✓	✓				✓		✓	ε -constraint and max-min fuzzy satisfying method
Pazouki &Haghifam	2016	✓			✓		✓	✓	✓		✓	✓	✓		✓	✓		✓	Monte carlo somulaton/ GAMS
Rakipour & Barati	2019	✓			✓			✓		✓	✓	✓	✓		✓	✓			Monte carlo somulaton/ GAMS
Rastegar et.al.	2016	✓			✓		✓	✓			✓	✓				✓	✓		GAMS
Sani et.al.	2019	✓			✓				✓		✓	✓						✓	Genetic algorithm
Shahmohammadi et.al.	2014	✓			✓		✓				✓	✓							GAMS
Skarvelis-kazakos et.al.	2016		✓		✓		✓	✓			✓	✓				✓		✓	Energy hub optimization algorithm
Vahid-Pakdel et.al.	2017	✓			✓			✓			✓	✓	✓		✓	✓	✓		GAMS
Wang et.al.	2018	✓			✓		✓			✓	✓	✓					✓		Graph theory
Our Article	2020		✓	✓	✓	✓	✓				✓	✓	✓	✓			✓		Two staged stochastic optimization

In Fig. (1) and (2), you can see the overview of an energy hub system and the energy hubs system used in this paper.

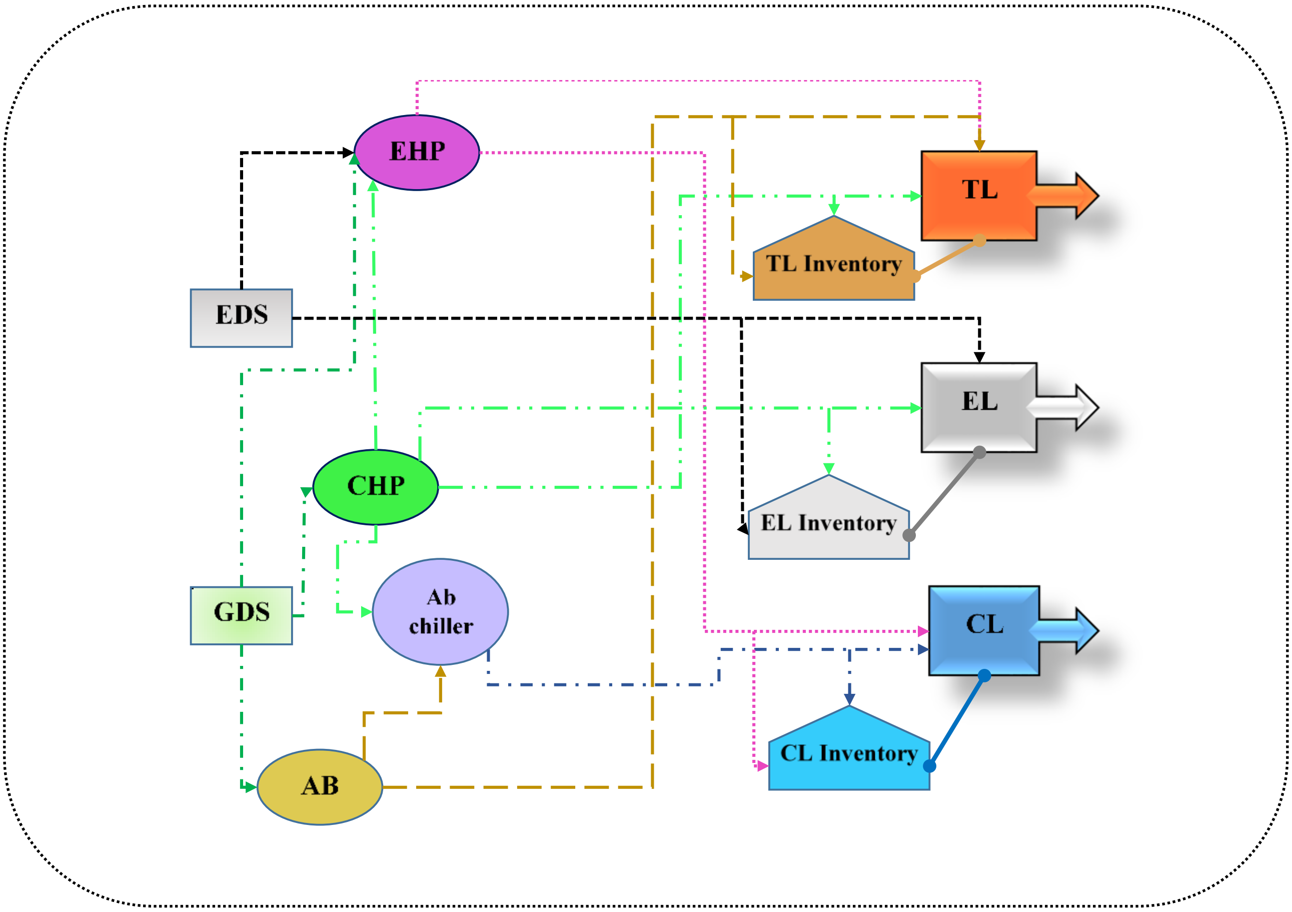

Fig. 1. The schematic of the system with an energy hub

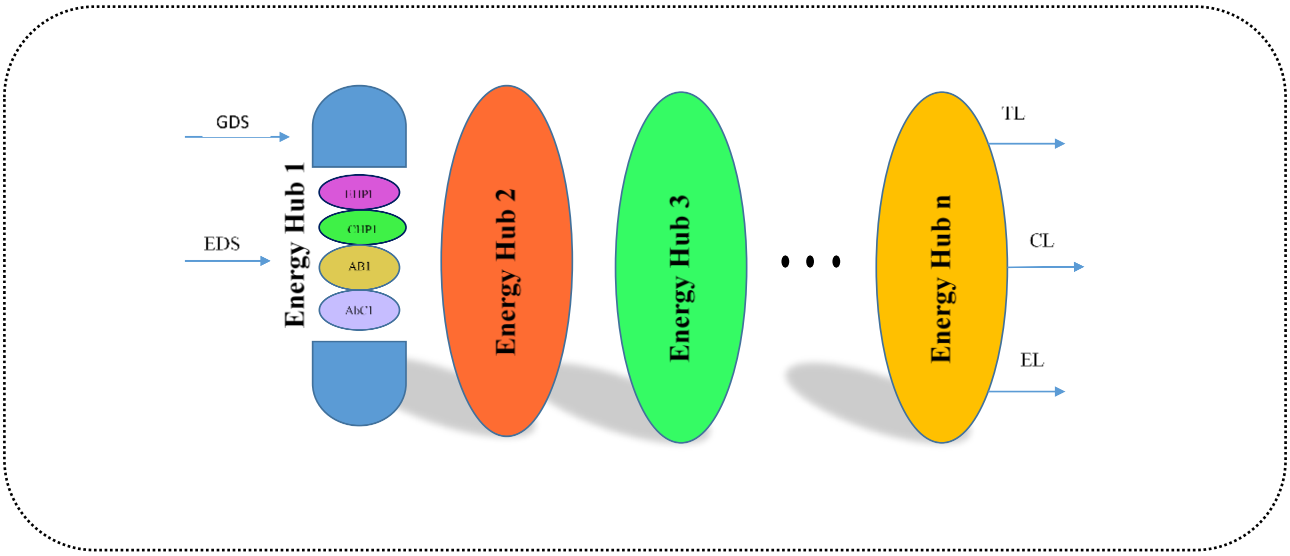

Fig. 2. The schematic of the energy hubs system

Table II - Model parameters

Model parameters	
Electric Heat pump	$EHP = \{EHP_1, EHP_2, EHP_3, EHP_4\}$
Combined heat power	$CHP = \{CHP_1, CHP_2, CHP_3, CHP_4\}$
Auxiliary boiler	$AB = \{AB_1, AB_2, AB_3, AB_4\}$
Absorption chiller $\{ABchiller_1, ABchiller_2, ABchiller_3, ABchiller_4\}$	$ABchiller$
Electricity distributed system	$EDS = \{EDS_1, EDS_2, EDS_3, EDS_4\}$
Gas distributed system	$GDS = \{GDS_1, GDS_2, GDS_3, GDS_4\}$
Electrical load	EL
Cooling load	CL
Thermal load	TL
Wasting load	air
Scenario sets	SS
Equipment set	$j = \{EHP, CHP, AB, ABchiller, EDS, GDS\}$
Output load set	$i = \{EL, TL, CL, air\}$
Maintenance policies	S
Periods	t
Variation of electricity to heat coefficient in CHP	$landa$
The capacity of power lines	CLC
The capacity of gas lines	GLC
EHP efficiency factor	$copEHP$
EHP efficiency coefficient in cold and heat mode	$copcool/heatEHP$
ABchiller efficiency factor	$copABchiller$
CHP electrical efficiency coefficient	$etaCHP$
AB efficiency factor	$etaAB$
Number of fixed length periods	N
The complete failure reduction coefficient	phi
The preventive maintenance reduction coefficient	omg
Fixed period length	$Kesi$
The nominal capacity of each equipment in energy hubs	k_j
Operating cost of each hub equipment	OC_j
The probability of each scenario	pr_{ss}
The price of natural gas for the production of heat at every time	$NGPr_t$
The price of natural gas for generating electricity at every time	$NGEPr_t$
The price of electricity at every time	EPr_t
Estimated electricity demand value for each t and ss	$EEL_{t,ss}$
Estimated heat demand value for each t and ss	$TTL_{t,ss}$
Estimated cold demand value for each t and ss	$CCL_{t,ss}$
Cost of lost order i at time interval t	$Cnot_{i,t}$

Table III - Model variables

Model variables	
Output power from j to j at time interval t in scenario ss	$E_{j,j,t,ss}$
Output power from j to i at time interval t in scenario ss	$EE_{i,j,t,ss}$
The output power of j at time interval t in scenario ss	$EEE_{j,t,ss}$
Output power for heat from j to j at time interval t in scenario ss	$Eheat_{j,j,t,ss}$
Output power for cold from j to j in time interval t in scenario ss	$Ecool_{j,j,t,ss}$
Output heat from j to j at time interval t in scenario ss	$H_{j,j,t,ss}$
Output heat from j to i at time interval t in scenario ss	$HH_{j,i,t,ss}$
Output heat from j at time interval t in scenario ss	$HHH_{j,t,ss}$
Output cold from j to j at time interval t in scenario ss	$CC_{j,j,t,ss}$
Output cold from j to i at time interval t in scenario ss	$CCC_{j,i,t,ss}$
Output cold of j at time interval t in scenario ss	$CCCC_{j,t,ss}$
CHP fuel consumption at time interval t in scenario ss	$F_{CHP,t,ss}$
AB fuel consumption at time interval t in scenario ss	$F_{AB,t,ss}$
The amount of electrical load not supplied at time interval t in the ss scenario	$ELnot_{t,ss}$
The amount of thermal load not supplied at time interval t in scenario ss	$TLnot_{t,ss}$
The amount of cold load not supplied at time interval t in scenario ss	$CLnot_{t,ss}$
The binary variable of maintenance policy s for equipment j	$Z_{s,j}$
The binary variable of output load shortage i at time interval t in scenario ss	$zp_{i,t,ss}$
The amount of electrical energy storage at time interval t in scenario ss	$EInventory_{t,ss}$
The amount of thermal energy storage at time interval t in scenario ss	$TInventory_{t,ss}$
The amount of cold energy storage at time interval t in scenario ss	$CInventory_{t,ss}$
Probability of shortage (lack of reliability)	$alpha$

Table IV. Information on the energy hub equipment

Operational properties	***input / Output***	***Usage costs***	***Equipment symbol***	***Equipment name***
Conversion of electrical current to heat and cold energy	Electricity from the electricity distribution system and CHP /eliminates the need for heat and cold load	/Cost of electricity (fuel) The operating cost of setup/ Cost of maintenance	EHP	Electric Heat pump
Conversion of natural gas energy to heat and electricity	Gas from gas or electricity/ distribution system to EHP, heat to AB.chiller, meet heat and electrical load requirements	Cost of natural gas (fuel)/ The operating cost of setup/ Cost of maintenance	CHP	Combined heat power
Conversion of natural gas energy to heat	Gas from the gas distribution system/heat to ABchiller and meet the heat requirement	Cost of natural gas (fuel)/ The operating cost of setup/ Cost of maintenance	AB	auxiliary boiler
Conversion of heat energy to cold	The heat from CHP and AB / Meet cooling requirement	Cost of electricity (fuel)/ The operating cost of setup/ Cost of maintenance	Ab chille	absorption chiller

Due to uncertainties such as customer demand for each energy load, such as electricity, heat, cold, and the probability of failure of each equipment at different rates, it is impossible to examine the model classically. For this reason, stochastic programming is used in this model. To consider different customer demand scenarios, we use the scenario-based method, and by defining different scenarios, we examine the required amount of each energy to resolve the maximum demand by making appropriate decisions. The probability of equipment failure is also investigated by a two-stage stochastic optimization method. For maintenance of each energy hub equipment, different policies are defined based on maintenance costs and the number of times subject to preventive maintenance in each equipment period. Preventive maintenance affects the total cost of the system and affects the available capacity of each equipment.

The following steps are taken to implement the model:

Step 1) All parameters of the problem are entered into the computing environment (MATLAB and GAMS) as inputs.

Step 2) The computation of the first step decisions is performed. These decisions include calculating the total cost of the system and the available capacity of each equipment.

In this paper, two concepts of corrective and preventive maintenance are used. Corrective maintenance is a type of repair that applies to equipment failure and returns the device to pre-failure conditions (as good as old conditions). Preventive maintenance is regular and periodic maintenance that reduces equipment failure probabilities to provide maximum equipment reliability and availability and reduces system failures and repair times. Then, the device returns to its original age (as good as new condition). According to Yalaoui et al. (2014) model, the failure rate is calculated from Equation (1):

$$r_j(t) = \frac{f_j(t)}{1 - F_j(t)} \quad \forall j, \forall t \tag{1}$$

$$\theta_j^r = \varphi k_j \qquad \theta_j^p = \omega k_j \quad \varphi, \omega \in [0,1] \tag{2}$$

The values $f_j(t)$ and $F_j(t)$ represent the probability function and the cumulative function of the time-dependent failure rate, respectively. As mentioned in the maintenance definition, repairs reduce the nominal capacity of the equipment shown in Equation (2).

After defining the probable failure functions, preventive maintenance policies are defined, and the expected costs for each equipment are calculated according to failure probabilities. This paper assumes that preventive maintenance is performed at the beginning of each period. If the problem has a time horizon N, there are n_j periods with length τ such that $N = n_j\tau$. Therefore, preventive maintenance periods are performed at times $1, n_j + 1, 2n_j + 1, \dots, N$, it means we will have $\left[\frac{N}{n_j}\right]$ preventive maintenance. The maintenance cost functions are shown in Table V.

The final Equation for calculating the expected total maintenance cost is shown in Equation (3):

$$\boldsymbol{c(n_j, j) = \left[\frac{N}{n_j}\right] c_j^p - \log[(1 - F_j(n_j\tau))^{\left[\frac{N}{n_j}\right]}(1 - F_j\left(N - \left[\frac{N}{n_j}\right] n_j\right)\tau)] c_j^r} \tag{3}$$

Table VI shows the available capacity values of each equipment when preventive or corrective maintenance is applied.

Table V. Maintenance cost functions at different time intervals

Total maintenance cost	*corrective maintenance cost*	*preventive maintenance cost*	*Length of time interval*
$C_{n_j} = c_j^p + c_j^r \int_0^{\tau} r_j(t)dt$	$c_j^r \int_0^{\tau} r_j(t)dt$	c_j^p	τ
$C_{n_j} = c_j^p + c_j^r \int_0^{n_j\tau} r_j(t)dt$	$c_j^r \int_0^{n_j\tau} r_j(t)dt$	c_j^p	$n_j\tau$

Table VI. The available capacity of equipment at different time intervals

corrective capacity reduction	*preventive capacity reduction*	*time interval*
$\theta_j^r \log(1 - F_j(\tau))$	θ_j^p	1
$\theta_j^r \log(\frac{1 - F_j((n-1)\tau)}{1 - F_j((n)\tau)})$	0	n_j

Therefore, the available capacity of each equipment is calculated by Equations (4) and (5):

$$K_j(1) = k_j - \theta_j^p - \theta_j^r \log(1 - F_j(\tau)) \quad (4)$$

$$K_j(n) = k_j - \theta_j^r \log(\frac{1 - F_j((n-1)\tau)}{1 - F_j((n)\tau)}) \quad (5)$$

The general schema of maintenance policy and available capacity is presented in fig. (3).

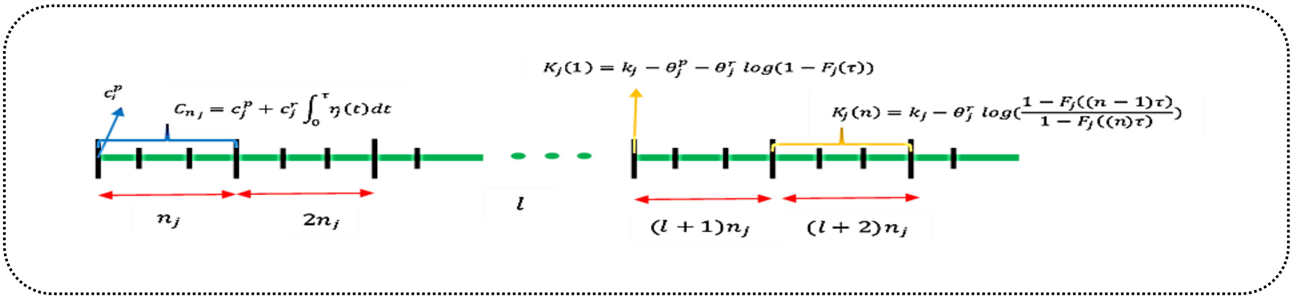

Fig. 3. The scheme of preventive and corrective maintenance policies

Step 3) Second stage decisions are made. The total cost of preventive maintenance policies and the available capacity are entered into the GAMS computing environment as input parameters, and the mixed-integer linear programming model is solved according to the objective function and Limitations. All variables, except the type of preventive maintenance cycle for each equipment, are calculated, such as the amount of energy generated from each equipment in the second stage decision making, according to the specified scenario.

$$Minf_1(x) = \sum_{ss}\sum_{t} pr_{ss}(F_{CHP,t,ss}NGEPr_t + F_{AB,t,ss}\,NGPr_t) \quad (6)$$

$$+\sum_{ss}\sum_{t} pr_{ss}(EE_{EDS,EL,t,ss} + E_{EDS,EHP,,t,ss})EPr_t \tag{7}$$

$$+\sum_{ss}\sum_{t} pr_{ss}(EEE_{CHP,t,ss} + HHH_{CHP,t,ss})OC_{CHP} \tag{8}$$

$$+\sum_{ss}\sum_{t} pr_{ss}(OC_{AB}HHH_{AB,t,ss}) \tag{9}$$

$$+\sum_{ss}\sum_{t} pr_{ss}(OC_{ABchiller}CCCC_{ABchiller,t,ss}) \tag{10}$$

$$+\sum_{ss}\sum_{t} pr_{ss}(HH_{EHP,TL,t,ss} + CCC_{EHP,CL,t,ss})OC_{EHP} \tag{11}$$

$$+\sum_{ss}\sum_{t} pr_{ss}(ELnot_{t,ss}Cnot_{EL,t} + CLnot_{t,ss}\, Cnot_{CL,t} + TLnot_{t,ss}Cnot_{TL,t}) \tag{12}$$

$$+\sum_{s}\sum_{j} C_{s,j} * z_{s,j} \tag{13}$$

$$Max\ f_2(x) = 1 - alpha \tag{14}$$

The first objective function includes model costs. Equation (6) shows the total cost of natural gas consumption as fuel to supply electricity and heat of CHP and AB equipment. Equation (7) shows the total cost of system input power to supply EHP and customer demand electricity. Since the direct transmission of electricity from the electricity distribution system to the customer's electrification grid is possible, part of the electricity can be supplied without using hub equipment. The equations (8 - 11) show the cost of transport production loads (operating costs) of the relevant equipment according to the type of energy they produce. Equation (12) shows the cost of lost orders (customer dissatisfaction) for electricity, gas, and cold output loads. Equation (13) shows the total cost of preventive maintenance policies entered from the first step and calculated at this step by deciding on the binary variable. Equation (14) represents the second objective function or total network reliability based on maximizing the minimum reliability.

Problem Limitations:

$$EEL_{t,ss} = EE_{EDS,EL,t,ss} + EE_{CHP,EL,t,ss} + ELnot_{t,ss} + EEL_{t-1,ss} \rightarrow ss, \text{to} \tag{15}$$

$$TTL_{t,ss} = HH_{AB,TL,t,ss} + HH_{EHP,TL,t,ss} + HH_{CHP,TL,t,ss} + TLnot_{t,ss} + TTL_{t-1,ss} \rightarrow ss, t \tag{16}$$

$$CCL_{t,ss} = CCC_{ABchiller,CL,t,ss} + CCC_{EHP,CL,t,ss} + HH_{CHP,TL,t,ss} + CLnot_{t,ss} + CCL_{t-1,ss} \rightarrow ss, t \tag{17}$$

$$EInventory_{t,ss} = EE_{EDS,EL,t-1,ss} + EE_{CHP,EL,t-1,ss} - EEL_{t-1,ss} \rightarrow t, ss \tag{18}$$

$$TInventory_{t,ss} = HH_{AB,TL,t-1,ss} + EE_{EHP,TL,t-1,ss} + EE_{CHP,TL,t-1,ss} - TTL_{t-1,ss} \rightarrow t, ss \tag{19}$$

$$CInventory_{t,ss} = CCC_{ABchiller,CL,t-1,ss} + EE_{EHP,CL,t-1,ss} - CCL_{t-1,ss} \rightarrow t, ss \tag{20}$$

$$ELnot_{t,ss} \leq M\left(zp_{EL,t,ss}\right) \rightarrow ss, t \tag{21}$$

$$TLnot_{t,ss} \leq M\left(zp_{TL,t,ss}\right) \rightarrow ss, t \tag{22}$$

$$CLnot_{t,ss} \leq M\left(zp_{CL,t,ss}\right) \rightarrow ss, t \tag{23}$$

$$\sum_{ss} pr_{ss}\, zp_{i,t,ss} \leq alpha \rightarrow \forall i, t \tag{24}$$

$$\sum_{s} z_{s,j} = 1 \rightarrow j \tag{25}$$

$$EEE_{CHP,t,ss} = EE_{CHP,EL,t,ss} + E_{CHP,EHP,t,ss} \rightarrow t, ss \tag{26}$$

$$E_{CHP,EHP,t,ss} = Eheat_{CHP,EHP,t,ss} + Ecool_{CHP,EHP,t,ss} \rightarrow t, ss \tag{27}$$

$$HHH_{CHP,t,ss} = HH_{CHP,air,t,ss} + HH_{CHP,TL,t,ss} + H_{CHP,ABchiller,t,ss} \rightarrow t, ss \tag{28}$$

$$EEE_{CHP,t,ss} = eta_{CHP} F_{CHP,t,ss} \rightarrow t, ss \tag{29}$$

$$HHH_{AB,t,ss} = eta_{AB} F_{AB,t,ss} \rightarrow t, ss \tag{30}$$

$$HHH_{CHP,t,ss} = landa_{CHP} EEE_{CHP,t,ss} \rightarrow t, ss \tag{31}$$

$$EEE_{CHP,t,ss} \leq \sum_{s} KK_{CHP,t,ss} * z_{CHP,s} \rightarrow t, ss \tag{32}$$

$$HHH_{AB,t,ss} \leq \sum_{s} KK_{AB,t,ss} * z_{AB,s} \rightarrow t, ss \tag{33}$$

$$HHH_{AB,t,ss} = H_{AB,ABchiller,t,ss} + HH_{AB,TL,t,ss} \rightarrow t, ss \tag{34}$$

$$HHH_{ABchiller,t,ss} \leq \sum_{s} KK_{ABchiller,t,ss} * z_{ABchiller,s} \rightarrow t, ss \tag{35}$$

$$HHH_{ABchiller,t,ss} = (H_{AB,ABchiller,t,ss} + H_{CHP,ABchiller,t,ss})cop_{ABchiller} \to t, ss \tag{36}$$

$$HH_{EHP,TL,t,ss} = (Eheat_{EDS,EHP,t,ss} + Eheat_{CHP,HP,t,ss})copcool/heat_{EHP} \to t, ss \tag{37}$$

$$CCC_{CHP,CL,t,ss} = (Ecool_{EDS,EHP,t,ss} + Ecool_{CHP,HP,t,ss})copcool/heat_{EHP} \to t, ss \tag{38}$$

$$HH_{EHP,TL,t,ss} + CCC_{EHP,CL,t,ss} \leq \sum_{s} KK_{EHP,t,s} * z_{EHP,s} \to t, ss \tag{39}$$

$$EEE_{EDS,t,ss} = EE_{EDS,EL,t,ss} + E_{EDS,EHP,t,ss} \to t, ss \tag{40}$$

$$E_{EDS,EHP,t,ss} = Eheat_{EDS,EHP,t,ss} + Ecool_{EDS,EHP,t,ss} \to t, ss \tag{41}$$

$$\sum_{EDS} EEE_{EDS,t,ss} \leq CLC \tag{42}$$

$$\sum_{AB}\sum_{CHP} F_{CHP,t,ss} + F_{AB,t,ss} \leq GLC \tag{43}$$

Limitation (15) indicates that the transmission values of the power distribution system and the CHP equipment in the hub plus the amount of electricity demand shortages must be equal to the electricity demand in each period. Since three equipment work together to generate heat and cold, so limitations (16) and (17) indicate that the total amount of heat and cool transferred from this equipment to TL and CL plus the amount of deficiency must be equal to the heat and cold demand in each period and scenario. Limitations (18-20) specify the amount of energy storage in each period concerning the generation and use in previous periods. Limitations (21-23) use the deficiency values to calculate the deficient binary variable for electricity, heat, and cold output load shortages. Limitation (24) calculates the minimum network reliability for the total number of lost orders in each period. Limitation (25) indicates that each equipment should use only one type of maintenance policy. Limitations (26-28) indicate the amount of electricity and heat output from the CHP and its distribution to meet customer needs or transfer to other equipment. Limitations (29-30) show the efficiency value of CHP and AB, calculated from multiplying the efficiency factor in fuel consumption. Limitation (31) shows the amount of heat generated in CHP using the electricity-to-heat conversion factor. Limitation (32-34) shows the total amount of electricity, heat, and cold produced by CHP, AB, and ABchiller according to the available capacity and the type of preventive maintenance. Limitation (35) shows the ABchiller efficiency coefficient concerning the input values of AB and CHP. Limitations (36-38) show EHP and CHP efficiency for the amount of heat and cold produced. Limitation (39) indicates the amount of heat and cold produced by CHP equipment according to available capacity. Limitation (40) indicates the total amount of input power from the distribution system to the grid. Limitation (41) indicates the total amount of input power from the EHP distribution system. Limitations (42-43) indicate the capacity Limitation of the system's electricity and gas lines.

IV. MULTIPLE ENERGY HUB DEMAND PLANNING SCHEDULING MODEL SOLUTION

Parameters are defined to solve multiple energy hub system models, and then the results of the final model solution are presented. This problem has 12 domains that are analyzed with three different demand scenarios. The standard parameters are given in (Amiri and Honarvar, 2018), and the rest of the parameters are generated randomly. Since customer demand is uncertain, different scenarios are defined based on the uniform distribution (2000, 10000). Weibull and gamma distributions are commonly used to determine equipment failure rates. In this paper, the Weibull distribution is used for failure. The equipment has a Weibull failure distribution with parameters (1,2) and (1,1). The next parameters are the defined policies for maintenance. This article uses 6 types of maintenance policies with different visit periods. These visits are considered monthly, every two months, every three months, every four months, every six months, and annually. Therefore, the total maintenance cost for each of these policies is defined and listed in Table VII.

Table VII. Total maintenance cost based on defined policies

	1	2	3	4	5	6
EHP1	8653.841	7453.841	7053.841	6853.841	6653.841	6453.841
AB1	3284.614	2684.614	2484.614	2384.614	2284.614	2184.614
CHP1	30446.14	25646.14	24046.14	23246.14	22446.14	21646.14
Abchiller1	4405.767	3505.767	3205.767	3055.767	2905.767	2755.767
EHP2	10896.15	9096.147	8496.147	8196.147	7896.147	7596.147
AB2	5526.92	4326.92	3926.92	3726.92	3526.92	3326.92
CHP2	36257.67	31157.67	29457.67	28607.67	27757.67	26907.67
Abchller2	4326.92	3726.92	3526.92	3426.92	3326.92	3226.92
EHP3	8653.841	7453.841	7053.841	6853.841	6653.841	6453.841
AB3	3284.614	2684.614	2484.614	2384.614	2284.614	2184.614
CHP3	30446.14	25646.14	24046.14	23246.14	22446.14	21646.14
Abchiller3	4405.767	3505.767	3205.767	3055.767	2905.767	2755.767
EHP4	8653.841	7453.841	7053.841	6853.841	6653.841	6453.841
AB4	3284.614	2684.614	2484.614	2384.614	2284.614	2184.614
CHP4	30446.14	25646.14	24046.14	23246.14	22446.14	21646.14
Abchiller4	4405.767	3505.767	3205.767	3055.767	2905.767	2755.767

Table VIII. The available capacity of the equipment in each period according to maintenance policies

	1	2	3	4	5	6
EHP1.1	3868.589	3868.589	3868.589	3868.589	3868.589	3868.589
EHP1.2	3868.589	4737.1779	4737.1779	4737.1779	4737.1779	4737.1779
EHP1.3	3868.589	3868.589	5605.7669	5605.7669	5605.7669	5605.7669
EHP1.4	3868.589	4737.1779	3868.589	6474.3559	6474.3559	6474.3559
EHP1.5	3868.589	3868.589	4737.1779	3868.589	7342.9448	7342.9448
EHP1.6	3868.589	4737.1779	5605.7669	4737.1779	8211.5338	8211.5338
EHP1.7	3868.589	3867.589	3868.589	5605.7669	3868.589	9080.1227
EHP1.8	3868.589	4737.1779	4737.1779	6474.3559	4737.1779	9948.7117
EHP1.9	3868.589	3868.589	5605.7669	3868.589	5605.7669	10817.301
EHP1.10	3868.589	4737.1779	3868.589	4737.1779	6474.3559	11685.89
EHP1.11	3868.589	3868.589	4737.1779	5605.7669	7342.9448	12554.479
EHP1.12	3868.589	4737.1779	5605.7669	6474.3559	8211.5338	13423.068

Since each hub has four types of equipment and each equipment is examined in 12 periods with 6 policies, and there are 4 hubs in the system, we will finally have a matrix with 12 × 4 × 4 = 192 rows and 6 columns. In order to display, the information is indicated to equipment. Each equipment's available capacity is given in terms of the nominal capacities and the type of performed maintenance in Table VII. Tables VI and VIII are called as inputs to the GAMS program after calculation in MATLAB software.

As seen in the second column and the first policy type (monthly maintenance periods), preventive maintenance is carried out at the beginning of each month, and each equipment reaches its primary age. Thus the available capacity of the equipment is constant at the beginning of each. However, this period is done every three months in the third policy, and every three months, the capacity reaches its initial value. Among the maintenance policies, 60% of the examples are optimized with every six months' maintenance policy, but the input equipment is checked with a monthly maintenance policy. Policy determination is directly related to maintenance costs and order supply capacity. Therefore, the model establishes the right balance between the type of maintenance policy, the cost imposed on the system to reduce failures, and the reliability improvement to customers' better accountability. The multi-hubs and single-hub modes compare the results, which shows a 36% reduction in cost to analyze the model's sensitivity. Another important factor that changes the model is the variation of electrical input fuel price. As electricity prices rise, the model's tendency to use natural gas-fired equipment increases. Thus, by increasing the price, the quantity of electricity demand-supply or electricity consumption is directly reduced from the power distribution system. These two analyzes are shown in fig. (4).

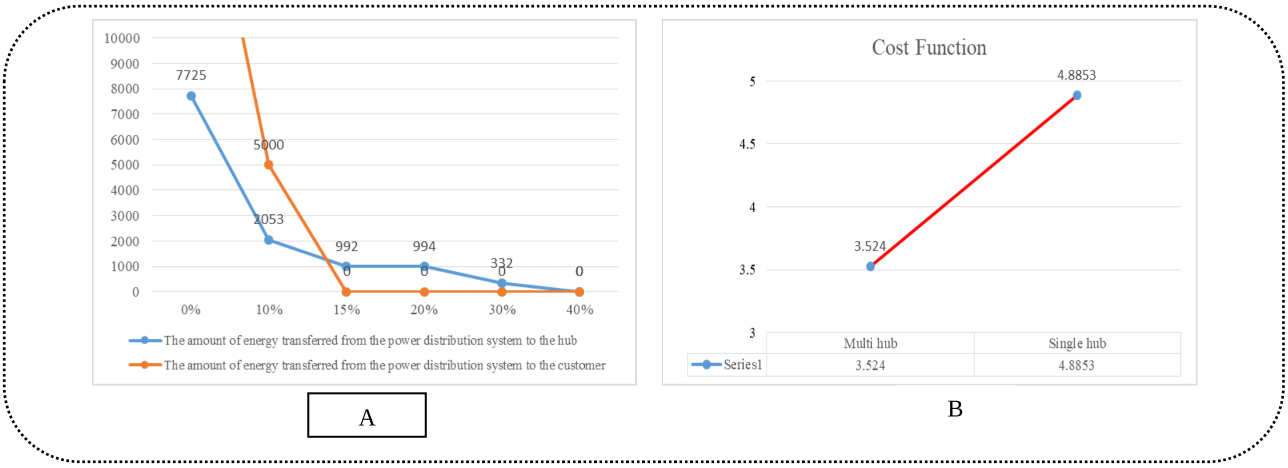

Fig. 4. The sensitivity analysis of the model (A: the impact of electricity cost on the electricity supply, B: single-hub and multi-hubs model analysis)

Table IX. The results of the transfer the second objective function (reliability) as a constraint

Num	*Reliability*	*The sum of load demands*	*The sum of load not supplied*	*Objective Function (*10^7)*
1	0	101600	101600	4.88
2	0.1	101600	13787.5	5.23
3	0.2	101600	13787.5	5.23
4	0.3	101600	15350	5.417
5	0.4	101600	15350	5.417
6	0.5	101600	15350	5.417
7	0.6	101600	8037.5	5.73
8	0.7	101600	8037.5	5.73
9	0.75	101600	8037.5	5.73
10	0.76	101600	0	6.1116
11	0.8	101600	0	6.1116
12	0.9	101600	0	6.1116
13	1	101600	0	6.1116

One of the analyzes that can be interesting in the model is the transfer of the second objective function (reliability) as a constraint. Therefore, equation 14 will be placed in limitation with the following format.

$$1 - alpha \leq \kappa \tag{44}$$

Instead of the value κ, we set different values ranging from 0 to 1 with a distance of 0.1, and the results are given in Table IX. The model performance procedure is shown in Figure 5. As the reliability increases, the model cost increases, and the total shortage (lost orders) decreases. The best result obtains in reliability=0.76. This amount will be different according to demand, cost of lost orders, and hub equipment capacity.

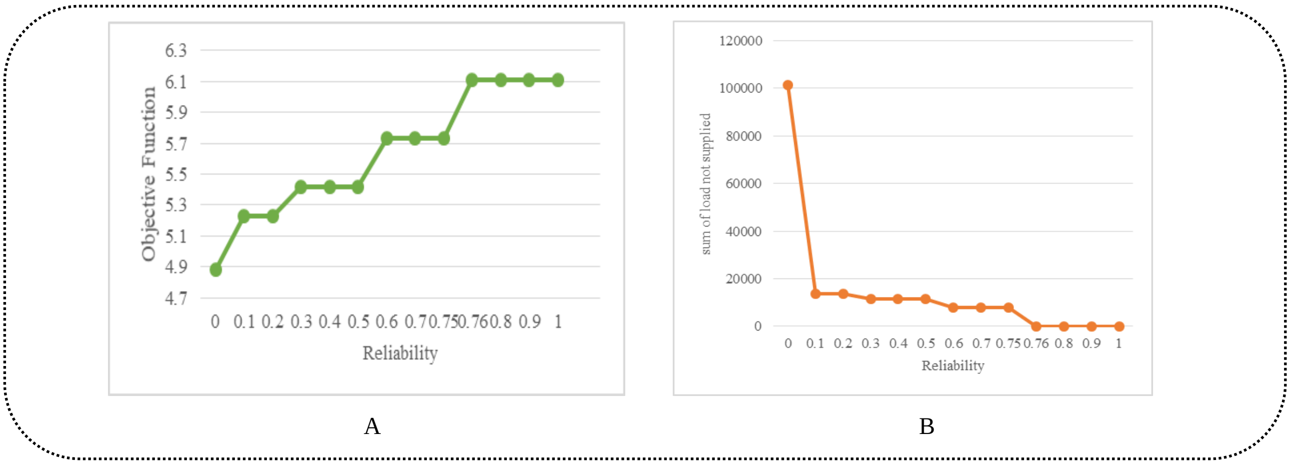

Fig. 5. The sensitivity analysis of the model (A: the impact of reliability on the objective function, B: the impact of reliability on shortages)

V. CONCLUSIONS AND FUTURE SUGGESTIONS

The purpose of this paper is to investigate the energy hub system despite the simultaneous use of multiple hubs and to meet the triple demand for electricity, heat, and cold in different periods. Due to different maintenance policies and possible equipment failure, at first, each of the maintenance costs and available capacity was calculated. After defining different scenarios for uncertain customer demand, the model seeks to reduce operating costs, fuel purchases, deficiency, and increase reliability to meet demand. A mixed-integer linear programming model is presented in this paper that is solved using GAMS and MATLAB software. Three different scenarios for demand and six different policies for preventive maintenance of input and internal equipment have been defined. These policies are considered monthly, every two months, seasonal, every four months, every six months, and annually. The model results show that 60% of the solved examples are optimal inspections every six months for internal equipment and monthly inspection policy for optimal input equipment. These results are affected by maintenance costs and the time required to perform maintenance. A comparison was made between multiple hubs and a single hub to show the model's effectiveness, which shows a 36% improvement in cost. This paper, according to its numerous applications and energy storage capabilities, can be used in various industries and residential homes. To further analysis of the model, the second objective function is represented as a constraint that decreases with increasing the total reliability values of the total lost order, and the total cost of the model increases. Depending on the priority of the decision-making for the spent cost and customer satisfaction, the reliability of the system can be selected.

For future research, the multiple energy hubs locating and designing each hub's structure can be explored. Also, heuristic and metaheuristic solutions can increase the speed of resolution and examine customers' demand in big dimensions like a country.

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