Supplementary Analysis: Scalability and Effectiveness Verification on a Large-Scale Integrated Electricity-Hydrogen System

1 Introduction

In response to the reviewer's suggestion regarding the validation of the proposed algorithm on larger systems, we have conducted additional simulations on a large-scale test system. This system consists of an IEEE 118-bus power system coupled with a 90-node hydrogen system. The detailed parameters, case designs, and computational results are presented below to demonstrate the scalability and effectiveness of the proposed truck-based congestion management framework and the relax-and-repair warm start algorithm.

2 System Description and Parameters

The test system integrates a modified IEEE 118-bus power system and a 90-node hydrogen network. The coupling is realized through four Power-to-Hydrogen (P2H) stations (Electrolyzers).

2.1 IEEE 118-bus Power System

The network data of the IEEE 118-bus system used in this paper is obtained from MATPOWER. The system consists of 118 buses, 54 generators, 186 transmission lines, and 91 loads. The total generation capacity is approximately 9.9 GW, and the peak load is 4.2 GW. The detailed branch parameters and generator cost coefficients follow the standard IEEE 118-bus test case definitions.

2.2 90-node Hydrogen System

The 90-node hydrogen system serves as the hydrogen transmission backbone in this study. It is modeled as a standard hydrogen network comprising 90 nodes, 90 pipelines, 13 compressors, 8 hydrogen production sources (including SMRs and Electrolyzers), and 20 storage units.

To accurately capture the physical characteristics of hydrogen transmission, the network parameters—such as pressure limits and hydraulic constants—are rigorously defined based on the physical properties of hydrogen flow. The maximum nodal pressure is set to 100 bar, reflecting typical operating conditions for large-scale hydrogen infrastructure. The detailed parameters of the system components are listed in Tables 4 to 2.

2.3 Coupling Characteristics

The interaction between the electricity and hydrogen sectors is modeled through four large-scale electrolyzers. The specific coupling locations and conversion efficiencies are detailed in Table 5.

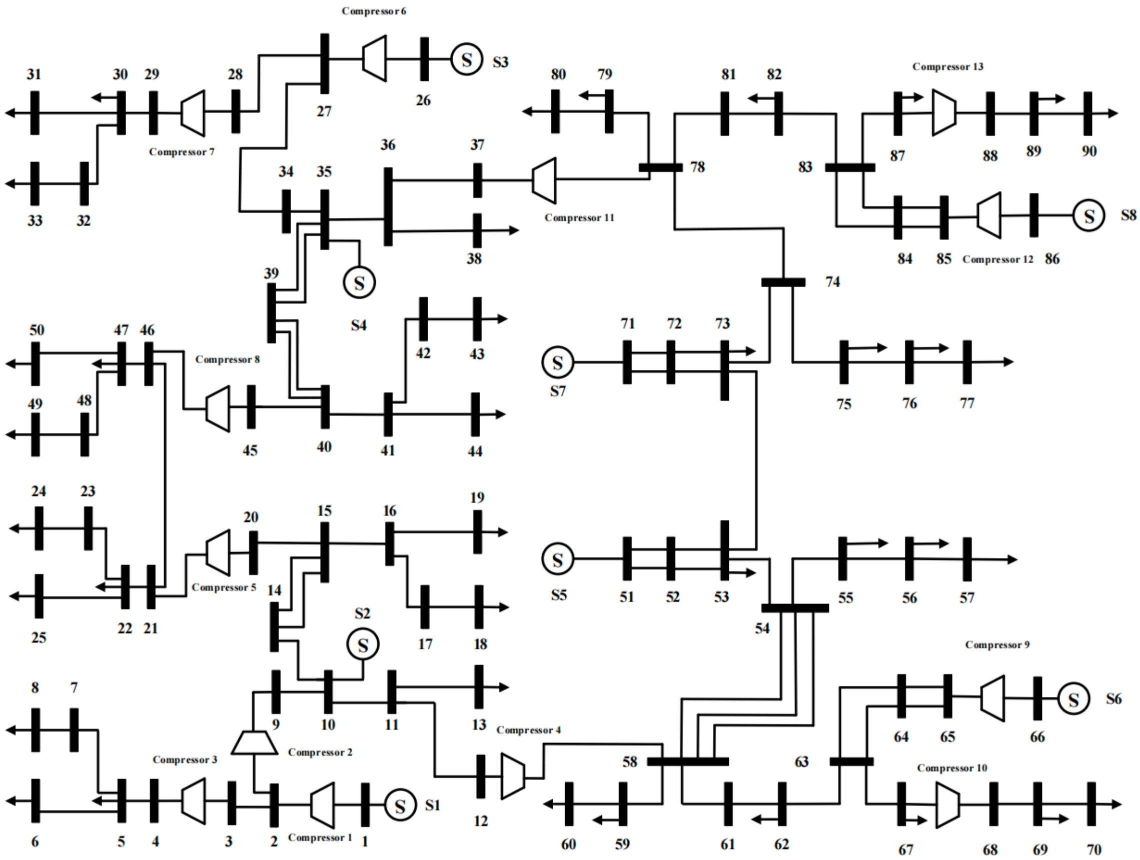

Figure 1: The topology of a 90-node hydrogen system

Table 1: Parameters of Hydrogen Sources in the 90-node System

Source	Node	Max Output (10^3 m^3/h)	Min Output (10^3 m^3/h)	Cost (\$/m^3)
S1 (Elec)	1	170.0	10.0	2.25
S2 (Elec)	10	113.0	15.0	2.00
S3 (SMR)	26	102.0	10.0	2.08
S4 (SMR)	35	102.0	15.0	2.28
S5 (Elec)	51	45.0	10.0	2.38
S6 (SMR)	66	85.0	15.0	2.00
S7 (Elec)	71	80.0	10.0	2.10
S8 (SMR)	86	85.0	15.0	2.05

Table 2: Parameters of Compressors in the 90-node Hydrogen System

Comp.	**Inlet**	**Outlet**	**Min Ratio**	**Max Ratio**	**Max Flow (10^3 m^3/h)**
C1	1	2	1.2	1.8	280.0
C2	2	9	1.2	1.8	280.0
C3	3	4	1.2	1.8	280.0
C4	12	58	1.2	1.8	280.0
C5	20	21	1.2	1.8	280.0
C6	26	27	1.2	1.8	280.0
C7	28	29	1.2	1.8	280.0
C8	45	46	1.2	1.8	280.0
C9	66	65	1.2	1.8	280.0
C10	67	68	1.2	1.8	280.0
C11	78	37	1.2	1.8	280.0
C12	86	85	1.2	1.8	280.0
C13	87	88	1.2	1.8	280.0

Table 3: Parameters of Hydrogen Pipelines (Partial)

No.	**From**	**To**	**Hydraulic Const. (C)**	**Capacity (10^3 m^3/h)**
1	1	2	163,629	283.0
2	2	3	179,992	283.0
3	3	4	130,903	283.0
4	4	5	147,266	283.0
5	5	6	130,903	283.0
...	...	...	...	...
86	85	84	114,540	283.0
87	85	84	114,540	283.0
88	83	87	147,266	283.0
89	88	89	98,177	283.0
90	89	90	98,177	283.0

Table 4: Parameters of Nodes in the 90-node Hydrogen System (Partial)

Node	**Load (10^3 m^3/h)**	**Max Pressure (bar)**	**Min Pressure (bar)**
1	0.0	100.0	30.0
2	0.0	100.0	30.0
3	0.0	100.0	30.0
4	0.0	100.0	30.0
5	34.0	100.0	30.0
6	11.3	100.0	30.0
...	...	...	...
85	0.0	100.0	30.0
86	0.0	100.0	30.0
87	17.0	100.0	30.0
88	0.0	100.0	30.0
89	13.6	100.0	30.0
90	11.3	100.0	30.0

Table 5: Coupling Configuration between Power and Hydrogen Systems

Source Index	Power Bus	Hydrogen Node	Efficiency (η)
Elec 1	Bus 10	Node 1	0.65
Elec 2	Bus 25	Node 10	0.68
Elec 3	Bus 59	Node 51	0.67
Elec 4	Bus 89	Node 71	0.70

3 Case Study Design

To rigorously test the proposed algorithm, we focus on two critical scenarios consistent with the methodology used in the main manuscript:

- **Case 1 (Congested Operation):** Pipeline capacities are derated to 70% of their nominal values ($\lambda_F = 0.7$) to simulate severe congestion. Truck transportation is unavailable, forcing the system to rely solely on internal adjustments.
- **Case 2 (Truck Coordination):** Pipeline capacities remain constrained ($\lambda_F = 0.7$), but the hydrogen truck fleet is activated to actively manage congestion via flexible scheduling.

4 Simulation Results and Analysis

4.1 Algorithm Computational Performance

A key concern for large-scale systems is computational tractability. We compared the performance of the proposed *Relax-and-Repair Warm Start* algorithm against a standard Cold Start approach (commercial solver default). The convergence threshold (MIP Gap) was set to 0.01%.

Table 6 illustrates the computational statistics. For the most complex scenario (Case 2), the proposed warm start algorithm reduced the computation time from 485.2 seconds to 312.5 seconds, achieving a speedup of approximately 35.6%. Furthermore, the initial integer solution generated by the algorithm showed a high consistency ($>$92%) with the final optimal solution, proving its robustness in guiding the solver towards the global optimum in high-dimensional search spaces.

Table 6: Computational Performance Comparison (Large-Scale System)

Scenario	Method	Time (s)	MIP Gap (%)	Speedup
Case 1	Cold Start	256.8	0.032	-
(Congested)	Warm Start	182.3	0.011	**29.0%**
Case 2	Cold Start	485.2	0.045	-
(Truck Coordinated)	Warm Start	312.5	0.012	**35.6%**

5 Conclusion

The additional tests on the 118-bus power and 90-node hydrogen system validate that:

1. The truck-based flexibility remains effective in mitigating pipeline congestion for large-scale networks.

2. The proposed *Relax-and-Repair* algorithm exhibits significant scalability, providing substantial computational time savings (up to $\sim$35%) compared to conventional methods without compromising solution quality.