Market Based Short Term Scheduling in Energy Hub in Presence of Responsive Loads and Renewable Resources

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ABSTRACT

Energy hub as a super node in electrical distribution level has strong potential to receive energy in various carriers and after convert and store, satisfy hub required demands. On the other hand, CO2 emission and fossil fuels reduction raise up the need for integration of renewable based electricity generation such as wind and solar to energy hubs. In this paper, economical operation of energy hub including, stochastic wind generation, Combined Heat and Power (CHP) unit, boiler, and heat and electricity storages are modelled and analyzed. Responsive loads are used for more flexibility of the studied energy hub. Numerical result is observed through GAMS software to serve a commercial load in different scenarios of wind speed to determine when and how much of which carrier should be provided by which technology.

Keywords: *Stochastic generation, Demand response, Storage, Energy hub, Optimal operation*

1. INTRODUCTION

Integration of variable generation to the grid over the past two decades has been created novel challenges in order to plan and operate the grid including the resources. Intelligent technologies are required to compensate the fluctuation and uncertainty characteristics. DERs have powerful potential to complement the properties [1]. In this paper, energy hub approach is implemented as an innovative approach [2] for declining hub operation cost. Energy hub is modelled beneath electricity and gas network, combined heat and power (CHP) in response to reliability enhancement, efficiency improvement, cost operation reduction and synergy effects between energy carriers to plan and operate recent cooperated technologies to conventional grid [3]. The model develops by renewable, storage and demand side [4] in domestic domain of hot and moderate climate. Demand response could be employed to superior demand and supply balancing in [5].

2. PROBLEM FORMULATION

The energy hub that is modelled in this part is shown in Fig.1:

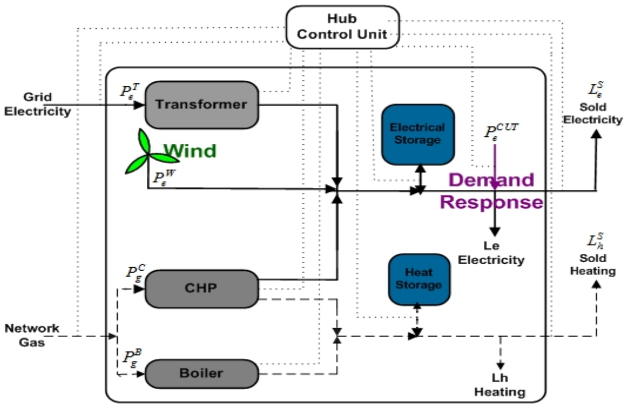

Fig.1 Proposed Energy Hub for Problem Formulation

2.1 Converter

$$\begin{bmatrix} L_\alpha \\ \vdots \\ L_\omega \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & \cdots & C_{\omega\alpha} \\ \vdots & \ddots & \vdots \\ C_{\alpha\omega} & \cdots & C_{\omega\omega} \end{bmatrix} \begin{bmatrix} P_\alpha \\ \vdots \\ P_\omega \end{bmatrix} \quad (1a)$$

$$P_\alpha = \sum_{k=1}^{N} P_{\alpha k} \quad (1b)$$

$$P_\alpha^{min} \le P_\alpha(H) \le P_\alpha^{max} \quad (1c)$$

Hub input carriers (P_α) are converted ($C_{\alpha\alpha}$) to hub output carriers (L_α) in (1a). Hub input carrier splints to N converter ($P_{\alpha k}$) in (1b).Hub inputs are constrained in(1c).

2.2 Renewables based generations

$$\begin{bmatrix} L_\alpha \\ \vdots \\ L_\omega \end{bmatrix} = \begin{bmatrix} P_\alpha^R \\ \vdots \\ P_w^R \end{bmatrix} \quad (2)$$

Renewables (P_α^R) can directly supply hub output (2).

2.3 Storage

$$\begin{bmatrix} S_\alpha(H) \\ \vdots \\ S_\omega(H) \end{bmatrix} = \begin{bmatrix} S_\alpha(H-1) \\ \vdots \\ S_\omega(H-1) \end{bmatrix} + \begin{bmatrix} S_\alpha^{ch}(H) \\ \vdots \\ S_w^{ch}(H) \end{bmatrix} - \begin{bmatrix} S_\alpha^{dis}(H) \\ \vdots \\ S_w^{dis}(H) \end{bmatrix} - \begin{bmatrix} S_\alpha^{loss}(H) \\ \vdots \\ S_w^{loss}(H) \end{bmatrix} \quad (3a)$$

$$S_\alpha^{loss}(H) = \alpha_\alpha^{loss} . S_\alpha(H) \quad (3b)$$

$$0 \le S_\alpha^{ch}(H) \le \frac{1}{\eta_\alpha^{ch}} * S_\alpha^{max} \quad (3c)$$

$$0 \le S_\alpha^{dis}(H) \le \eta_\alpha^{dis} * S_\alpha^{max} \quad (3d)$$

$$S_\alpha^{min} \le S_\alpha(H) \le S_\alpha^{max} \quad (3e)$$

Storages $S_\alpha(H)$ could be modelled (3a) via charge state ($S_\alpha^{ch}(H)$) and its constraint (3c), discharge state ($S_\alpha^{dis}(H)$) and its constraints (3d), storage loss($S_\alpha^{loss}(H)$) (3b) and loss coefficient (α_α^{loss}). Storage sizes are restricted (3e).

2.4 Demand Response

$$\begin{bmatrix} L_\alpha \\ \vdots \\ L_\omega \end{bmatrix} = \begin{bmatrix} D_{\alpha\alpha} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & D_{\omega\omega} \end{bmatrix} \begin{bmatrix} P_\alpha^{DR}(H) \\ \vdots \\ P_\omega^{CUT}(H) \end{bmatrix} \quad (4a)$$

Flexible load=1, Fixed load=0; (4b)

$$L_\alpha(H) = P_\alpha^{CUT}(H) \quad (4c)$$

$$L_\alpha^{New}(H) = L_\alpha(H) - P_\alpha^{CUT}(H) \quad (4d)$$

$$0 \le P_\alpha^{CUT}(H) \le LPFCUT * L_\alpha(H) \quad (4e)$$

Demand response in (4a) would be directly stated in (4c) with curtailment program ($P_\alpha^{CUT}(H)$) and its restrictions (4e).New electrical load is situated in (4d).

2.5 Completed Energy Hub

$$\begin{bmatrix} L_\alpha(H) \\ \vdots \\ L_\omega(H) \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & \cdots & C_{\omega\alpha} \\ \vdots & \ddots & \vdots \\ C_{\alpha\omega} & \cdots & C_{\omega\omega} \end{bmatrix} \begin{bmatrix} P_\alpha(H) \\ \vdots \\ P_\omega(H) \end{bmatrix} + \begin{bmatrix} P_\alpha^R(H) \\ \vdots \\ P_w^R(H) \end{bmatrix}$$

$$+ \begin{bmatrix} S_\alpha^{dis}(H) \\ \vdots \\ S_w^{dis}(H) \end{bmatrix} - \begin{bmatrix} S_\alpha^{ch}(H) \\ \vdots \\ S_w^{ch}(H) \end{bmatrix} + \begin{bmatrix} D_{\alpha\alpha} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & D_{\omega\omega} \end{bmatrix} \begin{bmatrix} P_\alpha^{DR}(H) \\ \vdots \\ P_\omega^{DR}(H) \end{bmatrix} \quad (5a)$$

$$\begin{bmatrix} S_\alpha(H) \\ \vdots \\ S_\omega(H) \end{bmatrix} = \begin{bmatrix} S_\alpha(H-1) \\ \vdots \\ S_\omega(H-1) \end{bmatrix} + \begin{bmatrix} S_\alpha^{ch}(H) \\ \vdots \\ S_w^{ch}(H) \end{bmatrix} - \begin{bmatrix} S_\alpha^{dis}(H) \\ \vdots \\ S_w^{dis}(H) \end{bmatrix} - \begin{bmatrix} \alpha_\alpha^{loss}.S_\alpha(H) \\ \vdots \\ \alpha_w^{loss}.S_w(H) \end{bmatrix} \quad (5b)$$

$$P_\alpha^{min} \le P_\alpha(H) \le P_\alpha^{max}$$
$$0 \le S_\alpha^{ch}(H) \le * S_\alpha^{max}$$
$$0 \le S_\alpha^{dis}(H) \le \eta_\alpha^{dis} * S_\alpha^{max}$$
$$S_\alpha^{min} \le S_\alpha(H) \le S_\alpha^{max}$$
$$0 \le P_\alpha^{DR}(H) \le LPFDR * L_\alpha(H) \quad (5c)$$

Energy hub entirely models in (5a), (5b) with its limitations (5c) which are essential of hub optimization.

2.6 Proposed Energy Hub

$$\begin{bmatrix} L_e + L_e^S \\ L_h + L_h^S \end{bmatrix} = \begin{bmatrix} \eta_{ee}^T & \eta_{ge}^C & 0 \\ 0 & \eta_{gh}^C & \eta_{gh}^B \end{bmatrix} * \begin{bmatrix} P_e^T \\ P_g^C \\ P_g^B \end{bmatrix} + \begin{bmatrix} P_e^W \\ 0 \end{bmatrix} +$$

$$\begin{bmatrix} S_e^{dis}(H) \\ S_h^{dis}(H) \end{bmatrix} - \begin{bmatrix} S_e^{ch}(H) \\ S_h^{ch}(H) \end{bmatrix} + \begin{bmatrix} P_e^{CUT} \\ 0 \end{bmatrix} \quad (6a)$$

$$\begin{bmatrix} S_e(H) \\ S_h(H) \end{bmatrix} = \begin{bmatrix} S_e(H-1) \\ \vdots \\ S_h(H-1) \end{bmatrix} + \begin{bmatrix} S_e^{ch}(H) \\ \vdots \\ S_h^{ch}(H) \end{bmatrix} - \begin{bmatrix} S_e^{dis}(H) \\ \vdots \\ S_h^{dis}(H) \end{bmatrix} - \begin{bmatrix} \alpha_e^{loss}.S_e(H) \\ \vdots \\ \alpha_h^{loss}.S_h(H) \end{bmatrix} \quad (6b)$$

$$P_e^W = \frac{1}{2} * \rho * A * V^3(H)$$
$$P_g = \sum_{k=1}^{2} P_{g2}$$
$$P_{g=} P_g^C + P_g^B$$
$$0 \le P_e^T(H) \le P_e^{max}$$
$$0 \le P_g(H) \le P_g^{max}$$
$$0 \le S_e^{ch}(H) \le \frac{1}{\eta_e^{ch}} * S_e^{max}$$
$$0 \le S_e^{dis}(H) \le \eta_e^{dis} * S_e^{max}$$
$$0 \le S_e(H) \le S_e^{max}$$
$$0 \le S_h^{ch}(H) \le \frac{1}{\eta_h^{ch}} * S_h^{max}$$
$$0 \le S_h^{dis}(H) \le \eta_h^{dis} * S_h^{max}$$
$$0 \le S_h(H) \le S_h^{max}$$
$$0 \le P_e^{CUT}(H) \le LPFCUT * L_e(H) \quad (6c)$$

Where,

L_e, L_h; Electrical and Heat Load
L_e^S, L_h^S; Sold Electricity and Heat to grid
η_{ee}^T; Electricity to Electricity Efficiency of Transformer
η_{ge}^C; Gas to Electricity Efficiency of CHP
η_{gh}^C; Gas to Heat Efficiency of CHP
η_{gh}^B; Gas to Heat Efficiency of Boiler
P_e^W; Wind Turbine Power
P_g; Imported Gas from grid
P_g^C; Imported Gas for CHP
P_g^B; Imported Gas for Boiler
P_e^T; Imported Electricity for Transformer
$\eta_e^{dis}, \eta_h^{dis}$; Electrical and heat storage discharge efficiency
$S_e^{dis}(H), S_h^{dis}(H)$;Discharge power of Electricity &Heat Storage
η_e^{ch}, η_h^{ch}; Electrical and heat storage charge efficiency
$S_e^{ch}(H), S_h^{ch}(H)$; Charge power of Electricity & Heat Storage
P_e^{CUT}; Curtailed power by Demand Response
$\alpha_e^{loss}, \alpha_h^{loss}$; Electricity and Heat Loss Coefficient
P_e^{max}; Maximum imported electricity from grid
P_g^{max}; Maximum imported gas from grid
S_e^{max}, S_h^{max}; Maximum size of electricity & heat storage
$LPFCUT$; Load participation factor of curtail able load

3. ENERGY HUB SCHEDULING

$$OF = \sum_{H=1}^{H=24} \pi.P \quad (7)$$

Energy hub is profitably scheduled based on minimum cost operation of objective function (OF). π is stated as price which is related to its power (P).

3.1 Proposed Energy Hub Scheduling

$$OF = \sum_{H=1}^{H=24} [g(H) * P_g^C(H)] + \sum_{H=1}^{H=24} [g(H) * P_g^B(H)]$$
$$+ \sum_{H=1}^{H=24} [e(H) * P_e^T(H) + \sum_{H=1}^{H=24} [cut(H) * P_e^{CUT}(H)$$
$$- \sum_{H=1}^{H=24} [hb * L_h^S(H)] \quad - \sum_{H=1}^{H=24} [(e(H) + eb) * L_e^S(H)] \quad (8)$$

Where,

g (H); Network gas price (cent/kwh)
e (H); Grid electricity price (cent/kwh)
cut (H); Curtailed demand price (cent/kwh)
hb; Heat benefit price (Cent/kwh)
eb; Electricity benefit price (Cent/kwh)

4. SIMULATION RESULTS

Proposed hub (Fig.1) is simulated as LP model of GAMS software. Hub outputs (Fig.2), hub input carriers prices, curtailment costs (Fig.3), wind turbine different power output (Fig.4), various curtailment costs (Fig.5) and hub parameter values are shown in Table.1 as input DATA.

TABLE.1 Hub Parameter Values

η_{ee}^{T}	η_{ge}^{C}	η_e^{ch}	η_e^{dis}	α_e^{loss}	S_e^{max}	P_e^{max}	eb	ρ
0.98	0.35	0.9	0.9	0.05	100	1000	13.2	1.225
η_{gh}^{B}	η_{gh}^{C}	η_h^{ch}	η_h^{dis}	α_h^{loss}	S_h^{max}	P_g^{max}	hb	A
0.9	0.4	0.9	0.9	0.05	200	1000	13.2	3

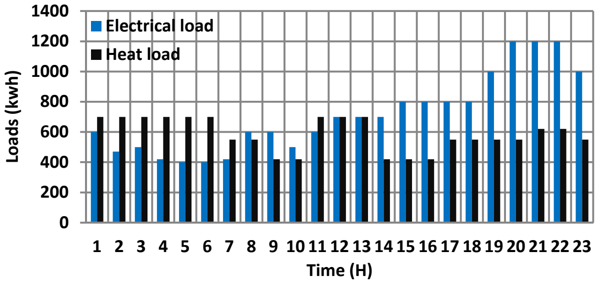

Fig.2 Electrical load and heat load at 24 hours a day

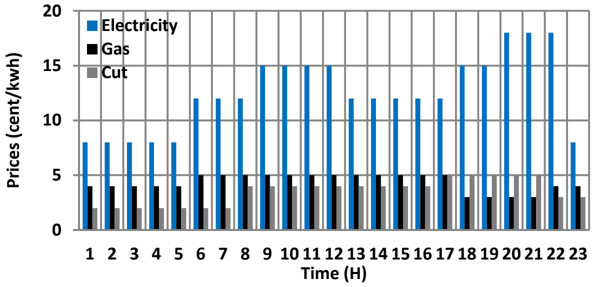

Fig.3 Electricity, gas and curtailment Costs at 24 hours a day

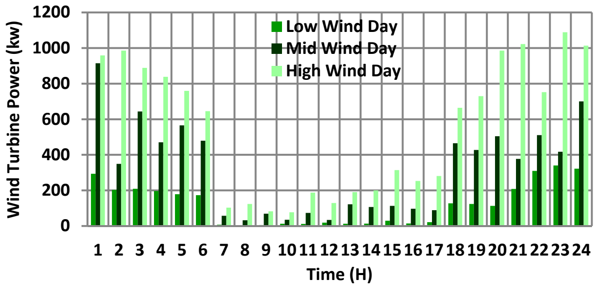

Fig.4 Wind turbine power output at 24 hours of different wind day

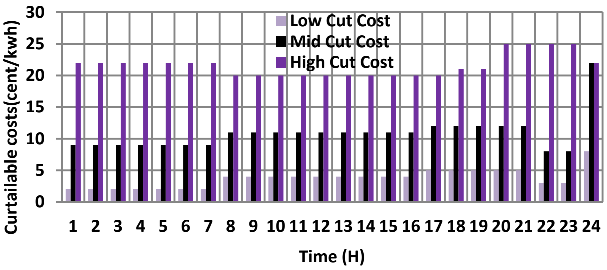

Fig.5 Different curtailment costs at 24 hours a day

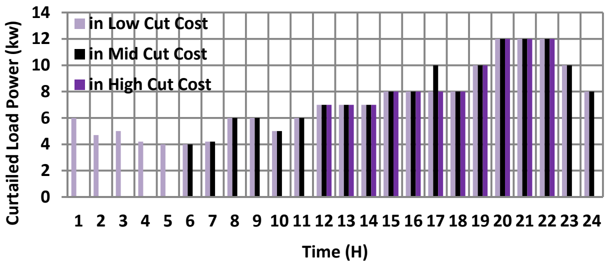

Fig.6 Curtailed load at 24 hours for different curtailment costs

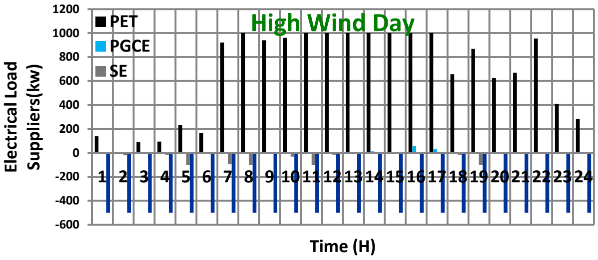

Fig.7 Electrical load suppliers at 24 hours a high wind day

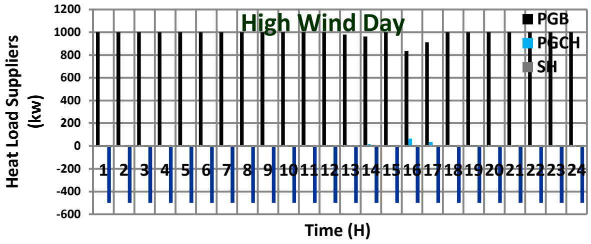

Fig.8 Heat load suppliers at 24 hours a high wind day

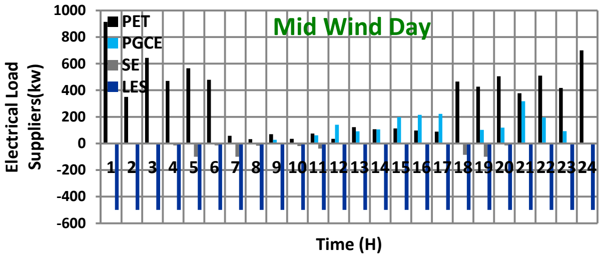

Fig.9 Electrical load suppliers at 24 hours a mid wind day

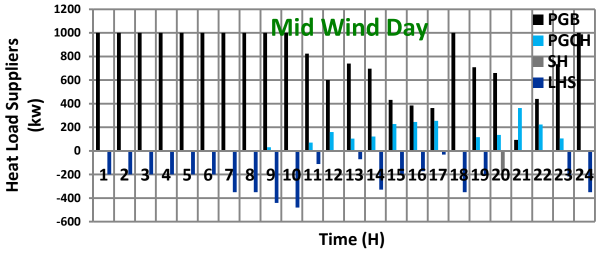

Fig.10 Heat load suppliers at 24 hours a mid wind day

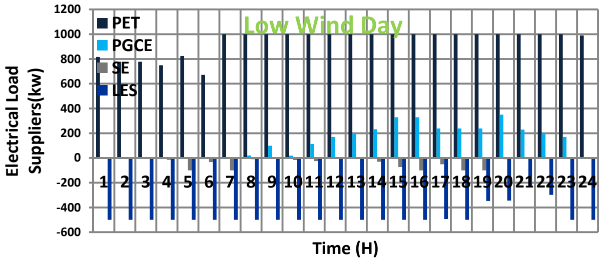

Fig.11 Electrical load suppliers at 24 hours a low wind day

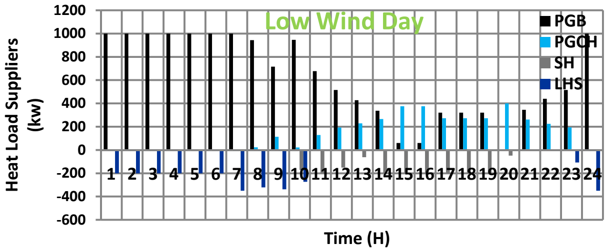

Fig.12 Heat load suppliers at 24 hours a low wind day

TABLE.2 Economical Result of Different Wind Days

	High Wind Day	Mid Wind Day	Low Wind Day
Cost	321494.142	364755.197	388362.769
Income	1323360.380	1289638.928	1169450.969
Income/Cost	4.116	3.536	3.011
OF	1001866.238	924883.731	781088.200

TABLE.3 Heat Load Supply Results

$L_h(H) = -{L_h}^S(H) + \eta_{gH}^B P_g^B(H) + \eta_{gh}^C P_g^C(H) + S_h^{dis} - S_h^{ch}$

No. Scenario	$L_h =$	$-L_h^S$	$+\eta_{gh}^C * P_g^C$	$+\eta_{gh}^B * P_g^B$	$+S_h^{dis}$	$-S_h^{ch}$
1.low (H=19)	550	0	272	288	0	10
(H=20)	550	0	400	0	150	0
(H=21)	620	0	262.095	0	47.619	0
2.Mid (H=19)	550	202.357	116.420	638.054	0	2.118
(H=20)	550	0	0	0	0	180
(H=21)	620	0	362.680	83.971	173.350	0
3.High(H=19)	550	350	0	900	0	0
(H=20)	550	0	0	0	0	0
(H=21)	620	280	0	900	0	0

Simulation results are illustrated in (Fig.6)-(Fig.12) to supply heat and electrical demands. Exact numerical results are sited in Table.2, 3, 4. Where PET, PGCE, SE, LES are consequently stated as imported electricity power for transformer, imported gas power for producing electricity by CHP, electrical storage content value and sold electricity to the grid. PGB, PGCH, SH, LHS explain imported gas to boiler, imported gas for producing heat by CHP, heat storage content value and sold heat to the grid.

When hub curtailment costs increase, participation of load to serve hub electrical output will decrease (Fig.6). Observing wind speed changes is exhibited in Fig.7-Fig.12. While rising wind, wind turbine output power enhances and it causes some changes in hub performance and operation costs. With increasing wind turbine output power, imported electricity carrier from grid will decrease because wind turbine provides required electricity demands. Electrical storages save additional produced electricity. More electricity than low and mid wind days is sold to the grid to achieve profit. CHP is run less than when wind speed is low and medium. Hence, heat storages are emptied to provide HUB heat loads. Extra required heat is satisfied by boiler in this state and more heat than low and medium wind is sold to the network to receive income. On the other hand, wind turbine produces less electricity in low wind days. Therefore, hub imports more network gas carrier more than high and mid wind days and more than electricity carrier because gas carrier price is lower than grid electricity price. Less electricity is sold to the grid in this stage. Hence, wind speed reduction causes cost operation enhancement (Table.2). In this respect, CHP produces more electricity and heat. Boiler is employed less than low and mid wind days. So, heat storages have less content values and less heat is sold to the network.

Table.3, 4 evaluate numerical results of hub heat and electrical required demands supply via various generation resources in 3 hours. The exact values of demands feeds are situated in the tables.

TABLE.4 Electrical Load Supply Results

$L_e(H) = -{L_e}^S(H) + \eta_{ee}^T P_e^T(H) + \eta_{ge}^C P_g^C(H) + P_e^W(H) - S_e^{ch}(H) + S_e^{dis}(H) + P_e^{CUT}(H)$

No. Scenario	$L_e =$	$-L_e^S$	$+\eta_{ee}^T * P_e^T$	$+\eta_{ge}^C * P_g^C$	$+P_e^W$	$+S_e^{dis}$	$-S_e^{ch}$	$+P_e^{CUT}$
1.low (H=19)	1000	347.34	980	238	124.34	0	5	10
(H=20)	1200	345.24	980	350	113.245	90	0	12
(H=21)	1200	238.87	980	229.333	208.013	9.524	0	12
2.Mid(H=19)	1000	500	980	101.868	427.418	0	19.286	10
(H=20)	1200	500	980	119	504.623	84.377	0	12
(H=21)	1200	500	980	317.345	377.384	13.271	0	12
3.High(H=19)	1000	500	850.392	0	729.608	0	90	10
(H=20)	1200	500	612.407	0	985.593	90	0	12
(H=21)	1200	500	656.043	0	1022.433	9.524	0	12

5. CONCLUSION

Fossil fuels reduction and CO2 emission has created various novel challenges in order to innovate new technologies and techniques in response to efficiency enhancement, reliability increase, pollution decrease and cost operation reduction. Distributed energy resources such as CHP, renewable generation are great example of the technologies. In spite of high benefit of renewable resources, uncertainty and variability characteristics have to be supported with complemented resources. DR and storages attributes make them well suited for the environment. In this respect, energy hub as a strong solution is employed to unite the technologies with traditional grid to superior demand and supply balancing target to minimize operation costs. Problem was mathematically formulated and simulation was run via LP model of GAMS software. Results show when and what technologies could be strongly satisfied hub required demands to achieve minimum cost operation based on grid prices and different wind days.

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