Steady-State Optimal Power Flow in Integrated Electricity and Gas Transmission Systems With Hydrogen Injections

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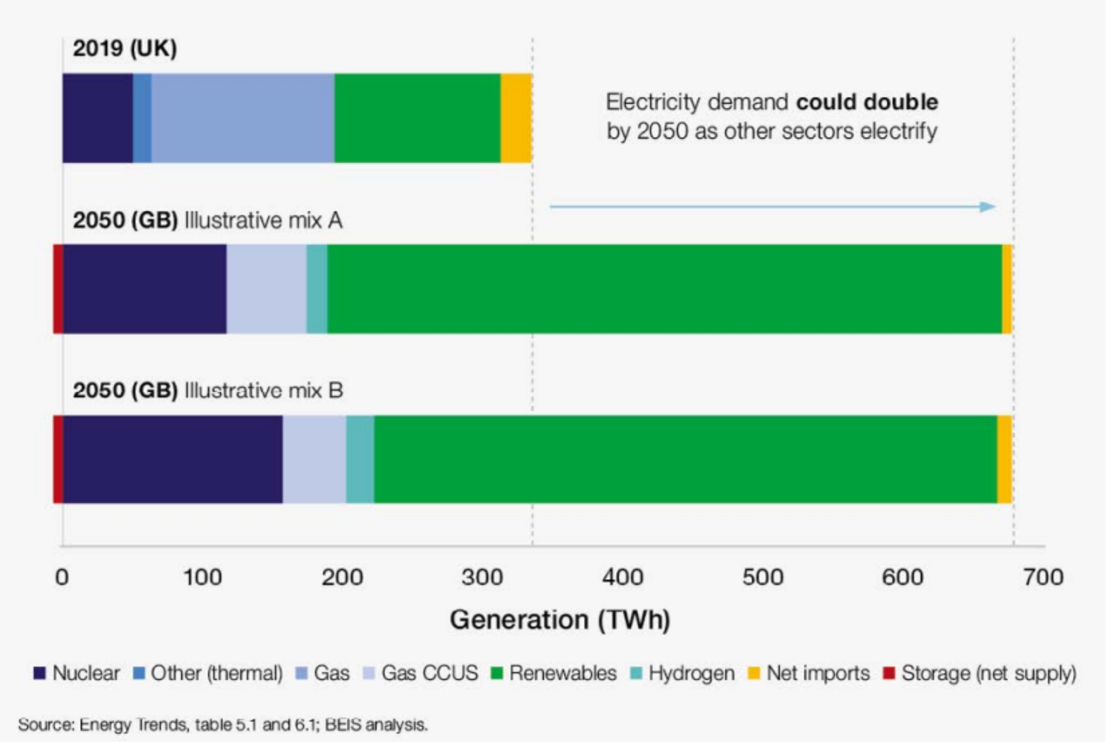
Introduction

- Hydrogen, as a clean and efficient energy source, has become an alternative to traditional fossil fuels, such as natural gas in many countries.

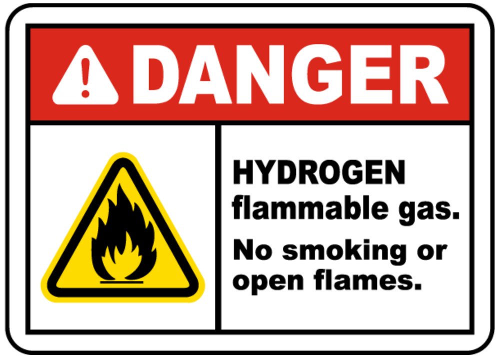


The UK government, as stated in its white paper, is working with the industry closely for achieving 5 GW of low-carbon hydrogen production capacity by 2030

Introduction

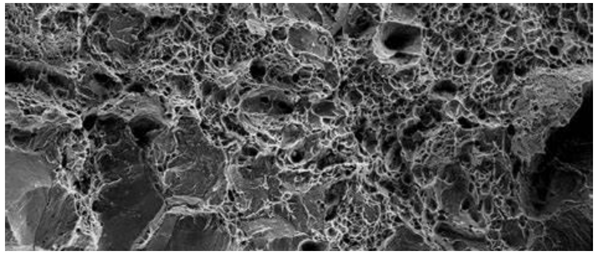
- blending the hydrogen into the gas pipelines can cause risks

fire hazards

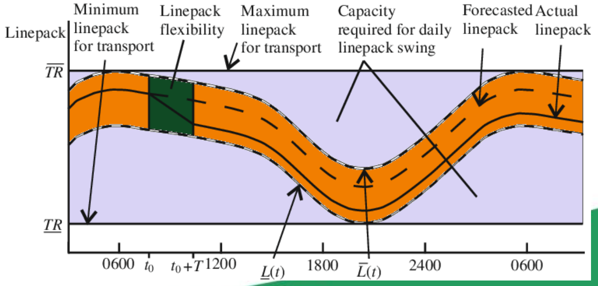


non-optimal combustions

Hydrogen embrittlement



change the gas flow pattern



Introduction

- Previous studies focus on the simulation of electricity and gas flow with hydrogen injections, while the operating condition optimization is not conducted.

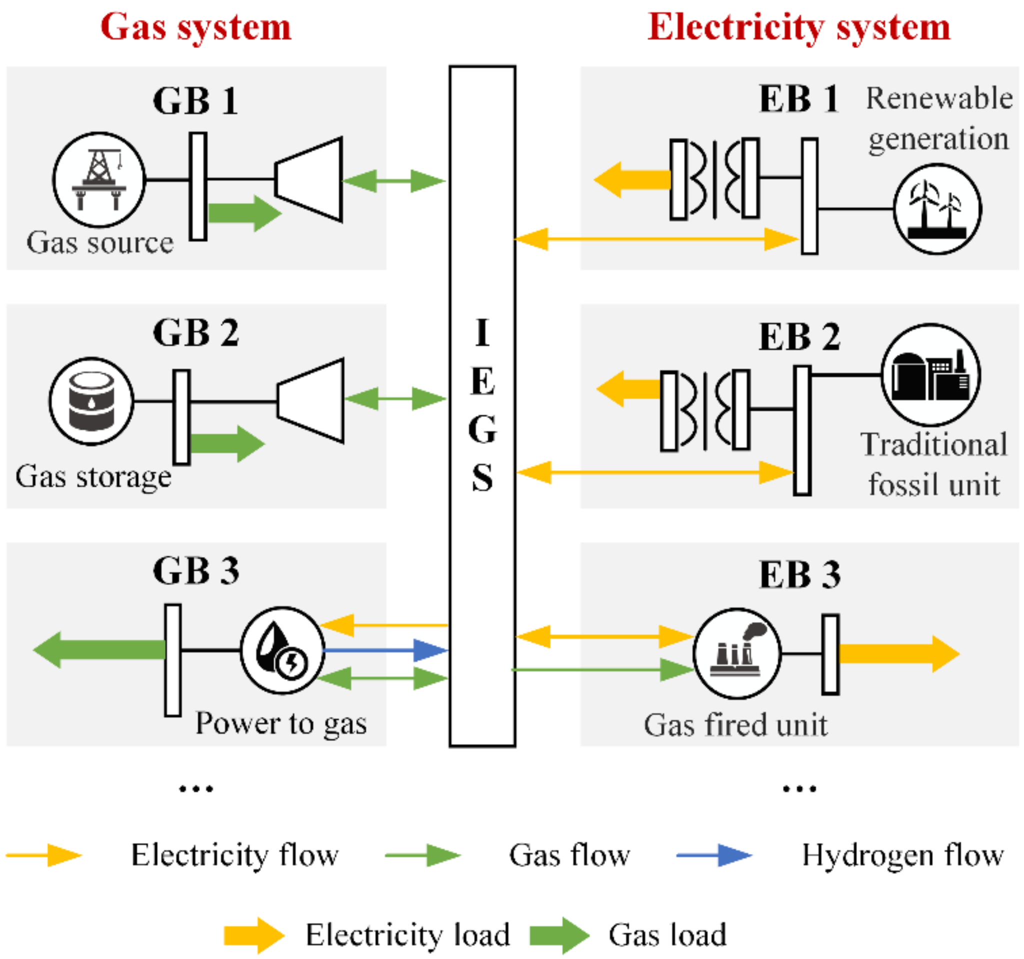
By this means, the operating condition of the IEGS can be aware, but can not provide the suggestions for optimization if the specified safety constraints are violated.

this paper proposes a steady-state optimal power flow technique for IEGS with distributed hydrogen injections.

- Firstly, the IEGS with hydrogen injections is specified. Then, the IEGS is modeled.
- More specifically, the gas demand and gas supply, as well as the nodal gas flow balance are formulated in terms of energy.
- The mixture of hydrogen and natural gas is also modeled. Moreover, the steady-state optimal power flow problem is formulated, considering the security constraints of the Wobbe index, the composition of hydrogen, and Gross Calorific Value (GCV) at various gas buses.
- Finally, the proposed technique is validated using IEEE 24-bus RTS and Belgium gas transmission system.

Contents

Model of the IEGS



Structure of the IEGS with hydrogen injections

The gas pipelines transport the gas from gas sources, including gas wells and gas storage at gas buses (GB) to various locations to satisfy the gas demand. The electricity and gas systems are coupled by gas-fired units (GFU) and PTGs. The GFU consumes the gas from the IEGS to generate electricity. PTG facilities consume electricity, usually from the surplus renewable generations, to produce hydrogen, or other synthetic gas, such as methane, which is injected into the gas pipeline for transportation and later use.

Model of the IEGS

- Model of the Gas System With Hydrogen Injections

Gas demand

Gas demand measured by energy

$$e_i^d = q_i^d GCV^{gas}$$

Gas demand measured by energy

Gross Calorific Value (GCV) of original natural gas

Gas source

$$e_i^s = GCV_i^s q_i^s$$

Gross Calorific Value (GCV) of the gas source

Model of the IEGS

- Model of the Gas System With Hydrogen Injections

Steady-state gas flow in a pipeline

Nodal gas pressure

$$\left(q_{i,j}\right)^2 = \frac{\pi^2 R^{air}}{64}\left(\frac{T^{STP}}{p^{STP}}\right)^2 \frac{\left(p_i^2 - p_j^2\right) D_{i,j}^5}{F_{i,j} S_{i,j} L_{i,j} T Z_{i,j}}$$

Gas flow rate in the pipeline

Model of the IEGS

- Model of the Gas System With Hydrogen Injections

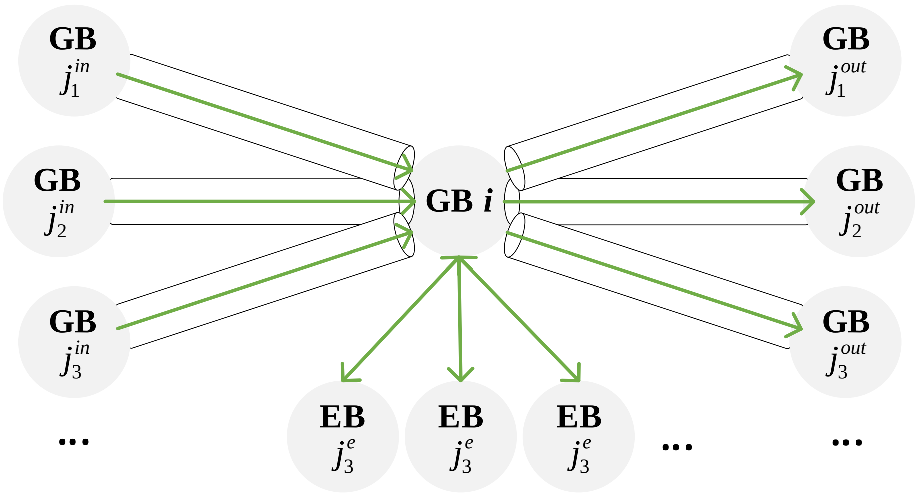
Nodal energy conservation in the energy form

$$e_i^s - e_i^d + \sum_{j^e \in \vartheta_i^e} \left(e_{j^e}^{ptg} - \sum_{j^e \in \Gamma_{j^e}^{gfu}} e_{j^e, j^{gfu}}^{gfu} \right) + \sum_{j^{in} \in \vartheta_i^{in}} e_{j^{in}, i} - \sum_{j^{out} \in \vartheta_i^{out}} e_{i, j^{out}} = 0$$

$$e_{j^{in}, i} = q_{j^{in}, i} GCV_{j^{in}}$$

$$e_{i, j^{out}} = q_{i, j^{out}} GCV_i$$

Nodal GCV of gas mixtures



The topological structure of GB and its connected pipelines

Model of the IEGS

- Model of the Gas System With Hydrogen Injections

Nodal gas mix

Molar fraction of hydrogen/gas:

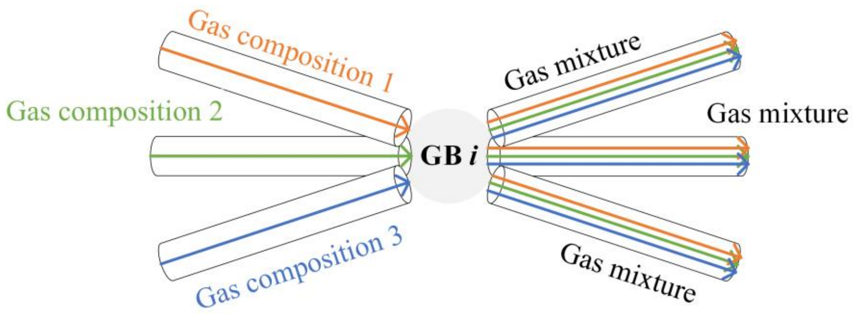
$$x_i^{hy} = \frac{\sum_{j^e \in \vartheta_i^e} q_{j^e}^{ptg} + \sum_{j^{in} \in \vartheta_i^{in}} x_{j^{in}}^{hy} q_{j^{in} i}}{\sum_{j^e \in \vartheta_i^e} q_{j^e}^{ptg} + q_i^s + \sum_{j^{in} \in \vartheta_i^{in}} q_{j^{in} i}} \qquad x_i^{gas} = \frac{q_i^s + \sum_{j^{in} \in \vartheta_i^{in}} x_{j^{in}}^{gas} q_{j^{in} i}}{\sum_{j^e \in \vartheta_i^e} q_{j^e}^{ptg} + q_i^s + \sum_{j^{in} \in \vartheta_i^{in}} q_{j^{in} i}}$$

Specific gravity:

$$S_{i,j} = \left(M^{hy} x_i^{hy} + M^{gas} x_i^{gas} \right) / M^{air}$$

Gross caloric value:

$$GCV_i = GCV^{hy} x_i^{hy} + GCV^{gas} x_i^{gas}$$



Nodal gas mixing process

Contents

- Introduction
- Model of the IEGS
- **Problem formulation**
- Case studies

Problem formulation

- Assumptions:

1) time constant; 2) ideal gas; 3) isothermal process

- Objective function

Gas purchasing cost

$$Min\ \ C^T = \sum_{i \in EB} \sum_{j \in \Gamma_i^{tfu}} cst_{i,j}\left(g_{i,j}^{tfu}\right) + \sum_{i \in GB} \rho_i q_i^s + \mu \sum_{i \in EB} q_i^{ptg}$$

Electricity generation cost

Subsidy for green hydrogen production

- State variables:

1) gas supply of gas sources ; 2) nodal gas pressure ; 3) electricity generation of traditional fossil unit ;

4) phase angle of voltage ; 5) electricity generation of GFU ; 6) hydrogen production of PTG ;

7) compositions of hydrogen and natural gas

Problem formulation

- Constraints
- Wobbe index

$$WI_i = GCV_i \ / \sqrt{S_{i,j}} \qquad \left| \frac{WI_i}{GCV^{gas} / \sqrt{M^{gas} / M^{air}}} - 1 \right| \le \xi_i$$

- upper limit for gas composition and GCV

$$0 \le x_i^{hy} \le \alpha_i \qquad \beta^{\min} \le GCV_i \le \beta^{\max}$$

- upper and lower boundaries for other variables

$$q_i^{s,\min} \le q_i^s \le q_i^{s,\max} \qquad 0 \le q_i^{ptg} \le q_i^{ptg,\max} \qquad 0 \le q_{i,j} \le q_{i,j}^{\max} \qquad \left| g_{i,j} \right| \le g_{i,j}^{\max}$$

$$x_i^{hy} + x_i^{gas} = 1 \qquad 0 \le x_i^{gas} \le 1 \qquad g_{i,j}^{gfu,\min} \le g_{i,j}^{gfu} \le g_{i,j}^{gfu,\max} \qquad g_{i,j}^{tfu,\min} \le g_{i,j}^{tfu} \le g_{i,j}^{tfu,\max}$$

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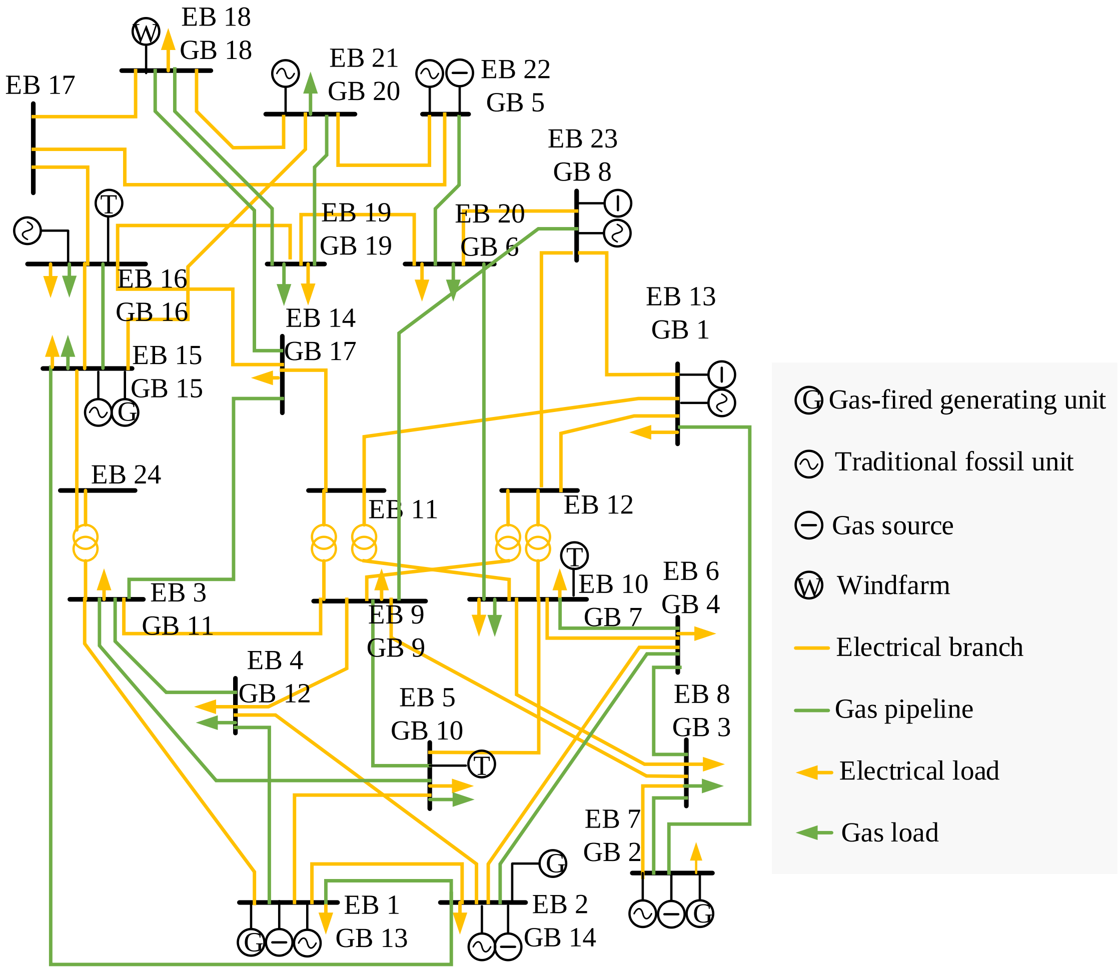
- **Case studies**

Case studies



- Parameter settings:

The test system consists of IEEE 24-bus RTS and the Belgium gas transmission system. The hydrogen production capacities of PTGs are set to 0.5 Mm^3/day. The GCVs of hydrogen and natural gas are 12.75 and 41.04 MJ/m3, respectively. The molecular weights of hydrogen, natural gas, and air are 2, 17.478, and 29 g/mol, respectively. The gas constant of air is 287 J/(kg*K). Temperature and pressure at STP are 288 K and 101325 Pa, respectively. The compressibility factor of gas is 0.8.

Case studies

Table 1. Gas production of gas sources

No	Located gas bus	Gas production (Mm³/day)
1	1	11.59
2	2	7.61
3	5	4.80
4	8	22.01
5	13	1.20
6	14	0.96

Table 2. Gas production of ptgs

No	Located gas bus	Located electricity bus	Gas production (Mm³/day)
1	7	10	0.02
2	10	5	0.50
3	16	16	0.50

Table 3. Gas flow of gas pipelines

Gas pipeline	From	To	Gas flow (MJ/m³)
1	1	2	11.59
2	2	3	19.21
3	3	4	15.29
4	5	6	4.60
5	6	7	0.27
6	7	4	-4.98
7	4	14	10.31
8	8	9	22.01
9	9	10	22.01
10	10	11	14.52
11	11	12	12.35
12	12	13	10.20
13	13	14	11.40
14	14	15	22.46
15	15	16	15.57
16	11	17	2.17
17	17	18	2.17
18	18	19	2.17
19	19	20	1.95

Table 4. Gas pressures and other parameters on gas buses

No	Gas pressure (bar)	Molar fraction of hydrogen	Molar fraction of natural gas	Specific gravity	GCV (MJ/m³)	Wobbe index (MJ/m³)
1	61.07	0.00	1.00	0.60	41.04	52.86
2	61.04	0.00	1.00	0.60	41.04	52.86
3	60.91	0.00	1.00	0.60	41.04	52.86
4	59.52	0.00	1.00	0.60	41.04	52.86
5	60.37	0.00	1.00	0.60	41.04	52.86
6	58.60	0.00	1.00	0.60	41.04	52.86
7	58.59	0.07	0.93	0.56	38.99	51.89
8	63.75	0.00	1.00	0.60	41.04	52.86
9	63.33	0.00	1.00	0.60	41.04	52.86
10	61.63	0.02	0.98	0.59	40.41	52.57
11	60.70	0.02	0.98	0.59	40.41	52.57
12	59.26	0.02	0.98	0.59	40.41	52.57
13	58.30	0.02	0.98	0.59	40.48	52.60
14	58.15	0.01	0.99	0.60	40.76	52.73
15	56.95	0.01	0.99	0.60	40.76	52.73
16	55.48	0.04	0.96	0.58	39.89	52.32
17	59.96	0.02	0.98	0.59	40.41	52.57
18	59.90	0.02	0.98	0.59	40.41	52.57
19	28.82	0.02	0.98	0.59	40.41	52.57
20	26.40	0.02	0.98	0.59	40.41	52.57

Thank you

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