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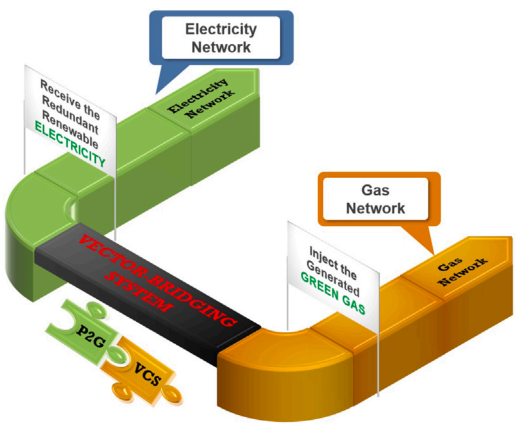
Value of regional constraint management services of vector-bridging systems in a heavily constrained network

Vahid Vahidinasab [a,*], Mahdi Habibi [b], Behnam Mohammadi-Ivatloo [c,d], Phil Taylor [e]

[a] Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham, UK
[b] Faculty of Electrical Engineering, Shahid Beheshti University, Tehran, Iran
[c] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
[d] Department of Energy Technology, Aalborg University, Aalborg, Denmark
[e] School of Computer Science, Electrical and Electronic Engineering, and Engineering Maths, University of Bristol, Bristol, UK

GRAPHICAL ABSTRACT



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ABSTRACT

While a lot of countries put renewable energy sources at the heart of their decarbonization strategies with directed incentive mechanisms, the variability of the renewable energy sources, remains a major challenge for electricity system operators in ensuring the security of supply. This challenge is particularly onerous when there is a coincidence between this variability and congestion of the tie-lines. Renewable generation spillage often leads to constraints being placed on the output of renewable energy sources. This situation causes a significant cost for electricity system operators due to the need for constraint payments to be made to renewable generations. These increased costs will ultimately be recovered from energy customers. Maintaining the balance in the aforementioned decarbonization, security of supply and affordability is a challenge that constitutes the energy trilemma. The integration of electric power systems with other energy infrastructures, e.g., natural gas, could be a promising solution for achieving a balanced performance in the energy trilemma, controlling the fluctuation of renewable energy sources, and increasing the flexibility of the integrated systems. Considering this, a hybrid bridging-operational framework based on the vector-bridging system concept is proposed. Also, a day-ahead integrated scheduling model is proposed that optimizes the integrated operation by considering

* Corresponding author.
E-mail addresses: vahid.vahidinasab@ntu.ac.uk (V. Vahidinasab), m_habibi@sbu.ac.ir (M. Habibi), mohammadi@ieee.org (B. Mohammadi-Ivatloo), pvc-research@bristol.ac.uk (P. Taylor).

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the constraint payment costs in a linear optimization model. Simulation results on a large test system indicated that the hybrid bridging-operational framework could reduce the total cost of the congested system by 65% and release up to 10% of the pipeline capacities while harvesting the wind generation and removing constraint payments to wind generators.

1. Introduction

Transmission congestion management, which in some regions is also called constraint management, is done in the conventional electric power systems by considering transmission lines and operation constraints in daily scheduling in the form of a unit commitment problem [1]. It is one of the required services by the Electricity System Operators (ESOs) to cope with the situations that some of the transmission networks are unable to transmit power from the generation side to the demand areas, due to congestion at one or more parts of the transmission networks [2]. Accordingly, generators may be asked to reduce their generation, even if they have a contract with the market, because, e.g., there is an error in the forecasting of load or renewable generation [3] and less electricity is required than what was expected, or since more power is being generated than the required energy in a particular region and the redundant generation could not be transmitted to the other areas due to congestion in tie-lines. Such a congestion-based constraint exists between Scotland and England, especially at times of unexpectedly high-wind and low-demand, in Scotland.

1.1. Motivation

According to the balancing mechanism, some generators (who are contracted into the market) might be asked by ESO to decrease their generation, since there is transmission congestion in an area or an error in the demand forecast that caused less electricity requirement than expected. In such cases, a generator will be paid an amount of money to reduce its output for constraint management purposes which is called Constraint Payment (CP).

Usually, at the (often unexpectedly) high wind days and low Scottish demand, a similar situation happened in which more electricity was being generated from wind generators in the Scotland area than could be consumed and simultaneously, the capacity of grid tie-lines between Scotland and England was insufficient to transfer the excess generated electricity that necessitates constraint management by the ESO. According to a report in [4], UK wind farms have received a total of £649 million over a decade of CP (up to December 2019) for discarding 8.7 TWh of electricity.

With approximately 16 GW of wind power in operation, the UK plans for over 30 GW of new wind power. The fact that large CP is already being made shows that significant network reinforcement will be necessary to accommodate 30 GW of additional capacity [5]. However, network reinforcement is an expensive and time-consuming action, and in the near future, CP could rise even further.

This research is inspired by the aforementioned CP issue and looks for a way to use the suppressed wind power (or in general Renewable Energy Source (RES)) production in an efficient way to tackle the energy trilemma by enhancing whole system efficiency, meeting decarbonization goals, and simultaneously reducing CP charges.

1.2. Literature survey

Low carbon RESs and fast dynamic gas-fired generators are seen as a desirable generation combination [6,7]. In countries that the peak of the gas and electricity demands happen at the same time, high dependency on gas generation can lead to congestion in the gas network, especially at gas supply bottleneck pipelines [8]. Due to the priority of domestic gas demands and terms of contracts, the supply of gas-fired generators can be interrupted by the ESO and this can jeopardize their availability at congestion points in gas networks [9]. Although the interdependency of gas and electricity should be considered in an integrated model [10–13], the privacy of market parties is concerned in [14–16]. The steady-state gas flow equation is nonlinear and makes the model complex [11]. So, the Second-Order Conic (SOC) programming model in [16,17], and linearization models in [12,13,15] are used to relieve the computational burden.

The Power-to-Gas (P2G) conversion includes two processes of electrolysis and methanization [18], and P2G is used as the facilitator of bidirectional energy flow between the electricity and gas network in [10–16,19,20]. Authors of [10] use P2G for energy export between the networks, while a multi-period optimal power flow considering P2G and storage capacity of gas pipelines is presented in [11]. A combined model of transient and steady-state gas flow is analyzed in [12], and [16] studies a pricing method for P2G productions based on the owner point of view. Different scenarios of gas pricing and gas pipeline congestion are analyzed in [19], and bidding strategy and economic analysis of P2G units are evaluated in [20].

The capacity of electrical storage facilities is limited, and the capability of P2G is used as an alternative solution for the absorption of surplus RESs' generation in [21–25]. Ref. [21] considers energy conversions inside the energy hubs in a robust model and applies a piece-wise linearization model of gas flow, which increases the complexity of the model. Authors of [22] analyze the application of P2G to mitigate the ramping of wind generation on a weekly operational horizon. The nonlinear presentation of gas flow complicates that model, and no penalty is considered for curtailment of RESs. Ref. [24] finds the best location and size of P2G units in the GB network in the daily scheduling horizon.

Table 1 presents a taxonomy of existing literature in the area and compares previous researches in this field to highlight the research gaps and novel aspects of this paper.

Table 1
Comparison of the proposed model of this paper with the literature.

Reference	Model	RESs	Electrical storage	P2G	Gas storage	VBS concept	Transmission congestion	Constraint payment
[9]	Linear	✓	✓	–	✓	–	–	–
[10]	Nonlinear	✓	✓	✓	✓	–	–	–
[11]	Nonlinear	✓	–	✓	✓	–	✓	–
[12]	Linear	✓	–	✓	–	–	–	–
[13]	Linear	✓	–	✓	–	–	–	–
[14]	Nonlinear	✓	–	✓	✓	–	✓	–
[15]	Linear	✓	–	✓	–	–	–	–
[16]	SOC	✓	–	✓	✓	–	–	–
[17]	SOC	✓	–	✓	–	–	–	–
[18]	Linear	✓	–	✓	✓	–	–	–
[19]	Linear	✓	–	✓	✓	–	–	–
[20]	Linear	✓	–	✓	✓	–	–	–
[21]	Nonlinear	✓	–	✓	✓	–	–	–
[22]	Nonlinear	✓	✓	✓	–	–	✓	–
[24]	Nonlinear	✓	✓	✓	✓	–	✓	–
[25]	Nonlinear	✓	–	✓	✓	–	✓	–
[26]	Nonlinear	–	✓	–	✓	–	✓	–
This paper	Linear	✓	✓	✓	✓	✓	✓	✓

1.3. Research gap

From the literature review, it can be seen that there is no research work in the area that analyzes the constraint management services of vector-coupling systems in heavily constrained networks. While some analyses have been carried out on the P2G application as a flexibility tool to cope with the intermittent RESs in the normal operation of the power system, there is no reference that proposes the regional constraint management services idea and uses the potential of integrated gas and electricity networks to cope with the congested situations of the electricity network in order to increase the efficiency of operation by reducing the CP to the curtailed renewable generation.

1.4. Contributions

Considering the deduced research gap, this paper proposes a framework for enabling the regional constraint management services in heavily constrained networks by using a Hybrid Bridging-Operational (HBO) framework. The HBO framework enhances the flexibility of the integrated operation of the power system with the natural gas network to achieve a balanced performance in the energy trilemma and controlling the fluctuation of RESs. The VBS elements consist of P2Gs and vector-coupling storage facilities (a type of gas storage). In addition to VBS components, electrical storage devices are considered in the power sector as a complementary solution to reduce constraint payment. The day-ahead operational planning proposed by this paper is developed based on a linear formulation. Different study cases are defined and compared to evaluate the impact of the various components on improving operational efficiency.

The main specifications and the novel aspects of this work are as briefly summarized in the following:

- The value of Vector-Bridging Systems (VBSs) and the holistic approach to energy systems, as a regional constraint management tool in providing regional constraint management services, is modeled and analyzed;
- A coordinated global–regional framework is proposed by embedding the constraint payment in the formulation of the integrated gas and electricity systems' operation, and the effect of the enhanced operation model on reducing the constraint payment is analyzed. This model would set the optimal performance of the VBS;
- A linearized formulation is proposed for the proposed hybrid bridging-operational framework to improve computational efficiency.

1.5. Organization of the paper

The remainder of the paper is organized as follows. Section 2 provides the regional constraint management using vector-bridging systems, and Section 3 presents coordinated constraint management using a hybrid bridging-operational approach. Simulation results are presented in Section 4 and discussion regarding the potential of VBS and future research directions are presented in Section 5. Finally, Section 6 concludes the paper.

2. Vector-bridging systems

This section presents the VBS concept and its formulation.

2.1. What is a vector-bridging system?

As the first solution to the explained problem, the concept of the vector-bridging system is proposed. The VBS, includes a pack of linked P2G and vector-coupling storage (VCS) technologies that would be able to act as a bridge between the gas and electricity vectors. A VBS is an inter-vector element with storage capability that is not the same as the commonly used storage devices. The VBS gets input and charges using redundant RES generations from the electricity vector and, in time of need, would be discharged and provide gas into the other vector.

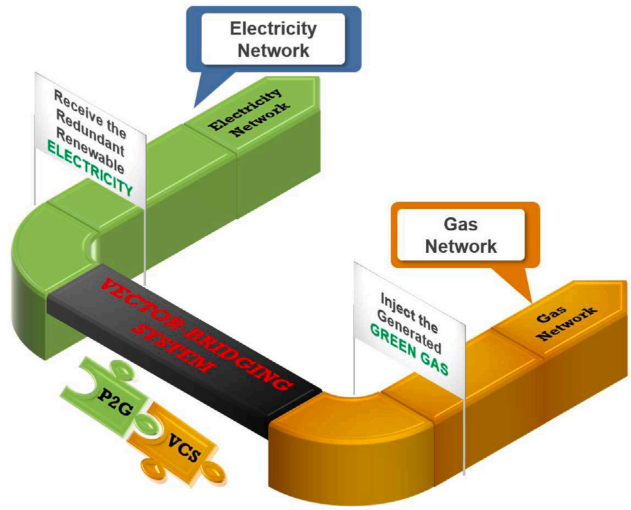

Fig. 1. Conceptual representation of the VBS.

The VBS concept is proposed to use redundant wind generation in congested areas and prevents CP to wind farms due to the congestion. Unlike the electrical grid sizing, the gas network capacity usually contains significant headroom due to the high development cost and is initially exploited at a lower pressure [26]. Therefore, according to the operator requirements, a VBS has the ability to convert the redundant green generations into green gas and inject it into the gas network or storing in the storage device for future local uses. The infographic of Fig. 1 demonstrates the VBS concept.

2.2. The VBS elements

The VBS elements is formulated in this subsection.

2.2.1. P2G

The generated amount of gas (hydrogen or methane) by the electrolysis or methanization process can be reflected by (1), and (2) limits the maximum hourly electrical power that can be consumed by P2Gs.

$$Q^{P2G}_{x,t} = Z^1 p^{P2G}_{x,t} \eta^{P2G}_x \tag{1}$$

$$0 \le p^{P2G}_{x,t} \le \overline{P}^{P2G}_{x,t} \tag{2}$$

2.2.2. Vector-coupling storage

The VCS is a type of gas storage facility and, therefore, unlike the electrical storage, provides considerable capacity and can play the role of suppliers in the daily operation. Constraints (3)–(7) reflect the model of VCS facilities. Constraints (6) and (7) imply that the maximum charging of gas storage facilities limited by the value of gas generation of P2Gs. In other words, VCS is embedded only for absorbing the extra production of the P2G unit.

$$QE^{GVS}_{sg,t} = QE^{GVS}_{sg,(t-1)} + Q^{GVS,ch}_{sg,t} - Q^{GVS,dis}_{sg,t} \tag{3}$$

$$\underline{QE}^{GVS}_{sg} \le QE^{GVS}_{sg,t} \le \overline{QE}^{GVS}_{sg} \tag{4}$$

$$0 \le Q^{GVS,dis}_{sg,t} \le \overline{Q}^{GVS,dis}_{sg} J^{GVS}_{sg,t} \tag{5}$$

$$0 \le Q^{GVS,ch}_{sg,t} \le \overline{Q}^{GVS,ch}_{sg} (1 - J^{GVS}_{sg,t}) \tag{6}$$

$$0 \le Q^{GVS,ch}_{sg,t} \le Q^{P2G}_{(sg\in\chi),t} \tag{7}$$

3. A coordinated constraint management using hybrid bridging-operational framework

As a complementary solution, a multi-vector framework for the scheduling of the integrated networks is proposed in which CP is inserted into the model of the integrated gas and electricity networks while the VBS acts as a bridging component as well.

This HBO framework is designed and formulated as a Mixed-Integer Linear Programming (MILP) problem and presented and discussed in the following subsections.

3.1. Objective function of the HBO

The objective function of the proposed HBO framework includes operational costs of the electricity system, gas system along with the CP to the wind generators during the congestion in the electricity network. In this model, the same CP is considered for all wind generators. But, in the systems that there are severe network bottlenecks and the policy is to motivate wind generation expansion in those areas, it is possible to define different CPs in each area (which can be defined in accordance with the locational marginal prices) as an incentive mechanism. This can be easily done by changing the λ^{CP} from a fixed value to a parameter.

$$\min_{\substack{I,st,sd\\J,P,Q}} \sum_t \Bigg(\underbrace{OF_t^{EN} + OF_t^{GN}}_{\text{GN\&EN Operation Costs}} + \underbrace{\sum_w \lambda^{CP} pc_{w,t}^{WP}}_{\text{CP to wind generators}} \Bigg) \tag{8}$$

The objective function of the electricity network is presented by (9), which includes the production cost of non-gas generation and costs of the startup, shutdown, and fixed-cost of both gas-fired and non-gas generators.

$$OF_t^{EN} = \sum_{i\notin\beta} f(p_{i,t}, I_{i,t}) + \sum_i (SU_i st_{i,t} + SD_i sd_{i,t} + N_i I_{i,t}) \tag{9}$$

Additionally, the objective function of the gas network is presented by (10), which includes the cost of gas purchase from gas wells and gas storage. Also, for the sake of better comparability of the costs related to power generation, the cost of fixed gas loads is subtracted from the objective function of the gas system.

$$OF_t^{GN} = \sum_{sg} \rho^{GN} Q_{sg,t}^{GVS,dis} + \sum_y \rho^{GN} Q_{y,t}^{Sup} - \sum_m \rho^{GN} QL_{m,t}^{Fxd} \tag{10}$$

3.2. Constraints of the electricity network

The regular constraints of electrical power generators, including gas generators as a Gas to Power (G2P) element, are presented by (11)–(16).

$$st_{i,t} - sd_{i,t} = I_{i,t} - I_{i,(t-1)} \tag{11}$$

$$st_{i,t} \le I_{i,\tau} \qquad \forall t \le \tau \le t + \underline{T}^{\text{on}} - 1 \tag{12}$$

$$sd_{i,t} \le 1 - I_{i,\tau} \qquad \forall t \le \tau \le t + \underline{T}^{\text{off}} - 1 \tag{13}$$

$$\underline{P}_i I_{i,t} \le p_{i,t} \le \overline{P}_i I_{i,t} \tag{14}$$

$$p_{i,t} - p_{i,(t-1)} \le Ru_i I_{i,(t-1)} + SRu_i st_{i,t} \tag{15}$$

$$p_{i,(t-1)} - p_{i,t} \le Rd_i I_{i,(t-1)} + SRd_i sd_{i,t} \tag{16}$$

$$pc_{w,t}^{WP} = \overline{P}_{w,t}^{WP} - p_{w,t}^{WP} \ge 0 \tag{17}$$

The minimum online and offline duration of generators preserved by (11)–(13), in which $I_{i,(t-1)}$ at $t = 0$ is the initial state of generators. The maximum and minimum stable generation of generators are considered by (14). The ramp rates in upward and downward containing the start-up and shut-down ramps are presented by (15) and (16). Eq. (17) evaluates the wind power generation and curtailment regarding the maximum hourly available (or better to say, hourly contracted wind power generation) wind power. Since in this work, the deterministic case is studied and the impact of uncertainties is not studied, therefore the reserve constraints are not modeled.

This paper considers the DC power flow, presented by (18), for the transmission system. The active power balance for electrical transmission buses is presented by (19).

$$fl_{l,t}^{EN} = S\sum_b (ML_b^l)\theta_b^t / X_l \tag{18}$$

$$\sum_{i\in\kappa} p_{i,t} - \sum_{x\in\phi} p_{x,t}^{P2G} + \sum_{s\in\psi} \left(p_{s,t}^{EVS,dis} - p_{s,t}^{EVS,ch}\right) + \sum_{w\in Y} p_{w,t}^{WP} = L_{b,t}^{EN} + \sum_l ML_b^l fl_{l,t}^{EN} \tag{19}$$

The performance of electrical energy storage is considered by (20)–(23) [27]. The maximum rates of hourly charging and discharging of storage facilities are evaluated by (21)–(22), and (23) reflects the feasible range of the reservoir.

$$e_{s,t}^{EVS} = e_{s,(t-1)}^{EVS} + p_{s,t}^{EVS,ch}\eta_s^{EVS,ch} - p_{s,t}^{EVS,dis}/\eta_s^{EVS,dis} \tag{20}$$

$$0 \le p_{s,t}^{EVS,ch} \le \overline{P}_s^{EVS,ch} J_{s,t}^{EVS} \tag{21}$$

$$0 \le p_{s,t}^{ESS,dis} \le \overline{P}_s^{EVS,dis}(1 - J_{s,t}^{EVS}) \tag{22}$$

$$\underline{E}_s^{EVS} \le e_{s,t}^{EVS} \le \overline{E}_s^{EVS} \tag{23}$$

3.3. Constraints of the gas network

The original dynamic nonlinear model of the gas network is very complex; hence, this paper employs the steady-state model of the high-pressure natural gas transmission system. In this way, the gas flow is calculated as presented by (24).

$$Q_{p,t}^{Pipe} = K_p Sgn(\pi_{f(p),t}, \pi_{r(p),t})\sqrt{|\pi_{f(p),t}^2 - \pi_{r(p),t}^2|} \tag{24}$$

where, the parameter K_p is the pipeline constant, and it is obtained based on the characteristics of natural gas and pipelines. In addition, the function of Sng determines the flow direction in pipelines and is defined as:

$$Sgn(\pi_{f(p),t}, \pi_{r(p),t}) = \begin{cases} 1, & \pi_{f(p),t} \ge \pi_{r(p),t} \\ -1, & \pi_{f(p),t} \le \pi_{r(p),t} \end{cases} \tag{25}$$

where, $\pi_{f(p),t}$ and $\pi_{r(p),t}$ are the variables of gas pressure of forwarding and receiving nodes of pipelines. The nodal gas pressure must be within the defined range as presented by (26) and (27).

$$\underline{\pi}_{f(p)} \le \pi_{f(p),t} \le \overline{\pi}_{f(p)} \tag{26}$$

$$\underline{\pi}_{r(p)} \le \pi_{r(p),t} \le \overline{\pi}_{r(p)} \tag{27}$$

Since the gas flow equation is nonlinear, a piecewise linear approximation based on convex triangles is applied in this paper [28]. In this way, if pressure of $\pi_{f(p),t}$ was greater than $\pi_{r(p),t}$, then gas flow equation of (24) will be expressed as:

$$Q_{p,t}^{Pipe} = K_p\sqrt{\pi_{f(p),t}^2 - \pi_{r(p),t}^2} = \sum_q \left(A^q\pi_{f(p),t}^q + B^q\pi_{r(p),t}^q + C^q q_{p,t}^q\right) \tag{28}$$

The gas pressure variable will be broken down with fixed ranges and is limited to the upper and lower bounds of the corresponding triangles as presented by (29) and (30).

$$\underline{\pi}_{f(p)}^q q_{p,t}^q \le \pi_{f(p),t}^q \le \overline{\pi}_{f(p)}^q q_{p,t}^q \tag{29}$$

$$\underline{\pi}_{r(p)}^q q_{p,t}^q \le \pi_{r(p),t}^q \le \overline{\pi}_{r(p)}^q q_{p,t}^q \tag{30}$$

As expressed by (31) and (32), if the pressure boundaries of qth triangle is matched to the nodal pressures of $\pi_{f(p),t}$ and $\pi_{f(p),t}$, then the corresponding binary variable of $q_{p,t}^q$ will be activated, and (33) ensures only one of the triangles can be selected for each p and t. Consequently, the corresponding coefficients of A^q B^q, C^q related to the qth triangle will be used for calculation of linearized gas flow using (28).

$$\sum_q \pi_{f(p),t}^q = \pi_{f(p),t} \tag{31}$$

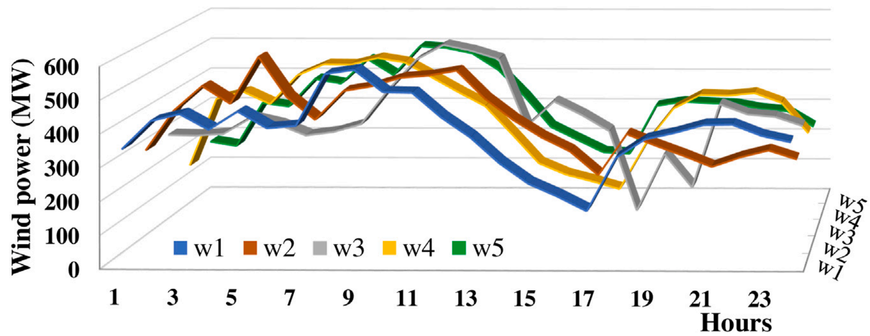

Fig. 2. Available wind power of different wind sites.

$$\sum_{q} \pi^{q}_{r(p),t} = \pi_{r(p),t} \tag{32}$$

$$\sum_{q} q^{q}_{p,t} = 1 \tag{33}$$

This paper considers the simplified model of the compressor and the pressures of inlet and outlet of compressors are arranged based on (34). Also, Eq. (34) implies that the gas flows through the compressors only in one direction.

$$\pi^{Cmp}_{Otlt(c),t} \geq \pi^{Cmp}_{Inlt(c),t} CR^{Cmp}_{c} \tag{34}$$

$$Q^{Cmp}_{c,t} \geq 0 \tag{35}$$

The relation between the consumed values of natural gas and electrical power generation of gas-fired generators is preserved by (36). The additional constraints of gas-fired generators are considered by (11)–(16).

$$p^{Gsgn}_{i,t} = Z^2 Q^{Gsgn}_{i,t} \eta^{Gsgn}_{i} \qquad \forall \ i \in \beta \tag{36}$$

The maximum and minimum supply of natural gas wells are presented by (37).

$$\underline{Q}^{Sup}_{y} \leq Q^{Sup}_{y,t} \leq \overline{Q}^{Sup}_{y} \tag{37}$$

Similar to the electrical power flow, the gas balance equation of (38) checks the equality of injection and withdrawal of natural gas for all nodes. The gas injection and withdrawal to the pipelines and compressors (incidence matrix MP^{p}_{m} and MC^{c}_{m} considers the gas flow with positive and negative sign for the forwarding and receiving nodes) are reflected by $Q^{Pipe}_{p,t}$ and $Q^{Cmp}_{c,t}$, respectively.

$$\begin{aligned}&\sum_{i \in \Gamma} Q^{Gsgn}_{i,t} + \sum_{sg \in \Lambda} (Q^{GVS,ch}_{sg,t} - Q^{GVS,dis}_{sg,t}) + QL^{Fxd}_{m,t} + \sum_{p} MP^{p}_{m} Q^{Pipe}_{p,t} \\ &+ \sum_{c} MC^{c}_{m} Q^{Cmp}_{c,t} = \sum_{y \in \sigma} Q^{Sup}_{y,t} + \sum_{x \in \Theta} Q^{P2G}_{x,t}\end{aligned} \tag{38}$$

4. Simulation results

The proposed framework has been tested on the IEEE 118-bus test system integrated a 10 nodes natural gas transmission system with 10 pipelines. The proposed test system has been expanded by adding five VBSs and five electricity storage devices. Fig. 2 presents the values of hourly available wind power for the five wind farms installed at buses 24, 26, 31, 71, and 113. The capacity of P2G units is 300 MW, and the information of storage facilities is presented in Table 2. In this work, the associated cost of CP is considered to be about 4 times the system average generation cost. The additional data of the test system are given in [29].

Five case studies are introduced to evaluate the performance of the proposed model, which are introduced in Table 3. Case-1 calculates the operational cost with the assumption that there is no congestion that suppresses the absorption of the available wind power. In Case-2, the congestion occurrence of electrical tie-lines is considered, and there are no options prepared for the ESO. The effect of electrical storage devices is added in Case-3. In Case-4, the VBS is also added, and finally, Case-5 represents the proposed HBO of this paper. The proposed models in this paper are MILP problems that are solved using the CPLEX solver on a laptop with the configuration of Intel *i7* CPU 2.4 GHz and 8 GB of RAM.

Table 2
Information of the storage devices.

Type	Locations	Capacity of each unit			Initial
		Charging	Discharging	Reservoir	reservoir
EVS	$b24, b26, b31, b71, b113$	300 MW	300 MW	3000 MWh	1500 MWh
GVS	$m4, m5, m6, m7, m8$	160 KCF	160 KCF	800 KCF	240 KCF

Table 3
Specifications of the different test cases.

Cases	Congestion situation	Electrical storage	VBS	Proposed HBO
Case-1	✗	✗	✗	✗
Case-2	✓	✗	✗	✗
Case-3	✓	✓	✗	✗
Case-4	✓	✓	✓	✗
Case-5	✓	✓	✓	✓

The evaluation of costs, including the operational costs of electricity and gas systems, the cost of constraint payment to the wind generators, and also the total cost for the different case studies, are conducted in Fig. 3. As can be seen, Case-1 contains the highest cost for the gas and the lowest cost for the electricity network among all the cases. It should be noted that in Case-1, about 15.5 GW (19.3%) of the total load supplied by the gas-fired generators. In Case-2, the occurrence of congestion in the tie-lines of the electricity network increases the sum of the operational costs of electricity and gas networks with about \$296,631 (27.6%), while a \$636,595 CP to wind generators is forced to the system. Therefore, the total operational cost of Case-2 is increased by 86.9% compared to Case-1.

In Case-3, the installation of electricity vector storage devices reduces the cost of both electrical and gas systems. The CP to wind generators and total cost are decreased to \$537,172 (−15.6% compared to Case-2) and \$1,886,309 (−6% compared to Case-2), respectively. It can be seen, the presence of electrical storage improves the operational costs, but the CP to wind generators is still high and contains about 28.5% of the total cost.

The installation of VBS units to the model of Case-3 creates Case-4, in which VBSs reduce the cost of the gas system, and it falls to \$104,299, but a little increase in electrical cost is revealed compared to Case-3. The reason is that the performance of electrical storage is reduced in the shadow of VBS performance. The highlighted achievement of Case-4 is the significant reduction of CP to wind generators, which falls to \$42,080 (−93.4% compared to Case-2).

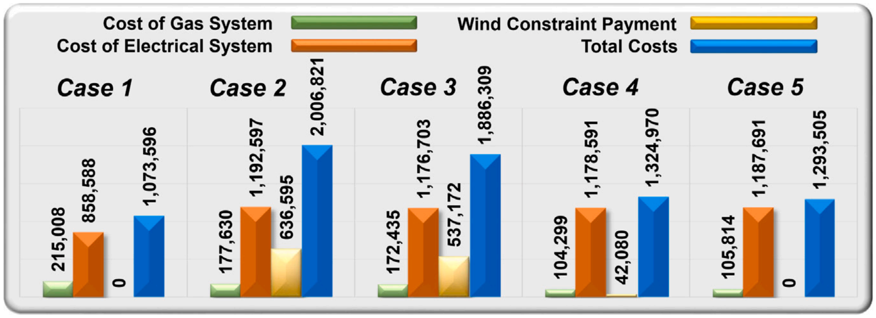

Fig. 3. Comparison of the costs of different case studies.

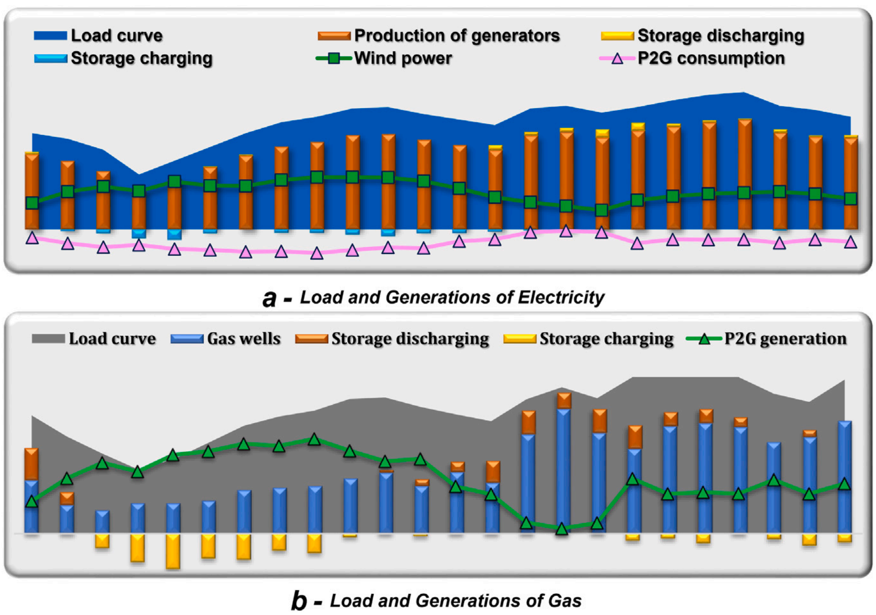

Fig. 4. Electricity and gas dispatches for the proposed comprehensive HBO framework in Case-5.

Although Case-4 results in a significant improvement of operational cost, the redundant wind power still imposes a penalty to the total cost. Therefore, the higher penetration of wind power may lead to considerable CP to wind generators.

This is an issue that is considered in the design and development of the proposed HBO model. When the proposed HBO model of Case-5 is analyzed, in which both of the VBS and preventive action against CP provided for performance optimization, the lowest total cost compared to all cases is achieved, and also the CP becomes zero in this case. The charts of hourly load and generations for electricity and gas systems of Case-5 are presented in Figs. 4a and 5a, respectively. As it can be seen, electricity vector storage devices are charged in the hours with redundant wind power, where VCS devices in the VBSs are charged in the same hours. Additionally, both electrical and gas storage devices are discharging in the peak-load hours. Fig. 4a clearly shows that P2Gs absorb the redundant wind generation and in the form of gas, this power will be injected into the gas system or will be stored in the VCS facilities. The values of injected gas to the network and the stored values in VCSs are presented in Fig. 5a.

The share of different technologies within the daily operation, separately for electricity and gas, is presented for Case-5 in Figs. 4b and 5b, respectively. The mix of electrical generation shows that a large portion of production after non-gas generators belongs to wind generation, which supplies 33.7% of the total load. In addition, VBSs absorb 11.2% of total generation, and the electrical storage absorbs and regenerates 1.7% of total generations. The share of P2Gs in supplying gas demands is 44.5%, and the VCS participates with absorption and withdrawal of 7.4% of the total gas demands.

The congestion of tie-lines is the most important barrier to wind power delivery. Fig. 6 compares the average loading of the tie-lines for cases dealing with congestion. It can be seen that the high-loading of tie-lines happens between hours 6 to 16, in which both load and wind power is high. In this period, the VBS units alongside the electrical storage devices lowering the loading of tie-lines. Furthermore, a drop can be seen in the loading of electrical tie-lines at hour 4, and the reason is that the demand is low in this hour. The redundant wind power is absorbed by storage facilities in this hour, and the corresponding power will be generated at peak-load hours as calculated for cases 3-5. It can be seen, Case-5 reveals a few different reactions in some hours, where the reason is that the wind power curtailments should be decreased to prevent the high penalty of wind constraint payments.

Fig. 7 presents the average loading of natural gas pipelines for different cases. It can be seen in Case-1, the highest loading of pipelines happens, and the drop is related to the low-load hours 3 to 5. Due to the electrical tie-lines congestion in Case-2, the usage of gas-fired generators located in congested areas is reduced, and this reveals as lower gas pipeline loading is this case. Case-3 slightly reduces the loading of pipelines in several hours. Up to 9.2% and 10.8% decrease in average loading of pipelines are achieved in Case-4 and Case-5, respectively. The reason is that the VBS units, as distributed gas resources, release the capacity of the natural gas pipelines.

The performance of electrical storage is evaluated for different cases in Fig. 8. It can be seen, the highest charging and discharging values

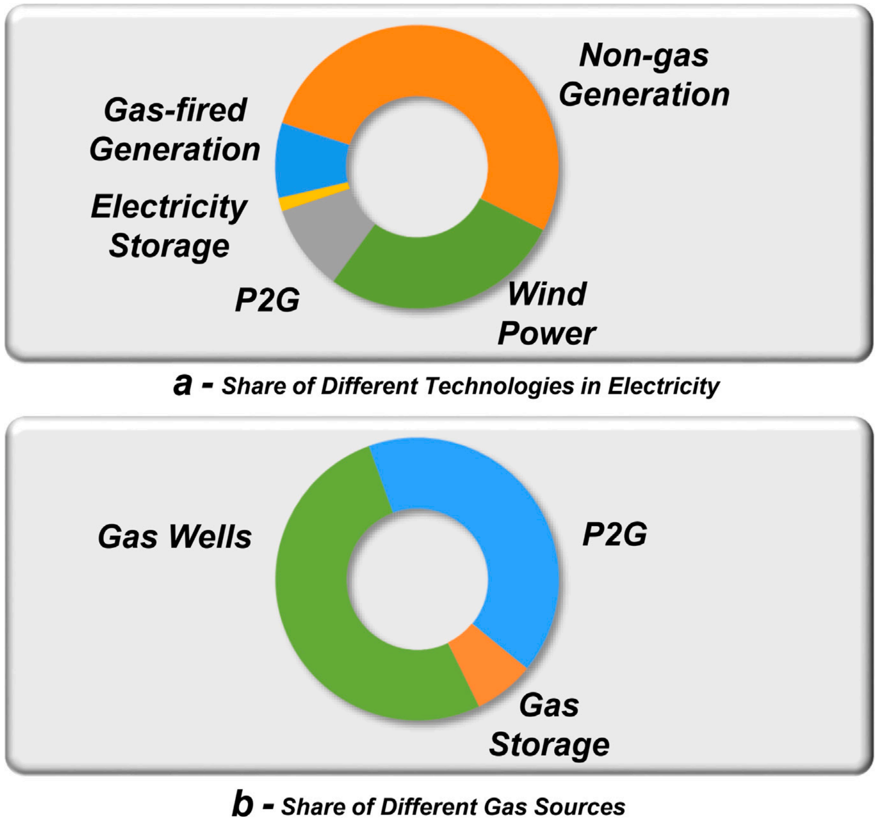

Fig. 5. Electricity and gas generation mix of the proposed comprehensive HBO framework in Case-5.

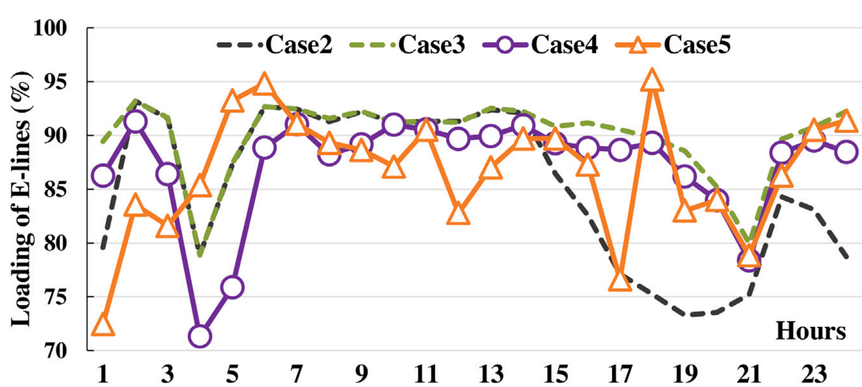

Fig. 6. Average loading of electrical tie-lines.

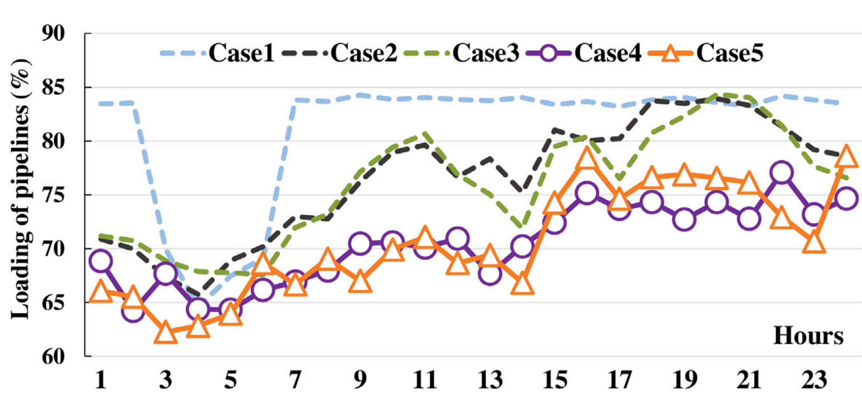

Fig. 7. Average loading of the natural gas pipelines.

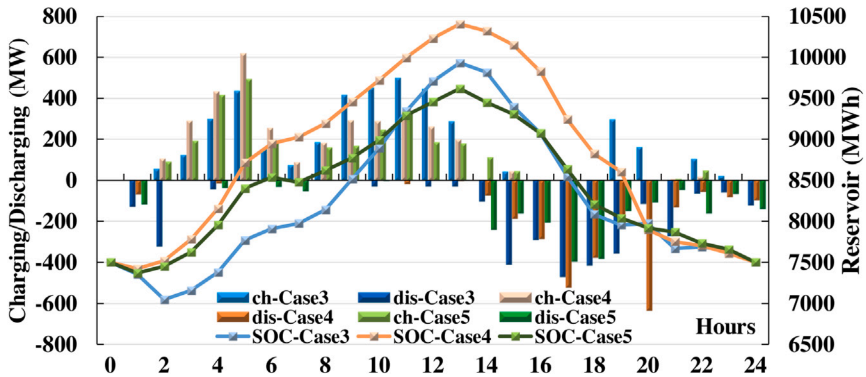

Fig. 8. Performance of electrical storage in different cases.

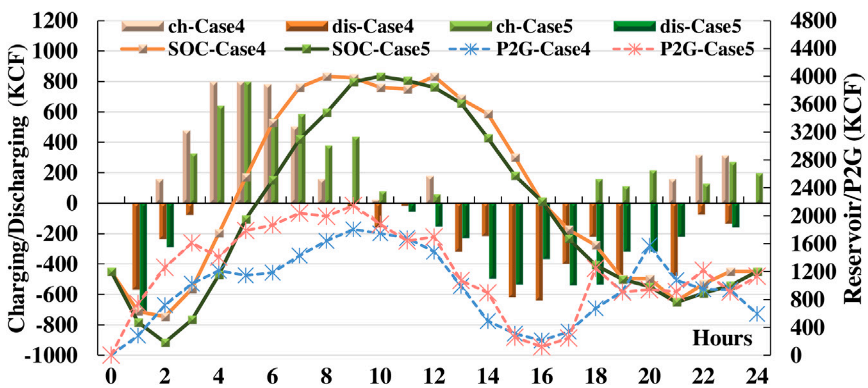

Fig. 9. Performance of VBS in different cases.

happen in Case-4, and that is because of releasing the capacity of electrical tie-lines and the possibility of delivering stored energy at peak-load hours. The lower values of Case-5 are related to the priority of absorbing the wind power for lowering curtailments.

Fig. 9 compares the performance of VBS in Case-4 and Case-5. It can be seen, the gas generation of P2Gs at hours 1 to 9 is higher in Case-5, and this confirms the previous justifications of absorption of redundant wind power at low load hours. Hence, higher charging of gas storage in hours 3 and 4 is calculated as expected.

The curtailment of wind power in Cases 2-4 is reported in Fig. 10. As it is expected, the highest values of suppressed wind power are obtained for Cases 2 and 3 and at the low-load hours and the hours with high available wind generation.

5. Discussion on the potentials of VBS and future research directions

Due to the spatial and temporal fluctuations in the generated power of RESs, high-capacity storage technologies have become a necessity. The VBS concept with the potential of converting the electrical power to a gaseous medium of hydrogen and methane is a viable solution to this need.

5.1. Discussion on the potentials of VBS

The VBS technology is able to [30]:

- Provide a vector-coupling role in dual-vector systems of gas and electricity for hedging the intermittent generation of RESs and also storing the redundant generation of them;
- Shift the transmission of energy from the electric power network to the gas network to support electricity grids during the congestion periods, which defers expansion of the electric transmission network infrastructures (see Fig. 11);
- Increase the share of renewable-sourced energy in the transport using synthetic methane from generated hydrogen from RESs.
- Use carbon dioxide as raw material and therefore participate more in decarbonization.

In this work, the potential of VBSs is assessed to improve the economic operation during periods of redundant wind power generation and congestion in electricity transmission lines. While adding the VBSs brings all the aforementioned aspects together, in this paper the effect of VBSs technologies on constraint management of the power systems and reducing the constraint payments to curtailed wind capacities has been highlighted.

5.2. Discussion on the future research directions

The potential of P2G technology to convert the redundant green electricity of RESs into Hydrogen makes it an enabling technology in the transition to low-carbon energy systems. P2Gs are able to bridge the gap between the energy vectors where decarbonization is hard and inject large amounts of renewable-sourced electricity to those sectors. Moreover, by injecting the produced green hydrogen into the gas networks, it would be able to reduce natural gas consumption. Another promising aspect of P2G is its potential use as a link to the transport sector, which can support hydrogen-fueled electric-vehicles, i.e., Fuel Cell Electric Vehicles (FCEVs), a low carbon mobility option while offering comparable driving performance to conventional vehicles.

5.2.1. Future directions from the technical point of view

According to the aforementioned discussion and considering the whole energy systems approach, the following directions can be followed in future studies in the area:

- A 3D analysis based on the environmental, technical, and economic pillars on the integrated gas, transport, and electricity

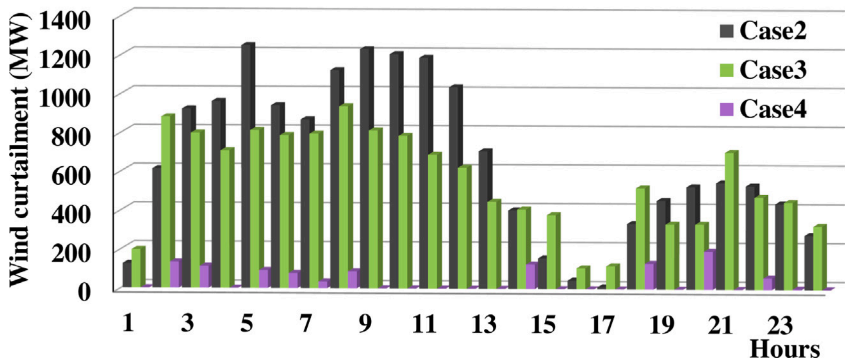

Fig. 10. Wind power curtailment in different cases.

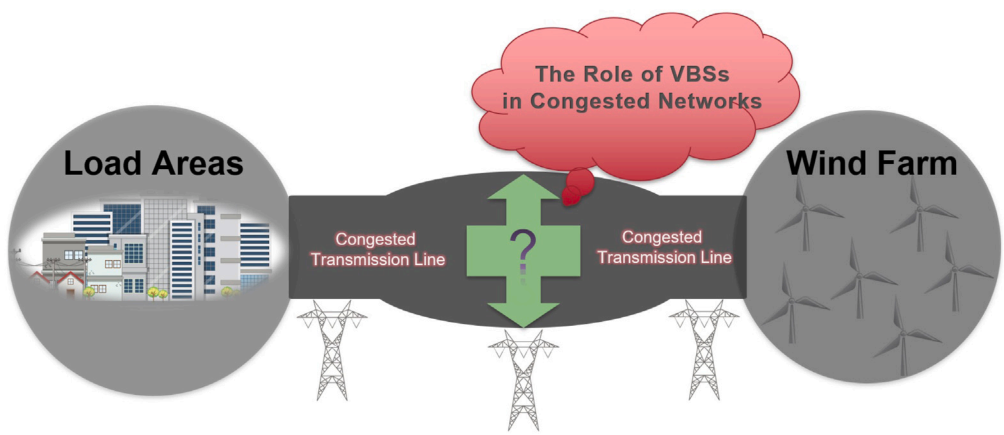

Fig. 11. A conceptual infographic for presentation of the indirect effect of VBS on congested power networks.

grids is an attractive study for unlocking the potentials of P2G technology in the decarbonization of the transport, heat and cool, and electricity systems.

- The other vector-specific storage technologies can be added to the model to unlock the potentials of coordinated operation of single/multi-vector storage devices in the operation of the integrated energy networks and see how they can reduce total operation cost while enhancing RESs hosting capacity.

5.2.2. Future directions from the computational point of view

Based on the experiences achieved on the modeling and computational studies, the following directions can be followed in future studies in the area:

- Due to the inherent uncertainties in the predicted values of the load and RESs generation, the proposed framework could be enriched by stochastic optimization to add the potential of decision making under uncertainty to the model.
- In order to enhance the computational efficiency when uncertainties are included in the model, the convexification of the model using second-order conic programming will be a valuable solution.

6. Conclusion

A hybrid bridging-operational framework for facing the energy trilemma was proposed in which the main goal was to find a comprehensive solution for reducing the constraint payment costs of the network in congestion situations of the electricity network and therefore increase the efficiency of operation. The main concluding remarks from the proposed comprehensive hybrid bridging-operational framework of this paper are summarized as follows:

- The electrical storage slightly reduced the constraint payment to wind generators while their performance was limited by tie-lines.
- The usage of vector-bridging systems decreased the operational cost by delivering wind power to the load through the gas pipelines and also significantly reduced the constraint payment to wind units.
- The application of vector-bridging systems reduced the loading of both electrical tie-lines and gas pipelines, and this additionally enhanced the performance of electrical storage.
- The comprehensive hybrid bridging-operational framework successfully captured the issue of constraint payment to wind generators by taking into account the corresponding costs along with electrical storage and vector-bridging systems.
- Last but not least, the hybrid bridging-operational framework reduced the total cost of the congested system by 65% and also released up to 10% of the pipeline capacities. Moreover, it could receive the load from the congested tie-lines and harvest all the green capacity of wind generators while removing constraint payments to wind generators.

CRediT authorship contribution statement

Vahid Vahidinasab: Conceptualization, Methodology, Data curation, Project management, Writing – original draft. **Mahdi Habibi:** Conceptualization, Methodology, Software, Writing – original draft. **Behnam Mohammadi-Ivatloo:** Conceptualization, Investigation, Writing – review & editing. **Phil Taylor:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Nomenclature

Symbols

ch, dis	Symbols of charging and discharging modes of gas storage facilities.
$Cmp, Pipe$	Symbol of gas compressors/pipelines.
EN, GN	Symbols of electricity and gas networks.
EVS, GVS	Symbols of electrical and gas storage facilities.
$Inlt, Otlt$	Symbols of inlet and outlet of gas.
on, off	Symbols of online and offline statuses units.
Sup	Symbol of gas suppliers.
$WP, Gsgn$	Symbols of wind farms and gas generators.
$\underline{\square}$, $\overline{\square}$	Symbols of lower/upper boundaries of a variable.

Indices and Sets

t, b, l, i, s, w	Indices of time, buses, lines, generators, storage, and wind farms of the electrical system.
c, m, y, sg	Indices of compressors, nodes, suppliers, and storage devices of the gas transmission system.
q	Index of linearized triangles.
p	Index of natural gas pipelines.
x	Index of power to gas units.
f, r	Sets of forwarding and receiving nodes of natural gas pipelines.
β	Sets of gas-fired generators.
χ	Set of P2Gs coupled with gas storage sg.
$\kappa, \phi, \psi, \Upsilon$	Sets of generators, P2Gs, storage devices, and wind farms connected to bus b.
$\Gamma, \sigma, \Theta, \Lambda$	Sets of gas-fired generators, gas wells, P2Gs, and gas storage devices connected to node m.

Parameters

A^q, B^q, C^q	Constants of gas flow linearized triangles.
K_p	Coefficients of gas flow of pipelines (kcf/psi).
ML^l_b	Bus connectivity matrix of lines.
MP^p_m, MC^c_m	Nodal connectivity matrices of pipelines and Compressors.
$L^{EN}_{b,t}$	Electrical demands (MWh).
$QL^{fxd}_{m,t}$	Fixed loads of natural gas (kcf).
$\overline{P}, \underline{P}$	Limits of power generation of generators (MW).
$\overline{P^{WP}_{w,t}}$	Maximum available wind power (MW).
$\overline{E}^{EVS}_{s,t}$ $\underline{E}^{EVS}_{s,t}$	Boundaries of stored energy of electrical storage (MWh).
$\overline{QE}^{GVS}_{sg,t}$ $\underline{QE}^{GVS}_{sg,t}$	Limits of stored gas of gas storage (kcf).
SRu_i, SRd_i	Start-up/shut-down ramp rates (MW).
Ru_i, Rd_i	Ramp rate limits of power generators (MW).
S	Base power of the per-unit system (MVA).
SU_i, SD_i, N_i	Costs of start-up/shut-down, and no-load cost.
X_l	Reactance of electrical transmission lines (p.u).
$\eta^{EVS,ch/dis}_s$	Efficiencies of electrical storage facilities.
$\eta^{GVS,ch/dis}_{sg}$	Efficiencies of gas storage facilities.
η^{P2G}_x	Efficiency of P2Gs.
λ^{CP}	CP penalty for wind ($/MWh).
ρ^{GN}	Price of natural gas in the gas system ($/kcf).
Z^1, Z^2	Energy conversion coefficients of power-to-gas (kcf/MW) and gas-to-power (MW/kcf).

Variables

$e^{EVS}_{s,t}$	Stored energy of electrical storage (MWh).
$QE^{GVS}_{sg,t}$	Stored gas of gas storage (kcf).
$f(\cdot)$	Piecewise form of quadratic cost functions.
$I_{i,t}, st_{i,t}, sd_{i,t}$	Binary variables of online, start-up, shut-down statuses of generators.
$J^{EVS}_{s,t}$	Binary variable that indicates charging mode of electrical storage devices.
$J^{GVS}_{sg,t}$	Binary variable that indicates charging mode of gas storage devices.
$OF^{EN} OF^{GN}$	Objective variable of electrical and gas systems ($).
$p_{i,t}$	Electrical power of generators (MW).
$p^{P2G}_{x,t}$	Electrical power generation of P2Gs (MW).
$p^{EVS,ch/dis}_{s,t}$	Electrical power charging/discharging of electrical storage (MW).
$p^{WP}_{w,t}$	Electrical power generation of wind farms (MW).
$pc^{WP}_{w,t}$	Wind power curtailment (MW).
$f^{EN}_{l,t}$	Electrical power flow of transmission lines (MW/h).
$Q^{Gsgn}_{i,t}$	Natural gas consumption of gas generators (kcf/h).
$Q^{Sup}_{y,t}$	Natural gas supply by gas wells (kcf/h).
$Q^{P2G}_{x,t}$	Natural gas generation by P2Gs (kcf/h).
$Q^{GVS,ch/dis}_{sg,t}$	Natural gas charging/discharging by gas storage (kcf/h).
$Q^{Pipe}_{p,t}$	Gas flow of pipelines (kcf/h).
$Q^{Cmp}_{p,t}$	Gas flow of compressors (kcf/h).
θ^t_b	Voltage angle of electrical buses (rad).
$\pi_{m,t}$	Nodal pressure of the gas network (psi).
$\pi^q_{m,t}$	Piecewise nodal pressure of the gas network (psi).

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