Supplementary File For

“Coordinated Scheduling of Multiple Frequency Services in Electricity-Gas-Hydrogen Systems Based on Federated Warm Starts”

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This supplementary file intends to further investigate the scalability of the proposed SplitNN-based warm start framework on more complicated network topologies. Here, we construct an electricity-gas-hydrogen coupled system, consisting of a 118-bus power system, a 90-node natural gas system, as well as a 20-node hydrogen system. These three systems are interconnected through 5 gas-fired units (gas-to-power), 4 electrolyzers (power-to-hydrogen) and 3 methanation reactors (hydrogen-to-gas), forming a closed-loop energy conversion channel. Network parameters of the power subsystem are retrieved from MatPower [1]. Network parameters of the 90-node gas subsystem are retrieved from Ref. [2], and its network topology is shown in Fig. 1. Network parameters of the 20-node hydrogen system are retrieved and adapted from the gas network in Ref. [3]; its network topology is shown in Fig. 2.

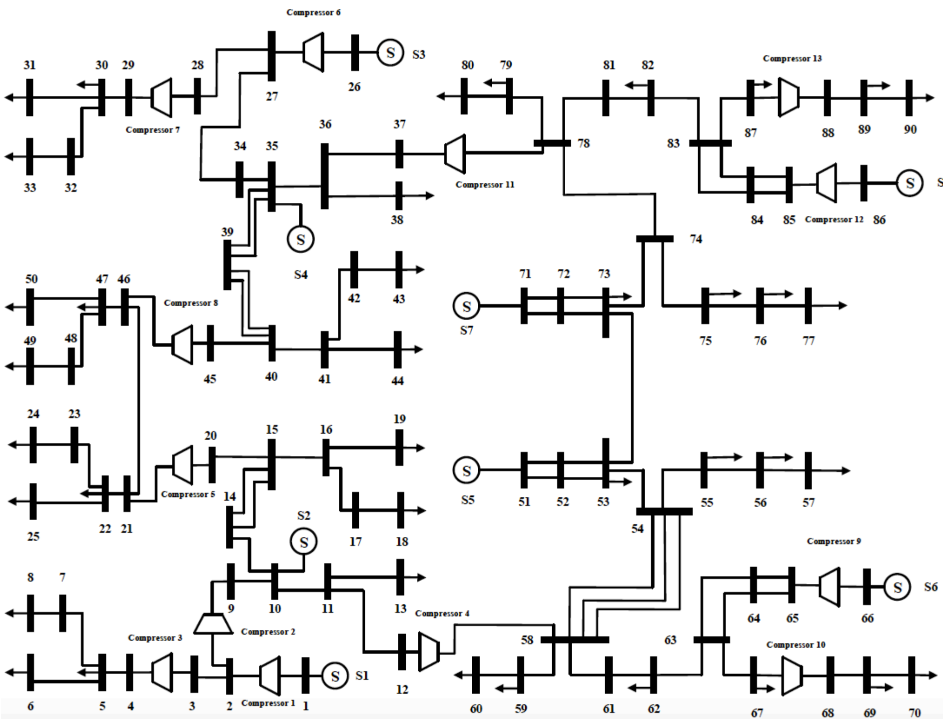

Figure 1: Network topology of the 90-node natural gas subsystem.

Consistent with the manuscript, we first quantify the transient frequency response characteristics of three different cases: the power system only (Case 1), the electricity-gas coupled system (Case 2), and the electricity-gas-hydrogen coupled system (Case 3). The results have been plotted in Fig. 3. One can see that all three cases manage to achieve the same level of RoCoF=0.125 Hz/s, as well as a quasi-steady state frequency of 49.8 Hz. However, the frequency nadir is significantly different from

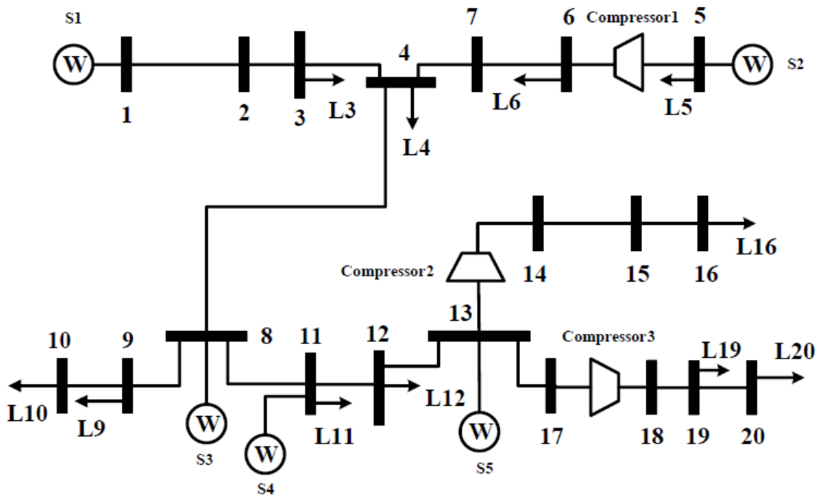

Figure 2: Network topology of the 20-node hydrogen subsystem.

each other. The electricity-gas-hydrogen coupled system, with the EFR reserves coming from gas and hydrgen systems, manages to achieve the highest nadir frequency of 49.79 Hz, outperforming the power system (49.70 Hz) and the electricity-gas coupled system (49.75 Hz). Its total reserve cost is also smaller by a degree of 25.2% and 7.5%, respectively.

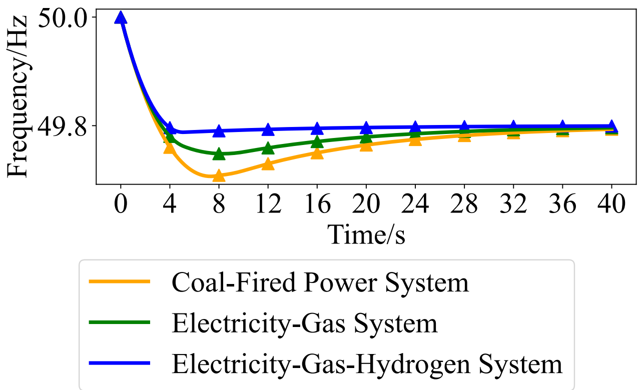

Figure 3: Transient frequency response of the three comparative cases, at 19:45 of the scheduling horizon.

Next, we intend to compare the differences of three McCormick methods in generating the warm starts. The four methods are, respectively: benchmark McCormick (Method 1), piecewise McCormick (Method 2), cold-start McCormick (Method 3) and warm-start McCormick (Method 4). The detailed results in terms of computational time, number of iterations, number of binary variables and warm start prediction gaps have been summarized in Table 1. One can find that, in line with the computational results of a medium-scale IES, warm-start McCormick envelopes do have the ability to control the relaxation gap down to an acceptable range (0.01 and 0.03, as compared to over 1.0 for benchmark methods). It is also capable of retaining only one round of iteration, thereby bringing the computational time to a minimum. On the other hand, the number of iterations for cold-start McCormick envelopes (Method 3) have been significantly rising; the piecewise McCormick envelope (Method 2), due to its annoying large number of binary variables, is not even able to control its computational time down to an acceptable level. All the above point to the further importance of

McCormick envelopes in large-scale IESs.

Table 1: Computation profiles of the McCormick envelope methods in the large-scale IES.

Method	**Num. Iteration**	**Time/s**	**Num. Binary**	**Gap** ($\boldsymbol{R}^t_{\text{Ele}}\boldsymbol{R}^t_{\text{Gen}}$)	**Gap** ($\boldsymbol{R}^t_{\text{Ele}}\boldsymbol{R}^t_{\text{Ele}}$)
Method 1	1	23.77	1,368	1.42	1.95
Method 2	———— Exceeds Acceptable Time Limits ————-				
Method 3	22	642.41	1,368	0.25	0.39
Method 4	1	23.70	1,368	0.01	0.03

References

[1] R. D. Zimmerman, C. E. Murillo-Sánchez, and D. Gan, "MATPOWER (Version X) User's Manual," *Cornell University, Ithaca, NY, USA*. [Online]. Available: http://www.pserc.cornell.edu/matpower/.

[2] L. Yang, Y. Xu, and H. Sun, "A dynamic linearization and convex relaxation-based approach for a natural gas optimal operation problem," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1802–1804, 2020.

[3] C. M. Correa-Posada and P. Sánchez-Martín, "Integrated power and natural gas model for energy adequacy in short-term operation," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3347-3355, 2015.