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Effect of Wind Turbine, Solar Cells and Storages in Short Term Operation of Coupled Electricity and Gas Infrastructures in Different Climates

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Abstract

The biggest challenges faced in big cities are greenhouse gas emission and growing energy needs. Efficient utilization of existing infrastructures has a prominent role in response to the challenges. Energy hub approach embraces performance of different energy networks. Energy hub is defined as a super node in electrical system receiving distinctive energy carriers such as gas and electricity in its input, and based on minimum cost decides when and how much of which energy carrier should supply the hub requirements. In this paper, we examine impact of renewable energy resources (wind and solar) and energy storages (electrical and thermal storages) on short term scheduling of energy hub. Effect of the technologies is also investigated on total operation costs of the energy hub in hot and cold climates. Mixed Integer Linear Programming (MILP) model is used for modeling proposed energy hub. CPLEX solver of GAMS software is employed to solve the problem. The results reveal that when and how much of which energy carrier should be exploited to satisfy hub required demands.

Keywords: Multi Carrier Energy Networks, Energy Hub, Wind, Solar, Energy Storage, Short Term Operation, GAMS

1. Introduction

In the past, gas and electricity infrastructures were utilized separately. Nowadays, advanced technologies provide opportunity for operation of the resources simultaneously. The eminent benefit of the technologies contains some advantages for bulk electric system such as reliability enhancement, operation costs reduction, efficiency increase. Smart grid is an umbrella for utilization of the resources and the technologies, and it transfers unidirectional electrical power system from fossil fuels generation plants to bidirectional environment through the technologies.

Smart grid provides opportunity for customers to participate electricity management or they sell their additional electricity to the grid to receive revenue. Energy hub approach is expanded as a robust solution for optimal operation of multi carrier energy infrastructures such as gas and electricity [1-3]. The hub has strong potential for integrating distributed generations such as renewable, energy storages and demand participation to reduce operation costs in response to different required demands such as electricity and heat [4-5]. Some application of the energy hub is categorized as follow:

- Power plants (co and tri generation)
- Industrial plants (steel works, paper mills, and refiners)
- Big buildings (airports, hospitals and shopping malls)
- Bounded geographic areas (rural, urban districts, town and cities)

- Isolated areas (plug-in electric vehicles, ship, airship and aircraft)

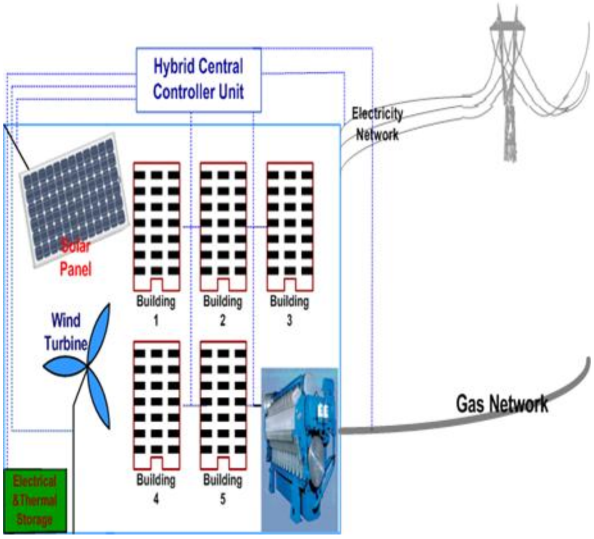

Fig.1. Proposed energy hub

Impact of renewable such as Photo Voltaic (PV) on optimization problem in energy hub approach is seen in [6-7]. Energy storage technologies such as battery, flywheel, and compressed air energy storage are rapidly developing commercial. The appliances of the energy storage technologies are broadly expanding invaluable for renewable fluctuations. Energy storages are modeled and formulated in order to discharge their batteries to smooth wind fluctuations [8-11]. Optimization problems are solved under energy hub approach in (Mixed Integer Nonlinear Programming) MINLP model and in (Mixed Integer Linear Programming) MILP model of MATLAB and GAMS software solvers in [3], [12] in sequent. Effect of wind power in different climates on energy hub operation costs and energy hub scheduling is considered in [13]. Operation of a hybrid energy system includes wind turbine, solar cells and energy storages is investigated in [14] without applying combination of gas and electricity infrastructures and energy hub approach.

This paper is aimed to utilization of various energy infrastructures equipped by renewable energy resources (wind and solar) as well as energy storage technologies (electrical and thermal storages). Effect of the technologies on hub operation costs as well as effect of the technologies on scheduling of electricity and gas infrastructures is also considered in this paper in two different climates (i.e. hot and cold climates). The remained of the paper is organized as follow: proposed energy hub (Fig. 1) is introduced in section II. Proposed hub is modeled in section III. Session IV discusses simulation results. Finally, conclusion is debated in session V.

2. Proposed Energy Hub

In this paper, proposed energy hub (Fig. 2) includes integration of electricity and gas infrastructures. The hub has strong potential to sell supplemental produced electricity to the grid. Combined Heat and Power (CHP) is used to link electricity and gas infrastructures, and CHP is considered as heart of energy hub. Transformer is used to convert electricity to desire level of electricity. Boiler is used to convert gas to heat. Renewable energy is employed to supply the hub requirements in both hot and cold climates. Wind power is used to provide the hub electricity demand. Solar power is also used to produce electricity demand. Electrical storage is used to charge and discharge electricity in required times. Thermal storage is used to charge and discharge heat in required times. Hub control unit manages the hub performance through information and communication technologies.

3. Proposed Energy Hub Model

In this session, proposed energy hub is mathematically modeled based on objective function (1) and its constraints (2a) to (6c) in following parts:

3.1. Minimizing Objective Function

Energy hub is economically scheduled based on minimum operation costs. Hub sometimes receives revenue from selling power to the grid. Objective function (1) is related to purchase or sell electricity power $P_e^T(H)$ and gas power $P_g(H)$ from network for CHP $P_g^C(H)$ and boiler $P_g^B(H)$ through hourly electricity $e(H)$ and gas $g(H)$ price. Hence, the hub could be powerfully scheduled in order to operate the technologies in response to minimum operation costs.

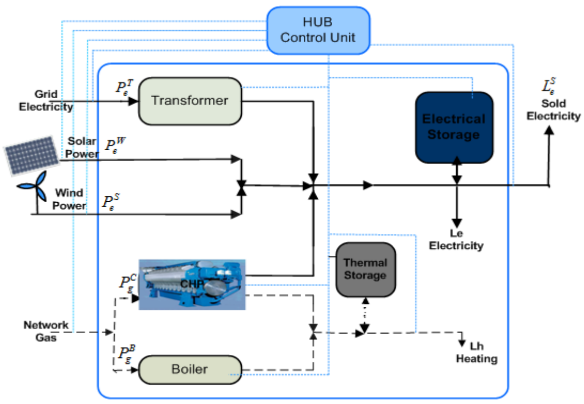

Fig.2. Proposed energy hub model

$$OF = \sum_{H=1}^{H=24} [e(H) * P_e^T(H)] + \sum_{H=1}^{H=24} [g(H) * P_g^C(H)] + \sum_{H=1}^{H=24} [g(H) * P_g^B(H)] \quad (1)$$

3.2. Electrical Demand Constraint

Electrical demand $L_e(H)$ is supplied by imported electricity for transformer from network $P_e^T(H)$ through transformer efficiency η_{ee}^T. Furthermore, electrical demand can be supplied by wind power ${P_e}^W(H)$ and solar power ${P_e}^S(H)$ via free cost. Electrical demand can be also supplied by produced electricity via CHP through imported network gas for CHP $P_g^C(H)$ and through its gas to electricity efficiency η_{ge}^C. Also, electrical demand can be supplied by discharging electrical storage power ${P_e}^{dis}(H)$ in required times. Extra electrical power is stored in electrical storage ${P_e}^{ch}(H)$. Supplement produced electricity is sold to electric network to achieve revenue.

$$L_e(H) = \eta_{ee}^T P_e^T(H) + \eta_{ge}^C P_g^C(H) + {P_e}^W(H) + {P_e}^S(H) + {P_e}^{dis}(H) - {P_e}^{ch}(H) \quad (2a)$$

3.2.1. Wind Model

$P^{wind}(H)$ denotes produced electricity power via wind turbine at every hour. When wind reaches to W_{ci}, wind turbine starts to produce power till rated power P_r of wind turbine , when wind increases till W_r, wind turbine produces rated power. When wind rises up more than W_{co}, wind turbine will be off and it doesn't produce power. z, y, x are related to wind turbine characteristics.

$$P^{wind}(H) = \begin{cases} 0 & w \le w_{ci} \\ P_r\left(a - b.w(H) + c.w^2(H)\right) & w_{ci} \le w \le w_r \\ P_r & w_r \le w \le w_{co} \\ 0 & w \ge w_{co} \end{cases} \quad (2a.1)$$

3.2.2. Solar Model

Produced electricity power by photo voltaic would be mathematically modeled with equation (2a.2), (2a.3) according to solar radiation angle and its degree (θ) in every hour $P^{pv}(H,\theta)$. Restriction for solar panel angle is stated in (2a.4). Where, rated power of photo voltaic is described by P_n. Vertical and horizontal radiations are expressed by $R_V(H)$ and $R_H(H)$ in sequence.

$$P^{pv}(H,\theta) = \frac{R(H,\theta)P_n}{1000} \quad (2a.2)$$

$$R(H,\theta) = R_V(H)cos\theta + R_H(H)sin\theta \quad (2a.3)$$

$$0 \le \theta \le \frac{\pi}{2} \quad (2a.4)$$

3.3. Heat Demand Constraint:

Hub heat demand $L_h(H)$ is provided by produced heat via CHP power $P_g^C(H)$ through its gas to heat efficiency η_{gh}^C. Heat demand can be also supplied by boiler power $P_g^B(H)$ through its gas to heat efficiency η_{gh}^B. Some part of heat demand can be supplied by discharge power of thermal storage ${P_h}^{dis}(H)$. Supplemental produced heat is saved in thermal storage ${P_h}^{ch}(H)$.

$$L_h(H) = \eta_{gh}^C P_g^C(H) + \eta_{gh}^B P_g^B(H) + {P_h}^{dis} - {P_h}^{ch}(H) \quad (2b)$$

3.4. Electrical Storage Constraint:

Electrical storage $P_e(H)$ is constrained by its remained power $P_e(H-1)$, charge power $P_e^{ch}(H)$and discharge power $P_e^{dis}(N,H)$ and its loss power through its efficiency α_e^{loss} (3a).

Electrical storage power is limited in (3a)-(3e). Electrical energy storage is restricted between minimum and maximum P_e^{max} power in (3b). Charge and discharge power should be limited between min and maximum power via their charge η_e^{ch} and discharge η_e^{dis} efficiencies in (3c) and (3d) in sequence. Binary variables of charge I_e^{ch} and discharge I_e^{dish} powers are used to prevent charge and discharge power at the same time in (3e).

$$P_e(H) = P_e(H-1) + P_e^{ch}(H) - P_e^{dis}(H) - \alpha_e^{loss}.P_e(H) \quad (3a)$$

$$0 \le P_e(H) \le P_e^{max} \quad (3b)$$

$$0 \le P_e^{ch}(H) \le I_e^{ch}(H) * \frac{1}{\eta_e^{ch}} * P_e^{max} \quad (3c)$$

$$0 \le P_e^{dis}(H) \le I_e^{dis}(H) * \eta_e^{dis} * P_e^{max} \quad (3d)$$

$$0 \le I_e^{ch}(H) + I_e^{dis}(H) \le 1 \quad (3e)$$

3.5. Thermal storage constraint:

Thermal storage power is restricted by its remained power $P_h(H-1)$, charge $P_h^{ch}(H)$ and discharge $P_h^{dis}(H)$ powers and loss power through its efficiency α_h^{loss} in (4a).

Thermal storage is limited between its in minimum and maximum P_h^{max} power in (4b), charge $P_h^{ch}(H)$ and discharge $P_h^{dis}(H)$ powers of thermal storage through charge η_h^{ch} and discharge η_h^{dis} efficiencies of thermal storage in (4c) and (4d).

Binary variables of charge I_h^{ch} and discharge I_h^{dis} are used to prevent charge and discharge performance at the same time (4e).

$$P_h(H) = P_h(H-1) + P_h^{ch}(H) - P_h^{dis}(H) - \alpha_h^{loss}.P_h(H) \quad (4a)$$

$$0 \le P_h(\mathrm{H}) \le P_h^{max} \quad (4b)$$

$$0 \le P_h^{ch}(H) \le I_h^{ch}(H) * \frac{1}{\eta_h^{ch}} * P_h^{max} \quad (4c)$$

$$0 \le P_h^{dis}(H) \le I_h^{dis}(H) * \eta_h^{dis} * P_h^{max} \quad (4d)$$

$$0 \le I_h^{ch}(H) + I_h^{dis}(H) \le 1 \quad (4e)$$

3.6. Pipeline Constraint:

Imported power from gas network and imported power form electricity network should be limited between its minimum and maximum constraints in (5a) and (5c) in sequence.

$$0 \le P_g(H) \le P_g^{max} \quad (5a)$$

$$P_g(H) = P_g^C(H) + P_g^B(H) \quad (5b)$$

$$0 \le P_e^T(H) \le P_e^{max} \quad (5c)$$

3.7. Converter Constraints:

Transformer S^T , boiler S^B and CHP S^Csizes are also restricted in (6a), (6b), (6c) for importing electricity and gas from the networks.

$$\eta_{ee}^T P_e^T(H) \le S^T \quad (6a)$$

$$\eta_{gh}^B P_g^B(H) \le S^B \quad (6b)$$

$$\eta_{gh}^B P_g^C(H) \le S^C \quad (6c)$$

4. Simulation Results

Simulation results are carried out on the proposed energy hub (Fig.2). Required data and parameters are provided in this part. Hourly electricity and gas price are illustrated in Fig.3. The electricity demand and heat required demands (i.e. hot and cold climates) are also illustrated in Fig. 4. Produced solar power and wind power in hot climate are shown in Fig.5. Also, produced solar and wind power in cold climate are displayed in Fig. 6. Other parameters are given in Table 1.

The hub parameters and required data as well as objective function and its constraints are taken into account in the simulation results.

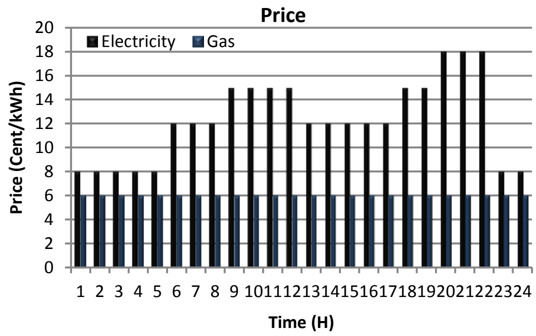

Fig.3. Hourly electricity and gas price

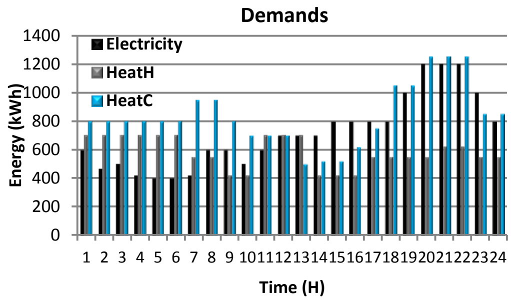

Fig.4.Electricity and heat demands (H: Hot climate,C:Cold climate)

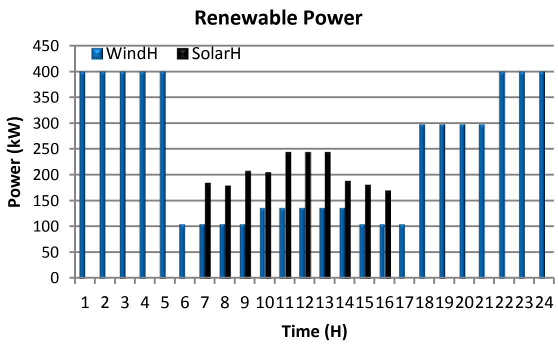

Fig.5. Solar and wind power in Hot climate

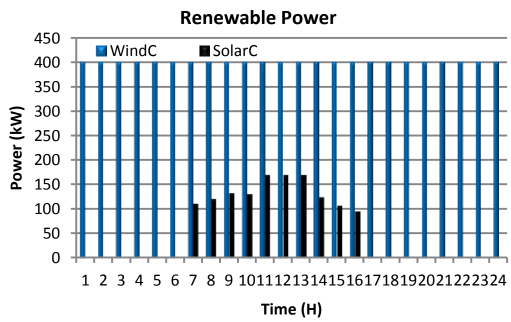

Fig.6. Solar and wind power in Cold climate

Table.1
Proposed Energy Hub Parameters

Parameters	Values	Parameters	Values
P_e^{max}	1350	P_n	180
P_g^{max}	1350	θ	0.96
P_e^{max}	200	P_r	400
P_h^{max}	200	a, b, c	0.032,0.0776 ,0.01745
S^T	1600	w_{ci}, w_{co}, w_r	4, 10, 22
S^B	1200	$\alpha_h^{loss}, \alpha_e^{loss}$	0.03
S^C	500	$\eta_e^{ch}, \eta_e^{dis}$	0.93, 0.8
$\eta_h^{ch}, \eta_h^{dis}$	0.9, 0.9	η_{ee}^T	0.98
η_{gh}^B	0.9	η_{gh}^C, η_{ge}^C	0.4, 0.35

Simulation results are revealed in the Table 2 as well as Fig. 7a to Fig. 10b as follow. Table 2 shows the hub operation costs in two different climates (hot and cold). Case 1 shows effect of the renewable (wind and solar) as well as energy storages (electrical and thermal) on the hub operation costs. Case 2 shows effect of wind and energy storages (electrical and thermal) on the hub operation costs. Case 3 shows effect of solar and energy storage technologies (electrical and thermal) on the hub operation costs. Case 4 shows effect of renewable (wind and solar) as well as storages (electrical and thermal) on the hub operation costs.

It can be observed from Table 2, the hub operation costs will sensibly decline via integration of the renewable and energy storage technologies in both cold and hot climate. Also, it can be employed form Table 2, wind power has a prominent role to remarkably decline the hub operation costs. Important role of renewable generations (wind and solar) on the hub operation costs are also investigated in the table. The reduction of %35 to %37 the hub operation costs is also seen in the Table as a result of integration of renewable (wind and solar) and energy storage technologies (electrical and thermal).

Table.2
Simulation Results with all the technologies (case 1), without Solar (Case 2), without Wind (Case 3) and without Wind and Solar (Case 4)

Case	**Hot Climate**	**Operation Costs**
1	EH	1798.28
2	EH-SOLAR	2077.07
3	EH-WIND	2492.46
4	EH-SOLAR,WIND	2771.25
Case	**Cold Climate**	**Operation Costs**
1	EH	1981.11
2	EH-SOLAR	2161.68
3	EH-WIND	3189.28
4	EH-SOLAR,WIND	3369.84

It can be observed from Fig. 7a and 7b, the hub purchases less electricity power form network while integrating renewable energy resources (wind and solar) in both hot and cold climates. The hub operation costs therefore decline via connection of the renewable to the hub. It can be employed form Fig. 7a, more electricity power is purchased in hot climate and less electricity power is sold to the grid in hot climate. Also, it can be seen from Fig. 7b, less electricity power is purchased from network in cold climate, and more electricity power is sold to the network.

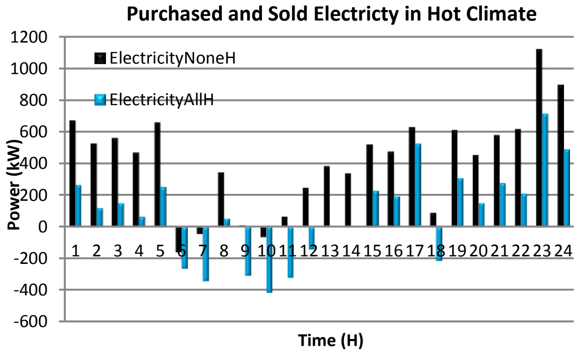

Fig.7a. Purchased and Sold Electricity in Hot Climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

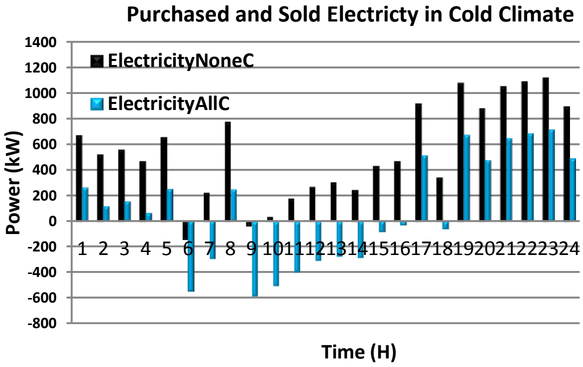

Fig.7b. Purchased and Sold Electricity in Cold Climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

It can be observed from Fig. 8a and Fig. 8b, gas power is purchased in hot climate less than cold climate. The reason is that heat demands in hot climate are less than heat demand in cold climate. Furthermore, the results show that purchasing gas power whit and without renewable is equal. It is revealed that adding the renewable and energy storage technologies don't effect on purchasing gas power from the network.

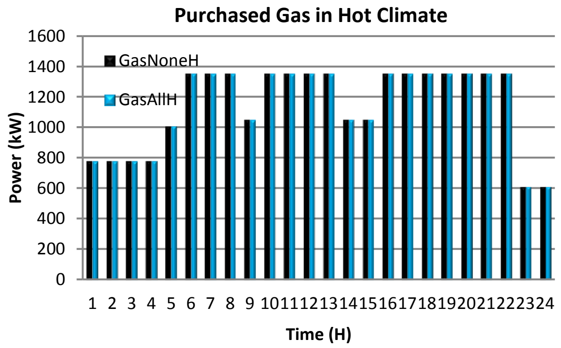

Fig.8a. Purchased gas power in Hot Climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

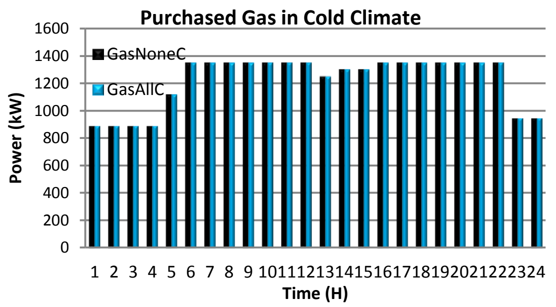

Fig.8b. Purchased gas power in cold climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

It can be seen from Fig. 9a and Fig. 9b, less gas power is imported to boiler in hot climate. It is demonstrated that boiler is used less in hot climate than cold climate. More heat demands in cold climate than hot climate are the reason. In addition, the Fig.s show that equal gas power is imported with and without integration of the renewable and energy storages.

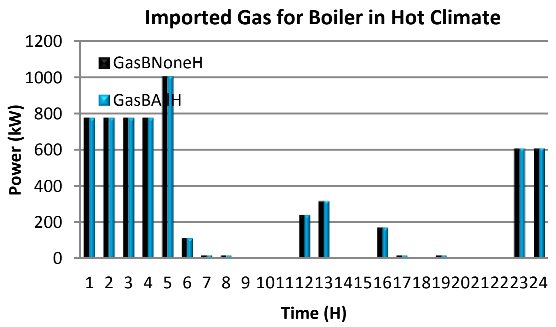

Fig.9a. Imported gas for Boiler in Hot climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

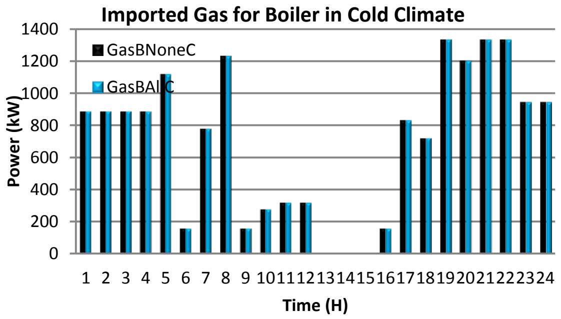

Fig.9b. Imported gas for Boiler in Cold climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

It can be observed from Fig.10a and Fig. 10b, CHP is used in hot climate more than cold climate. The reason is that the hub prefers to be supplied via CHP in hot climate. The Fig.s also show that importing gas power from network will be equal with and without the renewable and energy storage technologies.

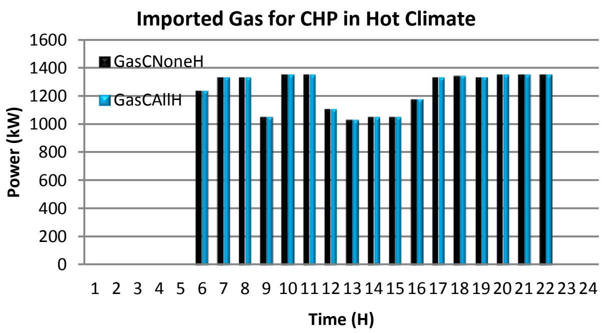

Fig.10a. Imported gas for CHP in Hot climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

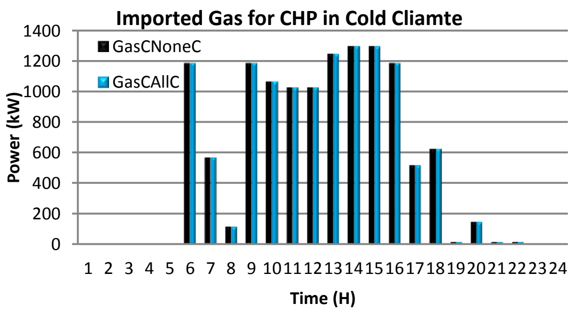

Fig.10b. Imported gas for CHP in Cold climate without renewable (wind and solar) and with all the technologies; black bar and blue bar in sequence

5. Conclusion

Greenhouse gas emission and growing energy needs cause prominent challenges for bulk power system. Efficient utilization of existing energy infrastructures as well as employment of renewable energy resources can be considered as a sufficient solution to cope with the challenges. Coupled electricity and gas infrastructures as well as integration of distributed energy resources (i.e. wind, solar) and energy storages (electrical and thermal storages) to bulk power system are investigated in this paper. Energy hub approach states combination of the gas and electricity networks. We examine effect of renewable energy resources (wind and solar) as well as energy storage technologies (electrical and thermal storages) on a proposed energy hub in two different climates. Additionally, the hub operation costs are also considered with and without renewable and energy storages in two different climates (i.e. hot and cold climates). The results show that integration of renewable energy resources, especially wind along with energy storages remarkably decline hub operation costs in both hot and cold climates. The reduction of %35 to % 37 will be as the result of the integration of the technologies to the hub. The results show that energy hub purchases less electricity from network since it connects to wind turbine, solar cells and energy storage technologies. The results also show that wind power in cold climate is more than hot climate, and solar power in cold climate is less than hot climate. The combination of the renewable energy resources enables them to produce a reliable power. In addition, results demonstrate that more electricity is purchased in hot climate, and less electricity is sold to the network in hot climate. Results also endorse that less electricity is purchased in cold climate, and more electricity is sold to the network in cold climate. The results show that less gas power is purchased in hot climate than cold climate due to more heat demands in cold climate. Results also approve that more gas power is imported for CHP in hot climate than cold climate, because wind power in hot climate is produced less than cold climate, and it is more beneficial that the hub uses CHP for producing electrical and heat demands simultaneously. The results also confirm that boiler is used in cold climate more than hot climate, because wind power is produced in cold climate more, and it is more beneficial that gas power is used for boiler to produce hub heat requirements.

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