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Optimal planning and scheduling of energy hub in presence of wind, storage and demand response under uncertainty

Samaneh Pazouki [a,*], Mahmoud-Reza Haghifam [b]

[a] Department of Electrical Engineering, Tehran South Branch, Islamic Azad University, Tehran, Iran
[b] Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran

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ABSTRACT

Energy Hub (EH) approach streamlines interconnection of heterogeneous energy infrastructures. The insight facilitates integration of Renewable Energy Resources (RERs) to the infrastructures. Consisting of different technologies, EH satisfies the hub output demands through transferring, converting, or storing the hub input energy carriers. Overall performance of power system depends upon optimal implementation of individual EHs. In this paper, a mathematical formulation is presented for optimal planning of a developed EH considering operation constraints. Two Objective Functions (OFs) are represented for deterministic and stochastic circumstances of wind power, electricity price, and the hub electricity demand. The OFs include costs associated with the hub investment, operation, reliability, and emission. The EH is constructed by Transformer (T), Combined Heat and Power (CHP), Boiler (B), and Thermal Storage (TS). The EH is developed by Wind Turbine (WT), Energy Storage (ES), and Demand Response programs (DR). The hub input energy carriers are electricity, gas, and water. The hub output demands are electricity, heat, gas, and water. CPLEX solver of GAMS is employed to solve Mixed Integer Linear Programming (MILP) model of the developed hub. A Monte Carlo simulation is used to generate scenarios trees for the wind, price, and demand. SCENRED tool and Backward/Forward technique of GAMS reduce scenarios to best ten scenarios. Simulation results demonstrate what technology with what capacity should be installed in the EH. The results substantiate when min/max capacities of the hub technologies are required to be installed in the hub. In the meantime, the results manifest when, what technology, and how much energy carrier should be operated to minimize the costs pertained to the hub investment, operation, reliability, and emission. Effectiveness of WT, ES, and DR in the deterministic and stochastic circumstances and influence of uncertainties of the wind, price, and demand are assessed on the hub planning. Finally, effect of gas network capacity and CHP is evaluated on the hub planning.

Introduction

The most significant concerns of metropolitan regions are exponential growth of energy requirements and greenhouse gases emission. The challenges lead us toward utilization of Renewable Energy Resources (RERs) such as wind and solar powers. Integration of the RERs to electric distribution networks not only avoids expansion of transmission lines, but it also prevents establishment of new fossil fuels power plants. The RERs are able to provide either clean energy or adequate amount of energy; however, fluctuations of the RERs primary resources make the output power of the RERs probabilistic and uncertain. As a result, the inherent characteristic of the RERs causes some adverse effects on stability of overall performance of electric power system.

One prominent solution to tackle the oscillations of the RERs is utilizing some cutting-edge technologies such as Electrical Energy Storage (ES) and Demand Response programs (DR) as the RERs complements. Combined Heat and Power system (CHP) is considered as an outstanding example of the distributed generations. In addition to integrating different energy infrastructures such as electricity, gas, and heat, CHP is able to smooth the RERs fluctuations. CHP, ES, and DR are not only able to smooth the RERs oscillations, they have strong potential to flatten fluctuations of power markets prices and customers demands. Furthermore, interconnection of heterogeneous energy infrastructures by CHP results in improving power system's reliability, stability, power loss, voltage profile, energy efficiency, operation costs, and emission.

As a consequence, efficient utilization of the RERs and existing energy networks cannot rely on one technology. Different technologies and innovative approaches are required to optimally plan

* Corresponding author.
E-mail address: samaneh.pazouki@gmail.com (S. Pazouki).

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Nomenclature

Indices

h	hour
d	day
s	season
sc	scenario
em	produced emission by CO_2, SO_2, and NO_2

Variables

I_e^{ch}	binary variable of charging ES
I_e^{dis}	binary variable of discharging ES
I_e^{shdo}	binary variable of shifting down the electricity demand
I_e^{shup}	binary variable of shifting up the electricity demand
I_h^{ch}	binary variable of charging TS
I_h^{dis}	binary variable of discharging TS
ELF	equivalent loss factor
OF	Objective Function
P^B	the optimized capacity of B
P^{CHP}	the optimized capacity of CHP
P^{ES}	the optimized capacity of ES
P^T	the optimized capacity of T
P^{TS}	the optimized capacity of TS
P^{WT}	the optimized capacity of WT
P_e^{Net}	purchased electricity power from the network
P_g^{Net}	purchased gas power from the network
P_g^{NetB}	purchased gas power from the network for B
P_g^{NetCHP}	purchased gas power from the network for CHP
P_w^{Net}	purchased water power from the network
P_h^{NetS}	sold heat power to the network
P_e^{ES}	available energy in ES
P_e^{ch}	charged energy amount of ES
P_e^{dis}	discharge energy amount of ES
P_e^{loss}	energy loss of ES
P_h^{TS}	available energy in TS
P_h^{ch}	charged energy amount of TS
P_h^{dis}	discharged energy amount of TS
P_h^{loss}	energy loss of TS
P_e^{shdo}	shifted down electricity demand by DR
P_e^{shup}	shifted up electricity demand by DR
P_e^{ENS}	electricity energy not supplied
P_e^{WT}	wind power

Constants

α_e^{loss}	loss efficiency of ES
α_h^{loss}	loss efficiency of TS
$\alpha_e^{\min}$	minimum factor of ES
$\alpha_e^{\max}$	maximum factor of ES
$\alpha_h^{\min}$	minimum factor of TS
$\alpha_h^{\max}$	maximum factor of TS
η_e^{ch}	charge efficiency of ES
η_e^{dis}	discharge efficiency of ES
η_h^{ch}	charge efficiency of TS
η_h^{dis}	discharge efficiency of TS
η_{ee}^{CON}	electricity efficiency of AC/AC converter
η_{ee}^{T}	electricity efficiency of T
η_{ge}^{CHP}	gas to electricity efficiency of CHP
η_{gh}^{B}	gas to heat efficiency of B
η_{gh}^{CHP}	gas to heat efficiency of CHP
π_e^{DR}	cost of shifting electricity demand
π_e^{ENS}	cost of electricity energy not supplied
π_e^{Net}	hourly electricity price
π_e^{ES}	cost of charging and discharging ES
π_{em}	cost of CO_2, SO_2, and NO_2 emissions
π_g^{Net}	price of network gas power
π_h^{Net}	price of selling heat power to the network
π_h^{TS}	cost of charging and discharging TS
π_w^{Net}	price of network water power
A^{CHP}	availability of CHP
A^{Net}	availability of electricity network
A^{WT}	availability of WT
CC	investment cost of the hub components
MC	maintenance cost of the hub components
RC	replacement cost of the hub components
EF_{em}^{Net}	emission factor for electricity network
EF_{em}^{CHP}	emission factor for CHP
EF_{em}^{B}	emission factor for B
$ELF^{\max}$	maximum ELF
EL	economic life of the project
EL_n	economic life of the hub components
if	inflation rate
ir	real interest rate
ir_{no}	nominal interest rate
k_n	single payment present worth for the hub components
LPF^{shdo}	load participation factor for shifting down the electricity demand
LPF^{shup}	load participation factor for shifting up the electricity demand
P^{BMax}	maximum capacity permitted for installation of B
P^{CHPMax}	maximum capacity permitted for installation of CHP
P^{TMax}	maximum capacity permitted for installation of T
P^{ESMax}	maximum capacity permitted for installation of ES
P^{TSMax}	maximum capacity permitted for installation of TS
P^{WTMax}	maximum capacity permitted for installation of WT
P_e	hourly electricity demand
P_h	hourly heat demand
P_g	hourly gas demand
P_w	hourly water demand
$P_e^{Net\max}$	maximum capacity of electricity network
$P_g^{Net\max}$	maximum capacity of gas network
$P_w^{Net\max}$	maximum capacity of water network
$P_h^{Net\max}$	maximum capacity of heat network
$\Pr o_{EP}$	reduced electricity price scenarios
$\Pr o_{WP}$	reduced wind power scenarios
$\Pr o_{ED}$	reduced electricity demand scenarios
PWA	present worth annual payment
r_n	replacement number of the hub components
w	hourly wind speed
w_{ci}, w_{co}	required min/max wind speed for WT
w_r	rated wind speed
x, y, z	WT characteristics

the technologies and to subtly balance demand and supply at the moment [1]. In fact, dealing with financial, technical, and environmental issues regarding energy results in coordinate utilization of different energy sectors and technologies.

Existing approaches for modeling different energy infrastructures such as electricity, heat, cooling, and transportation are considered in [2]. Micro Grid (MG) and Virtual Power Plant (VPP) are propounded as some examples of the approaches in which can be implemented at various levels of district, city, and region. The latest approach is manifested as Energy Hub "EH" in [3]. EH as an influential approach for interconnection of multi-carrier energy networks was first presented in the Vision of Future Energy Network (VoFEN) project. EH receives different energy carriers such as gas and electricity within the hub input. Based on the minimum operation costs, the hub then decides when and what technology should be operated to supply the hub demands such as electricity and heat. In fact, EH approach streamlines complicated operation and planning of multi-carrier energy networks [4,5]. EH approach can be applied on complex buildings such as airports, hospitals, shopping centers, industrial factories, and power plants. The EHs can be interconnected to each other as bounded geographical areas such as rural and urban regions.

Most previous studies concentrate on optimal operation of multi-carrier energy systems. For instance, a model for economic and environmental dispatch of interconnected EHs (including electricity network) is stated in [6]. The model interconnects 11 centers as EHs. The proposed EHs can supply the electricity demands by produced power from wind, solar, nuclear, coal, electricity network, and energy storages. Effect of energy storage capacities and prediction horizon on the operation costs of a single EH and three interconnected EHs is addressed in [7]. Ref. [8] presents a heat demand side management in an EH so that operation costs are minimized when the EH is operated under energy price uncertainty. To minimize operation costs, an electrical load management is applied on an EH integrated by electric vehicle in [9]. In [10], a formulation for optimal operation of industrial EHs such as a flour mill and a water pumping facility is represented. Considering emission, energy costs, and peak curtailment, a mathematical model for optimal operation of a residential EH is propounded in [11]. Applying wind uncertainty, an economic dispatch model for 11 interconnected EHs (including CHP, T, B, and WT) is outlined and solved in [12]. A robust optimization model for optimal power flow between interconnected EHs (including CHP, T, B, and heat exchanger) is devoted in [13]. Considering deterministic and stochastic environments, optimal operation of an EH integrated by WT, ES, and DR is considered in [14]. For smoothing uncertainty of wind power, a stochastic unit commitment approach is applied on optimal operation of gas and electricity infrastructures in [15]. Through a stochastic day-ahead scheduling model, optimal scheduling and flexibility of natural gas infrastructure is considered for smoothing variable renewable generation in [16]. Ref. [17] introduces a demand response model for electricity and gas infrastructures in order to maximize daily profit for both EH owner and utility companies. In [18], a mathematical formulation is pinpointed for optimal operation of Plug-In Electric Vehicles (PEVs) parking lot as a bulk energy storage in multi-carrier energy networks.

Despite the prominence of optimal planning of EHs, a few studies have focused on a model for optimal planning of the EHs. For instance, a formulation for optimal size and operation of a single EH (including CHP, B, absorption chiller, and TS) is presented in [19]. In accordance to reliability constraints, a typical EH (including CHP, B, ES, TS, and T) is optimally planned and operated in [20]. Considering investment costs, system reliability, and voltage penalties, a CHP is optimally placed, sized, and operated in a 33 buses system containing gas and electricity networks in [21]. Ref. [22] presents a model for reliability-based optimal planning of EHs (including CHP, generation units, and B) and interconnected EHs (including transmission lines). Considering emission reduction, peak curtailment, and energy autonomy increase, the best EH is optimally selected among several introduced EH (including CHP, solar, hydro power, wood chips, ES, and B) in [23]. In [24], a matrix model for optimal size of power generation unit of a CCHP (Combined Cooling, Heat, and Power system) is presented by considering the weight factors of emission, installation and operation costs.

As a result, the successful utilization of different energy infrastructures integrated to the RERs is dependent upon the optimal planning and operation of individual EHs. However, consideration of previous studies reveals that optimal planning and operation of EHs, developed by WT, ES, and DR, under uncertainties of wind power, electricity price, and electricity demand have not been investigated. Therefore, optimal planning of the developed EH considering operation constraints within deterministic and stochastic circumstances of the wind, price, and demand is represented in this paper. To solve the problem, two Objective Functions (OFs) are formulated in both deterministic and stochastic circumstances. The OFs consist of costs associated with the hub investment, operation, reliability, and emission. Effect of WT, ES, and DR and uncertainties of wind power, electricity price, and the hub electricity demand are evaluated on the hub planning, operation, reliability, and emission in six different cases. Effectiveness of gas network capacity and CHP is also assessed on the hub planning. The rest of paper is organized as follows: Section "The proposed energy hub model" depicts problem formulation based on the EH approach. Two OFs and the constraints are formulated within deterministic and stochastic circumstances in Section "The proposed objective functions under deterministic and stochastic circumstances". Simulation results with details are discussed in Section "Simulation results". Conclusion is debated in Section "Conclusion".

The proposed energy hub model

The proposed EH, shown in Fig. 1, receives wind power through Wind Turbine (WT) and network energy carriers (electricity, gas, and water) in the hub input to satisfy the hub output demands: electricity, heat, gas, and water. Transformer (T), CHP, AC/AC converter, and Boiler (B) are employed to convert the wind and energy carriers to the hub desirable requirements. Electrical Storage (ES), Thermal Storage (TS), and Demand Shifting of DR programs (DR) are utilized to preserve the surplus energy and to consume it in the required times. The hub has potential to sell the extra electricity and heat to the network.

The proposed objective functions under deterministic and stochastic circumstances

Two OFs are represented to optimally plan the developed EH within the deterministic and stochastic circumstances. The OFs consist of costs associated with the hub investment, operation,

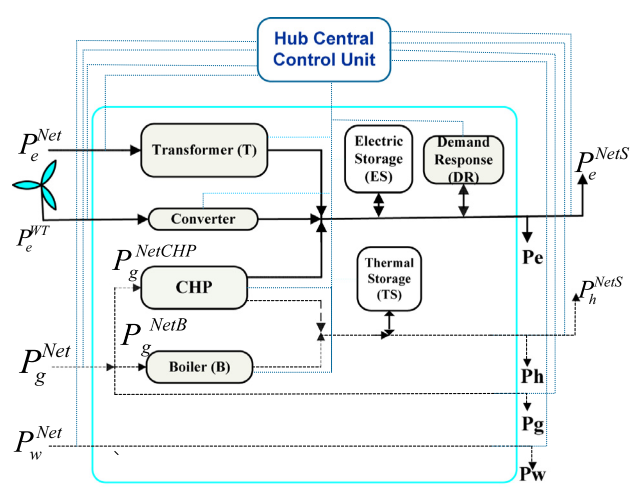

Fig. 1. The proposed energy hub.

reliability, and emission. The formulation is organized for the GAMS software environment. Paramount probabilistic parameters of smart power networks are taken into account in the stochastic scheme. Fluctuations of wind power, electricity price, and electricity demand are considered as the probabilistic parameters.

The proposed EH planning under the deterministic circumstances

The EH is optimally planned by the proposed OF in Eq. (1) and by operation constraints in Eqs. (5)–(13b)for the deterministic circumstances.

The proposed objective function

The OF, shown in Eq. (1), constitutes costs pertained to the hub investment (*CC*, *RC*, and *MC*), operation, reliability (*ENS*), and emission (*em*). *ENS* denotes Electricity Energy Not Supplied (ENS). *CC*, *RC*, and *MC* denote installation, replacement, and maintenance costs of the hub components. In the equations, indices of *WT, CHP, B, T, ES, TS, CON*, and *AMI* respectively denote WT, CHP, B, T, ES, TS, AC/AC Converter, and Advanced Metering Infrastructure.

ir denotes real interest rate of the project in Eq. (2). ir_{no} and if are nominal interest and annual inflation rates in sequence. *PWA* denotes present worth annual payment in Eq. (3). *EL* is economic life of the project. K_n denotes single payment present worth of the hub components in Eq. (4). For each the hub component, economic life (EL_n) and replacement number (r_n) are considered as well. n addresses all the hub components: WT, CHP, B, T, ES, TS, CON, and AMI.

Investment costs of each the hub component are considered in the OF in Eq. (1). P^{WT}, P^{CHP}, P^{B}, P^{T}, P^{ES}, and P^{TS} respectively denote the required capacities of WT, CHP, B, T, ES, and TS. For each the hub component, *CC*, *RC*, *MC*, *PWA*, and *K* are applied. Operation, ENS, and emission costs are considered in the OF in Eq. (1) as well. π_e^{Net}, π_g^{Net}, π_w^{Net}, and π_h^{Net} denote prices of electricity, gas, water, and heat powers in sequence. P_e^{Net}, P_g^{Net}, P_w^{Net}, and P_h^{NetS} respectively signifies purchased electricity power, gas power, water power, and sold heat power to the network. π_e^{ES} shows price of charge (P_e^{ch}) and discharge (P_e^{dis}) of ES. π_h^{TS} states price of charge (P_h^{ch}) and discharge (P_h^{dis}) of TS. π_e^{DR} marks price of shifting up (P_e^{shup}) and shifting down (P_e^{shdo}) electricity demand. π_e^{ENS} shows price of electricity energy not supplied of customers (P_e^{ENS}). π_{em} denotes emission costs of CO_2, SO_2, and NO_2. EF_{em}^{Net}, EF_{em}^{CHP}, and EF_{em}^{B} represents emission factors of electricity grid, CHP, and B respectively [25]. h, d, and s are hour, day, and season in the equations.

$$\begin{aligned}
Min\ Of: OF = {} & P^{WT}[CC_{WT}+RC_{WT}K_{WT}(ir,EL_{WT},r_{WT})+MC_{WT}PWA(ir,EL)]\\
&+P^{CHP}[CC_{CHP}+RC_{CHP}K_{CHP}(ir,EL_{CHP},r_{CHP})+MC_{CHP}PWA(ir,EL)]\\
&+P^{B}[CC_{B}+RC_{B}K_{B}(ir,EL_{B},r_{B})+MC_{B}PWA(ir,EL)]\\
&+P^{T}[CC_{T}+RC_{T}K_{T}(ir,EL_{T},r_{T})+MC_{T}PWA(ir,EL)]\\
&+P^{ES}[CC_{ES}+RC_{ES}K_{ES}(ir,EL_{ES},r_{ES})+MC_{ES}PWA(ir,EL)]\\
&+P^{TS}[CC_{TS}+RC_{TS}K_{TS}(ir,EL_{TS},r_{TS})+MC_{TS}PWA(ir,EL)]\\
&+[CC_{CON}+RC_{CON}K_{CON}(ir,EL_{CON},r_{CON})+MC_{CON}PWA(ir,EL)]\\
&+[CC_{AMI}+RC_{AMI}K_{AMI}(ir,EL_{AMI},r_{AMI})+MC_{AMI}PWA(ir,EL)]\\
&+\left\{\sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24}[\pi_e^{Net}(h)P_e^{Net}(h,d,s)]+[\pi_g^{Net}\left(P_g^{Net}(h,d,s)\right)]\right.\\
&+\left[\pi_w^{Net}P_w^{Net}(h,d,s)]-[\pi_h^{Net}P_h^{NetS}(h,d,s)]\right.\\
&+\left[\pi_h^{TS}\left(P_h^{ch}(h,d,s)+P_h^{dis}(h,d,s)\right)\right]\\
&+\left[\pi_e^{ES}\left(P_e^{ch}(h,d,s)+P_e^{dis}(h,d,s)\right)\right]\\
&+\left[\pi_e^{DR}\left(P_e^{shdo}(h,d,s)+P_e^{shup}(h,d,s)\right)\right]+[\pi_e^{ENS}P_e^{ENS}(h,d,s)]\\
&+\left[\textstyle\sum_{em=1}^{3}\pi_{em}(EF_{em}^{Net}P_e^{Net}(h,d,s)+EF_{em}^{CHP}P_g^{NetCHP}(h,d,s)\right.\\
&\left.+EF_{em}^{B}P_g^{NetB}(h,d,s))]\right\}PWA(ir,EL)
\end{aligned} \tag{1}$$

$$ir = \frac{ir_{no}-if}{1+if} \tag{2}$$

$$PWA(ir,EL) = \frac{(1+ir)^{EL}-1}{ir(1+ir)^{EL}} \tag{3}$$

$$k_n = \sum_{n=1}^{N}\frac{1}{(1+ir)^{r_nEL_n}} \tag{4}$$

Constraints

Wind power.

Electricity power produced by WT (P_e^{WT}) depends on the WT rated power and wind speed. WT starts to generate electricity from receiving a minimum wind speed (w_{ci}), continues to produce electricity until it receives rated wind speed (w_r). Receiving rated wind speed, WT produces electricity in the rated power of WT. If WT receives wind speed less than the minimum amount (w_{ci}) or more than maximum amount (w_{co}), it will be turned off. x, y, and z are associated with the WT characteristics.

$$P_e^{WT}(h,d,s) = \begin{cases} 0 & w < w_{ci} \\ P^{WT}(z-yw(h,d,s)+xw^2(h,d,s)) & w_{ci} \leqslant w < w_r \\ P^{WT} & w_r \leqslant w < w_{co} \\ 0 & w \geqslant w_{co} \end{cases} \tag{5}$$

Demands constraints.

The hub electricity demand constraint. The hub electricity demand, shown in Eq. (6a), can be produced by electricity network, CHP, WT, ES, and DR. The rest of unsupplied electricity demand can be curtailed in necessary times. P_e denotes electricity demand. P_e^{Net}, P_g^{NetCHP}, and P_e^{WT} stand for purchased electricity from the network, purchased gas from the network for CHP, and wind power respectively. P_e^{dis} and P_e^{ch} are ES discharged and charged energies. P_e^{shup} and P_e^{shdo} show shifted up and shifted down electricity demands. P_e^{ENS} is electricity energy not supplied. A^{Net}, A^{CHP}, and A^{WT} denote availability of electricity network, CHP, and WT in sequence. η_{ee}^{T}, η_{ge}^{CHP}, and η_{ee}^{CON} are respectively electricity efficiency of T, gas to electricity efficiency of CHP, and electricity efficiency of CON.

$$\begin{aligned}
P_e(h,d,s) = {} & \left[A^{Net}\eta_{ee}^{T}P_e^{Net}(h,d,s)\right] + \left[A^{CHP}\eta_{ge}^{CHP}P_g^{NetCHP}(h,d,s)\right]\\
&+\left[A^{WT}\eta_{ee}^{CON}P_e^{WT}(h,d,s)\right]\\
&+\left[P_e^{dis}(h,d,s)-P_e^{ch}(h,d,s)\right]\\
&+\left[P_e^{shdo}(h,d,s)-P_e^{shup}(h,d,s)\right]+\left[P_e^{ENS}(h,d,s)\right]
\end{aligned} \tag{6a}$$

The hub heat demand constraint. The hub heat demand, shown in Eq. (6b), can be supplied by CHP, B, and TS. P_h shows the hub heat demand. P_g^{NetCHP} and P_g^{NetB} denote purchased gas power from the network for CHP and B. P_h^{dis} and P_h^{ch} are discharged and charged energies of TS. η_{gh}^{CHP} and η_{gh}^{B} are gas to heat efficiencies of CHP and B. The surplus produced heat (P_h^{NetS}) can be sold to the network as well.

$$\begin{aligned}
P_h(h,d,s) = {} & \left[A^{CHP}\eta_{gh}^{CHP}P_g^{NetCHP}(h,d,s)\right]+\left[\eta_{gh}^{B}P_g^{NetB}(h,d,s)\right]\\
&+\left[P_h^{dis}(h,d,s)-P_h^{ch}(h,d,s)\right]-\left[P_h^{NetS}(h,d,s)\right]
\end{aligned} \tag{6b}$$

The hub gas demand constraint. The hub gas demand, shown in Eq. (6c), can be served by purchased network gas minus required gas for CHP and B. P_g is the hub gas demand. P_g^{Net} denotes purchased gas power from the network.

$$P_g(h,d,s) = \left[P_g^{Net}(h,d,s)\right] - \left[P_g^{NetCHP}(h,d,s) + P_g^{NetB}(h,d,s)\right] \tag{6c}$$

The hub water demand constraint. The hub water demand, shown in Eq. (6d), is directly supplied by network water. P_w is the hub water demand. P_w^{Net} denotes purchased water power from the network.

$$P_w(h,d,s) = \left[P_w^{Net}(h,d,s)\right] \tag{6d}$$

Networks constraints.
Amounts of purchased electricity, gas, water from the networks and sold heat power to the network are respectively constrained by the networks capacities in Eqs. (7a)–(7d). $P_e^{Net\max}$, $P_g^{Net\max}$, $P_w^{Net\max}$, and $P_h^{Net\max}$ are maximum capacities of the electricity, gas, water, and heat networks respectively.

$$0 \leqslant P_e^{Net}(h,d,s) \leqslant P_e^{Net\max} \tag{7a}$$

$$0 \leqslant P_g^{Net}(h,d,s) \leqslant P_g^{Net\max} \tag{7b}$$

$$0 \leqslant P_w^{Net}(h,d,s) \leqslant P_w^{Net\max} \tag{7c}$$

$$0 \leqslant P_h^{NetS}(h,d,s) \leqslant P_h^{Net\max} \tag{7d}$$

Converters constraints. The purchased network electricity, network gas for CHP and B should be limited by the installed optimized capacities of T (P^T), CHP (P^{CHP}), and B (P^B) in Eqs. (8a)–(8c).

$$\eta_{ee}^{T} P_e^{Net}(h,d,s) \leqslant P^T \tag{8a}$$

$$\eta_{ge}^{CHP} P_g^{NetCHP}(h,d,s) \leqslant P^{CHP} \tag{8b}$$

$$\eta_{gh}^{B} P_g^{NetB}(h,d,s) \leqslant P^B \tag{8c}$$

The hub components constraints.
The required and optimized capacities of the hub components are signified by P^T, P^{CHP}, P^B, P^{WT}, P^{ES}, and P^{TS} for T, CHP, B, WT, ES, and TS in sequence. The optimized capacities of the hub components should be limited by maximum amounts permitted to be installed in the hub. These permitted maximum amounts for each the hub component are respectively P^{TMax}, P^{CHPMax}, P^{BMax}, P^{WTMax}, P^{ESMax}, and P^{TSMax} in Eqs. (9a)–(9f).

$$P^T \leqslant P^{TMax} \tag{9a}$$

$$P^{CHP} \leqslant P^{CHPMax} \tag{9b}$$

$$P^B \leqslant P^{BMax} \tag{9c}$$

$$P^{WT} \leqslant P^{WTMax} \tag{9d}$$

$$P^{ES} \leqslant P^{ESMax} \tag{9e}$$

$$P^{TS} \leqslant P^{TSMax} \tag{9f}$$

Storages constraints.
Electrical storage constraints. ES is utilized to preserve the surplus produced electricity and release it in the required times [26]. Available energy in ES (P_e^{ES}) is estimated based on the available energy in the last hour, the amount of charged and discharged energy at the present moment, and the amount of the energy loss of ES in Eq. (10a). Energy loss (P_e^{loss}) is expressed in Eq. (10b). Available energy in ES should be limited between minimum and maximum accessible energy amount of ES in Eq. (10c). $\alpha_e^{\min}$ and $\alpha_e^{\max}$ show the min/max factors of min/max energy amount of ES. Charged (P_e^{ch}) and discharged (P_e^{dis}) energy amount of ES should be also restricted by Eqs. (10d) and (10e) in sequence. Binary variables of charge (I_e^{ch}) and discharge (I_e^{dis}) of ES avoid charging and discharging performances of ES at the same time in Eq. (10f). η_e^{ch} and η_e^{dis} respectively show charge and discharge efficiencies of ES.

$$P_e^{ES}(h,d,s) = P_e^{ES}(h-1,d,s) + P_e^{ch}(h,d,s) - P_e^{dis}(h,d,s) - P_e^{loss}(h,d,s) \tag{10a}$$

$$P_e^{loss}(h,d,s) = \alpha_e^{loss} P_e^{ES}(h,d,s) \tag{10b}$$

$$\alpha_e^{\min} P^{ES} \leqslant P_e^{ES}(h,d,s) \leqslant \alpha_e^{\max} P^{ES} \tag{10c}$$

$$\alpha_e^{\min}\eta_e^{ch} P^{ES} I_e^{ch}(h,d,s) \leqslant P_e^{ch}(h,d,s) \leqslant \alpha_e^{\max}\eta_e^{ch} P^{ES} I_e^{ch}(h,d,s) \tag{10d}$$

$$\alpha_e^{\min}\eta_e^{dis} P^{ES} I_e^{dis}(h,d,s) \leqslant P_e^{dis}(h,d,s) \leqslant \alpha_e^{\max}\eta_e^{dis} P^{ES} I_e^{dis}(h,d,s) \tag{10e}$$

$$0 \leqslant I_e^{ch}(h,d,s) + I_e^{dis}(h,d,s) \leqslant 1 \tag{10f}$$

Thermal storage constraints. Available energy of TS (P_h^{TS}) shown in Eq. (11a) is determined by considering the available energy at the last hour, charged and discharged energy at the present moment, and energy loss of TS. Energy loss (P_h^{loss}) is calculated by Eq. (11b). Available energy of TS should be limited by minimum and maximum accessible energy amount of TS in Eq. (11c). $\alpha_h^{\min}$ and $\alpha_h^{\max}$ show the min/max factors of min/max energy amount of TS. Charged (P_h^{ch}) and discharged (P_h^{dis}) energy amounts of TS are also restricted by Eqs. (11d) and (11e) respectively. Binary variables of charge (I_h^{ch}) and discharge (I_h^{dis}) of TS prevent the charging and discharging performances at the meantime in Eq. (11f). η_h^{ch} and η_h^{dis} respectively show charge and discharge efficiencies of TS.

$$P_h^{TS}(h,d,s) = P_h^{TS}(h-1,d,s) + P_h^{ch}(h,d,s) - P_h^{dis}(h,d,s) - P_h^{loss}(h,d,s) \tag{11a}$$

$$P_h^{loss}(h,d,s) = \alpha_h^{loss} P_h^{TS}(h,d,s) \tag{11b}$$

$$\alpha_h^{\min} P^{TS} \leqslant P_h^{TS}(h,d,s) \leqslant \alpha_h^{\max} P^{TS} \tag{11c}$$

$$\alpha_h^{\min}\eta_h^{ch} P^{TS} I_h^{ch}(h,d,s) \leqslant P_h^{ch}(h,d,s) \leqslant \alpha_h^{\max}\eta_h^{ch} P^{TS} I_h^{ch}(h,d,s) \tag{11d}$$

$$\alpha_h^{\min}\eta_h^{dis} P^{TS} I_h^{dis}(h,d,s) \leqslant P_h^{dis}(h,d,s) \leqslant \alpha_h^{\max}\eta_h^{dis} P^{TS} I_h^{dis}(h,d,s) \tag{11e}$$

$$0 \leqslant I_h^{ch}(h,d,s) + I_h^{dis}(h,d,s) \leqslant 1 \tag{11f}$$

Demand response constraints.
Some part of electricity demand can be reduced in the moment when electricity demand is high and it can be consumed in the moment when electricity demand is not high. The total reduced demand should be equal to the total increased demand in Eq. (12a). P_e^{shdo} and P_e^{shup} present shifted down and shifted up electricity demands respectively. LPF^{shdo} and LPF^{shup} are electricity load participation factors for shifting down and shifting up in sequence. Electricity demand can be shifted up and shifted down by

Eqs. (12b) and (12c) respectively. Binary variables of shifting up (I_e^{shup}) and shifting down (I_e^{shdo}), shown in Eq. (12d), prevent the shifting up and shifting down performances at the same time [27].

$$\sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24} P_e^{shup}(h,d,s) = \sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24} P_e^{shdo}(h,d,s) \tag{12a}$$

$$0 \leqslant P_e^{shup}(h,d,s) \leqslant LPF^{shup} P_e(h,d,s) I_e^{shup}(h,d,s) \tag{12b}$$

$$0 \leqslant P_e^{shdo}(h,d,s) \leqslant LPF^{shdo} P_e(h,d,s) I_e^{shdo}(h,d,s) \tag{12c}$$

$$0 \leqslant I_e^{shup}(h,d,s) + I_e^{shdo}(h,d,s) \leqslant 1 \tag{12d}$$

ENS constraints.
Electricity energy not supplied as an important factor for assessing the hub reliability is stated in Eq. (13a). Equivalent Loss Factor (*ELF*) is defined as ratio of energy not supplied to electricity demand. *ELF* amount is different in rural areas and developed countries. *ELF* should be restricted by the maximum amount in Eq. (13b).

$$ELF = \frac{1}{T}\sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24} \frac{P_e^{ENS}(h,d,s)}{P_e(h,d,s)} \tag{13a}$$

$$ELF \leqslant ELF^{\max} \tag{13b}$$

The proposed EH planning under the stochastic circumstances

In order to solve the problem under the probabilistic circumstances, two stage stochastic programming is employed in this paper [28]. The OF formulated for the stochastic circumstances in Eq. (14) is almost similar to the proposed OF within the deterministic environment in Eq. (1). The most significant differences are associated with the effective probabilistic parameters and the variables affected by the probabilistic parameters. ES, DR, and ENS are the hub components, which are most likely affected by the probabilistic parameters of the wind, price, and demand to guarantee the feasibility of the model. Similar to the OF in deterministic circumstances, the OF in stochastic circumstances consist of costs pertained to the hub investment, operation, ENS, and emission. The variables associated with the required capacities of the hub components are applied on the OF in Eq. (14). For each the hub component within the stochastic circumstances, *CC, RC, MC, PWA*, and *K* are applied on the OF. The variables, which are not affected by the stochastic scenarios of the wind, price, and demand, are taken into account as decision makers of stage one within the OF. Stage two constitutes the variables, affected by the probabilistic parameters of the wind, price, and demand. P_e^{Net}, P_g^{Net}, P_w^{Net}, and $P_h^{NetSold}$ are considered as variables of stage one. ES, DR, and ENS variables are taken into account as variables of stage two. Electricity price scenarios ($\pi_e^{Net}(h,sc)$) along with their probabilities ($\mathrm{Pro}_{EP}(sc)$) are also applied on the OF in Eq. (14). The EH is optimally planned by the proposed OF in Eq. (14) and the operation constraints in Eqs. (15)–(23b) for stochastic circumstances.

Uncertainty

A Monte Carlo simulation is utilized to generate scenarios trees [29]. Scenarios trees for wind speed, electricity price, and the hub electricity demand in summer, winter, spring, and autumn are produced. GAMS SCENRED tool and Backward/Forward technique are used to reduce large numbers of generated scenarios to best ten scenarios within the stochastic circumstances [30,31].

The proposed objective function

$$\begin{aligned}
Min\ of: OF = {} & P^{WT}[CC_{WT} + RC_{WT}K_{WT}(ir,EL_{WT},r_{WT}) + MC_{WT}PWA(ir,EL)] \\
&+ P^{CHP}[CC_{CHP} + RC_{CHP}K_{CHP}(ir,EL_{CHP},r_{CHP}) + MC_{CHP}PWA(ir,EL)] \\
&+ P^{B}[CC_{B} + RC_{B}K_{B}(ir,EL_{B},r_{B}) + MC_{B}PWA(ir,EL)] \\
&+ P^{T}[CC_{T} + RC_{T}K_{T}(ir,EL_{T},r_{T}) + MC_{T}PWA(ir,EL)] \\
&+ P^{ES}[CC_{ES} + RC_{ES}K_{ES}(ir,EL_{ES},r_{ES}) + MC_{ES}PWA(ir,EL)] \\
&+ P^{TS}[CC_{TS} + RC_{TS}K_{TS}(ir,EL_{TS},r_{TS}) + MC_{TS}PWA(ir,EL)] \\
&+ [CC_{CON} + RC_{CON}K_{CON}(ir,EL_{CON},r_{CON}) + MC_{CON}PWA(ir,EL)] \\
&+ [CC_{AMI} + RC_{AMI}K_{AMI}(ir,EL_{AMI},r_{AMI}) + MC_{AMI}PWA(ir,EL)] \\
&+ \Bigg\{ \sum_{sc=1}^{10}\sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24} \Big(\Big[\pi_e^{Net}(h,sc)\mathrm{Pro}_{EP}(sc)P_e^{Net}(h,d,s)\Big] \\
&+ \Big[\pi_e^{ES}(P_e^{ch}(h,d,s,sc) + P_e^{dis}(h,d,s,sc))\Big] \\
&+ \Big[\pi_e^{DR}(P_e^{shdo}(h,d,s,sc) + P_e^{shup}(h,d,s,sc))\Big] + \Big[\pi_e^{ENS}P_e^{ENS}(h,d,s,sc)\Big]\Big) \\
&+ \sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24}\Big(\Big[\pi_g^{Net}P_g^{Net}(h,d,s)\Big] + \Big[\pi_w^{Net}P_w^{Net}(h,d,s)\Big] \\
&- [\pi_h^{Net}P_h^{NetS}(h,d,s)] + \Big[\pi_h^{TS}\Big(P_h^{ch}(h,d,s) + P_h^{dis}(h,d,s)\Big)\Big] \\
&+ \Big[\sum_{em=1}^{3}\pi_{em}(EF_{em}^{Net}P_e^{Net}(h,d,s) + EF_{em}^{CHP}P_g^{NetCHP}(h,d,s) \\
&+ EF_{em}^{B}P_g^{NetB}(h,d,s))\Big]\Big)\Bigg\} PWA(ir,EL)
\end{aligned} \tag{14}$$

Constraints
Wind power.
Produced electricity by WT in the stochastic circumstances, shown in Eq. (15), is almost formulated similar to the produced electricity by WT in the deterministic circumstances. The difference is just that the stochastic scenarios of wind speed should be applied in the equation.

$$P_e^{WT}(h,d,s,sc) = \begin{cases} 0 & w < w_{ci} \\ P^{WT}(z - yw(h,d,s,sc) + xw^2(h,d,s,sc)) & w_{ci} \leqslant w < w_r \\ P^{WT} & w_r \leqslant w < w_{co} \\ 0 & w \geqslant w_{co} \end{cases} \tag{15}$$

Demands constraints.
The hub electricity demand constraint. The electricity demand can be supplied through network electricity, CHP, wind power, ES, and DR in Eq. (16a). Some part of electricity demand can be curtailed in the required times. Different produced scenarios ($P_e(h,d,s,sc)$) of electricity demand together with their probabilities ($\Pr o_{ED}(sc)$) should be applied on the hub electricity demand constraint. Different wind power scenarios ($P_e^{WT}(h,d,s,sc)$) along with their probabilities ($\Pr o_{WP}(sc)$) should be considered in the equation as well. ES, DR, and ENS flexibly correspond to the fluctuations and guarantee feasibility of the electricity demand constraints under the aforementioned parameters uncertainties.

$$\begin{aligned}
\Pr o_{ED}(sc)P_e(h,d,s,sc) = {} & \Big[A^{Net}\eta_{ee}^{T}P_e^{Net}(h,d,s)\Big] \\
&+ \Big[A^{CHP}\eta_{ge}^{CHP}P_g^{NetCHP}(h,d,s)\Big] \\
&+ \Big[A^{WT}\eta_{ee}^{con}\Pr o_{WP}(sc)P_e^{WT}(h,d,s,sc)\Big] \\
&+ \Big[P_e^{dis}(h,d,s,sc) - P_e^{ch}(h,d,s,sc)\Big] \\
&+ \Big[P_e^{shdo}(h,d,s,sc) - P_e^{shup}(h,d,s,sc)\Big] \\
&+ \Big[P_e^{ENS}(h,d,s,sc)\Big]
\end{aligned} \tag{16a}$$

The hub heat demand constraint. The hub heat demand within the stochastic circumstances, shown in Eq. (16b), is supplied similar to the hub heat demand in the deterministic circumstances. The hub heat demand can be supplied by CHP, B, and TS. Surplus produced heat can be also sold to the heat network.

$$P_h(h,d,s) = \left[A^{CHP}\eta_{gh}^{CHP}P_g^{NetCHP}(h,d,s)\right] + \left[\eta_{gh}^{B}P_g^{NetB}(h,d,s)\right] + \left[P_h^{dis}(h,d,s) - P_h^{ch}(h,d,s)\right] - \left[P_h^{NetS}(h,d,s)\right] \quad (16b)$$

The hub gas demand constraint. The hub gas demand can be supplied by purchased network gas minus purchased network gas for CHP and B in Eq. (16c). The hub gas demand in the stochastic circumstances is supplied similar to the hub gas demand in the deterministic circumstances.

$$P_g(h,d,s) = \left[P_g^{Net}(h,d,s)\right] - \left[P_g^{NetCHP}(h,d,s) + P_g^{NetB}(h,d,s)\right] \quad (16c)$$

The hub water demand constraint. The hub water demand within the stochastic circumstances, shown in Eq. (16d), is supplied similar to the water demand in the deterministic circumstances.

$$P_w(h,d,s) = \left[P_w^{Net}(h,d,s)\right] \quad (16d)$$

Networks constraints.
Purchased electricity, gas, water, and heat from the networks should be respectively limited by networks capacities in the Eqs. (17a)–(17d).

$$0 \leqslant P_e^{Net}(h,d,s) \leqslant P_e^{Net\max} \quad (17a)$$

$$0 \leqslant P_g^{Net}(h,d,s) \leqslant P_g^{Net\max} \quad (17b)$$

$$0 \leqslant P_w^{Net}(h,d,s) \leqslant P_w^{Net\max} \quad (17c)$$

$$0 \leqslant P_h^{Net}(h,d,s) \leqslant P_h^{Net\max} \quad (17d)$$

Converters constraints. The amount of purchased electricity, purchased gas for CHP and B from the networks should be respectively limited by the installed optimized T, CHP, and B in the hub in Eqs. (18a)–(18c).

$$\eta_{ee}^{T}P_e^{Net}(h,d,s) \leqslant P^{T} \quad (18a)$$

$$\eta_{ge}^{CHP}P_g^{NetCHP}(h,d,s) \leqslant P^{CHP} \quad (18b)$$

$$\eta_{gh}^{B}P_g^{NetB}(h,d,s) \leqslant P^{B} \quad (18c)$$

The hub components constraints.
The optimized capacities of each the hub component should be restricted by amounts of maximum capacities in Eqs. (19a)–(19f). Based on the permitted maximum amounts, the program is able to decide how much capacities are appropriate for each the hub component.

$$P^{T} \leqslant P^{TMax} \quad (19a)$$

$$P^{CHP} \leqslant P^{CHPMax} \quad (19b)$$

$$P^{B} \leqslant P^{BMax} \quad (19c)$$

$$P^{WT} \leqslant P^{WTMax} \quad (19d)$$

$$P^{ES} \leqslant P^{ESMax} \quad (19e)$$

$$P^{TS} \leqslant P^{TSMax} \quad (19f)$$

Storages constraints.
Electrical storage constraints. ES performance in stochastic circumstances is approximately formulated similar to the ES performance in the deterministic circumstances in Eqs. (20a)–(20f). The difference is just associated with consideration of the stochastic scenarios (*sc*) in the equations. ES should be able to respond to the uncertainties of the electricity price, electricity demand, and wind power.

$$P_e^{ES}(h,d,s,sc) = P_e^{ES}(h-1,d,s,sc) + P_e^{ch}(h,d,s,sc) - P_e^{dis}(h,d,s,sc) - P_e^{loss}(h,d,s,sc) \quad (20a)$$

$$P_e^{loss}(h,d,s,sc) = \alpha_e^{loss}P_e^{ES}(h,d,s,sc) \quad (20b)$$

$$\alpha_e^{\min}P^{ES} \leqslant P_e^{ES}(h,d,s,sc) \leqslant \alpha_e^{\max}P^{ES} \quad (20c)$$

$$\alpha_e^{\min}\eta_e^{ch}P^{ES}I_e^{ch}(h,d,s,sc) \leqslant P_e^{ch}(h,d,s,sc) \leqslant \alpha_e^{\max}\eta_e^{ch}P^{ES}I_e^{ch}(h,d,s,sc) \quad (20d)$$

$$\alpha_e^{\min}\eta_e^{dis}P^{ES}I_e^{dis}(h,d,s,sc) \leqslant P_e^{dis}(h,d,s,sc) \leqslant \alpha_e^{\max}\eta_e^{dis}P^{ES}I_e^{dis}(h,d,s,sc) \quad (20e)$$

$$0 \leqslant I_e^{ch}(h,d,s,sc) + I_e^{dis}(h,d,s,sc) \leqslant 1 \quad (20f)$$

Thermal storage constraints. TS performance in the stochastic circumstances is also formulated similar to the TS performance in the deterministic circumstances in Eqs. (21a)–(21f).

$$P_h^{TS}(h,d,s) = P_h^{TS}(h-1,d,s) + P_h^{ch}(h,d,s) - P_h^{dis}(h,d,s) - P_h^{loss}(h,d,s) \quad (21a)$$

$$P_h^{loss}(h,d,s) = \alpha_h^{loss}P_h^{TS}(h,d,s) \quad (21b)$$

$$\alpha_h^{\min}P^{TS} \leqslant P_h^{TS}(h,d,s) \leqslant \alpha_h^{\max}P^{TS} \quad (21c)$$

$$\alpha_h^{\min}\eta_h^{ch}P^{TS}I_h^{ch}(h,d,s) \leqslant P_h^{ch}(h,d,s) \leqslant \alpha_h^{\max}\eta_h^{ch}P^{TS}I_h^{ch}(h,d,s) \quad (21d)$$

$$\alpha_h^{\min}\eta_h^{dis}P^{TS}I_h^{dis}(h,d,s) \leqslant P_h^{dis}(h,d,s) \leqslant \alpha_h^{\max}\eta_h^{dis}P^{TS}I_h^{dis}(h,d,s) \quad (21e)$$

$$0 \leqslant I_h^{ch}(h,d,s) + I_h^{dis}(h,d,s) \leqslant 1 \quad (21f)$$

Demand response constraints.
DR programs should be formulated in the way that they are able to respond to fluctuations of the electricity price, electricity demand, and wind power in Eqs. (22a)–(22d). Therefore, stochastic scenarios (*sc*) of the electricity price, electricity demand, and wind power should be considered in the equations.

$$\sum_{sc=1}^{10}\sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24}P_e^{shup}(h,d,s,sc) = \sum_{sc=1}^{10}\sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24}P_e^{shdo}(h,d,s,sc) \quad (22a)$$

$$0 \leqslant P_e^{shup}(h,d,s,sc) \leqslant LPF^{shup}P_e(h,d,s,sc)I_e^{shup}(h,d,s,sc) \quad (22b)$$

$$0 \leqslant P_e^{shdo}(h,d,s,sc) \leqslant LPF^{shdo}P_e(h,d,s,sc)I_e^{shdo}(h,d,s,sc) \quad (22c)$$

$$0 \leqslant I_e^{shup}(h,d,s,sc) + I_e^{shdo}(h,d,s,sc) \leqslant 1 \quad (22d)$$

ENS constraints.
ELF in the stochastic circumstances, shown in Eq. (23a), is almost formulated similar to the *ELF* in the deterministic circumstances. The difference is just associated to consideration of the stochastic

scenarios (*sc*). The ENS should be able to flexibly correspond to fluctuations of the wind, price, and demand. The *ELF* limitation, shown in Eq. (23b), should be considered as well.

$$ELF = \frac{1}{T}\sum_{s=1}^{4}\sum_{d=1}^{365}\sum_{h=1}^{24}\frac{\sum_{sc=1}^{10} P_e^{ENS}(h,d,s,sc)}{\sum_{sc=1}^{10} P_e(h,d,s,sc)} \tag{23a}$$

$$ELF \leqslant ELF^{\max} \tag{23b}$$

Simulation results

The proposed EH, shown in Fig. 1, is optimally planned by considering six different cases introduced in Table 1. For optimal planning of the EH, formulation of the OFs and the relevant constraints are considered within the deterministic and stochastic circumstances.

In case 1, WT, ES, DR, and stochastic parameters of the wind power, electricity price, and electricity demand are not applied. In case 2, WT, ES, and DR are applied on the EH to evaluate effectiveness of the aforementioned components on the hub planning in the deterministic circumstances. In cases 3, 4, and 5, effect of stochastic parameters of the wind, price, and demand are assessed on the EH planning in presence of WT, ES, and DR. In case 6, impact of the all uncertainties are considered on the hub planning in presence of WT, ES, and DR.

The hub output demands including electricity, heat, water, and gas are respectively displayed in Figs. 2–4. Hourly electricity price is shown in Fig. 5. Wind speed is depicted in Fig. 6. The other required parameters for the simulation are presented in Table 2.

The proposed EH is formulated as a Mixed Integer Linear Programming (MILP) model. Simulation is carried out through CPLEX solver of GAMS. A Monte Carlo simulation generates scenarios trees of wind power, electricity price, and electricity demand. SCENRED tool and Backward/Forward technique of GAMS reduce scenarios to best ten scenarios of the wind, price and demand. The simulation has been implemented in a laptop with Core i7-3537U 2 GHz CPU, 8 GB RAM, and 4 MB Cash in less than 1 s. ±10% variance is applied on the wind, price and demand probabilities.

Table 3 presents optimized size of the hub components in the six different cases. Table 4 represents individual and overall costs of the hub planning in the cases. Individual costs pertain to the hub investment, operation, ENS, and emission. Operation of the hub components in the different cases are illustrated through Tables 5–10. In Tables 5–10, part *a* demonstrates the hub performance in winter, part *b* shows the hub performance in summer, and part *c* displays the hub performance in the spring and autumn. Summary performance of the hub components in the different seasons is exhibited through part *d* of the tables. In part *d* of Tables 5–10, L, M, and H denote low, medium, and high operation of the technologies. Tables 11 and 12 reflect effectiveness of increasing gas network capacity on the hub planning. Table 11 reveals optimum size of the hub components after increase of gas network capacity. Table 12 shows the relevant planning costs after the increment of gas network capacity. Table 13 compares the hub components before and after the increase of gas network capacity.

Table 1
Six different cases for the hub optimal planning.

Cases	Integration of WT, ES, and DR	Electricity price uncertainty	Electricity demand uncertainty	Wind power uncertainty
(1) EH				
(2) EH	✓			
(3) EH	✓	✓		
(4) EH	✓		✓	
(5) EH	✓			✓
(6) EH	✓	✓	✓	✓

Results of the proposed hub planning in the six different cases

Case 1

In this case, installation and utilization of WT, ES, and DR are not considered in the deterministic circumstances. From Table 3, CHP with medium capacity is installed to supply some part of the hub electricity and heat demands. T with maximum capacity is installed to supply the rest of electricity demand. B and TS with the maximum capacities are installed to supply the rest of heat demand.

Table 5(a, b, c, and d) demonstrates operation results of the hub components in this case. The table corroborates some reasons for installation and utilization of the aforementioned technologies. In summer, the hub would rather utilize CHP to supply the hub heat and electricity demands. Since the electricity demand is more than the heat demand in the summer, it is economical to provide the hub demands by CHP. The rest of unsupplied electricity demand is provided by medium utilization of T, especially in peak hours. The rest of unsupplied heat demand by CHP is prepared by medium utilization of B and TS, especially in peak heat demand times. In winter, the hub tends toward utilizing maximum capacity of B and TS to supply the hub heat demand and employing maximum capacity of T to prepare the hub electricity demand. Medium utilization from CHP is also implemented to provide the hub demands. Since the hub heat demand in winter is more than other seasons, it is more beneficial to utilize maximum capacity of B and TS to supply the heat demand. Therefore, CHP in winter is utilized less than other seasons and the hub electricity demand is most supplied by maximum utilization from T. In spring and autumn, the hub would rather employ mediocre amounts of networks energy carriers. To do this, medium utilization from CHP, T, B, and TS is carried out to supply the hub electricity and heat demands.

Table 4 illustrates that investment costs in this case are less than investment costs in other cases. However, operation costs in this case are two times its investment costs. One of the most significant reasons is that the hub tends toward curtailing the hub peak electricity demand instead of increasing size of the hub technologies. Emission is the highest in this case compared to other cases. Because, the hub should directly purchase electricity and gas energy carriers from the relevant networks to supply the hub demands.

Case 2

In this case, installation and utilization of WT, ES, and DR programs are considered in the deterministic circumstances. As shown in Table 3, WT with maximum capacity and T with medium size are installed and utilized to supply the hub electricity demand. B with maximum capacity is installed and utilized to provide the hub heat demand.

Table 6(a, b, c, and d) represents operation results of the hub components in this case. The table provides some reasons for installation and utilization of the mentioned hub components. The operation results show that the hub installs and utilizes maximum capacity of WT to supply the hub electricity demand, especially in winter when wind power is the most. Medium capacity of T is installed and employed to provide the rest of unsupplied electricity demand. To avoid installation of surplus capacity of the WT and T, the hub curtails the peak electricity demand or shifts the demand to off-peak hours, especially in summer when the electricity peak demand is the most. Maximum capacity of the B is

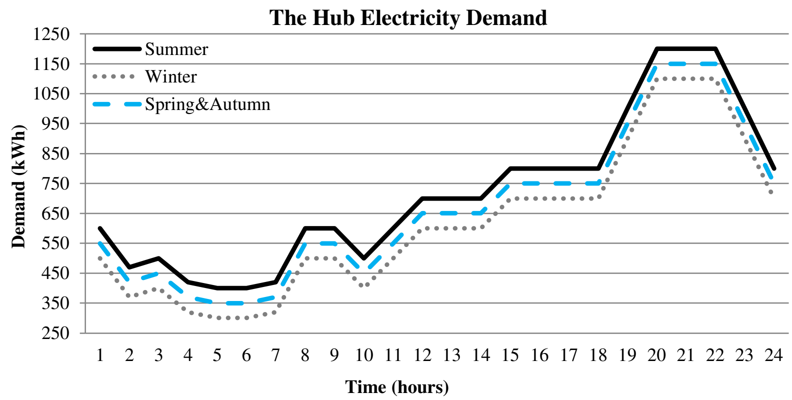

Fig. 2. The hub electricity demands in different seasons at 24 h a day.

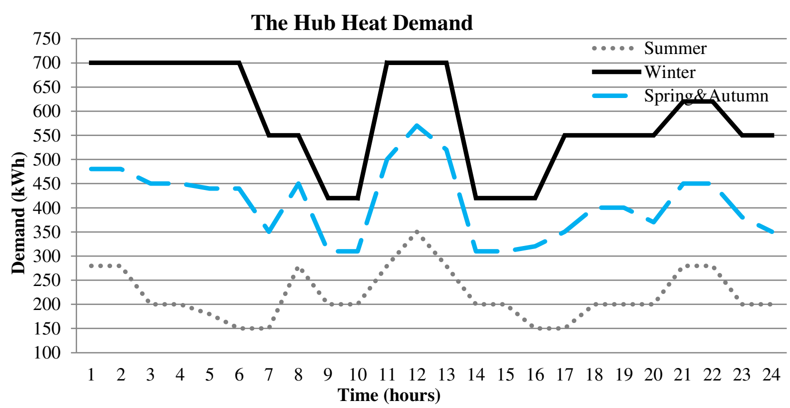

Fig. 3. The hub heat demands in different seasons at 24 h a day.

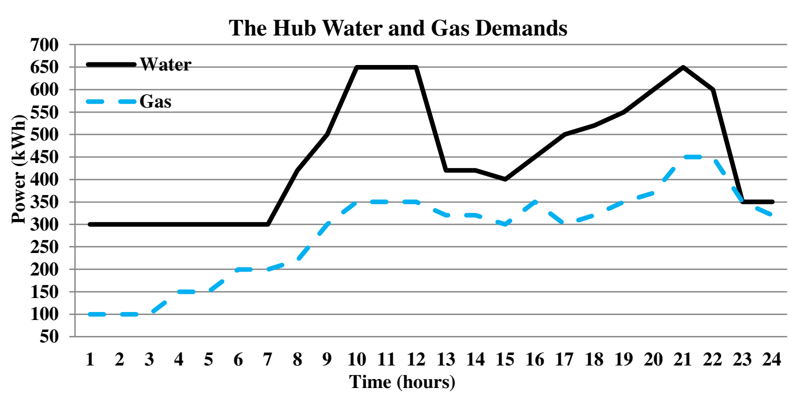

Fig. 4. The hub water and gas demands in different seasons at 24 h a day.

installed and utilized to supply the hub heat demand, especially in winter days when the hub heat demand is more than other seasons. It can be perceived from different cases within Table 3, curtailment of the hub electricity demand is reduced if CHP and energy storages, especially ES, are installed and utilized in the hub.

Table 4 manifests that enhancement of the hub potential in case 2 for integration of WT, ES, and DR increases investment costs compared to case 1. However, operation and emission costs in case 2 have declined to half of the costs in case 1. Furthermore, case 2 has a decline in overall costs compared to case 1. The outcome demonstrates the prominence of WT, ES, and DR for EHs in reducing emission, operation, and overall costs in the deterministic circumstances.

Case 3

The hub planning under electricity price uncertainty is considered in case 3. From Table 3, CHP with medium capacity is installed and utilized to supply the hub electricity and heat demands. WT with maximum capacity and T with minimum size are installed and utilized to supply the hub electricity demand. B with about maximum capacity and TS with minimum capacity are installed and employed to provide the hub heat demand. Compared to case 2, case 3 installs and utilizes CHP with medium capacity and T with less capacity than case 2.

Considering operation results of the hub components in case 3, Table 7(a, b, c, and d) manifests the reasons for installation and operation of the pinpointed hub elements. The hub preference is

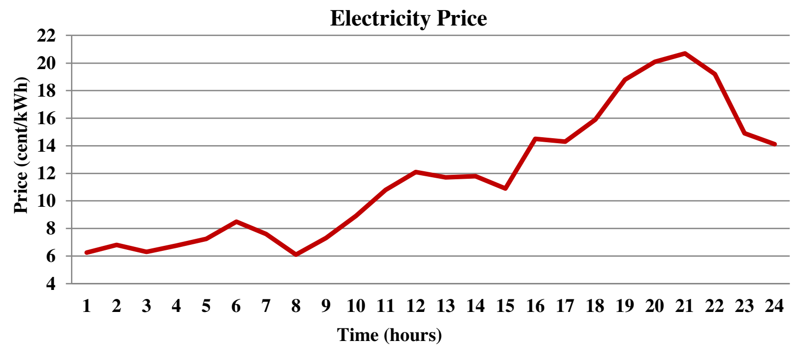

Fig. 5. Electricity price at 24 h a day.

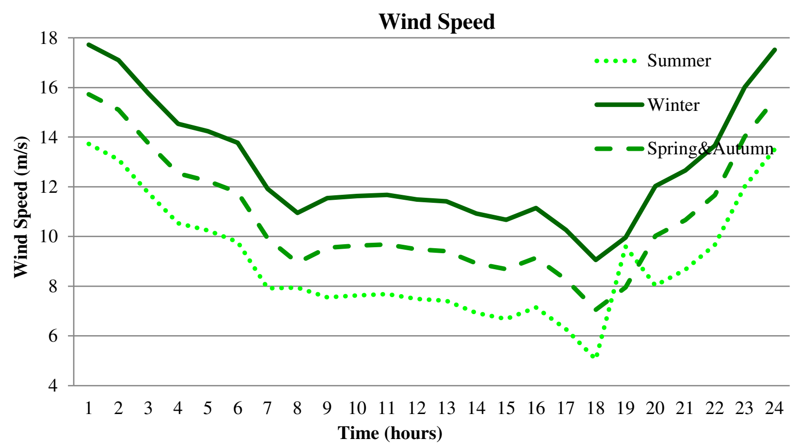

Fig. 6. Wind speed at 24 h a day.

Table 2
The required parameters for the hub optimal planning.

α_e^{loss}	0.02	$\pi_{em}^{NO_2}$	4.2	EF_{em}^{CHPco2}	1.596	RC_{AMI}	100	MC_{CHP}	0.03
α_h^{loss}	0.02	π_h^{Net}	5	EF_{em}^{CHPso2}	0.008	RC_B	300	MC_{CON}	0.012
α_e^{min}	0.1	π_g^{Net}	5	EF_{em}^{CHPno2}	0.440	RC_{CHP}	2000	MC_{ES}	0.01
α_h^{min}	0.1	π_e^{ES}	3	EF_{em}^{Netco2}	1.432	RC_{CON}	150	MC_{TS}	0.01
α_e^{max}	0.9	π_h^{TS}	3	EF_{em}^{Netso2}	0.454	RC_{ES}	800	MC_T	0.012
α_h^{max}	0.9	π_w^{Net}	4	EF_{em}^{Netno2}	21.8	RC_T	700	MC_{WT}	0.02
η_e^{ch}	0.9	A^{CHP}	0.96	ELF^{max}	0.01	RC_{TS}	600	r_{AMI}	2
η_e^{dis}	0.9	A^{Net}	0.99	EL	20	RC_{WT}	2000	r_B	1
η_h^{ch}	0.9	A^{WT}	0.96	EL_{AMI}	15	P^{MaxB}	700	r_{CHP}	1
η_h^{dis}	0.9	CC_{AMI}	270	EL_B	20	P^{MaxCHP}	800	r_{CON}	2
η_{ee}^{CON}	0.9	CC_B	500	EL_{CHP}	20	P^{MaxT}	900	r_{ES}	2
η_{ee}^{T}	0.9	CC_{CON}	200	EL_{CON}	15	P^{MaxWT}	900	r_T	1
η_{ge}^{CHP}	0.45	CC_{CHP}	2500	EL_{ES}	10	P^{MaxTS}	500	r_{TS}	2
η_{gh}^{B}	0.85	CC_{ES}	1000	EL_T	20	P^{MaxES}	400	r_{WT}	1
η_{gh}^{CHP}	0.3	CC_T	900	EL_{TS}	15	$P_e^{Net\,max}$	1000	w_{ci}	4
π_e^{DR}	3	CC_{TS}	800	EL_{WT}	20	$P_g^{Net\,max}$	1200	w_{co}	10
π_e^{ENS}	20	CC_{WT}	2500	LPF^{shdo}	0.1	$P_h^{Net\,max}$	1000	w_r	22
π_e^{ES}	2	EF_{em}^{Bco2}	1.755	LPF^{shup}	0.1	$P_w^{Net\,max}$	1000	x	0.07
π_{em}^{CO2}	0.014	EF_{em}^{Bso2}	0.011	ir_{no}	0.14	MC_{AMI}	0.012	y	0.01
π_{em}^{SO2}	0.99	EF_{em}^{Bno2}	0.62	if	0.12	MC_B	0.012	z	0.03

supplying the most hub electricity demand through WT, DR, and CHP. Dealing with electricity price uncertainty, the hub avoids either installing T with maximum capacity or purchasing electricity energy carriers from the network. Therefore, WT with maximum capacity together with DR is installed and utilized to supply the hub electricity demand, especially in winter when there is sufficient amount of wind. CHP with mediocre size is installed and employed to provide the hub electricity demand, especially in summer when there is no adequate amount of wind available. T with minimum capacity is installed and utilized to supply the rest of unsupplied electricity demand, especially in peak moments. B with maximum capacity is installed and utilized to supply the

Table 3
Results of optimum size of the proposed hub technologies.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Wind Turbine (WT)	–	897.5	900	900	900	722.3
CHP	259.3	–	382.50	382.5	396	396
Transformer (T)	900.0	624.4	290.94	269.8	607.5	632.4
Boiler (B)	587.8	700	672.55	653.5	619.5	619.5
Electrical Storage (ES)	–	–	–	400	379.4	400
Thermal Storage (TS)	453.8	–	78.69	500	139.5	139.5

hub heat demand, especially in winter. The hub heat demand in winter is higher than other seasons and the hub electricity demand is most supplied by WT and DR. Therefore, the hub would rather utilize the CHP less than the B to supply the heat demand in the winter. TS with minimum capacity is also installed and utilized to support the CHP and B.

Table 4 indicates that the hub in this case compared to case 2 utilizes more technologies in response to the electricity price uncertainty. Therefore, the more expenses are required for the investment in the hub planning. However, the less operation and ENS costs are remarkably resulted. Installation and utilization of different technologies are considered as a great reason for reducing the hub operation and ENS costs. Emission in this case has increased a little more than the emission in case 2. Since CHP is utilized more and more gas energy carrier is purchased from the gas network, the emission in this case is increased. It can be implied from Table 4, the hub in case 3 has remarkable operation costs reduction compared to case 2. Installation of CHP and decrement of T size are the most significant reasons for the hub operation costs reduction in case 3 compared to case 2. Indeed, the consequence confirms the eminence of simultaneous supply of the hub electricity and heat demands by CHP.

Case 4

The hub is optimally planned by considering the electricity demand uncertainty in this case. Table 3 shows that WT with maximum capacity, ES with maximum size, and T with minimum size are installed and utilized to supply the hub electricity demand. B close to maximum capacity and TS with maximum size are installed and utilized to provide the hub heat demand. Also, CHP with medium size is installed and utilized to provide the hub electricity and heat demands. The hub in case 4 compared to case 2 installs and utilizes CHP with medium capacity, increases energy storages capacities to the maximum capacities, decreases T capacity to the minimum capacity. Minimum capacity of T confirms that the hub prefers to utilize other hub components and another energy carrier instead of purchasing electricity from the network. Gas energy carrier, WT, ES, DR, and CHP are regarded as other factors and elements to supply the electricity demand. The outstanding components installed in this case (under the electricity demand uncertainty) are energy storages (ES and TS). Smoothing oscillations of the electricity demand, energy storages reduce operation costs.

Operation results of the hub in the case are displayed in Table 8 (a, b, c, and d). Table 8(a, b, c, and d) declares some reasons for installation and utilization of the technologies in the case. In summer, medium utilization of WT, ES, and DR is performed to supply the hub electricity demand. Since there is no adequate amount of wind in the summer, about maximum utilization of CHP is implemented to supply the rest of unsupplied electricity demand. The rest of unsupplied electricity demand by CHP, WT, ES, and DR is provided by minimum utilization of T, especially in peak times. Producing electricity and heat at the same time, CHP close to maximum utilization supplies the most hub heat demand. As it can be seen from Table 8, the least amount of heat is produced by the B. In fact, minimum utilization of B is carried out in the summer. Medium utilization of TS as CHP backup is implemented in summer when CHP is performing. In winter, maximum capacity of WT along with maximum capacity of ES and DR is utilized to supply the electricity demand. The reason is that winter wind power is the most than other seasons. The rest of unsupplied electricity demand is provided by medium utilization of CHP. Minimum utilization of T is required to supply the rest of unsupplied electricity demand in peak times. Medium utilization of CHP and maximum utilization of B and TS are required to supply the hub heat demand in winter. In spring or autumn, medium utilization of the hub components are necessitated to supply the electricity and heat demands because wind power, electricity demand, and heat demand have mediocre amounts.

It can be observed from Table 4, investment costs in case 4 compared to case 2 has been approximately increased by two times. However, the operation costs in case 4 has been reduced to the half amount of case 2. Installation of energy storages with the maximum capacities is considered as an eminent reason to remarkably alleviate the operation costs. ENS costs are also declined in case 4 compared to case 2 because different technologies are installed and utilized in response to the electricity demand uncertainty. Emission in case 4 has increased a little more than emission of case 2 due to uncertainty of the demand and purchasing more gas energy carrier from the network. Compared to case 2, total costs in this case have been intensely decreased through utilization of different technologies in response to the electricity demand uncertainty. Comparison between case 4 and other cases shows that the most significant reason to reduce the operation costs is associated with the CHP installation, T capacity reduction, and installation of maximum capacities of energy storages.

Case 5

The hub components are optimally planned under the wind uncertainty in this case. From Table 3, most technologies with about the maximum capacities are installed and utilized in response to the hub requirements under the wind uncertainty circumstances. Table 3 shows that case 5 under the wind uncertainty installs WT with maximum capacity. However, the hub in the case avoids maximum utilization of WT in order to escape from the wind uncertainty. Instead, CHP, ES, DR, and T near to the maximum capacities are installed and utilized to supply the hub electricity demand. In the meantime, the CHP produces electricity and heat. In addition, B and TS close to the maximum capacities are utilized to provide the hub heat demand. Case 5 compared to case 2 installs

Table 4
Results of planning costs pertained to the hub investment, operation, ENS, emission, and total costs.

The hub planning costs for 20 years	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Investment costs (M$)	3.180	4.872	5.98	7.02	7.092	6.46
Operation costs(M$)	6.396	3.143	1.16	3.51	21.88	20.61
ENS costs (M$)	1.67	1.67	0.279	0.324	0.74	0.87
Emission costs ($)	58581.3	23317.0	25334.9	28293.9	42807.0	46647.9
Total costs (M$)	11.3	9.71	7.43	3.86	29.29	27.40

Table 5a
The proposed hub scheduling of **case 1** in a **summer** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1		673.4					383.8	45.3	
t2		248.0				576.3	127.0	45.3	
t3		561.1					236.3	45.3	
t4		191.9				576.3	32.9	45.3	
t5		169.4				576.3	9.4	45.3	
t6		169.4				576.3		53.8	13.3
t7		191.9				576.3		62.2	13.3
t8		673.4					310.6	45.3	
t9		393.9				576.3	32.9	45.3	
t10		281.7				576.3	32.9	45.3	
t11		393.9				576.3	127.0	45.3	
t12		506.1				576.3	209.4	45.3	
t13		506.1				576.3	127.0	45.3	
t14		506.1				576.3	32.9	45.3	
t15		618.4				576.3	32.9	45.3	
t16		618.4				576.3		53.8	13.3
t17		618.4				576.3		62.2	13.3
t18		618.4				576.3	13.1	45.3	
t19		786.7			50	576.3	32.9	45.3	
t20		1000			60	576.3	32.9	45.3	
t21		1000			60	576.3	127.0	45.3	
t22		1000			60	576.3	127.0	45.3	
t23		842.8				576.3	32.9	45.3	
t24		618.4				576.3	32.9	45.3	

Table 5b
The proposed hub scheduling of **case 1** in a **winter** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1		363.1				408.4	691.5	10.1	
t2		217.2				408.4	691.5	20.0	
t3		250.8				408.4	691.5	29.8	
t4		185.3				358.4	691.5	24.6	
t5		162.9				358.4	691.5	19.6	
t6		187.1				308.4	691.5	65.6	
t7		153.7				423.6	576.3	186.3	
t8		421.3				288.4	691.5	408.4	
t9		460.0				208.4	691.5	408.4	
t10		189.4				535.1	314.8	337.0	
t11		484.3				158.4	691.5	267.0	
t12		596.5				158.4	691.5	207.2	
t13		582.0				188.4	691.5	214.0	
t14		393.9				576.3	303.6	408.4	
t15		660.1				258.8	641.1	400.4	
t16		518.9				550.0	300.0	408.4	
t17		610.3				361.4	538.5	408.4	
t18		618.2				345.1	534.8	408.4	
t19		814.7			45	298.7	551.2	360.7	
t20		1000			55	356.4	473.5	178.5	
t21		1000			55	356.4	393.5		
t22		1000			55	356.4	393.5		
t23		858.0				313.6	536.3		
t24		611.0				360.0	520.0		

Table 5c
The proposed hub scheduling of **case 1** in a **spring and autumn** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1		617.2					564.7		
t2		191.9				576.3	361.2		
t3		505.0					529.4		
t4		135.8				576.3	325.9		
t5		113.3				576.3	314.2		
t6		113.3				576.3	314.2		
t7		135.8				576.3	208.3		
t8		617.2					529.4		
t9		337.8				576.3	161.2		
t10		225.5				576.3	161.2		
t11		421.1				404.5	445.4		
t12		595.0				277.2	572.7		
t13		528.5				414.5	465.4		
t14		450.0				576.3	161.2		
t15		562.2				576.3	215.6	45.3	
t16		562.2				576.3	273.6	128.2	
t17		562.2				576.3	323.6	221.8	
t18		562.2				576.3	303.6	247.8	
t19		733.4			47.5	576.3	273.6	248.3	
t20		946.6			57.5	576.3	253.6	261.6	
t21		946.6			57.5	576.3	173.6	129.5	
t22		946.6			57.5	576.3	173.6		
t23		786.7				576.3	243.6		
t24		562.2					208.3		

Table 5d
Summary performance of the proposed hub in **case 1** in **different seasons**.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
Summer	–	M	–	–	H	H	L	L	L
Winter	–	H	–	–	M	M	H	H	–
Spring or autumn	–	M	–	–	M	M	M	M	–

Table 6a
The proposed hub scheduling of **case 2** in a **summer** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	897.5	−253.0		60			329.4		
t2	897.5	−413.5		47			329.4		
t3	897.5	−376.5		50			235.2		
t4	897.5	−475.3		42			235.2		
t5	897.5	−500.0		40			211.7		
t6	679.2	−500.0		40			176.4		
t7	453.2	−475.3		42			176.4		
t8	455.9	−253.0		60			329.4		
t9	414.1	−253.0		60			235.2		
t10	422.3	−376.5		50			235.2		
t11	427.4	−276.6					329.4		
t12	407.6	−196.9					411.7		
t13	400.3	−196.9					329.4		
t14	351.5	−196.9					235.2		
t15	329.2	−84.7					235.2		
t16	373.4	−84.7					176.4		
t17	292.7	−84.7					176.4		
t18	198.7	176.5		31			235.2		
t19	654.9	176.5		−100	50		235.2		
t20	465.0	179.0		−120	60		235.2		
t21	537.9	179.0		−120	60		329.4		
t22	664.8	179.0		−120	60		329.4		
t23	897.5	139.7					235.2		
t24	897.5	−84.7					235.2		

and utilizes CHP and compared to case 3 and case 4 increases the maximum capacity of CHP. The T capacity is increased in the case compared to case 3 and case 4 so that the hub has another option to avoid probabilistic wind power. ES and TS in the case compared to case 2 are utilized more. Indeed, CHP and energy storages have substantial effect on the costs reduction under the wind uncertainty circumstances.

The results of optimal operation of the hub in case 5 are presented in Table 9(a, b, c, and d). The table elaborates some proofs for installation and utilization of the aforementioned components. In summer, about maximum capacity of CHP is utilized to supply the hub electricity and heat demands simultaneously; because, there is no adequate and deterministic wind power in summer. DR, minimum utilization of WT, and medium utilization of ES are required to supply the rest of hub electricity demand. Minimum utilization of T is implemented at the moments when electricity demand is not supplied by the technologies. Since CHP is utilized more in summer, the hub heat demand is supplied by CHP as well. Medium utilization of TS as CHP backup is also carried out to provide the hub heat demand. In winter, medium utilization of WT is performed. Maximum utilization of ES plus DR are needed

Table 6b
The proposed hub scheduling of **case 2** in a **winter** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	897.5	−253.0		50			823.5		
t2	897.5	−413.5		37			823.5		
t3	897.5	−376.5		40			823.5		
t4	897.5	−475.3		32			823.5		
t5	897.5	−500.0		30			823.5		
t6	897.5	−500.0		30			823.5		
t7	897.5	−475.3		32			647.0		
t8	897.5	−253.0		50			647.0		
t9	897.5	−253.0		50			494.1		
t10	897.5	−376.5		40			494.1		
t11	897.5	−276.6		29			823.5		
t12	897.5	−196.9					823.5		
t13	897.5	−196.9					823.5		
t14	897.5	−196.9					494.1		
t15	897.5	−84.7					494.1		
t16	897.5	−84.7					494.1		
t17	897.5	−84.7					647.0		
t18	585.6	217.7					647.0		
t19	703.3	176.5		−90	45		647.0		
t20	897.5	179.0		−110	55		647.0		
t21	897.5	179.0		−110	55		729.4		
t22	897.5	179.0		−110	55		729.4		
t23	897.5	139.7					647.0		
t24	897.5	−84.7					647.0		

to supply the hub electricity demand and to smooth wind power fluctuations. Because, there is more wind power with more fluctuations in the season than other seasons. Therefore, maximum utilization of B and medium utilization of TS are most necessitated to supply the hub heat demand. Since the WT supplies the most hub electricity demand, CHP is utilized less than B and TS in winter. The rest of unsupplied electricity demand is provided by medium utilization of CHP and T. In spring and autumn, all the hub elements with the medium sizes are installed and utilized to supply the hub electricity and heat demands due to medium amounts of the wind power, the electricity demand, and the heat demand.

It can be observed from Table 4, case 5 compared to case 2 has a remarkable increment on investment costs. But, the increase of investment costs in case 5 compared to case 3 and case 4 is not considerable. Table 4 reveals tremendous increase in the hub operation costs in case 5 compared to case 2, even cases 3, 4, and 6 under the uncertainties. Since different technologies are utilized in response to the wind uncertainty, ENS outstandingly decreases in the case compared to case 2. However, emission has been increased in comparison with cases 2, 3, and 4. To avoid utilization of WT under the wind uncertainty, more electricity and gas energy carriers are purchased from the networks and the emission is thus increased. Although emission produced in case 5 is high, the emission is less than generated emission in case 1 (the hub without WT, ES, and DR). The result confirms the eminence of WT, ES, and DR in reducing the emission, even under the uncertainty of price (case 3), demand (case 4), wind (case 5), and the all uncertainties (case 6). Ultimately, total costs in case 5 (under the wind uncertainty circumstances) have remarkably increased in comparison with the other cases.

Table 6d
Summary performance of the proposed hub in **case 2** in **different seasons**.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
Summer	M	L	–	H	H	–	L	–	–
Winter	H	L	–	H	H	–	H	–	–
Spring or Autumn	M	M	–	H	H	–	M	–	–

Case 6

The all uncertainties of wind power, electricity price, and electricity demand are considered for the hub planning in this case. Comparison between case 3, case 4, case 5, and case 6 in Tables 3 and 4 demonstrates that wind uncertainty is the most influential and dominant factor in increment of total costs and in the hub performance. Therefore, the hub performance in this case is similar to case 5, the hub performance under wind uncertainty. In response to the uncertainties, most of the hub technologies with the maximum capacities have been selected. The operation and total costs in this case compared to case 5 have improved. Emission has increased in this case compared to cases 2, 3, 4, and 5, however it is less than case 1 without WT, ES, and DR. The prominence of WT, ES, and DR on emission reduction is also demonstrated in this case. Comparison between the aforementioned cases in Table 4 shows the importance of WT, ES, and DR in reducing the ENS under

Table 6c
The proposed hub scheduling of **case 2** in a **spring and autumn** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	897.5	−191.3		55			564.7		
t2	897.5	−351.8		42			564.7		
t3	897.5	−314.8		45			529.4		
t4	897.5	−413.5		37			529.4		
t5	897.5	−438.2		35			517.6		
t6	897.5	−438.2		35			517.6		
t7	698.5	−220.6		37			411.7		
t8	572.0	124.3		55			529.4		
t9	649.2	49.4		55			364.7		
t10	659.6	−84.1		45			364.7		
t11	666.0	−7.2		19			588.2		
t12	641.0	−7.2					670.5		
t13	631.7	116.8					611.7		
t14	569.0	177.6					364.7		
t15	540.1	317.9					364.7		
t16	597.2	262.5					376.4		
t17	492.1	364.5					411.7		
t18	364.3	488.4					470.5		
t19	456.9	457.5		−100	47.5		470.5		
t20	897.5	221.1		−120	57.5		435.2		
t21	897.5	221.1		−120	57.5		529.4		
t22	897.5	221.1		−120	57.5		529.4		
t23	897.5	195.8					447.0		
t24	897.5	−28.6					411.7		

Table 7a
The proposed hub scheduling of **case 3** in a **summer** day.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	900	−500.0		146.8		760.0	70.5	7.8	
t2	900	−500.0		110.7		428.2	180.2	9.3	
t3	900	−500.0		73.9		504.6	59.1	10.7	
t4	900	−500.0		48.4		300.9	131.0	12.2	
t5	900	−500.0		51.8		249.9	125.4	13.5	
t6	681.0	−500.0		49.5		695.4		14.9	56.9
t7	454.4	−334.2		34.2		850		16.2	103.3
t8	457.1	−114.5		53.8		850	31.3	17.6	
t9	415.2	−73.9		38.8		850		18.8	53.3
t10	423.5	−205.4		39.6		850		70.8	1.6
t11	428.5	−82.9		38.1		816.4	33.5	63.0	
t12	408.7	12.4				777.2	72.7	7.8	
t13	401.4	−15.6				850	30.0	8.2	
t14	352.4	31.8				850		9.6	53.3
t15	330.1	165.7				850		11.1	53.3
t16	374.4	122.7				850		12.5	103.3
t17	293.5	201.2				850		13.9	103.3
t18	199.3	202.7		−30.6		850		15.2	53.3
t19	705.2	−85.7		−131.5	22.5	850		23.2	46.5
t20	466.3	323.2		−98.8		830		70.8	
t21	539.4	323.2		−106.6		750		15.5	
t22	666.6	243.9		−154.8		663.6	86.3	7.8	
t23	900	−162.5				850		7.8	54.8
t24	900	−386.9				850		7.8	54.8

Table 7b
The proposed hub scheduling of **case 3** in a **winter** day.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	900	−462.6		248		427.2	672.7		
t2	900	−500		158		173.3	791.2	24	
t3	900	−500		125.7		249.7	791.2	70.1	
t4	900	−500		86.6		46	791.2	55.4	
t5	900	−500		95.5		46	791.2	27.4	
t6	900	−500		88.5			791.2		
t7	900	−500		55.7		46	630.8		
t8	900	−500		81.7		504.3	469		
t9	900	−500		83.4		504.3	316		
t10	900	−500		74.8		250.5	490	70.8	
t11	900	−283.9		78.4		58.7	791.2	59.8	
t12	900	−271.1				148.1	701.8	0.8	
t13	900	−242.3				88.7	791.2		
t14	900	−488.4				596.3	283.6		
t15	900	−272.1		67.5		495.9	404	70.8	
t16	900	−353.7				550	300	69.4	
t17	900	−274.1				385.8	514.1	70.8	
t18	587.2	−35.6		−84.1		357.4	522.5	70.8	
t19	705.2	74.4		−105		311	538.9	70.8	
t20	900	11.3		−213.4	51.2	398.6	431.3	6.9	
t21	900	216.7		−235.2		44.4	705.5		
t22	900	222.9		−272.2		31.8	718.1		
t23	900	222.9				313.6	536.3		
t24	900	−261.6				360	520		

the uncertainty of price, demand, and wind as well. Comparison of the studied cases confirms that the wind uncertainty has adverse effect on overall costs for the hub planning and operation. Therefore, meticulous tools and techniques are required to predict the accurate wind power. The result manifests that meticulous prediction of wind power is not only beneficial for the hub planning, it also has particular advantage for overall performance of electric power system.

The proposed hub requirements for min/max capacities of the hub technologies

Min/max capacities of WT

As it can be observed from Tables 3 and 11, maximum capacity of WT is installed when wind is entirely forecasted such as cases 2, 3, and 4. Minimum capacity of WT is installed and utilized by the hub under the wind uncertainty such as cases 5 and 6. It confirms the prominence of wind accurate prediction for WT installation. Probability of installation and utilization of WT is heightened when accurate prediction of wind speed is accomplished.

Min/max capacities of CHP

From Tables 3 and 11, maximum capacity of CHP is installed under the uncertainties circumstances: cases 3, 4, 5, and 6, especially under the wind uncertainty in cases 5 and 6. CHP is observed as the best resource to complete the wind power fluctuations. CHP installation is obviated or minimum capacity of CHP is required to be installed when wind is completely forecasted such as case 2.

Table 7c
The proposed hub scheduling of **case 3** in a **spring and autumn** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	900	−255.4					564.7		
t2	900	−401.3					564.7		
t3	900	−367.6					529.4		
t4	900	−457.4					529.4		
t5	900	−479.9					517.6		
t6	900	−479.9					517.6		
t7	700.4	−264					411.7		
t8	573.5	61.1					529.4		
t9	651	−14					364.7		
t10	661.4	−136.3					364.7		
t11	667.8	−30.3					588.2		
t12	642.7	106.2					670.5		
t13	633.4	115.2					611.7		
t14	570.6	176.2					364.7		
t15	541.5	316.5					385.3	17.2	
t16	598.8	−93.8				731.8	118.1	16.8	
t17	493.4	−2.6				754.5	145.4	16.5	
t18	365.3	180.7				632.7	247.2	16.2	
t19	458.2	323.2				615.8	234.1		
t20	900	122.2				610	220		
t21	900	252.6				340.9	409		
t22	900	252.6				340.9	409		
t23	900	−108.4				622.7	227.2		
t24	900	−381.8				723.6	156.3		

Table 7d
Summary performance of the proposed hub in **case 3** in **different seasons**.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
Summer	M	M	–	H	L	H	L	M	M
Winter	H	L	–	H	L	M	H	M	–
Spring or Autumn	M	L	–	–	–	L	M	L	–

Min/max capacities of B

From Tables 3 and 11, maximum capacity of B is installed when the wind power is entirely predicted such as cases 2, 3, and 4. Since most the electricity demand is supplied by the WT, the hub prefers to install the maximum capacity of B to supply the hub heat demand. In the cases that CHP supplies the most hub electricity demand, the installation of B is no longer required because the CHP produces electricity and heat simultaneously. Minimum capacity of B is installed when there is no sufficient amount of wind available (case 1) or wind power is probabilistic (cases 5 and 6). Thus, the hub prefers to employ CHP to produce the hub electricity and heat demands in the meantime. It can be implied that B is more likely utilized when wind power is deterministic. CHP is most utilized when wind power, electricity demand, or electricity price are probabilistic or there is no WT, ES, and DR programs in the hub.

Min/max capacities of T

Maximum capacity of T is installed and utilized when WT, ES, and DR are not in the hub. Minimum capacity of T is installed and utilized when WT, ES, and DR are utilized in the hub, when demand and electricity price are probabilistic (cases 3 and 4), or when gas network capacity is increased (case 3 to case 6 from Table 11). The result reflects that the hub preferably avoids installation of T and utilization of network electricity in presence of gas energy network, CHP, WT, ES, and DR programs.

Min/max capacities of ES

Maximum capacity of ES is installed and utilized when wind and demand fluctuate (cases 4, 5, and 6). By increasing gas network capacity, maximum capacity of ES is just installed and utilized in the demand uncertainty and not under the wind uncertainty. In fact, gas energy network fulfills the hub requirements in response to wind power fluctuations instead of ES utilization. When the wind is deterministic (case 2) and the price is probabilistic (case 3), the minimum capacity of ES is installed and utilized. As a result, ES is no longer required when the wind power is entirely forecasted and deterministic. In contrast, if gas energy network capacity is not adequate enough to smooth wind fluctuations, ES is considered as a paramount component to satisfy the hub requirements for the wind oscillations. On the other hand, if the gas network has an appropriate capacity, ES is no longer required and role of CHP and gas networks as great partners for wind power fluctuations is revealed.

Min/max capacities of TS

Maximum capacity of TS is utilized and installed in case 1 where there is no WT, ES, and DR in the hub and in case 4 where

Table 8a
The proposed hub scheduling of **case 4** in a **summer** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	900	−500	164.3	75.1		850	89.4	50	
t2	900	−500	259.0	98.2		505.3	163.4	59.3	
t3	900	−500	211.6	63.7		623.4	27.6	68.5	
t4	900	−500	194.2	41.8		329.2	131.4	77.5	
t5	900	−500	246.6	40.1		274.1	127.4	86.3	
t6	681.0	−500	261.4	42.2		737.1		95.0	60.5
t7	454.4	−326.3	181.2	24.3		850		103.5	94.4
t8	457.1	−109.9	234.1	46.2		850	41.8	111.8	
t9	415.2	−99.6	165.6	26.0		850		122.9	41.4
t10	423.5	−258.4	205.6	18.2		850		174.4	
t11	428.5	−70.9	213.8	18.7		850		146.5	
t12	408.7	−45.7	156.9	9.2		850		50.5	
t13	401.4	15.1	171.1	9.6		850	30	50.0	
t14	352.4	82.3	143.2	11.8		850		59.3	44.4
t15	330.1	239.9	132.9	11.3		850		68.5	44.4
t16	374.4	58.4	135.0	−7.6		850		77.5	94.4
t17	293.5	179.2	132.6	−9.5		850		86.3	94.4
t18	199.3	208.3	83.7	−18.4		850		95.0	44.4
t19	705.2	43.2	315.1	−34.6		850		117.3	30.3
t20	466.3	299.7	133.3	−87.5	7.3	830		163.1	
t21	539.4	299.7	61.8	−93.7	15.6	750		106.0	
t22	666.6	299.7	101.1	−76.0	9.2	750		50.0	
t23	900	−151.5	148.5	−53.3		850		50.0	54.0
t24	900	−456.4	98.4	−98.0		850		50.0	

Table 8b
The proposed hub scheduling of **case 4** in a **winter** day.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	900	−490.1	9.9	104.4	11.3	427.2	672.7		
t2	900	−500	170.2	146		273.7	768.8	34.9	
t3	900	−500	182.5	94.5		331.1	768.8	86	
t4	900	−500	297.3	86.5		130.2	768.8	77	
t5	900	−500	545.9	93.3		113.6	768.8	63.4	
t6	900	−500	617.6	78.9		48.8	768.8	30.9	
t7	900	−500	410.4	51.1		169.8	768.8	181.7	
t8	900	−500	383	39.7		429.8	550.1	223.8	
t9	900	−500	402.6	40.7		477.3	422.6	300.3	
t10	900	−500	434.2	38.3		261.4	588.5	450	
t11	900	−413.4	346	21.7		81.1	768.8	419.4	
t12	900	−500	331	30.6		707.8	142.1	51.5	
t13	900	−194.1	334.8	43.5		111.1	768.8	37.6	
t14	900	−298.5	372.9	30.8		319.6	560.3	186.1	
t15	900	−101.1	360.6	22.4		131.1	768.8	450	
t16	900	403.2	394.9	−25.8		550	300	441.1	
t17	900	−336.3	344.5	−10.8		358.5	541.4	450	
t18	587.2	69.1	291.3	−13.6		343.6	536.3	450	
t19	705.2	80	221.2	−67.6	3.9	297.2	552.7	450	
t20	900	73.2	304.2	−136.8	14	368.3	461.6	395	
t21	900	−291.9	119.9	−196.8	5.5	750			
t22	900	191.7	86.4	−219.6	14.2	31.8	718.1		
t23	900	−7.9	162.1	−29.4		313.6	536.3		
t24	900	−224.5	1.88	3		360	520		

Table 8c
The proposed hub scheduling of **case 4** in a **spring and autumn** day.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	900	−500	127.8	177.1		693.3	319.9		
t2	900	−500	277.5	124.9		390.3	426.9		
t3	900	−500	310.7	116.6		398.9	388.6		
t4	900	−500	223.8	69.8		213.7	453.9		
t5	900	−500	271.3	60.7		132.3	530.1	49.3	
t6	900	−500	286.5	59.9		164.4	768.8	306	
t7	700.4	−500	220.4	41.4		631	368.9	450	
t8	573.5	−182.2	211	50.5		680	300	450	
t9	651	−343.4	264.1	54.6		810.9	89	450	
t10	661.4	−411.1	280.1	49.3		733.6	116.3	450	
t11	667.8	−159.4	311.3	38.2		404.5	445.4	441.1	
t12	642.7	−303.1	295.2	23.2		850		123.7	
t13	633.4	−42.6	325.6	35.4		465.4	414.5	93.8	
t14	570.6	−171.6	286.1	20.7		796.3	83.6	92	
t15	541.5	299.7	274.8	17.1		160	739.9	450	
t16	598.8	−112.7	338.8	−18.1		731.8	118.1	441.1	
t17	493.4	21.3	314.7	−9.4		722.1	177.8	450	
t18	365.3	156.1	203.8	−26		616.3	263.6	450	
t19	458.2	121.7	221.2	−71.5		754.5	95.4	350.5	
t20	900	−178.7	272.6	−148.9	4	830		225	
t21	900	−284	49.7	−162.9	7.9	750			
t22	900	84.4	16.2	−185.5	37.1	340.9	409		
t23	900	−117	10.7	3.7		622.7	227.2		
t24	900	−325	2.3	−101.5		723.6			

Table 8d
Summary performance of the proposed hub in **case 4** in **different seasons**.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
Summer	M	L	M	M	L	H	L	M	M
Winter	H	L	H	H	L	M	H	H	–
Spring or Autumn	M	L	M	M	L	M	M	M	–

demand is probabilistic. Minimum capacity of TS is installed and utilized in case 2 where wind power is deterministic and in case 3 where electricity price is stochastic (case 3). When wind is deterministic (case 2) and price is probabilistic (case 3), it needs to minimum or no energy storages (ES and TS). By increasing gas network capacity (Tables 11 and 12), installation and utilization of TS are no longer required for any cases. As a consequence, the result confirms the importance of energy storages under the demand uncertainties if gas network capacity is not appropriate enough to satisfy the hub requirements. Conversely, if the gas network capacity is appropriate enough, role of CHP and gas network is ignited as substantial factors in response to the fluctuations of wind, price, and demand. Indeed, the hub diminishes or eliminates installation and utilization of energy storages when the gas energy network capacity is increased.

Effectiveness of increase of gas network capacity on the proposed hub planning

Tables 11 and 12 demonstrate effectiveness of increasing gas network capacity on optimal planning of the hub. Table 11 reveals

Table 9a
The proposed hub scheduling of **case 5** in a **summer** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	697.3	−276.1	301.1	67.4		880	35.5	13.9	
t2	671.4	−500	311.9	86.1	3.2	880	22.2	16.5	
t3	421.2	−246.2	215.8	32.6		880		19.1	61
t4	328.5	−263.8	159.4	11.7		880		21.6	61
t5	369.2	−327.9	184.0	17.7	0.9	880		24.1	81.
t6	353.2	−281.2	184.1	30.6		880		26.5	111
t7	232.1	−141.4	120.9	22.1		880	22.2	28.9	111
t8	255.6	111.3	179.4	49.3		880		31.2	
t9	184.4	150.5	129.8	37.5		880		73.1	20.6
t10	225.8	8.8	179.6	36.0		850		125.6	
t11	221.6	129.0	187.7	31.7		799.9	50	125.6	
t12	189.2	243.5	154.8	30.0		850		30	
t13	211.3	203.1	182.0	31.3		879.6	0.3	13.9	
t14	173.0	249.9	150.6	24.7		880		16.5	61
t15	163.7	426.8	174.7	25.9		880		19.1	61
t16	191.6	306.5	208.2	−2.1		850		21.6	102
t17	161.5	334.0	183.1	−0.4		880		24.1	111
t18	109.3	356.3	123.2	−5.2		880		26.5	61
t19	374.8	239.3	387.0	−84.0		850		79.1	0.8
t20	234.8	543.9	208.3	−96.6		830		125.6	
t21	253.4	361.5	42.6	−106.6	10.2	750		69.2	
t22	367.6	522.6	70.9	−117.4	5.1	750		13.9	
t23	548.3	156.1	136.0	−35.8		850		13.9	54.7
t24	692.0	−241.7	117.0	−20.1		880		13.9	63.7

Table 9b
The proposed hub scheduling of **case 5** in a **winter** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	724.6	−159.9	652	85.3	9.4	371.1	728.8	30.2	
t2	624	−335.2	656.9	67.2	6.2	371.1	728.8	59.9	
t3	459.1	−186.4	411.1	55.8	4.9	371.1	728.8	89	
t4	395.5	−148.3	352.5	48.6	3.2	321.1	728.8	102.9	
t5	465.4	−199.7	615.6	34.3		327.4	722.5	113	
t6	431.3	−309.8	509.6	14.7		478.2	521.7		
t7	254.4	−109.9	299.7	11.6		545.4	454.5		
t8	238.7	300.8	374.0	20.1		281.5	698.4	125.6	
t9	243.7	91.1	398	12.2		622.7	277.2	125.6	
t10	273.2	−68.5	440.7	16.5		545.4	304.5	125.6	
t11	229.1	321.8	357.7	7.9		121.1	728.8	79.9	
t12	254.8	375.8	392.8	30.4		121.1	728.8	35.1	
t13	245.7	411.9	389.1	17.9		151.1	728.8		
t14	256.6	185.9	426.1	20.7		596.3	283.6		
t15	201.2	448.1	340.6	8.9		394.3	505.6	125.6	
t16	246.9	263.7	400.2	7.1		550	300	123.1	
t17	225.2	393.7	352.6	9		381.8	518.1	125.6	
t18	175.5	390.6	235.8	4.2		355.4	524.5	125.6	
t19	170.5	564	168.4	0.6		309	540.9	125.6	
t20	283.4	675	236.6	−61		316.4	513.5	104.9	
t21	312.3	675	106.4	−97.3		124.2	625.7	53	
t22	361.5	675	50.1	−143.2	8.8	128.3	621.6		
t23	572.7	374.9	255.6	41.4		313.6	536.3		
t24	540.7	97.7	336.6	75		360	520		

optimum size of the hub components. Table 12 shows the relevant planning costs. Changes of the hub components before/after increasing gas network capacity can be observed from comparison of Tables 3 and 11. Changes of the hub planning costs before/after increasing gas network capacity can be evaluated from comparison of Tables 4 and 12. Comparison of optimum size of the hub components before/after increasing gas network capacity is also summarized in Table 13.

Compare the hub components in case 1 and case 2 before/after increasing gas network capacity from Tables 3 and 11. No sensible change is observed in the hub components before/after the increase of gas network capacity. From comparison of Tables 4 and 12, either there is no sensible change in the hub planning costs in the case 1 and case 2. It confirms that there is no tangible change in the hub components before/after increasing gas network capacity in deterministic circumstances of the wind, price, and demand. The most significant changes, which are elaborated in the follow, are related to the hub planning under the stochastic circumstances.

The hub is optimally planned in case 3 under the price uncertainty and the increase of gas network capacity (Tables 11 and 12). WT, CHP, and B with the maximum capacities are installed to supply the hub demands. Case 3 of Table 11 compared to Table 3 increases CHP medium capacity to maximum capacity, remains WT and B maximum capacities, and eliminates the T and TS. Results of case 3 of Table 12 compared to Table 4 indicate that investments costs have increased, emission has increased a little, the ENS has no a sensible change, operation and total costs have immensely decreased.

Under electricity demand uncertainty and increasing gas network capacity, the hub is optimally planned in case 4 (Tables 11

Table 9c
The proposed hub scheduling of **case 5** in a **spring and autumn** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	643.1	80.5	219.6	85.3			564.7		
t2	566.3	−27.5	280.5	67.2			564.7		
t3	545.3	5.5	287.5	55.8			529.4		
t4	373.9	107	267.3	48.6			529.4		
t5	366	56.6	256.1	34.3			517.6		
t6	340.7	52.9	207.4	14.7			517.6		
t7	209.7	208.8	101.6	11.6			411.7		
t8	182.8	457.6	92	20.1			529.4		
t9	217.7	409.6	110	12.2			364.7		
t10	215.8	305.6	97	16.5			364.7		
t11	234.8	392.6	98	7.9			588.2		
t12	232.3	529.6	117.2	30.4			670.5		
t13	240.8	506.2	85	17.9			611.7		
t14	204.3	549.2	87.2	20.7			364.7		
t15	173.3	675	60.3	8.9			364.7		
t16	209	641.5	70.6	7.1			376.4		
t17	184.8	674.9	65.9	9			411.7		
t18	118.1	675	48.8	4.2		108.1	529.4		
t19	148.8	675	46.4	0.6		500.3	349.6		
t20	237	675	41.2	−61		610	220		
t21	251.1	675	23.1	−97.3		546.4	203.5		
t22	348.7	675	11.5	−143.2		358.9	391		
t23	491	615	82.4	41.4			447		
t24	664.4	215.6	126.2	75			411.7		

Table 9d
Summary performance of the proposed hub in **case 5** in **different seasons**.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
Summer	L	L	M	M	L	H	L	M	M
Winter	M	M	H	M	L	M	H	M	–
Spring or Autumn	M	M	M	M	–	L	M	–	–

and 12). From Table 11, WT, CHP, B with the maximum capacities, and ES with the medium capacity are installed and utilized to supply the hub demands. Case 4 of Table 11 compared to Table 3 increases the CHP medium capacity to maximum capacity, remains WT and B maximum capacities, decreases ES maximum capacity to medium capacity, and eliminates T and TS. In case 4, comparison of Tables 4 and 12 declares that investment costs have no sensible change, ENS has improved, emission has increased, operation and total costs have remarkably declined.

The hub is optimally planned under the wind uncertainty and increasing gas network capacity in case 5 (Tables 11 and 12). From Table 11, case 5 installs and utilizes CHP with maximum capacity, WT and B with the medium capacities, and T and ES with the minimum capacities to supply the hub demands. Case 5 of Table 11 compared to Table 3 increases CHP medium capacity to the maximum capacity, decreases WT maximum capacity to medium capacity, reduces T maximum capacity to minimum capacity, declines B maximum capacity to medium capacity, diminishes ES maximum capacity to minimum capacity, and eliminates TS to supply the hub demands. For case 5, comparison between Tables 4 and 12 demonstrates that investment costs have decreased, operation costs have immensely declined, ENS has increased a little, emission has increased, and total costs have immensely reduced.

Table 10a
The proposed hub scheduling of **case 6** in a **summer** day.

	P_e^W	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	559.6	−91.9	403.2	73.1	7.4	880	35.5	13.9	
t2	538.8	−436.3	321.07	41.5	1.9	880	22.2	16.5	
t3	338.0	−117.2	228.1	51.9		880		19.1	61.0
t4	263.7	−153.1	210.0	29.7		880		21.6	61.0
t5	296.3	−230.6	252.7	33.8		880		24.1	81.0
t6	283.4	−237.7	216.1	31.2		880		26.5	111.0
t7	186.3	−63.0	163.2	23.8		880		28.9	111.0
t8	205.1	94.1	200.5	46.2		880	22.2	31.2	
t9	148.0	176.1	145.6	31.5		880		73.1	20.6
t10	181.2	−41.2	171.4	21.6		850	50.0	125.6	
t11	177.9	99.4	133.4	5.1		799.9		125.6	
t12	151.9	231.3	101.6	10.9		850		30.0	
t13	169.6	269.9	127.3	26.8		879.6	0.3	13.9	
t14	138.9	286.3	112.2	12.1		880		16.5	61.0
t15	131.4	545.5	144.8	37.4		880		19.1	61.0
t16	153.8	284.1	147.0	−0.04		850		21.6	102.0
t17	129.6	338.2	135.5	3.8		880		24.1	111.0
t18	87.7	318.6	88.8	−12.8		880		26.5	61.0
t19	300.8	310.8	238.4	−77.1	1.9	850		79.1	0.8
t20	188.4	598.6	105.4	−86.7	4.6	830		125.6	
t21	203.3	701.7	68.7	−80.6	7.6	750		69.2	
t22	295.1	660.8	117.0	−85.6	4.3	750		13.9	
t23	440.0	255.1	160.5	−83.3		850		13.9	54.7
t24	555.4	−108.4	116.6	−14.6		880		13.9	63.7

Table 10b
The proposed hub scheduling of **case 6** in a **winter** day.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	581.5	−20.5	596.2	68.8	11.4	371.1	728.8	30.2	
t2	500.8	−192.7	720.1	48.4	6.9	427.2	672.7	29.6	
t3	368.5	−11	580.5	60.1	5.4	371.1	728.8	59.3	
t4	317.5	−76	521.7	48.9	3.6	321.1	728.8	73.8	
t5	373.5	−136.5	748.6	41.8		321.1	728.8	87.9	
t6	346.1	−242.7	595	22.8		432.6	567.3		
t7	204.2	−74.3	293.8	17.7		545.4	454.5		
t8	191.6	319.7	348.2	23.5		281.5	698.4	125.6	
t9	195.6	167.7	431.6	21.4		622.7	277.2	125.6	
t10	219.2	30.6	472.7	19.2		545.4	304.5	125.6	
t11	183.8	266.5	378.9	10		121.1	728.8	79.9	
t12	204.5	414.3	321.6	26.5		121.1	728.8	35.1	
t13	197.2	457.4	332.9	19.7		151.1	728.8		
t14	206	253.1	400.3	24.8		596.3	283.6		
t15	161.5	493.1	376	11.9		394.3	505.6	125.6	
t16	198.1	239.6	381.7	13.2		550	300	123.1	
t17	180.7	299.1	270.6	3.5		381.8	518.1	125.6	
t18	140.8	561.7	276.4	10		355.4	524.5	125.6	
t19	136.9	702.7	251.8	3.9		336.8	513.1	110.6	
t20	227.4	702.7	363	−90.8		449.8	380.1	18.3	
t21	250.7	702.7	181.2	−123		21.1	728.8	23.7	
t22	290.1	702.7	74.6	−178	2.7	75	674.9		
t23	459.6	511.7	402.3	33		313.6	536.3		
t24	434	233.2	315.4	66		360	520		

Table 10c
The proposed hub scheduling of **case 6** in a **spring and autumn** day.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
t1	516.1	165.7	135.9	68.8			564.7		
t2	454.5	81.2	266.2	48.4			564.7		
t3	437.7	103	266.4	60.1			529.4		
t4	300.1	211.1	292.4	48.9			529.4		
t5	293.7	125	303	41.8			517.6		
t6	273.4	120.9	246.2	22.8			517.6		
t7	168.3	253.5	139.8	17.7			411.7		
t8	146.7	515.9	141.7	23.5			529.4		
t9	174.7	461.7	169.6	21.4			364.7		
t10	173.2	368.6	166.1	19.2			364.7		
t11	188.5	464.3	174.4	10			588.2		
t12	186.4	528.3	150.6	26.5			670.5		
t13	193.3	577.8	135.7	19.7			611.7		
t14	164	595.3	127.4	24.8			364.7		
t15	139.1	702.7	98.1	11.9		23.5	507.1	125.6	
t16	167.7	314.4	106.9	13.2		731.8	118.1	123.1	
t17	148.3	330.1	98.5	3.5		745.4	154.5	125.6	
t18	94.8	469.3	64.9	10		628.1	251.8	125.6	
t19	119.4	669.5	68	3.9		581.7	268.2	125.6	
t20	190.2	702.7	82.8	−90.8		628.7	201.2	113	
t21	201.6	702.7	61.3	−123		546.4	203.5		
t22	279.8	702.7	29.4	−178		340.9	409		
t23	394.1	364	17.3	33		622.7	227.2		
t24	533.2	104.1	122.9	66		723.6	156.3		

Table 10d
Summary performance of the proposed hub in **case 6** in **different seasons**.

	P_e^w	P_e^{Net}	P_e^{ES}	P_e^{SH}	P_e^{ENS}	P_g^{CHP}	P_g^B	P_h^{TS}	P_h^{Net}
Summer	M	M	M	M	L	H	L	M	M
Winter	M	M	H	M	L	M	H	M	–
Spring or Autumn	M	M	M	M	–	L	M	L	–

Dealing with the wind uncertainty is considered as a reasonable reason for the increase of the ENS. More utilization of CHP in this case is considered as a reasonable reason for emission increase. Entirely, increase of CHP maximum capacity and decrement of other hub components capacities in the case result in immense decrease of the hub operation costs and the hub planning total costs.

Table 11
Results of optimum size of the proposed energy hub technologies by increasing gas network capacity.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
WindTurbine (WT)	–	897.5	897.5	900	372.5	651.7
CHP	259.3	–	823.5	832.5	846	846
Transformer (T)	900	624.4	–	–	284.7	154.7
Boiler (B)	527	700	700	685.2	372.2	380.6
Electrical Storage (ES)	–	–	–	207.7	58.3	349.5
Thermal Storage (TS)	–	–	–	–	–	–

For case 6, the hub is optimally planned under the all uncertainties and increasing gas network capacity (Tables 11 and 12). The hub in case 6 of Table 11 installs and utilizes CHP and ES with the maximum capacities, WT and B with the medium capacities, T with the minimum capacity. Case 6 of Table 11 compared to Table 3 increases CHP medium capacity to maximum capacity, remains WT with the medium capacity and ES with the maximum capacity, decreases T medium capacity to minimum size and B maximum capacity to medium size, and eliminates TS to supply the hub demands. Case 6 in Table 12 compared to Table 4 illustrates that there is no sensible change in investment costs, ENS and emission have a little increase, operation and total costs have decreased immensely. Increment of CHP maximum capacity and decrement of other hub components capacities have a substantial effect on reducing the operation and total planning costs of the proposed hub.

As it was remarked in the previous statements, there is no sensible change in the hub operation and total costs in cases 1 and 2 of Table 12 compared to Table 4 when gas network capacity is increased. However, the hub operation and planning costs have a remarkable reduction in the cases 3, 4, 5, and 6 of Table 12 compared to Table 4 under the uncertainties. The most significant reason is associated with the increase of CHP maximum capacity when gas network capacity is increased. Since gas network capacity is increased, the maximum capacity of CHP can be increased. The hub supplies most the hub electricity and heat demands by CHP through purchasing more network gas. Therefore, the need for installation of other the hub components is sensibly diminished or entirely eliminated. Therefore, the operation and planning costs are extremely declined. The result also corroborates that the increase of either gas network capacity or CHP capacity is more beneficial for the hub planning under the stochastic circumstances rather than the hub planning in the deterministic circumstances.

The most outstanding result is observed from comparison of overall costs between case 2 of Tables 4 and 12 with case 6 of Tables 4 and 12. The result confirms that the overall costs of case 6 of Table 12 have extremely declined compared to case 6 of Table 4 and declined a little less than case 2 of Tables 4 and 12. The result manifests effectiveness of increasing gas network capacity on overall costs of the hub planning under the uncertainty circumstances (price, demand, and wind). In other words, the result confirms that when the hub deals with the uncertainty challenges, especially wind uncertainty, the most influential factor to reduce the overall costs is increasing gas network capacity. With increasing gas network capacity, the hub requirement for installation of maximum capacities of WT, B, T, ES, and TS is reduced and installation of CHP with more capacity satisfies the most hub demands. The authority of CHP as an influential component of the hub within the stochastic circumstances is sparkled by increasing gas network capacity.

Comparison of the results of Tables 3 and 4 with Tables 11 and 12 reveals the role of EHs in future energy networks. Integration of gas and electric networks through CHP diminishes overall costs within the stochastic circumstances of wind, price, and demand.

Table 12
Results of the proposed hub planning costs pertained to the hub investment, operation, ENS, emission, and total costs by increasing gas network capacity.

Evaluation of hub total costs for 20 years	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Investment costs (M$)	2.6	4.8	7.2	7.5	5.5	6.8
Operation costs (M$)	6.2	3.1	−12.3	−17.5	10.3	1.7
ENS costs (M$)	1.67	1.67	0.27	0.27	0.33	0.30
Emission costs ($)	58717	23317	31009	35261	55957	55945
Total costs (M$)	10.62	9.703	−4.36	−9.53	16.14	8.85

Table 13
Comparison of optimum size results of the proposed hub technologies in Tables 3 and 11 before/after the increase of gas network capacity.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6	
	T3	T11	T3	T11	T 3	T11	T 3	T11	T3	T11	T3	T11
WindTurbine (WT)			**Max**	**Max**	**Max**	**Max**	**Max**	**Max**	Med	Med	Med	Med
CHP	Min	Min			Med	**Max**	Med	**Max**	Med	**Max**	Med	**Max**
Transformer (T)	**Max**	**Max**	Med	Med	Min		Min		**Max**	Min	Med	Min
Boiler (B)	Med	Med	**Max**	**Max**	**Max**	**Max**	**Max**	**Max**	**Max**	Med	**Max**	Med
Electrical **Storage (ES)**							**Max**	Med	**Max**	Min	**Max**	**Max**
Thermal Storage (TS)	**Max**				Min		**Max**		Min		Med	

P.S: Min: Minimum capacity, Max: Maximum Capacity, Med: Medium Capacity.

The result affirms the superiority of planning and operation of gas and electricity networks dependently, especially under the uncertainties.

Conclusion

In this paper, a mathematical formulation was represented for optimal planning of a developed EH considering operation constraints. The EH consists of different technologies: converters (CHP as heart of EHs, B, and T), direct pipelines (gas and water), and energy storages such as TS. The EH was developed by WT, ES, and DR. Two OFs were presented for deterministic and stochastic environments of the wind power, electricity price, and electricity demand. The OF includes costs associated with the hub investment, operation, reliability, and emission. CPLEX solver of GAMS was employed to solve the MILP model of the hub. SCENRED tool and Backward/Forward method were applied to reduce scenarios tree, generated by the Monte Carlo, to best scenarios. Simulation results manifest that:

- In deterministic circumstances, integration of WT, ES, and DR increases the hub planning investment costs, however there is a desirable reduction in operation, emission, and total costs. Installation and utilization of WT instead of T are considered as a main reason for the costs reduction. B is most probably installed and utilized to supply most the hub heat demands without/with integration of WT, ES, and DR. The result substantiates the eminence of WT, ES, and DR to reduce the costs in the deterministic circumstances.
- Dealing with the various uncertainties and medium gas network capacity, the hub components respond to the hub planning differently as follows: WT, CHP, and B respond to the price uncertainty. WT, CHP, B, and energy storages (ES and TS) respond to the electricity demand uncertainty. WT, CHP, B, and ES respond to the wind uncertainty. Planned under the all uncertainties, WT, CHP, B, T, ES, and TS are all installed and utilized to satisfy the hub required demands. It is concluded that the more uncertainties future hubs are dealt with, the more hub components are required to supply the hub demands when the gas network capacity is not adequate enough.
- When gas network capacity is increased, the hub components are also variously deployed in response to the various uncertainties as follows: WT, CHP, and B respond to the price uncertainty. WT, CHP, B, and ES respond to the electricity demand uncertainty. WT, CHP, and B respond to the wind uncertainty. WT, CHP, B, and ES respond to the all uncertainties. It is deduced that the hub components for the hub deployment are diminished when gas network capacity is increased.
- Increase of gas network capacity and the uncertainties in the hub planning arise the emission. Whereas, interconnection of WT, ES, and DR in deterministic environment intensely reduces the emission before/after the increase of gas network capacity. Overall, in both determinate and stochastic circumstances, the produced emission in cases including WT, ES, and DR is less than the cases not including WT, ES, and DR. It corroborates strong effectiveness of WT, ES, and DR on emission reduction even if the hub either encounters with the uncertainties or gas network capacity is increased.
- The uncertainties arise the ENS and declines the hub reliability. However, the ENS is decreased and the reliability is enhanced under the uncertainties within this hub planning. Installation and utilization of WT, ES, and DR are considered as an outstanding reason for the hub reliability improvement under the uncertainties.
- When the hub is planning under the uncertainties before gas network capacity is increased, the planning costs are probably increased or decreased. For instance, the demand uncertainty causes the planning costs to be immensely decreased and the planning costs are intensely increased under the wind uncertainty. It demonstrates that the meticulous forecast of the uncertainties terms provides an opportunity toward better planning of the EHs so that the planning costs are normally reduced.
- Consider the hub deployment before/after increment of gas network capacity in deterministic circumstances. B and T are installed within the hub not including WT, ES, and DR. T is replaced by WT in the hub including WT, ES, and DR. As a result, since there is no sensible change in the hub deployment, there will no remarkable change in the planning costs before/after increase of gas network capacity in the deterministic circumstances. However, interconnection of WT, ES, and DR has a notable change on the planning costs before/after increase of gas network capacity. It is inferred that WT, ES, and DR are considered as influential factors for planning costs reduction in deterministic environment before/after increase of gas network capacity. Therefore, if meticulous prediction of the uncertainties

terms is implemented, increase of gas network capacity is no longer required to decline the planning costs. And, WT, ES, and DR have a substantial effect on the planning costs reduction within the deterministic circumstances.

- The planning costs vary in the different stochastic cases. Before increase of gas network capacity, the planning costs under the demand and price uncertainties are very close to the deterministic case including WT, ES, and DR. To diminish the planning costs under the demand and price uncertainties, CHP medium capacity, WT, ES, and DR are adequate enough and increase of gas network capacity is no longer required. However, the increment of gas network intensely descends the planning costs in all the stochastic cases, especially the wind and the all uncertainties. When gas network capacity is increased, the planning costs under the wind and the all uncertainties are even reduced less than the deterministic case including WT, ES, and DR. Because, by increasing gas network capacity, the CHP maximum capacity is ascended and other hub components capacities are descended or eliminated. Thus, the hub planning costs are immensely diminished.

To summarize, T and B are most likely installed within the hub not including WT, ES, and DR in deterministic environment. WT and B are more probably installed and utilized within the hub including WT, ES, and DR in deterministic circumstance. WT is taken into account as an outstanding technology to reduce the planning costs in deterministic circumstance. Once the hub is planning under the uncertainties and gas network capacity has a mediocre capacity, role of CHP and interconnected gas and electricity networks are sparkled. CHP mediocre capacity, WT, ES, and DR are most likely considered for the planning costs reduction under the uncertainties when gas network capacity is medium. CHP performance is even more scintillated when the gas network capacity is ascended. Remarkable increment of the hub planning costs produced through the wind and the all uncertainties is intensely reduced by operation of CHP maximum capacity. In response to the high expenses of the hub planning within the uncertainties environment, CHP with maximum capacity subtly eliminates the dependency of the hub components with their maximum capacities and masterly satisfies the most hub demands exclusively. All the aforementioned reasons afford valuable insight on superiority role of CHP on the costs reduction within the uncertainties circumstances, especially the wind and the all uncertainties. Furthermore, the results lead power systems operators and planners toward utilization of the RERs within interconnected gas and electricity networks for the upcoming smart power systems.

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