Effect of Power-to-Gas Technology in Energy Hub Optimal Operation and Gas Network Congestion Reduction

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Abstract: Natural gas will play a key role in the transition to a lower-carbon economy, constituting a natural alternative to coal and acting as a backup resource to the intermittent nature of renewable generation. These energy carriers can be structurally linked together by Power-to-X technologies because of their interaction to increase energy efficiency. For this purpose, this paper proposes an innovative model to optimally manage the electricity and natural gas grids in a cost-efficient manner. In this model, an energy hub has water, electricity, and gas oil as inputs, supplying electric and thermal loads. Besides, the energy hub uses the Power-to-gas (P2G) technology to produce natural gas, selling it to a gas network to reduce the congestion in gas pipelines and the energy hub owner's costs. A demand response program has been also applied in this model to shift the loads from on-peak times to off-peak ones. Various technologies such as energy storage and distributed generation have been used in the modeling to reach the goals targeted by operators. Furthermore, a scenario generation method has been applied to model the uncertainty of wind turbine output. The proposed problem has been finally formulated as mixed-integer linear programming that has been solved under GAMS software by using CPLEX solver to reach the global optimality. The results obtained from simulations demonstrate that the proposed model can significantly reduce the operation cost, while properly alleviating gas network congestion.

Keywords: Energy hub, gas network, congestion management, demand response, Power-to-gas.

Nomenclature

Indices

j,k	Index of horizontal divisions for linearization
n,m	Index of gas nodes
$P2G$	Index of power-to-gas
t	Index of time (Hour)
SOC	Index of state of charge
w	Index of water

Parameters

a_{dg}, b_{dg}, c_{dg}	Fuel cost coefficients of the diesel generator
A	Constant of the gas flow equation

C_{nm}	Weymouth Constant
$f_{D,n}^{t}$	Gas load in node n at hour t (kW)
$f_{S,n}^{min}, f_{S,n}^{max}$	Minimum, Maximum allowable generation of gas in node n (kW)
Pr_b	Gas pressure at the base condition (kPa)
T_b	Gas temperature at the base condition (K)
D_{nm}	Inside diameter of the pipeline from the node n to m (mm)
E_{nm}	Efficiency of the pipeline from the node n to m
l_{nm}	Length of the pipeline from the node n to m (m)
$T_{a,nm}$	Average absolute temperature of the pipeline from the node n to m (K)
Z_a	Average compressibility factor
γ_{nm}	Friction factor of the pipeline from the node
g	Natural gas specific gravity
k	Shape parameter
$P_{dg}^{min}, P_{dg}^{max}$	Lower, Upper bound of the diesel generator generation (kW)
P_n^t	Nominal power of the wind turbine (kW)
Pr_n^{min}, Pr_n^{max}	Minimum, Maximum allowable pressure of gas in node n (kPa)
v_n	Nominal speed of wind (m/s)
α	Molar ratio of water to hydrogen
$\alpha_{shu}, \alpha_{shd}$	Coefficient of load shifting in DR program
β	Power required to produce hydrogen (kW)
P_{load}^{t}	Electric load (kW)
π_{P2G}	Price of gas generated by P2G ($/kWh)
π_w	Price of water ($/kWh)
π_e^t	Price of electricity ($/kWh)
π_{gs}^t	Price of gasoil ($/kWh)
η_{ch}	Battery charging efficiency
η_{dch}	Battery discharging efficiency
η_{P2G}	Conversion coefficient of hydrogen to natural gas
λ	Scale parameter
v_{in}/v_{out}	The minimum/maximum rotation speed of the wind turbine(m/s)

Variables

E_{SOC}^{t}	Amount of energy stored in the energy storages (kWh)
$f_{S,n}^{t}$	Gas generated in node n at hour t (kW)
e_j^t	Segments of electrical generation of the diesel generator (kW)
f_{nm}^{t}	Amount of gas flow in pipelines (kW)
G_{P2G}^{t}	Gas generated by P2G (kW)
O_{dg}^{t}	Gasoil used by the diesel generator (kW)
$H_{ch,hs}^{t}$	Charging hydrogen of the hydrogen storage (kW)
$H_{dch,hs}^{t}$	Discharging hydrogen of the hydrogen storage (kW)
H_w^t	Hydrogen generated by electrolyzer (kW)
H_{P2G}^{t}	Hydrogen used by P2G (kW)
H_{fc}^{t}	Hydrogen used by the fuel cell (kW)
l_{shu}^t, l_{shd}^t	Binary value to prevent simultaneous increase and decrease of load profiles in DR program
l_{ch}^t, l_{dch}^t	Binary value to prevent simultaneous charge and discharge of energy storage
P_{P2G}^{t}	Electricity used in the electrolyzer

Pr_n^t	Pressure in the gas nodes (kPa)
$P_{ch,Bat}^t$	Charging power of the battery (kW)
$P_{dch,Bat}^t$	Discharging power of the battery (kW)
P_{eh}^t	Power used by the electric heater (kW)
P_{dg}^t	Power generated by the diesel generator (kW)
P_{wt}^t	Power generated by the wind turbine (kW)
W_{net}^t	Amount of water imported to the energy hub (kW)
O_{net}^t	Amount of gasoil imported to the energy hub (kW)
P_{grid}^t	Amount of electricity imported to the energy hub (kW)
P_{shd}^t, P_{shu}^t	Power shifted by DR program (kW)
$T_{ch,ts}^t$	Charging heat of the thermal storage (kW)
$T_{dch,ts}^t$	Discharging heat of the thermal storage (kW)
T_{fc}^t	Heat generated by the fuel cell (kW)
T_{shd}^t, T_{shu}^t	Heat shifted by DR program (kW)
T_{fur}^t	Heat generated by the furnace (kW)
T_{eh}^t	Heat generated by the electric heater (kW)
v^t	Rotating speed of the wind turbine (m/s)

1. Introduction

Natural gas and electricity are important energy carriers that meet almost all human energy needs. On the other hand, given the profound link between natural gas and electricity, their simultaneous operation can have many advantages for producers and consumers. For example, the use of electricity in the natural gas system compressors to increase pressure and the use of natural gas in gas-fired power plants are examples of this link. Various other technologies have deepened on the link between the natural gas system and electricity, which has improved both systems economically and technically. Combined heat and power (CHP) systems [1, 2], as well as power-to-gas (P2G) technology [3, 4], are examples of these technologies that have attracted much attention.

Integrated operation of energy carriers both prevents the overuse of them and has many advantages for consumers, and they can decrease their operating costs [5]. The P2G technology is one of the technologies that has emerged in the field of integrated energy system operation. This technology has been considered because it uses water that is an available energy carrier. Also, carbon dioxide, which is a principal factor in air pollution, is applied in P2G technology [6]. As a result, utilizing P2G technology has a lot of profits for both consumers and producers, such as reducing billing costs and air pollution.

There has been valuable and significant research into the field of integrated energy system operation, some of which will be discussed here. Ref [7] presents a coordinated control approach to improve the dynamic response performance under electrical energy disturbances for integrated energy systems in the presence of natural gas, electricity, and heat. Ref [8] presents a robust optimization model for multiple energy hubs, taking into account environmental and economic constraints as well as demand response program in which electricity prices are uncertain. In Ref [9], an energy hub has been divided into three sub-hub, electric hub, thermal hub, and cooling hub. In this modeling, the demand response program for electric and cooling loads is used. In Ref [10], a new optimization model is presented for the design of integrated energy systems with thermal, cooling, and electric subsystems to simultaneously achieve environmental, technical, and economic objectives. Ref [11] presents a game theory-based planning model for integrated energy systems in which the P2G system is considered as an independent customer in the integrated energy system in the deregulated market environment. Ref [12] presents a two-stage optimization method for the economical operation of regional integrated energy systems.

In Ref [13], a demand response strategy for distribution network management is proposed in which the distribution system utilizes the energy hub flexibility in the form of demand response using an optimized two-level recursive structure to improve the operation. The authors in [14] have proposed a multi-objective mathematical model for energy hub planning with precautionary protection policies. In Ref [15], a two-level mixed-integer linear programming model is proposed in the energy hub for multi-region multiple energy system planning, in which the multiple energy systems are considered as a directional graph with multiple layers. Ref [16] presents a new method for energy optimization to supply demand and minimize energy consumption, environmental costs, and payment costs in multiple energy systems. A method for solving the optimal power flow problem is proposed in [17] in adjacent energy hubs to reduce energy costs by using the flexibility of energy sources in smart cities and considering random constraints. Ref [18] presents a novel method for decentralized optimized energy flow in large-scale integrated energy systems in the carbon trading market to utilize the economic and environmental benefits of the system.

In Ref [19], a new method is presented for assessing reliability in integrated energy systems. Ref [20] presents a real-time scheduling model of energy hubs in the dynamic pricing market. Ref [21] investigated the effect of hydrogen created from wind power on the quality of natural gas, and two key indicators are used to measure the quality of natural gas called Wobbe index and Combustion potential to study its effect. In Ref [22], a framework based on the hybrid scenario-based/interval /information gap decision theory is proposed to examine the optimal operation of smart energy hubs with the economic and technical constraints of the distribution network and uncertainties. Ref [23] presents a two-level game between retailers and consumers with stable loads in the form of a multicarrier energy system. Ref [24] demonstrates a supervisory control scheme to reduce voltage regulation problems in ring DC microgrid and energy hub. Ref [25] presents the standardized matrix method based on the energy hub concept using graph theory and multiple energy system topologies expressive matrices to generate the conjugate matrix automatically. Ref [26] proposes a linear and automated modeling approach to formulate energy conversion in energy hubs using the flexibility of the energy hub.

Although there are valuable works that have considered the energy management of hub systems, but there are still many problems that should be addressed carefully. For example:

- The main gap in the previous works is that they have examined the management of energy hubs separately and have not considered the limitations caused by the gas or heat networks on the optimal management of energy hubs. In other words, they mostly had an *equipment-oriented* view rather than a *system-oriented* view of the energy hub management issue.
- Besides, the previous works have mostly used *large-scale* stochastic programming (such as Monte Carlo simulation, etc.) that imposes significant computational challenges into the short-term operation problem. Moreover, the previous works have mainly minimized the expected costs regardless of the worst possible scenarios which will put the system at risk when these scenarios occur.

- On the other side, the effect of power-to-gas (P2G) cutting-edge technologies as well as demand flexibilities have not been extensively investigated on the *revenue-adequacy* and *cost-recovery* of energy hubs. This is also should be done considering technical constraints and congestion of energy networks, which this issue has not been properly addressed in the literature.

To solve these shortcomings remained from the previous works, we have done the following contributions:

- The short-term scheduling of multi-carriers energy hubs is done considering the technical constraints of electricity network and congestion of gas grid from system operator point of view instead of energy hub owners. In doing so, we developed an effective model for the gas network based on *Weymouth* model to assess the impact of energy hubs and P2G technologies on the congestion alleviation and cost reduction. It should be mentioned that the Taylor series is used to linearize the model to make it computationally tractable.
- An improved scenario reduction algorithm based on SCENRED has been applied in this work to make the proposed model computationally efficient. The SCENRED contains three algorithms to reduce scenarios which in this paper fast backward algorithm is used to specify a subset of the initial scenario set and allocates new probabilities to the preserved scenarios that is the closest to the initial distribution in terms of a natural or canonical probability metric. Actually, it receives the original scenarios from the designer associated with parameters controlling the reduction, and refunds a reduced scenario set for use in subsequent solves or data manipulation. Our approach to scenario reduction controls the goodness-of-fit of the approximation by a certain distance of probability distributions and domesticates the cost fluctuation as well as avoiding distasteful cost distribution. From the mathematical perspective, the proposed model is convex and, therefore, can be efficiently optimized using convex or linear programming like CPLEX.

- The proposed plan connects the energy hubs to the natural gas network not only to reduce the energy hub costs, but also to alleviate the gas pipeline congestion by utilizing P2G technology to produce natural gas using electricity. On the other hand, the proposed algorithm for energy hub management uses a linearized price-based demand response program that increases system efficiency and reduce operating costs by stimulating and encouraging electrical and thermal responsive loads through financial incentives to manage their own consumptions when the electricity price at pool is high or the system at risk (i.e., due to the occurring congestion on some network lines).

The remainder of this paper is organized as follows. The modeling and formulation are presented in sections 2 and 3, respectively. The simulation results for the proposed model are provided in section 4. Discussion about the modeling and results has presented in section 5. Finally, the conclusion appears in section 6.

2. Modeling the Components of the System

Nowadays, energy management is a serious subject in human societies because of the depletion of fossil fuel resources as the main energy resource. Therefore, the optimal operation of the resources can help to save them. The energy hub is a novel structure in energy management that receives various energy carriers at its inputs and then processes them, and finally supplies demands. Different devices are used in the energy hub such as storage units, renewable resources, and converters to feed demands. The energy hub linking various energy carriers helps consumers to manage their consumption, and as a result, reduce their operating costs, air pollution, etc. Also, this subject causes to prevent wasting energy resources.

In this paper, a novel model of an energy hub has been shown in which the energy hub supply electric and thermal loads by using three energy carriers including electricity, water, and gas oil. The structure of the energy hub has been composed of various equipment such as storage, a wind turbine, a diesel generator, etc. Also, this energy hub uses P2G technology to produce natural gas from water and electricity, and sell it to a gas network. The gas injected from the energy hub reduces the congestion in the gas network pipelines. Also, the energy hub owner applies a linearized price-based DR program to shift the loads from on-peak hours to off-peak hours. This work causes the profile of loads to be flat.

The proposed model has been displayed in Fig. 1. In this section, the mathematics formulations of the components will be expressed.

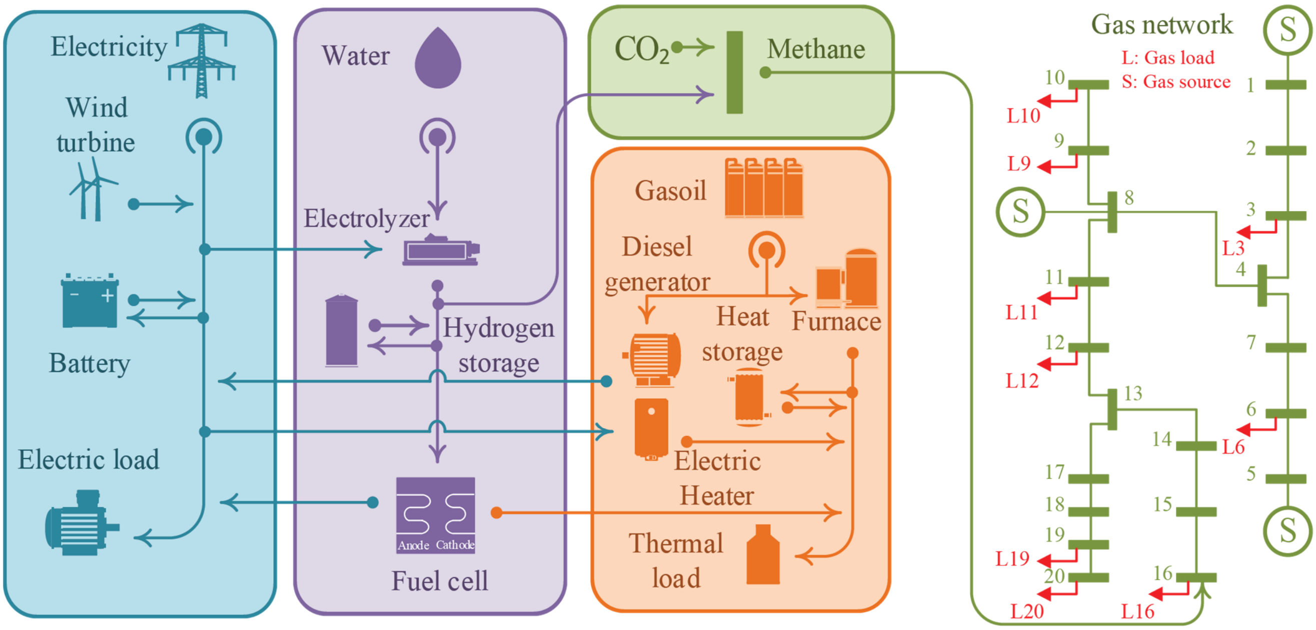

Fig. 1. Overview of the proposed model based on multi-energy carriers systems.

A. Energy Storage

The energy storage units are a crucial component of microgrids [27, 28] that have been taken into consideration for their economic benefits. The use of energy storage units greatly reduces the cost of purchasing energy from the network, as at a time when the energy price is low these units operate as a consumer and are charged. Also, at a time when the energy price is high, they operate as a producer and are discharged and meet demand. The mathematical equations of the energy storage are given below [29].

Equation (1) indicates the state of charge (SOC) of the storage. Equation (2) shows the minimum and maximum amount that the energy storage can store. Equation (3) implies that the amount of energy stored in the battery at hour 24 is equal to its initial value. Equations (4) and (5) indicate the maximum charge and discharge power of the energy storage per hour, respectively, and Equation (6) prevents simultaneous charging and discharging of the energy storage.

$$E_{SOC}^{t+1} = E_{SOC}^{t} + (\eta_{ch} P_{ch}^{t} - \frac{P_{dch}^{t}}{\eta_{dch}}).\Delta t \qquad (1)$$

$$E_{SOC}^{\min} \le E_{SOC}^{t} \le E_{SOC}^{\max} \quad (2)$$

$$E_{SOC}^{24} = E_{SOC}^{0} \quad (3)$$

$$0 \le P_{ch}^{t} \le P_{ch}^{\max} I_{ch}^{t} \quad (4)$$

$$0 \le P_{dch}^{t} \le P_{dch}^{\max} I_{dch}^{t} \quad (5)$$

$$I_{ch}^{t} + I_{dch}^{t} \le 1 \quad (6)$$

It should be noted that in this paper three energy storages have been used, including battery [30], heat storage [31], and hydrogen storage [32], and to prevent the repetition of equations, the energy storage equations have been written once.

B. Diesel Generator

The diesel generator [33] is another device used in this modeling to generate electricity using natural gas. The production capacity of the diesel generator must be sufficient to provide the maximum load. The input-output characteristics of the diesel generator production is shown in equation (7) and the power generation interval by it in equation (8).

$$O_{dg}^{t} = a_{dg}.(P_{dg}^{t})^2 + b_{dg}.P_{dg}^{t} + c_{dg} \quad (7)$$

$$P_{dg}^{\min} \le P_{dg}^{t} \le P_{dg}^{\max} \quad (8)$$

As can be seen, the diesel generator cost function is quadratic. While the modeling had done in this paper, is linear modeling. Therefore, the above cost function cannot be used in the simulation and must be linearized. A method called the Cartesian method has been used for linearization. In this method, the shape of the quadratic function, which is parabolic, is approximated by small lines. The mathematical equations of the linear model to the diesel generator cost function are as follows [1]. Equation (9) shows the linearized cost function of the diesel generator. In equation (10), the power produced per hour is also shown. The power interval obtained is shown in each of the slices approximated by the equation (11).

Also, the amount of production cost at the minimum diesel generator power is obtained from equation (12). Finally, equations (13) and (14) show the maximum and minimum diesel generator production power, respectively.

$$O_{dg}^{t} = A_0 + \sum_{j=1}^{J} m_j e_j^t \tag{9}$$

$$P_{dg}^{t} = Pl_0 + \sum_{j=1}^{J} e_j^t \tag{10}$$

$$0 \le e_j^t \le Pl_j - Pl_{j-1} \tag{11}$$

$$A_0 = a_{dg}.(P_0)^2 + b_{dg}.P_0 + c_{dg} \tag{12}$$

$$Pl_J = P_{dg}^{\max} \tag{13}$$

$$Pl_0 = P_{dg}^{\min} \tag{14}$$

It should be noted that the furnace [34] is formulated like the diesel generator, and its equations are the same.

C. *Wind Turbine uncertainty modelling*

One of the most important renewable energy sources is wind turbines that generate electricity using the wind [35]. In this paper, a wind turbine is used as one of the cleanest and most efficient sources of electricity generation whose mathematical model is as follows [15].

$$P_{WT}^{t} = \begin{cases} 0 & v^t < v_{in}, v^t > v_{out} \\ \dfrac{v^t - v_{in}}{v_n - v_{in}} P_n & v_{in} \le v^t < v_n \\ P_n & v_n \le v^t < v_{out} \end{cases} \tag{15}$$

The wind turbine uses wind speed to generate electricity. But the wind speed is an uncertain parameter, which cannot be accurately stated.

Therefore, in this paper an improved scenario generation algorithm based on SCENRED has been applied to cope with the wind power uncertainty [36]. The SCENRED contains three algorithms to reduce scenarios which in this paper fast backward algorithm is used to specify a subset of the initial scenario set and allocates new probabilities to the preserved scenarios that is the closest to the initial distribution in terms of a natural or canonical probability metric. Actually, it receives the original scenarios from the designer associated with parameters controlling the reduction, and refunds a reduced scenario set for use in subsequent solves or data manipulation. Our approach to scenario reduction controls the goodness-of-fit of the approximation by a certain distance of probability distributions and domesticates the cost fluctuation as well as avoiding distasteful cost distribution.

The probability density function (PDF) used for wind speed in this paper is the Weibull PDF [36] whose mathematical equation is as follows.

$$f(x,k,\lambda)=\frac{k}{\lambda}(\frac{x}{\lambda})^{k-1}e^{-(x/\lambda)^{k}} \tag{16}$$

In this paper, the shape parameter (k) and scale parameter (λ) equal 5 and 2, respectively.

D. Power to Gas (P2G)

The P2G technology [37] is one of the new technologies that has been considered for the connection between the gas and electricity networks. In this technology, the water molecules are decomposed by electrolysis into hydrogen and oxygen ($2H_2O \rightarrow 2H_2+O_2$), and then the hydrogen molecules from the decomposition of water are stored. In general, the stored hydrogen molecules combine with carbon dioxide molecules that can be shown as ($4H_2+CO_2 \rightarrow CH_4+2H_2O$), and from this reaction, methane, or natural gas and water, is obtained. The methane obtained can be used in various ways. Fig. 2 shows the steps of P2G technology, and also the mathematical equations of it are as follows.

$$W_{net}^{t}=\alpha H_{w}^{t} \tag{17}$$

$$P_{P2G}^{t}=\beta H_{w}^{t} \tag{18}$$

Equation (17) shows that some of the water has become usable hydrogen, and part of the hydrogen produced has also been wasted. Equation (18) also gives the amount of electricity required to break down water molecules.

E. Demand Response Program

To reduce the burden on-peak hours of consumption, consumers need to shift some of their unnecessary consumption from on-peak times to off-peak times. This load transfer may be through incentives or load control on the demand side [38].

Shifting loads from on-peak times to off-peak times not only reduce operating costs, but also improve the reliability of the system when the system is at the risk. This method is also used in this paper for load transfer/curtailment to reduce both the operating costs and congestion of the lines. The mathematical equations for the proposed price-based DR program are as follows [39].

$$\sum_{t=1}^{24} P_{shd}^{t} = \sum_{t=1}^{24} P_{shu}^{t} \tag{19}$$

$$0 \le P_{shd}^{t} \le \alpha_{shd} P_{load}^{t} I_{shd}^{t} \tag{20}$$

$$0 \le P_{shu}^{t} \le \alpha_{shu} P_{load}^{t} I_{shu}^{t} \tag{21}$$

$$I_{shd}^{t} + I_{shu}^{t} \le 1 \tag{22}$$

Equation (19) shows that the consumption power transmitted from on-peak hours to off-peak hours must be equal. Equations (20) and (21) represent the maximum load transfer per hour. Equation (22) also implies that the reduction in load during peak hours and the increase in load during off-peak hours should not occur simultaneously.

F. Natural Gas Network

The natural gas network has operational constraints on pipelines and natural gas distribution, whose mathematical relationships are as follows [40].

Equation (23) shows the amount of flowing gas in pipeline between *n* and *m*. Equation (24) expresses the Weymouth constant of the pipeline between *n* and *m*. Finally, Equation (25) denotes the gas equilibrium in each node of the gas network. Also, Equations (26) and (27) show the constraints of gas generation units and the node pressure of the gas network.

$$f_{nm}^{t} = C_{nm} \sqrt{\left(Pr_{n}^{t}\right)^{2} - \left(Pr_{m}^{t}\right)^{2}} \qquad (23)$$

$$C_{nm} = A.\left(\frac{T_b}{Pr_b}\right).D_{nm}^{2.5}.E_{nm}.\left(\frac{1}{l_{nm}.T_{a\,nm}.Z_a.\gamma_{nm}.g}\right)^{0.5} \qquad (24)$$

$$f_{S,n}^{t} - f_{D,n}^{t} = \sum_{m=1}^{N} f_{nm}^{t} \qquad (25)$$

$$f_{S,n}^{min} < f_{S,n}^{t} < f_{S,n}^{max} \qquad (26)$$

$$Pr_{n}^{min} < Pr_{n}^{t} < Pr_{n}^{max} \qquad (27)$$

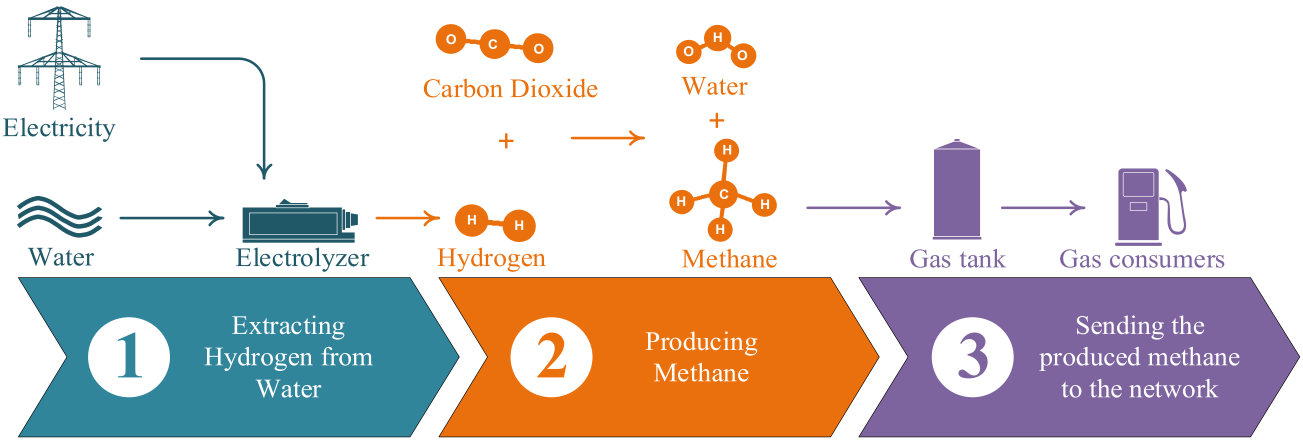

Fig. 2. Steps of P2G technology to convert the energy from one state to another.

Since the modeling performed in this paper is a mixed-integer linear programming model, all the mathematical equations used in this paper must also be linear. However, equation (28), which relates to the amount of gas pressure in each node, is a nonlinear equation that must be linearized.

In this paper, the Taylor series and Big-M method [41] is used to linearize the non-convex equations. The linearized model of the equation (23) is as follows [42].

$$f_{nm}^{t} \approx C_{nm}\left(\frac{Pr_{n,0}}{\sqrt{Pr_{n,0}^{2}-Pr_{m,0}^{2}}}\left(Pr_{n}^{t}-Pr_{n,0}\right)-\frac{Pr_{m,0}}{\sqrt{Pr_{n,0}^{2}-Pr_{m,0}^{2}}}\left(Pr_{m}^{t}-Pr_{m,0}\right)\right) \tag{28}$$

3. Problem Formulation

A. Equilibrium of Power, Heat, and Hydrogen

The most important constraint in this modeling is power and heat balance constraints. This constraint means that the power and heat produced and purchased must be equal to the power and heat consumed and sold. The mathematical equations are provided as follows.

$$P_{grid}^{t}+P_{wt}^{t}+P_{dch,Bat}^{t}+P_{dg}^{t}+P_{shd}^{t}+P_{fc}^{t}=P_{load}^{t}+P_{shu}^{t}+P_{dch,Bat}^{t}+P_{eh}^{t}+P_{P2G}^{t} \tag{29}$$

$$T_{fur}^{t}+T_{fc}^{t}+T_{dch,ts}^{t}+T_{eh}^{t}+T_{shd}^{t}=T_{load}^{t}+T_{shu}^{t}+T_{ch,ts}^{t} \tag{30}$$

$$H_{w}^{t}+H_{dch,hs}^{t}=H_{ch,hs}^{t}+H_{P2G}^{t}+H_{fc}^{t} \tag{31}$$

$$G_{P2G}^{t}=\eta_{P2G}H_{P2G}^{t} \tag{32}$$

B. Objective Function

The purpose of this modeling is to reduce operating costs, including the cost of purchasing electricity from the grid, purchasing water and gas oil. Also, the amount of congestion in the gas grid pipelines is added to the objective function as a penalty. On the other hand, the owner of the energy hub earns income by selling natural gas produced by P2G technology, which contributes significantly to lower operating costs. The mathematical equation of the objective function is as follows.

$$Cost=\sum_{t=1}^{24}\begin{pmatrix}\pi_{e}^{t}P_{grid}^{t}+\pi_{gs}^{t}O_{net}^{t}+\pi_{w}W_{net}^{t}+\\ \pi_{cong}\sum f_{nm}^{t}-\pi_{P2G}G_{P2G}^{t}\end{pmatrix} \tag{33}$$

$$O_{net}^{t} = O_{fur}^{t} + O_{dg}^{t} \tag{34}$$

Subject to: (1)-(32)

Fig. 3 shows the flowchart of the proposed model. According to this figure, at first, modeling information including wind turbine scenarios, distributed generation resource information, energy carrier prices, and natural gas network information is received by the model. In the next step, non-linear equations are linearized by different linearization methods.

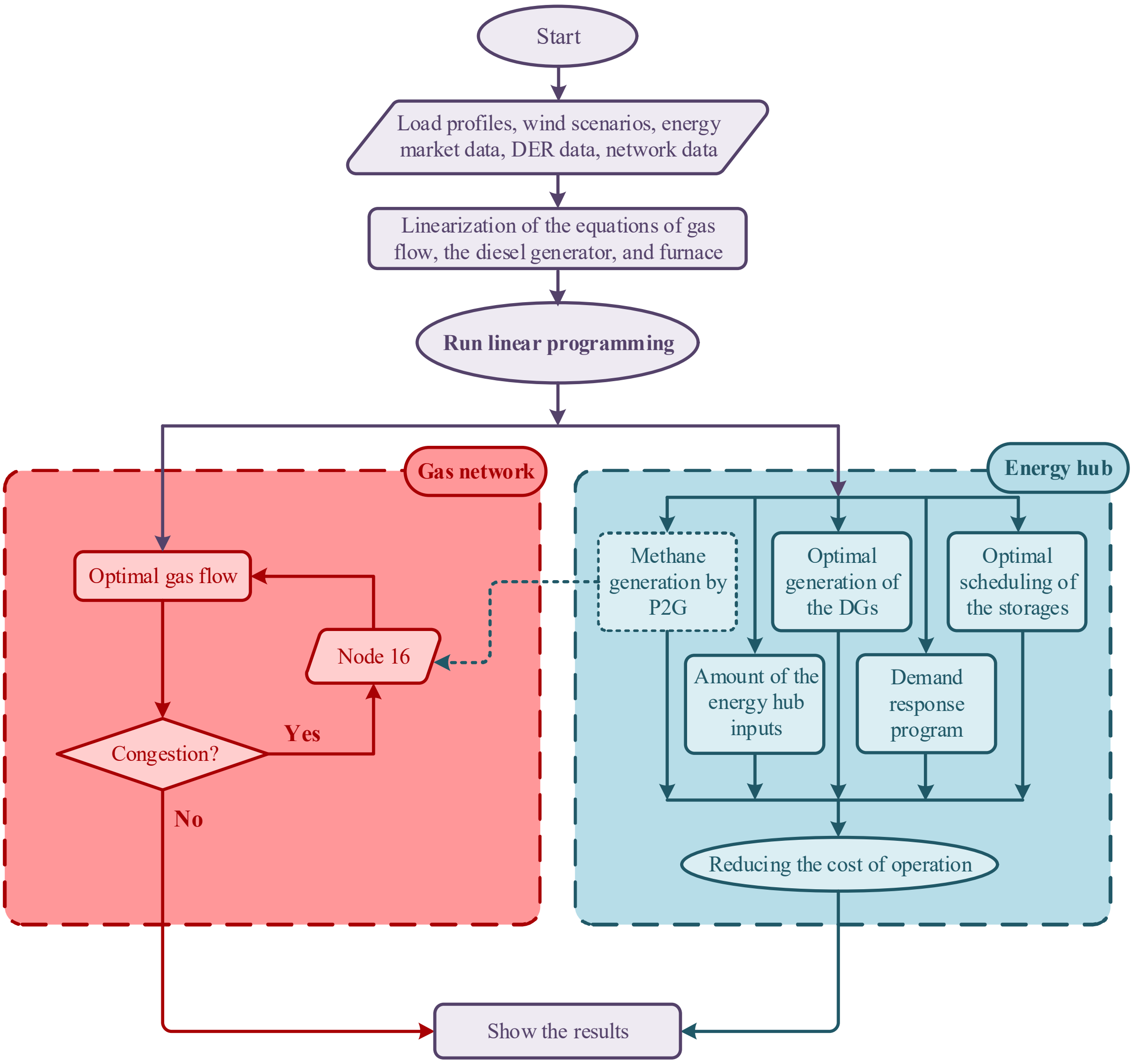

Fig. 3. Outline of the proposed scheme for management of multi-energy carriers systems.

Then linear programming is performed to optimize. At this stage, optimal planning for energy hub is done to determine the optimal amount for energy carriers, charging and discharging of storage units, the amount of the generation of the distributed generation resources, and also the amount of load transferred from peak times to off-peak times to reduce operating costs. Also, the optimal gas flow is applied to the natural gas network to determine the amount of gas that is flowed in the pipelines. Then according to the amount of gas in the pipelines, it is determined how much natural gas must produce using P2G to reduce the congestion in the pipelines.

4. Numerical Results

A. Problem Data

To evaluate the efficiency of the proposed model, an energy hub consisting of various equipment was used. In this modeling, the energy hub owner is trying to reduce costs by managing his resources and by increasing the sales of natural gas to the 20-node gas network.

In addition, the operator of the gas network efforts to reduce the congestion in the gas network pipelines by purchasing natural gas from the energy hub. This problem is modeled as a mixed-integer linear program and solved in GAMS software by the CPLEX solver. The prices of energy carriers including electricity, water, gas oil, and natural gas are given in Fig. 4. In other side, Fig. 5 illustrates the electric and thermal load profiles. It should be noted that the extra information about the modeling has been presented in Ref [43].

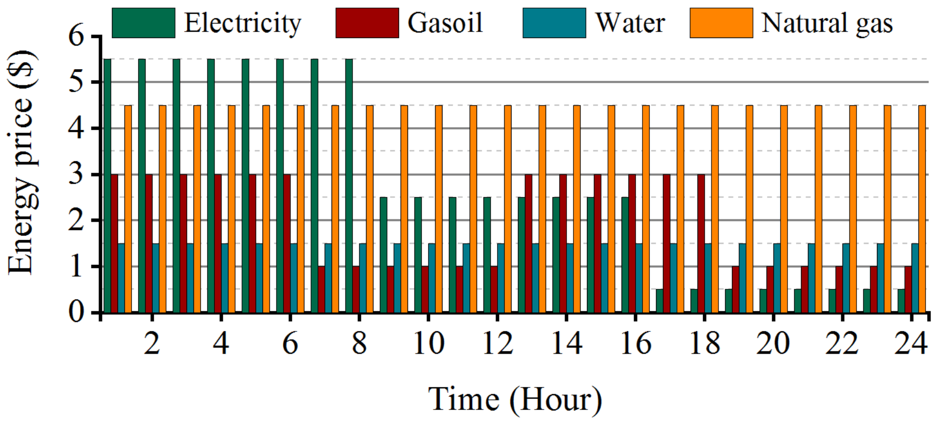

Fig. 4. Price of energy carriers.

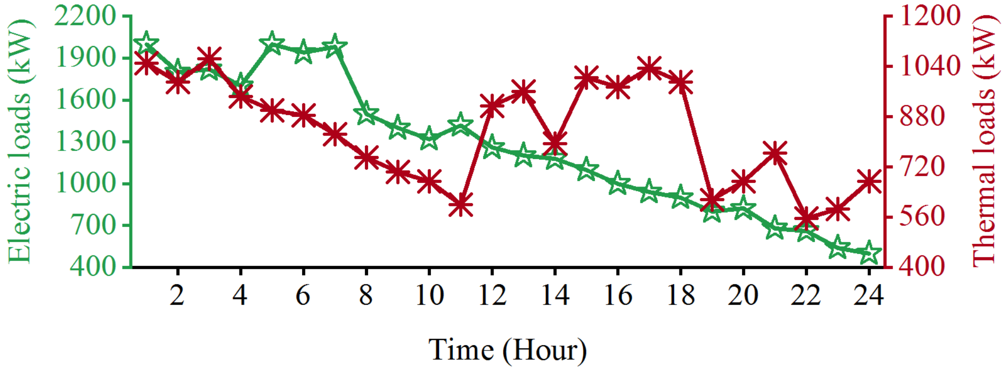

Fig. 5. Electric and thermal load profiles.

B. Numerical Results

As mentioned, this problem is a mixed-integer linear programming problem that is modeled for optimal operation of energy hubs and simultaneously reducing congestion in natural gas pipelines. The results show that the proposed model has a significant impact on meeting the modeling goals. Fig. 6 shows the amount of each energy carrier purchased by the energy hub at different hours.

As can be seen, when the price of electricity is low, the energy hub uses electricity to feed its loads. It also uses Gasoil to feed loads when its price is low. For example, as shown in Fig. 6, from hours 1 to 8 when the electricity price is high, the energy hub reduces the energy purchase of electricity, and the rest of the hours when the electricity price is low, it increases the energy purchase of electricity. Also, from hours 1 to 6 when the price of gas is high, the energy hub reduces the purchase of gas, and from hours 7 to 12, when the price of gasoil is low, the energy hub increases the purchase of gas. In the case of water as well, its consumption depends on the amount of electricity consumed. Therefore, when the price of electricity is low, purchased water is low, and when electricity is inexpensive, purchased water is high.

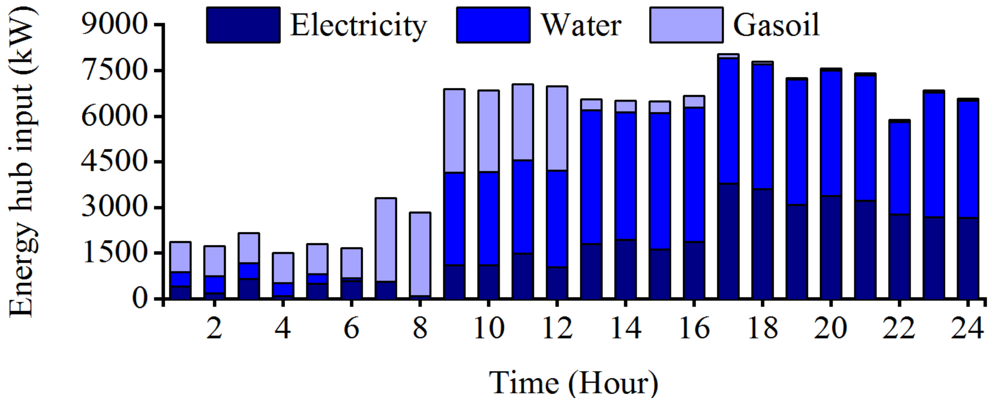

Fig. 6. Amount of energy carriers imported to the energy hub.

Fig. 7 shows the output power of the distributed generation (DG) resources in each hour. As can be seen, DGs regulated their generation with the price of energy carriers. In other words, when the price of energy carriers is high, DG units reduce their output, and also when the price of the energy carriers is low, they increase their production which the surplus power is stored within the storages. According to Fig. 7, from hours 1 to 16 when the price of electricity is high, electric heater reduces its output power, and from hours 17 to 24 when the price of electricity is low the electric heater enhances its generation to feed the thermal loads in this time interval.

The fuel cell supplies the thermal and electric load from hours 1 to 6 when the prices of electricity and gas oil are high by using the hydrogen stored by the hydrogen storage. In the other hours, the fuel cell does not generate any heat and electricity because the generated hydrogen is used to charge the hydrogen storage and produce natural gas to sell to the natural gas network. Also, from 1 to 6 and from 13 to 18, when the price of gas oil is high, the furnace decreases its heat generation, and also from 7 to 12 and from 19 to 24, when the price of gas oil is low, the furnace increases its heat generation. In the case of the diesel generator should be said that because from hours 1 to 12 the price of gas oil is lower than the price of electricity, the diesel generator increases electricity generation to reduce the amount of electricity purchasing. In the other hours, when the gas oil price is higher than electricity, the diesel generator reduces its production.

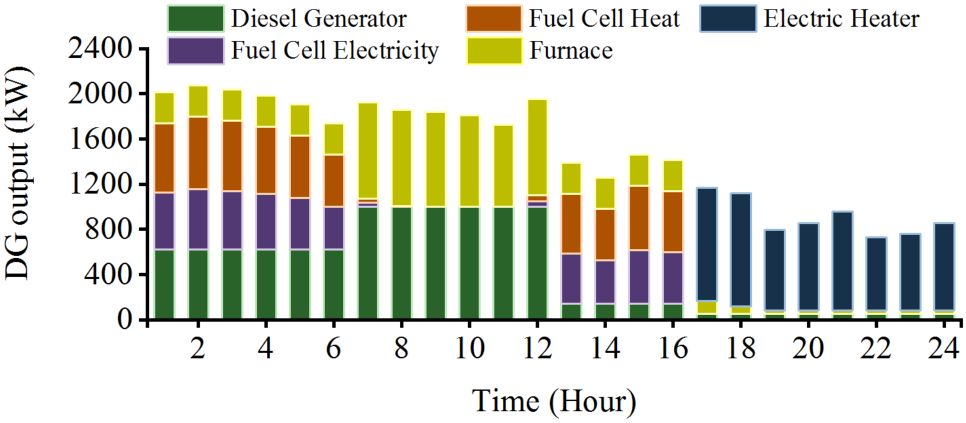

Fig. 7. Output power of distributed generations.

Fig. 8 shows the process of charging and discharging of the storage units. As can be seen, when the price of the energy carriers is low, the energy storage units are charged, and when the price of the energy carriers is high, they are discharged to reduce the operating costs. Fig. 8 shows the stored energy of the battery. As can be seen, from hours 1 to 8, when the price of the electricity is high, the battery is discharged to feed the loads, and from hours 17 to 24, when the price of the electricity is low, the battery is charged. In Fig. 8, the charging and discharging of the heat storage have been seen. As can be seen, from hours 1 to 6 and 13 to 18, when the price of gas oil is high, the heat storage is discharged, and from hours 7 to 12 and 19 to 24, when the price of the gas oil is low, it is charged.

These processes cause the production of energy transfers to peak times at a low cost. As a result, it reduces the cost of operation. Fig. 8 also shows the charging and discharging of the hydrogen storage. Due to the dependency between the amount of water and electricity needed to produce hydrogen, when the price of electricity is high, the hydrogen storage is discharged, and this hydrogen is used by the fuel cell to feed the loads. Also, when the price of the electricity is low, the storage is charged with the produced hydrogen by the electrolyzer.

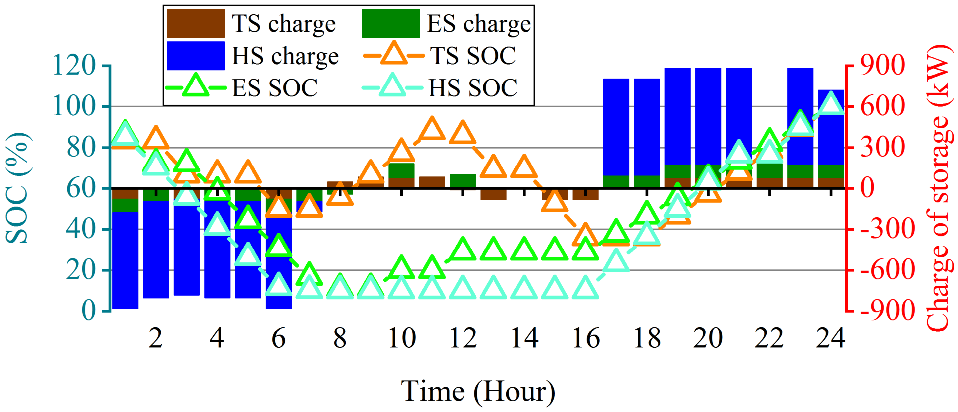

Fig. 8. State of charge of the energy storages.

Fig. 9 indicates the electric and thermal load profiles, respectively, before and after the DR program. As can be seen, after the DR program, loads have shifted from on-peak hours to off-peak hours. This subject contributes significantly to lower operating costs.

According to Fig. 9, from hours 1 to 8, when the power consumption is high, the electric loads are shifted to other hours where power consumption is low. Similar to the electric loads, from 1 to 6 and from 13 to 18, when the consumption of the thermal loads is high, a part of the thermal loads are shifted to other times to help that the load profiles become flat, as well as the cost of operation is decreased.

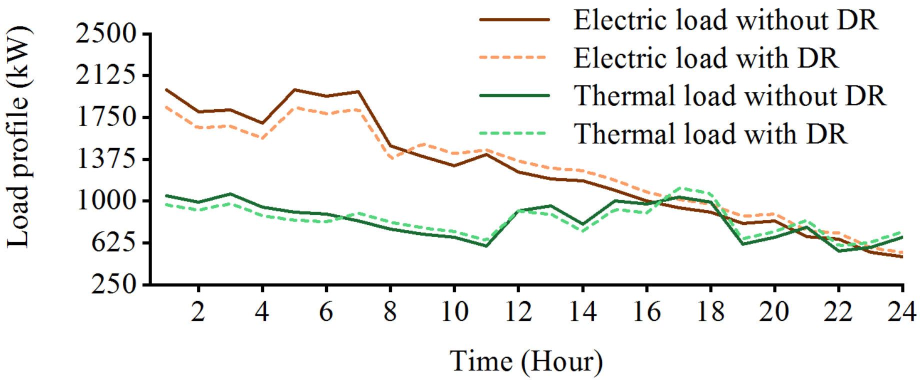

Fig. 9. Load profile in the presence of the DR program.

Fig. 10 depicts the amount of gas flow in the natural gas network pipelines. As can be seen, after using P2G to produce natural gas using electricity and water and injecting it into the natural gas network, congestion in the pipelines has significantly decreased, and this subject can have both technically and economically advantages for the natural gas network.

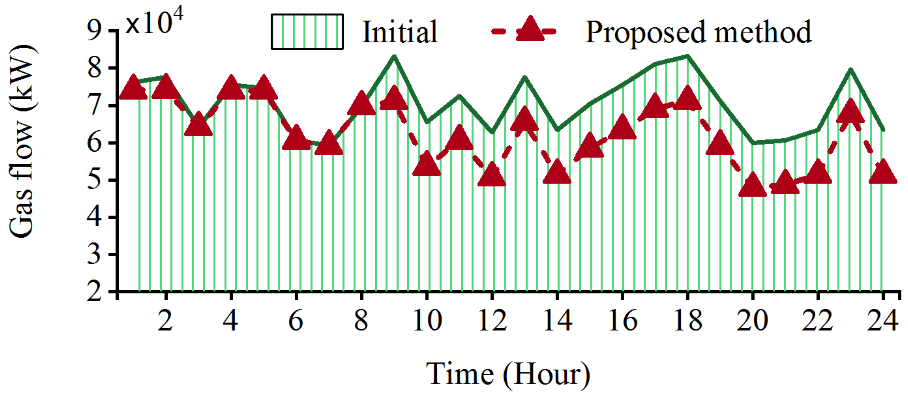

Fig. 10. Gas flow in the pipelines.

Regarding Fig. 10, from hours 1 to 8, when the price of electricity is high, the natural gas generated by the P2G technology is low. But in other hours, by reducing the price of the electricity, the energy hub increases the purchase of electricity. This subject helps the energy hub to increase natural gas production by P2G technology. Due to this subject, the congestion in the pipeline of natural gas has been decreased from hours 9 to 24.

Finally, Fig. 11 shows the operating costs before and after using P2G. As can be seen, after the use of P2G, the energy hub costs have significantly decreased.

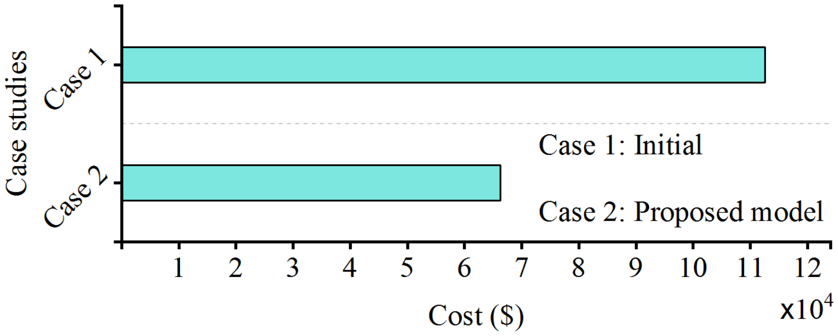

Fig. 11. Cost of operation in different cases.

5. Conclusion

Nowadays the development of cutting-edge technologies such as power-to-x resources and energy hubs, lead to realizing the benefits of integrated energy infrastructure that can interact together in synergistic way. The energy Hub has been considered as an energy management center to couple different energy systems in order to increase the flexibility and efficiency in supplying their own demand. The energy hub can receive various energy carriers at its input and manage or convert them according to the requirements of consumers. Moreover, the energy hub can interact with energy networks and exchange energy with the aim of maximizing its own profit and minimizing the operation cost of system. In this paper, the effect of connecting multiple energy system through energy hubs is investigated from system-oriented perspective. In this modeling, the owner of energy hub tries to increase its own profit by managing its energy carriers as well as selling the natural gas produced from P2G to the gas grid. On the other hand, the natural gas network alleviates the congestion in the network pipelines by purchasing gas from the energy hub. The energy hub uses various equipment and technologies to achieve this goal, including DR program, renewable resources and energy storage systems. The proposed model is linearized by the Taylor series and Cartesian method to make it computationally tractable and consequently solved by CPLEX solver. In this modeling, the case system for the natural gas system was a 20-node grid connected to a distribution system by energy hubs and P2G units. The results obtained from simulations illustrated that selling the gas produced in the P2G units to the natural gas grid can significantly alleviate the congestion on the pipelines and also selling the electricity to the power grid can be very beneficial such that it increases cost saving by 18.45%. Moreover, the heat storage was not committed due to depreciation cost and loss cost, which indicates that the modeling storage commitment is necessary to prevent uneconomic operation of energy storages. Another interesting observation is that the cost saving of energy storage charging is 1.84 times of the cost saving of storage discharging. Finally, the electricity demand of energy hub is shifted from high price periods to the low and medium periods by switching to other energy carriers, storing electricity and managing controllable appliances, which is beneficial for both energy consumers and electricity network.

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