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Evaluation of Hydrogen Storage Technology in Risk-constrained Stochastic Scheduling of Multi-Carrier Energy Systems Considering Power, Gas and Heating Network Constraints

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Abstract: The operation of energy systems considering a multi-carrier scheme takes several advantages of economical, environmental, and technical aspects by utilizing alternative options is supplying different kinds of loads such as heat, gas, and power. This study aims to evaluate the influence of power to hydrogen conversion capability and hydrogen storage technology in energy systems with gas, power and heat carriers concerning risk analysis. Accordingly, conditional value at risk (CVaR)-based stochastic method is adopted for investigating the uncertainty associated with wind power production. Hydrogen storage system, which can convert power to hydrogen in off-peak hours and to feed generators to produce power at on-peak time intervals, is studied as an effective solution to mitigate the wind power curtailment because of high penetration of wind turbines in electricity networks. Besides, the effect constraints associated with gas and district heating network on the operation of the multi-carrier energy systems has been investigated. A gas-fired combined heat and power (CHP) plant and hydrogen storage are considered as the interconnections among power, gas and heat systems. The proposed framework is implemented on a system to verify the effectiveness of the model. The obtained results show the effectiveness of the model in terms of handling the risks associated with multi-carrier system parameters as well as dealing with the penetration of renewable resources.

Keywords: Hydrogen storage technology, multi-carrier system, risk analysis, renewable energy sources, stochastic scheduling.

Nomenclature

t	Time horizon
g	Gas provider
i	Production plant
wf	Wind plant
b	Bus of power grid
m, n	Node of gas grid
h	Node of heat grid
j	Electricity demand
gl	Gas demand
hl	Heat demand
L	Line of power grid
gs	Gas storage
ph	Hydrogen storage
pl	Pipe of gas grid
hp	Pipe of heat grid
NT	Entire time intervals
NJ	Entire electricity demand
NGL	Entire gas demand
NHL	Entire heat demand
NE	Entire non-gas-fired plants
NG	Entire gas-fired units
NC	Entire CHP plants

NGC	Entire CHP and gas-fired plants
NGS	Entire gas storage
NU	Entire number of production units
NWF	Entire number of wind plants
NHP	Entire number of pipes of heat grid
NPL	Entire number of pipes of gas grid
NB	Entire number of buses of power grid
$a_i, b_i, c_i, d_i, e_i, f_i$	Cost coefficients of the production plant *i*
$P_i^{\max}, P_i^{\min}$	Min/Max power supply of plant *i*
$B_{hs}^{\text{Max, charge}}, B_{hs}^{\text{Max, discharge}}$	Max charging/discharging rate of heat storage *hs*
$GS_{gs,\max}^{out}, GS_{gs,\max}^{in}$	Max gas production/supply of gas storage *gs*
$B_{hs}^{\text{Max}}, B_{hs}^{\text{Min}}$	Min/Max capacity of heat storage *hs*
$E_{gs}^{\max}, E_{gs}^{\min}$	Min/Max capacity of gas storage *gs*
MUT_i, MDT_i	Min up/down time of the plant *i*
$PF_L^{\max}$	Transfer capacity of power line *L*
X_L	Reactance of line *L*
$D_{j,t}$	Power load *j* at time *t*
$HL_{hl,t}$	Heat demand *hl*
$HLQ_{hl,t}$	Mass flow of heat load *hl*
$T_h^{\max}, T_h^{\min}$	Min/Max temperature of heat grid at node *h*
$\pi_m^{\max}, \pi_m^{\min}$	Min/Max pressure of gas grid at node *m*
$GW_g^{\max}, GW_g^{\min}$	Min/Max gas provide of gas petroleum *g*
$GL_l^{\max}, GL_l^{\min}$	Min/Max gas load *l*
$HP_{hp}^{\max}, HP_{hp}^{\min}$	Min/Max capacity of heat pipe *hp*
$P_{wf,t}$	Forecasted wind power
Le_{hp}	Length of pipe *hp*

$PF_L^{\max}$	Capacity of power line *L*
$P_{i,t}$	Power supply of plant *i*
$I_{i,t}$	On/off status of plant *i*
$H_{i,t}$	Heat generation of CHP *i*
$PF_{L,t}$	Power flow of power line *L*
$X_{i,\,t-1}^{on}$, $X_{i,\,t-1}^{off}$	On/off time of plant *i*
$HP_{hp,t}$	Mass flow of heat pipe
$T_{h,t}$	Water temperature of heat grid node *h*
$T_{h,t}^{back}$	Returning water temperature of heat grid node *h* at time *t*
$HQ_{i,t}$	Mass flow of CHP plant
$GS_{gs,t}^{out}, GS_{gs,t}^{in}$	Supply/storage of gas in storage *gs*
$GL_{l,t}$	Gas demand *L*
$GW_{g,t}$	Gas supply of gas supplier *g*
$\pi_{m,t}$	Gas pressure of gas grid node *m*
$F_{pl,t}$	Gas flow of line *pl*
SU_i, SD_i	Start-up/shut-down cost of non-gas-fueled plant *i*
SUG_i, SDG_i	Start-up/shut-down fuel usage of gas-fueled plant *i*
$\delta_{b,t}$	Angle of bus *b*

1. Introduction

1.1. Motivation

The interconnection among energy networks is rising because of the high integration of novel facilities such as combined heat and power (CHP) plants, energy storage, renewable energy sources, and gas-fueled generation units [1, 2]. The integrated energy networks take advantage of using alternative sources of energy in providing various types of energy loads. Also, it should be mentioned that by optimizing the operation of energy networks separately, optimal operation of the total energy network cannot be ensured because integrated energy carrier is not considered in such optimization. An important aspect of the integration of energy networks includes the integration between power and heat networks as well as power and gas systems. The high penetration of gas-fired units and power-to-gas plant is effective in raising the integration level of gas and power systems. According to the statistics reported in the United States, the usage of gas is one-third of utility-scale in power generation plants in 2018 [3]. On the other hand, the advantages of the CHP plants in terms of economic and environmental aspects are lucrative for industrial, commercial and residential loads by connecting to boilers and district heating networks (DHN) [4, 5]. To this end, this study investigates the influence of power to hydrogen conversion ability and hydrogen storage in combined power, gas and heat systems under a risk-based framework. Power to hydrogen (P2H) technology is a promising solution for eliminating the wind power curtailment that is beneficial to conversion of the extra power of wind units to hydrogen, and use it at on-peak hours of power system. Accordingly, the interconnection level of power, gas and heat systems is growing by penetration of P2H technology and gas-fired CHP plant.

1.2.Literature review

The interconnection among power, gas and heat networks is of great importance, which has deeply evaluated in the literature. In [6], the authors have presented a security-based scheduling of combined gas and power networks considering networks consequences such as an outage of gas lines and power losses. A combined scheduling model of this system is introduced in [7] for improving the operation model, where wind power uncertainty is studied, and demand response for both gas and power carriers is discussed. An energy flow scheme for power and gas systems based on Newton–Raphson model has been proposed in [8]. In [9], the application of power-to-gas facility in scheduling of combined power and gas systems has been evaluated by proposed a robust model. The authors have studied expansion planning of such systems in [10] based on integrated mixed-integer linear programming. In [11], the authors have minimized the scheduling cost of the multi-carrier systems and maximized the owners profit of the system based on a bi-level scheme. To study a combined power system based on a bi-level programming, where the upper/lower levels deal with the power and gas systems, the authors has presented a model in [12]. In [13], multi-carrier energy systems with water, power, gas and heat carriers has been studied based on evaluating the role of energy storage technologies. A bi-level model for multi-carrier systems has been presented in [14], where expansion planning and operation of the system are studied in the upper and lower levels. A robust operation model of multi-carrier energy systems has been introduced in [15] considering the uncertainty of load, where the effect of water desalination systems and thermal storage have been investigated. A linearization approach is introduced in [16] to analysis the non-linear limits of the gas system. In [17], a two-stage stochastic programming is proposed for energy and reserve coordination in power and gas networks. A two-stage model for combined gas and power networks is proposed in [18] by studying the uncertain parameters. The authors have proposed an innovative energy management model in [19] for smoothening gas and power load patterns by taking advantage of interconnection among power and gas networks and technologies such as the power to gas and CHP units.

Recently, the proportion of hydrogen storage and renewable energy resources has been investigated in several studies [20, 21]. The prior endeavor in the area of coordinating hydrogen storage and photovoltaic cells has been performed in 1990 [22]. Utsira, Norway is the first location for installing the largest hydrogen-wind, which was performed by Norwegian Norsk Hydro company with the German Enercon company. This system can operate in isolated mode with a

90% availability index [23]. In 2007, another project for the integration of hydrogen storage to wind turbines was accomplished in Nakskov, Denmark [24]. The integration of hydrogen carrier in energy networks has been increased by using power to hydrogen technology, fuel cells, and penetration of hydrogen-powered vehicles. Power to hydrogen (P2H) system employs electrolysis to convert the extra electrical energy of an energy network generated by wind turbines to hydrogen, which is beneficial to the whole network in terms of managing the demand pattern. The stored hydrogen can be utilized by a fuel cell to produce power for satisfying the on-peak system load. The utilization of such technology in hydrogen-based industry or gas networks can be defined as one of the main features of P2H [25]. Researchers have concentrated on the application of P2H technology in energy networks in the literature. In [26], the integration of P2H technology and WTs in energy networks have been evaluated considering demand-side management and uncertainty characteristics in the network. The authors have proposed a security-constrained model of energy system operation in [27] considering the P2H technology, where the uncertainty effects of the system parameters have not been addressed. The investigation of the P2H system in energy hubs to accommodate the significant integration of wind energy sources has been accomplished in [28]. The authors have introduced a new energy management framework for controlling isolated microgrids including photovoltaic systems and wind power plants as well as hydrogen generation and storage unit in [29], where the storage is considered for maximizing the benefits of available renewable power sources. The authors in [30] have studied the influence of the presence of power to gas system on operation cost and security of networked energy hubs, which verifies that methanization ability of such systems can be profitable for the network at time intervals with a shortage in gas supply. In [31], a novel assessment method of electrical energy network voltage stability in the existence of wind turbines and uncertain heat and power loads have been proposed, which is studied using a stochastic programming approach. To the best knowledge of the authors, no study has investigated the effect of P2H technology in the scheduling of the multi-carrier energy networks in a transmission-constrained unit commitment scheme.

Considering the uncertain nature of some energy systems parameters such as power output of wind turbines, energy market price and load, different methodologies have been proposed in the literature to deal with risk analysis of uncertain parameters in energy networks. In [32], a risk-based stochastic scheme for the scheduling of energy hubs is presented for hubs with wind units, energy market, power and thermal energy storage facilities considering demand response. In this reference, the risk related to uncertain parameters is minimized for the solution of risk-based energy hub operation using downside risk constraints (DRC) approach. Similarly, DRC method is applied in [33] for handling the risk constrained by uncertain parameters in the solution of the electrical energy procurement of large consumers, where an analysis of economic risk is evaluated in line with a stochastic programming. In [34], the authors have proposed a risk-analysis scheme for the scheduling of a multi-carrier energy hub that focuses on the combination of compressed air energy storage, where the heat and power demand response applications are considered. The risk analysis in the scheduling of energy systems with integration of plug-in electric vehicles (PEVs) is performed in [35] based on a risk-constrained stochastic model, where DRC is employed to obtain appropriate decisions for the PEV aggregator based on various amounts considered for risk. According to the complexity of modeling the uncertainty of solar units and power price in studying optimal bidding of concentrating solar power units, the authors have applied a scenario-based stochastic programming in [36]. So, this reference has presented a risk-constrained stochastic scheme to obtain optimal offering curves when selling power to the market considering the uncertain parameters. A robust OPF model is proposed in [37] based on limiting the frequency and severity of branch flow limit violations using a CvaR scheme. In this reference, the CvaR model has controlled the risk in the operation model when wind power deviates from its predicted amount. A risk-based hybrid approach has been proposed in [38] to address wind power and gas demand uncertainties in gas and power-based energy systems studying power-to-gas facility and demand response programs. The authors of [39] have proposed a robust model for managing the power market price in a P2H-based micro-energy hub in the presence of integrated demand response. A hybrid information gap decision theory-stochastic model has been applied in [40] for clearing power-and heat-based energy markets under uncertainty of wind power production, as well as heat and power loads.

1.3.Contributions

High penetration rate of renewable energy sources, gas/coal-fired power production units, cogeneration plants, and energy storage systems to multi-carrier energy networks benefits them economically. In addition, such systems benefit from using alternative options in providing different energy carriers such as hydrogen storage technology, which is effective in obtaining the minimum cost and maximizing the capability of network in satisfying different types of energy carriers. Moreover, handling the optimal operation of energy systems separately cannot confirm the optimal operation of the completely multi-energy system because the interdependency among energy carriers are not considered. As the best knowledge of the authors, the evaluation of power to hydrogen storage as well as risk analysis in multi-carrier energy systems have not been discussed in the literature. So, the main objective of this paper is to study the role of power to hydrogen storage in multi-carrier networks and to evaluate its influence on optimal sets points of energy systems. Also, as the main feeder for power to hydrogen storage is wind power in multi-carrier energy systems, studying the risk associated with wind power uncertainty is of great importance, for which CvaR is implemented in this study. All in all, this resaerch studies the effect of P2H storage in power, gas and heat systems under a CVaR-based stochastic programming approach. The most contributions of this study can be highlighted as:

- The increasing penetration of wind power in energy systems has appeared several challenges in the electrical energy systems, which is solved by considering P2H technology, and based on inherent characteristic of every energy storage technology it can convert the extra wind power to hydrogen, and use it in on-peak hours of the power system to produce power by gas-fired turbines. So, the influence of P2H technology on optimal set points of the multi-carrier network equipment is investigated, and the variation of system operation cost with respect to the addition of P2H is evaluated.
- The CHP plant is based on gas fuel and in line with hydrogen storage, which are the two major connections between different energy carriers. The hydrogen storage unit stores extra wind power in the form of hydrogen and increases the amount of fuel to be sent to gas power plants by converting hydrogen into gas fuel. So, it is expected that by adding P2h technology to a multi-carrier network, the participation of CHP plants in the supply energy demands of the system and energy market will be increased.
- The constraints of all three heat, gas, and electricity systems and the impact of these system constraints are evaluated on the optimal schedule of units and the cost of the combined energy network.
- Since the power output of wind turbines has am uncertain characteristic, a solution methodology is needed for mitigating the wind power curtailment. Such an issue comes more important when a high penetration of wind turbines is penetrated to the energy systems. Accordingly, the presented scheme has considered a stochastic programming

based on CVaR for analyzing the risk associated with the uncertainty of wind power production.

1.4.Organization

This study is organized as: Section 2 provides the problem formulation of the presented model for the transmission-constrained unit commitment of multi-carrier networks. The case study and results, as well as the performance evaluation of the introduced scheme, are given in Section 3. The conclusion of the introduced scheme and this study are provided in Section 4.

2. Problem formulation based on stochastic programming

The main purpose of the presented model is minimizing the operation cost of the combined energy system with hydrogen storage technology. The objective function of the model is given in (1), for which the first part relates to the operation cost of non-gas-fired plants. The second one is the operation cost of the hydrogen storage system, and the third one includes the operation cost of the gas providers. It is noteworthy that the operation cost of the gas-fueled plants is contained in the operation cost of the gas providers since such units are considered a load for the gas system.

$$\min \sum_{s=1}^{NS} \pi_s \begin{bmatrix} \sum_{t=1}^{NT}\sum_{i=1}^{EU}\left[F\left(P_{i,t,s}\right)+SU_{i,t}+SD_{i,t}\right]+\sum_{t=1}^{NT}\sum_{ph=1}^{NPH}\left[C_{ph}^{-}PH_{ph,t,s}^{-}+C_{ph}^{+}PH_{ph,t,s}^{+}\right] \\ +\sum_{t=1}^{NT}\sum_{gw=1}^{NGW}C_{gw}^{Well}GW_{gw,t,s} \end{bmatrix} \tag{1}$$

2.1.Constraints

The power supply limits of the generation units should be considered as (2). The linear equations of a convex feasible operating region of the CHP plant are given by (3)-(6) [41]. The limitations of the ramp-up/down of all the production units are studied by (7)-(8). In addition, (9) and (10) limits the minimum up/down-time for generation plants [42], and (11)-(16) define the start-up/shut-down costs of the non-gas fueled and gas- fueled plants.

$$P_i^{\min} I_{i,t} \le P_{i,t,s} \le P_i^{\max} I_{i,t} \tag{2}$$

$$P_{i,t,s} - P_i^A - \frac{P_i^A - P_i^B}{H_i^A - H_i^B} \times (H_{i,t,s} - H_i^A) \le 0 \quad i \in NC \tag{3}$$

$$P_{i,t,s} - P_i^B - \frac{P_i^B - P_i^C}{H_i^B - H_i^C} \times (H_{i,t,s} - H_i^B) \ge -(1 - I_{i,t}) \times M \quad i \in NC \tag{4}$$

$$P_{i,t,s} - P_i^C - \frac{P_i^C - P_i^D}{H_i^C - H_i^D} \times (H_{i,t,s} - H_i^C) \ge -(1 - I_{i,t}) \times M \quad i \in NC \tag{5}$$

$$0 \le H_{i,t,s} \le H_i^A \times I_{i,t} \quad i \in NC \tag{6}$$

$$P_{i,t,s} - P_{i,t\text{-}1,s} \le \left[1 - I_{i,t}(1 - I_{i,t-1})\right] R_i^{up} + I_{i,t}(1 - I_{i,t-1}) P_i^{\min} \tag{7}$$

$$P_{i,t-1,s} - P_{i,t,s} \le \left[1 \text{-} I_{i,t-1}(1 - I_{i,t})\right] R_i^{dn} + I_{i,t-1}(1 - I_{i,t}) P_i^{\min} \tag{8}$$

$$I_{i,t} - I_{i,t-1} \le I_{i,t+TU_{i,u}} \tag{9}$$

$$TU_{i,u} = \begin{cases} u & u \le MUT_i \\ 0 & u > MUT_i \end{cases} \tag{10}$$

$$I_{i,t-1} - I_{i,t} \le 1 - I_{i,t+TD_{i,u}} \tag{11}$$

$$TD_{i,u} = \begin{cases} u & u \le MDT_i \\ 0 & u > MDT_i \end{cases} \tag{12}$$

$$\begin{aligned} &SUC_{i,t} \ge SU_i\,(I_{i,t} - I_{i,t\text{-}1}) \quad i \in NEF \\ &SUC_{i,t} \ge 0 \end{aligned} \tag{13}$$

$$\begin{aligned} &SDC_{i,t} \ge SD_i\,(I_{i,t\text{-}1} - I_{i,t}) \quad i \in NEF \\ &SDC_{i,t} \ge 0 \end{aligned} \tag{14}$$

$$\begin{aligned} &SUL_{i,t} \ge SUG_i\,(I_{i,t} - I_{i,t\text{-}1}) \quad i \in NGF \\ &SUL_{i,t} \ge 0 \end{aligned} \tag{15}$$

$$SDL_{i,t} \geq SDG_i \; (I_{i,t\text{-}1} - I_{i,t}) \quad i \in NGF$$
$$SDL_{i,t} \geq 0 \tag{16}$$

Equations (17) and (18) show the limitation of the conversion of power to hydrogen and hydrogen to gas. Equation (19) shows the amount of energy available in the hydrogen storage system. Equation (20) shows the amount of produced gas during the conversion process of hydrogen to natural gas. The limits of hydrogen storage system capacity are also illustrated by (21).

$$PH_{ph}^{+\min} \, I_{ph,t,s}^{+} \leq PH_{ph,t,s}^{+} \leq PH_{ph}^{+\max} \, I_{ph,t,s}^{+} \tag{17}$$

$$PH_{ph}^{-\min} \, I_{ph,t,s}^{-} \leq PH_{ph,t,s}^{-} \leq PH_{ph}^{-\max} \, I_{ph,t,s}^{-} \tag{18}$$

$$HS_{ph,t,s} = HS_{ph,t\text{-}1,s} + \eta_{ph}^{+} PH_{ph,t,s}^{+} - \frac{PH_{ph,t,s}^{-}}{\eta_{ph}^{-}} \tag{19}$$

$$HG_{ph,t,s} = \varphi PH_{ph,t,s}^{-} \tag{20}$$

$$HS_{ph}^{\min} \leq HS_{ph,t,s} \leq HS_{ph}^{\max} \tag{21}$$

The heat balance considering the heat generation, heat load, and heat flow through the district heating network is given by (22). The relation of the heat and mass flow in the district heating system is formulated as (23) and (24). Also, the mass flow rate and length of the heat pipeline are effective in defining the temperature drop as (25). The heat loss is given by (26), and the limitation of the temperature of system nodes is defined in (27). In addition, the limits of water flow through the heat lines are given by (28).

$$\sum_{i=1}^{NC_h} HQ_{i,t,s} - \sum_{hl=1}^{NHL_h} HLQ_{hl,t,s} = \sum_{hp=1}^{NHP_h} HP_{hp,t,s} \tag{22}$$

$$HQ_{i,t,s} \times (T_{h,t,s} - T_{h,t}^{back}) \times c - 3600 \times H_{i,t,s} = 0 \;\; i \in NC \tag{23}$$

$$HLQ_{hl,t,s} \times (T_{h,t,s} - T_{h,t}^{back}) \times c - 3600 \times HL_{hl,t,s} = 0 \tag{24}$$

$$1000 \times c \times HP_{hp,t,s} \times \Delta T_{hP,t,s} = 3.6 \times k_{hp} \times (1+\beta) \times Le_{hp} \tag{25}$$

$$(R_1 + R_2)k_{hp} = T_{hp} - T_0 \tag{26}$$

$$T_h^{\min} \le T_{h,t,s} \le T_h^{\max} \tag{27}$$

$$HP_{hp}^{\min} \le HP_{hp,t,s} \le HP_{hp}^{\max} \tag{28}$$

The natural gas flow within the gas transmission lines is given by (29)-(30) as a function of gas pressure. In addition, natural gas flow with consideration of compressor is mentioned in (31). The limit of the gas supplier and limits of nodes pressure which are given by (33), (34), and (35) formulates the balance of natural gas in the gas network.

$$F_{pl,t,s} = \operatorname{sgn}(\pi_{m,t,s}, \pi_{n,t,s})\, C_{m,n} \sqrt{\left|\pi_{m,t,s}^2 - \pi_{n,t,s}^2\right|} \tag{29}$$

$$\operatorname{sgn}(\pi_{m,t,s}, \pi_{n,t,s}) = \begin{cases} 1 & \pi_{m,t,s} \ge \pi_{n,t,s} \\ -1 & \pi_{m,t,s} \le \pi_{n,t,s} \end{cases} \tag{30}$$

$$F_{pl,t,s} \ge \operatorname{sgn}(\pi_{m,t,s}, \pi_{n,t,s})\, C_{m,n} \sqrt{\left|\pi_{m,t,s}^2 - \pi_{n,t,s}^2\right|} \tag{31}$$

$$\pi_m^{\min} \le \pi_{m,t,s} \le \pi_m^{\max} \tag{32}$$

$$GW_g^{\min} \le GW_{g,t,s} \le GW_g^{\max} \tag{33}$$

$$GL_l^{\min} \le GL_{l,t,s} \le GL_l^{\max} \tag{34}$$

$$\sum_{g=1}^{NGW_m} GW_{g,t,s} + \sum_{gs=1}^{NGS_m} \left(GS_{gs,t,s}^{out} - GS_{gs,t,s}^{in} \right) - \sum_{gl=1}^{NGL_m} GL_{gl,t,s} = \sum_{pl=1}^{NPL_m} F_{pl,t} \tag{35}$$

The power balance of the system considering the power supply of the plants, hydrogen storage power, wind power output as well as the load and power flow through the power network lines is given by (36). The power flow equation and its limitations are mentioned in (37)-(38). It is worth to note that the slack bus angle is zero.

$$\sum_{i=1}^{NU_b} P_{i,t,s} + \sum_{ph=1}^{NPH_b} \left(PH^{+}_{ph,t,s}\right) + \sum_{wf=1}^{NWf_b} P_{wf,t,s} - \sum_{j=1}^{NJ_b} EL_{j,t,s} = \sum_{l=1}^{NL_b} PF_{L,t,s} \tag{36}$$

$$PF_{L,t,s} = (\theta_{b,t,s} - \theta_{b',t,s}) / X_L \tag{37}$$

$$-PF_{L,t,s} \leq PF_L^{\max} \leq PF_{L,t,s} \tag{38}$$

2.2.CVaR based formulation

This study applies the CVaR method for modelling the variability risk of operation cost for a determined confidence level α. CvaR is average operation cost of (1−α)×100% scenarios with highest cost. The following function can be considered as the basis of the CVaR calculation:

$$\text{CVaR} = \text{minimum}_{\varsigma,\eta_s} \qquad \varsigma + \frac{1}{1-a}\sum_{s=1}^{NS} \pi_s \eta_s \tag{39}$$

$$\left[\begin{array}{l} \sum_{t=1}^{NT}\sum_{i=1}^{EU}\left[F\left(P_{i,t,s}\right) + SU_{i,t} + SD_{i,t}\right] + \sum_{t=1}^{NT}\sum_{ph=1}^{NPH}\left[C^{-}_{ph}PH^{-}_{ph,t,s} + C^{+}_{ph}PH^{+}_{ph,t,s}\right] \\ + \sum_{t=1}^{NT}\sum_{gw=1}^{NGW} C^{Well}_{gw} GW_{gw,t,s} \end{array}\right] - \varsigma \leq \eta_s \tag{40}$$

$$\eta_s \geq 0 \tag{41}$$

Where, the optimal amount of ς is cost of CVaR with a determined confidential level a. Also, η_s defines the difference of the cost in each scenario and ς with a positive difference; otherwise, it is zero. Accordingly, the objective function can be updated by taking CVaR into account as:

$$\min\,(1-\beta)\sum_{s=1}^{NS}\pi_s \left[\begin{array}{l} \sum_{t=1}^{NT}\sum_{i=1}^{EU}\left[F\left(P_{i,t,s}\right) + SU_{i,t} + SD_{i,t}\right] + \sum_{t=1}^{NT}\sum_{ph=1}^{NPH}\left[C^{-}_{ph}PH^{-}_{ph,t,s} + C^{+}_{ph}PH^{+}_{ph,t,s}\right] \\ + \sum_{t=1}^{NT}\sum_{gw=1}^{NGW} C^{Well}_{gw} GW_{gw,t,s} \end{array}\right] + \beta\left(\varsigma + \frac{1}{1-a}\sum_{s=1}^{NS}\pi_s\eta_s\right) \tag{42}$$

(2)-(38) and (40)-(41) (43)

3. Case study and obtained results

For evaluating the performance of the presented scheme, a 30-node heating, 6-node electricity, and 6-node gas networks are considered, which is shown in Fig. 1. Data on the specifications of the networks and generation units are given in [28] and [43]. The electrical, gas, and thermal demands as well as the wind generation power for the 24-hours' time interval are shown in Fig. 2. A hydrogen storage system with maximum charge and discharge capacity of 50 MW and capacity of 300 MWh are located on bus 1. Hydrogen storage efficiency is assumed to be 80% in both charging and discharging conditions, which converts the input electricity to natural gas under a 64% efficiency. The following three case studies are studied for evaluating the introduced scheme:

- ❖ Case 1: Day-ahead schedule of network-constrained multi-carrier energy network without hydrogen storage;
- ❖ Case 2: Day-ahead schedule of network-constrained multi-carrier energy network with the presence of hydrogen storage;
- ❖ Case 3: Risk-based day-ahead schedule of a network-constrained multi-carrier energy network with the existence of hydrogen storage.

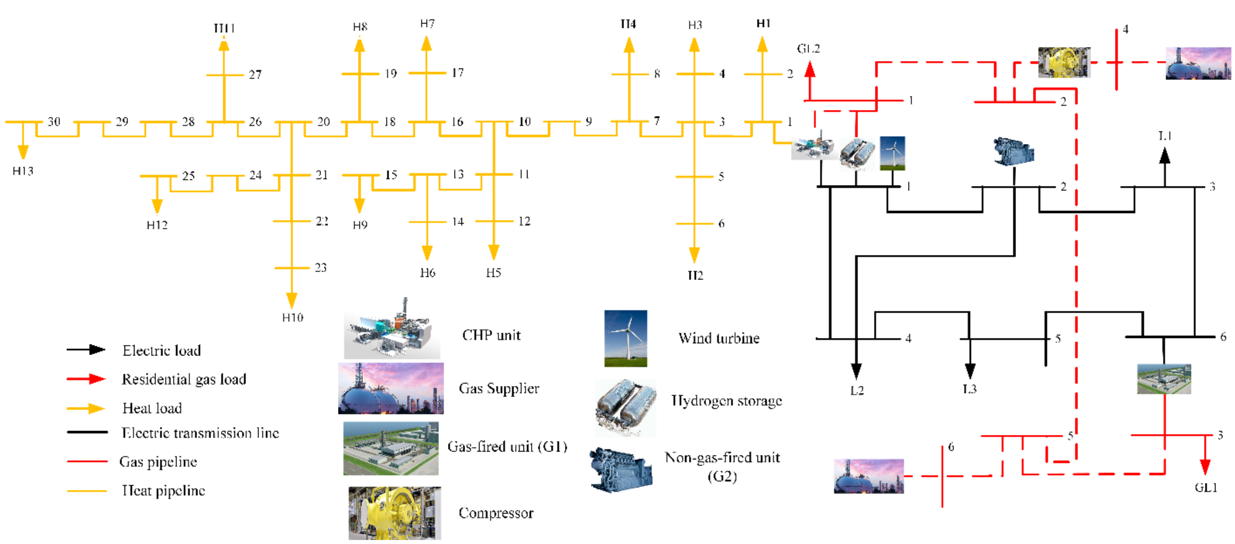

Fig. 1. The studied energy network

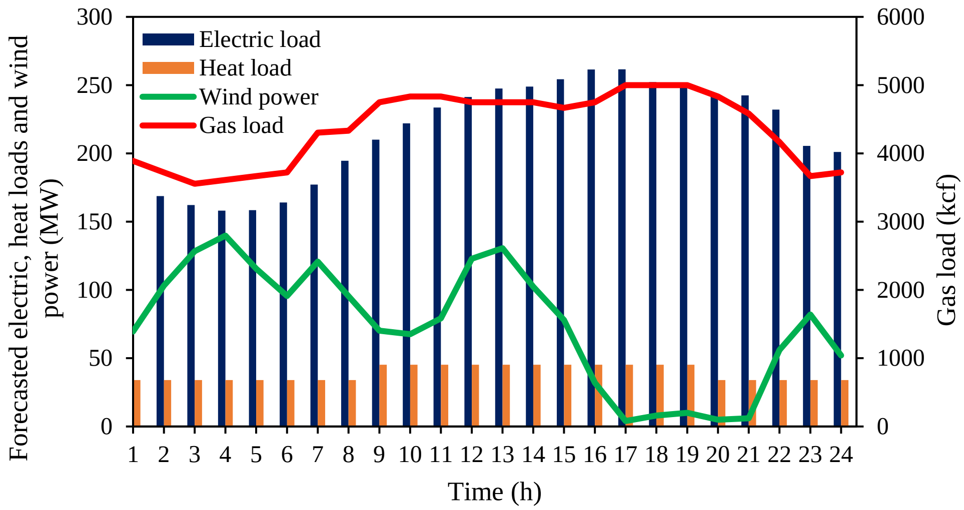

Fig. 2. The forecasted energy demands of the studied multi-carrier energy system

3.1. Case 1: Schedule of multi-carrier energy network without hydrogen storage

Hydrogen storage system and wind uncertainty are not considered in this case. The schedule of the plants considering the limitations of the energy networks is demonstrated in Fig. 3. The CHP unit has been involved in providing the energy of the system throughout the studied time period. The plant G1 contributes to power supply of the system between t=10 h and t=22 h by occurring an increment in the grid's power load and decrement of the wind power generation. The power plant G2 is cooperated in power load supply as the most expensive power plant between t=12 h and t=22 h. While more expensive power plants have been involved in power load supply between t=10 h and t=22 h, the CHP plant has not been used at its maximum capacity (i.e., 220 MW) at such hours for two main reasons. First, as depicted in Fig. 4, the power flow between buses 1 and 4 is at its maximum capacity between t=10 h and t=16 h as well as t=22 h and t=23 h. The second reason is the limitation of the gas flow sent to this generation plant, which increases the power dispatch of the power plant G2, as demonstrated in Fig. 5. As can be seen, between t=17 h and t=20 h, when demand for non-plant load for natural gas has increased, the power generated by the non-gas power plant G2 has increased due to the reduction in CHP power generation capacity, leading to an increase in the system operation cost. The role of heat loss on the heat dispatch of the CHP is shown in Fig. 6, which shows the generated heat by CHP is increased in the presence of heat loss. The impact of considering gas and heat system constraints on the operation cost of the system is shown in Table 1. As can be seen, considering the limits of the gas network and the heat losses of the heating system, the operation cost is $257758.45, which has increased by 1.4% compared to the condition that these limitations had not been considered. The comparison between the wind power dispatch and the available wind power is demonstrated in Fig. 7. The wind power dispatch is less than the available wind power at t=1 h to t=7 h as well as t=12 to t=13 h. The wind power cut-off in this case is 312.523 MWh, due to the congestion of power lines at t=12 h and t=13 h and technical limitations of the CHP plant at t=1 h and t=7 h.

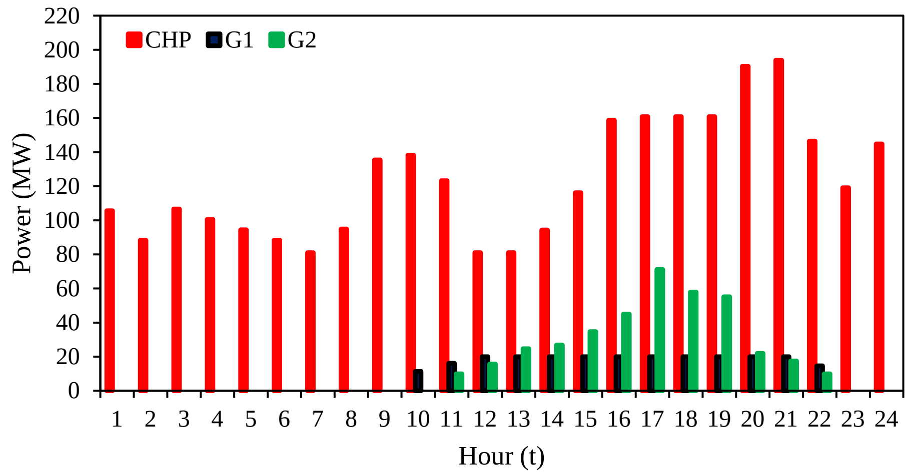

Fig. 3. Power supply of the generation plants G1, G2 and CHP

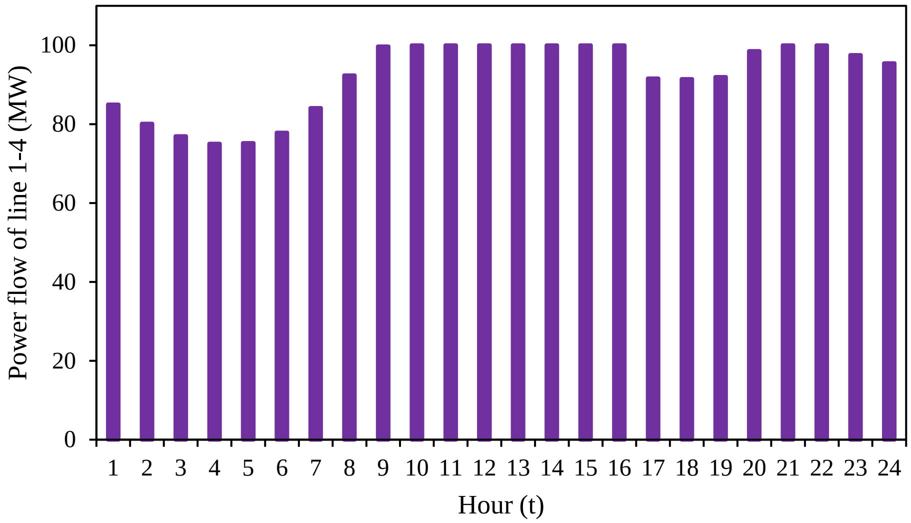

Fig. 4. Power flow of line between buses 1 and 4 during the scheduling time horizon

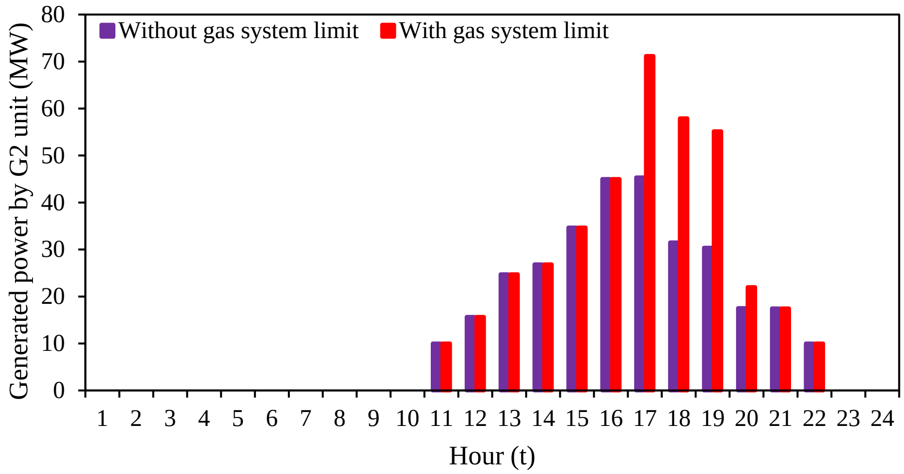

Fig. 5. The impact of the gas system constraints on the power dispatch of expensive plant G2

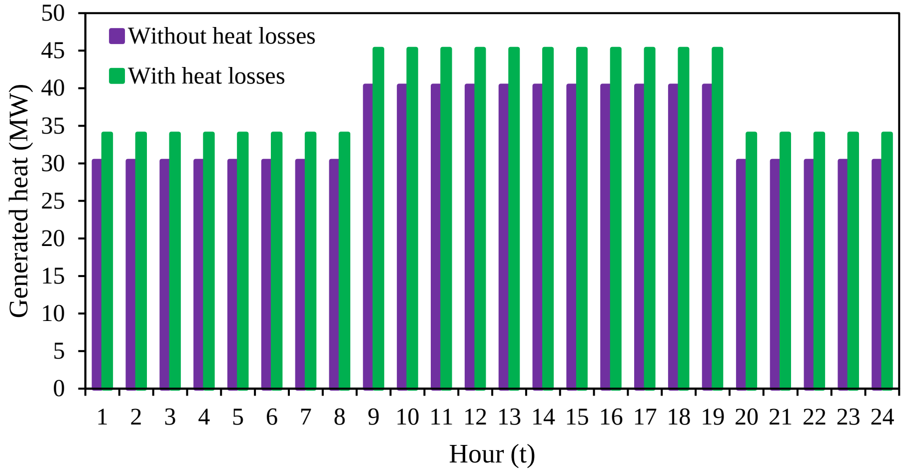

Fig. 6. The impact of the heat system losses on the heat dispatch of CHP

Table 1. The impacts of the energy systems constraints on the cost

	Power system	Gas and power system	All the three systems
Cost ($)	254036	256421	257758

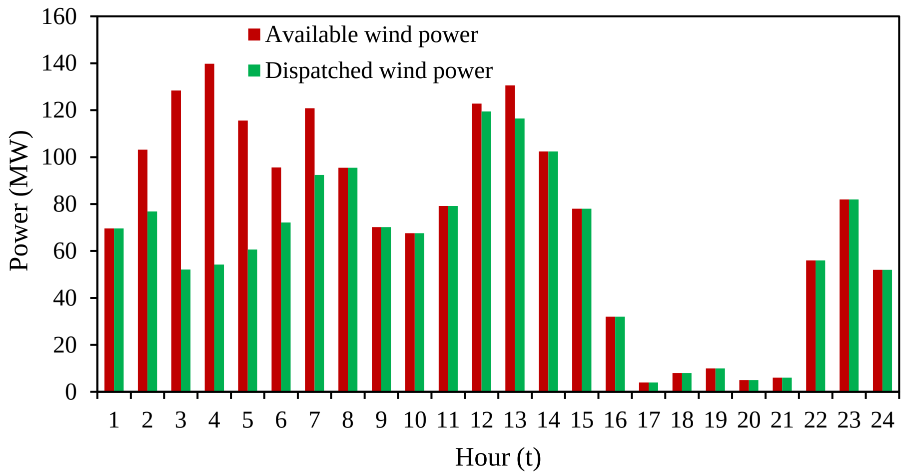

Fig. 7. The wind power dispatch and available wind power during the scheduling time horizon

3.2. Case 2: Schedule of multi-carrier energy network with hydrogen storage

Here, the influence of the hydrogen storage on the network operation is analyzed without considering the uncertainty of the wind power output. Hourly schedule of the hydrogen storage is depicted in Fig. 8. When high wind power output is available, the storage system operates in power to hydrogen conversion mode that converts extra wind power to hydrogen, thereby increasing the dispatch of wind power. The influence of the presence of hydrogen storage on wind power dispatch is depicted in Fig. 9. The total wind power cut-off has been reduced from 312.523 MWh in the first case to 66.797 MWh in the second one. In addition, as shown in Fig. 10, the CHP plant faces a restricted supply of fuel gas in t=20 h and t=17 h, which increases power dispatch of CHP through conversion of stored hydrogen to gas. The system cost is reduced from $257758 in the first case to $255460 in this case.

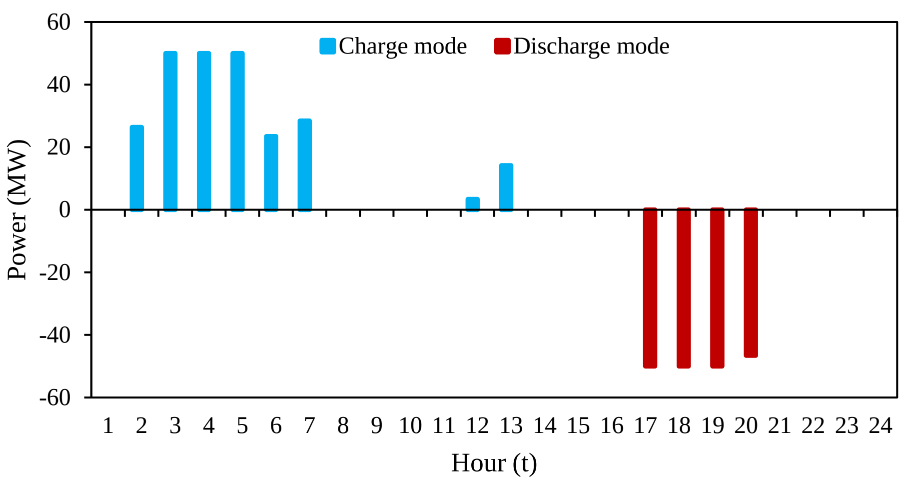

Fig. 8. Hourly scheduling of the hydrogen storage system

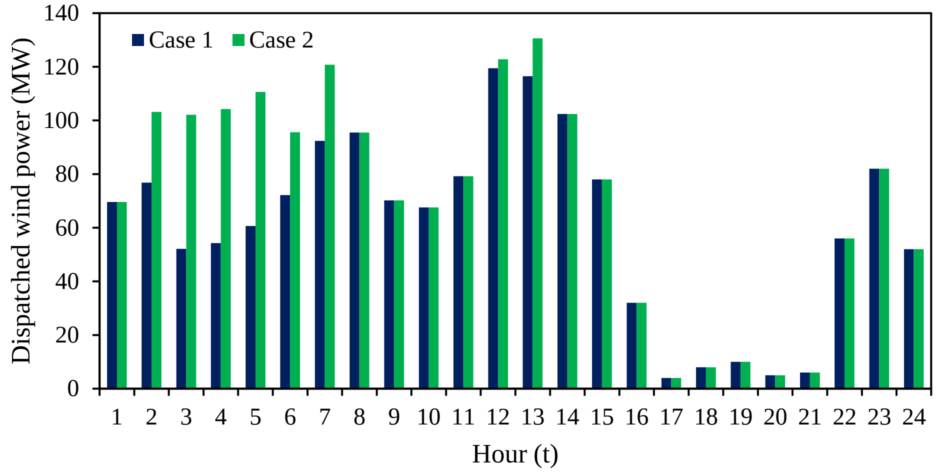

Fig. 9. The influence of the presence of hydrogen storage on wind power dispatch

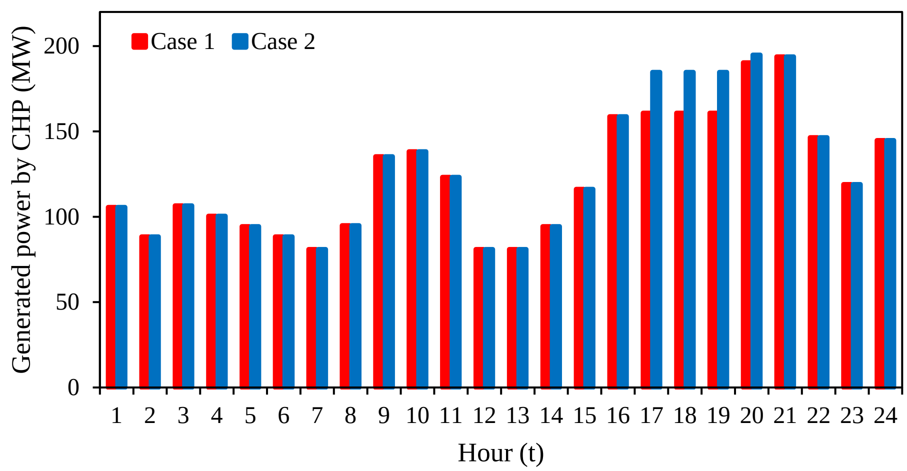

Fig. 10. CHP power generation in Cases 1 and 2

3.3.Case 3: Risk-based schedule of multi-carrier energy network with hydrogen storage

In this case, the wind power uncertainty is studied. Monte Carlo methodology is employed to produce 100 scenarios. The forecast error of the wind power relates to a normal distribution function with a standard deviation of 10% and a mean of zero. The SCENRED tool of GAMS software is utilized for reducing scenarios number to ten. Table 2 shows the impacts of constraints of gas and heat networks on the expected operation cost without the presence of hydrogen storage system with β=0. Concerning the gas system constraints and the heat losses of the district heating system, the expected operation cost has increased. Under these conditions, the expected wind power curtailment is 313.611 MW. Table 3 also shows the effect of considering hydrogen storage on operation cost and expected wind power curtailment. Considering the hydrogen storage system, the expected operation cost has been reduced to $25,5459. The wind power curtailment has also been reduced to 66.797 MWh, which shows the effect of hydrogen storage technology on increasing wind dispatch. In order to manage the wind power uncertainty under a risk aversion approach, we changed the β coefficient from 0.1 to 0.9. Figure 11 also depicts the impact of changes in β on the operation cost of the combined energy system for a constant value of α=0.9. CVaR is the expected operation cost in 10% of scenarios with the highest operating cost. The increase in β increases the operation cost. In fact, higher operation costs occur at a lower risk level, and lower operation cost occurs at a higher risk level. Therefore, the operator of the integrated energy system adopts a more conservative approach with a lower risk level by increasing the β parameter, which will increase the system operation cost.

Table 2. The effect of the grids' constraints on expected operation cost under wind power uncertainty

	Power system	Gas and power system	All the three systems
Cost ($)	254037	256423	257759

Table 3. The effect of the hydrogen storage on expected operation cost under wind power uncertainty

	Without HES	With HES
Total operation cost ($)	257759	255459
Curtailed wind power (MW)	313.611	66.797

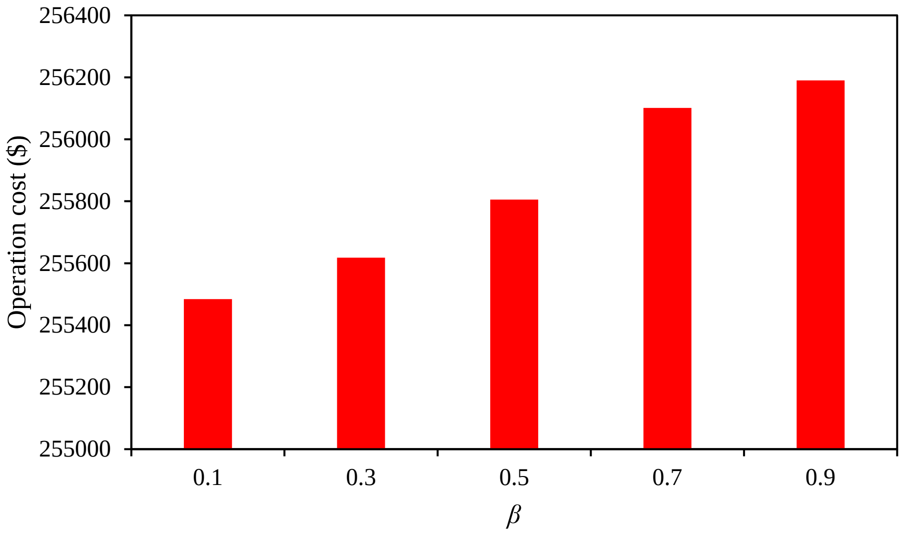

Fig. 11. The effect of β coefficient on CVaR-based stochastic problem on the cost of the network

3.4. Discussion

A scenario-based risk analysis scheme was proposed in this paper to deal with uncertainty associated with power output of wind turbines integrated to a multi-carrier energy system. For handling the risks involved in the uncertainties, the CVaR approach is applied that can benefit the multi-carrier system operator with vast authority in making appropriate decisions concerning risks. Accordingly, the purpose model considered a forecast error for the power output of wind turbines based on normal distribution function. So, the wind power uncertainty is managed under a risk-aversion methodology, where the CVaR is the expected cost of the multi-carrier energy system operation in 10% of scenarios with the highest operating cost. The results verify that the increase of Cvar parameter β has a direct relationship with the operation cost. The investigations toward the risk analysis of multi-carrier energy systems operation showed that higher system operation cost happens at a lower risk level, and lower system operation cost happens at a higher risk level. Accordingly, the system operator considers a more conservative method with a lower risk level by rising the risk parameter β, which will increase the system operation cost.

4. Conclusion

This study proposed an optimal operation scheme for multi-carrier energy systems integrated with hydrogen storage technology concerning limits of the electricity, gas and district heating networks. Considering the pressure limits of the gas network, at time intervals when the non-plant gas load was increased, a reduction in the fuel delivered to the CHP plant is observed, resulting in increased system operation cost. On the other hand, considering the losses of the district heating network, the heat generated by the CHP plant increased, which increased the amount of consumed fuel and consequently it increased the system operation cost. The hydrogen storage as an emerging technology has played a significant role in decreasing the operation cost of the energy system and increasing the penetration of wind energy. This storage technology prevented wind power curtailment by converting and storing excess wind power to hydrogen. Additionally, the hydrogen storage technology played a considerable role in improving the power dispatch of the CHP unit through the conversion of stored hydrogen into gas at times when the CHP plant faced limited supply of natural gas, which reduced the operation cost of the combined energy system. In order to manage the uncertainty of wind power, a CVaR-based stochastic approach was used to present a conservative method. The results showed that by increasing the β-operator of the multi-carrier network, a more robust and cost-effective scheduling approach is taken.

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