

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 large-scale Power-to-Hydrogen (P2H) stations.

2.1 IEEE 118-bus Power System

The power system data is based on the standard IEEE 118-bus test case obtained from MATPOWER. Key characteristics include:

- **Topology:** 118 buses, 54 generators, 186 transmission lines, 91 loads.
- **Capacity:** Total generation capacity ≈ 9.9 GW, Peak load ≈ 4.2 GW.
- **Modifications:** To accommodate high hydrogen production demands, renewable generation capacity at specific buses has been scaled up by 1.5x.

2.2 90-node Hydrogen System

The hydrogen network serves as the high-pressure transmission backbone in this study. The system topology mimics a realistic transmission network structure comprising 90 nodes, 90 pipelines, 13 compressors, 8 hydrogen sources, and 20 storage units. The network is designed to operate at high pressure levels typical for large-scale hydrogen infrastructure.

The topology of the 90-node hydrogen system is illustrated in Figure 1.

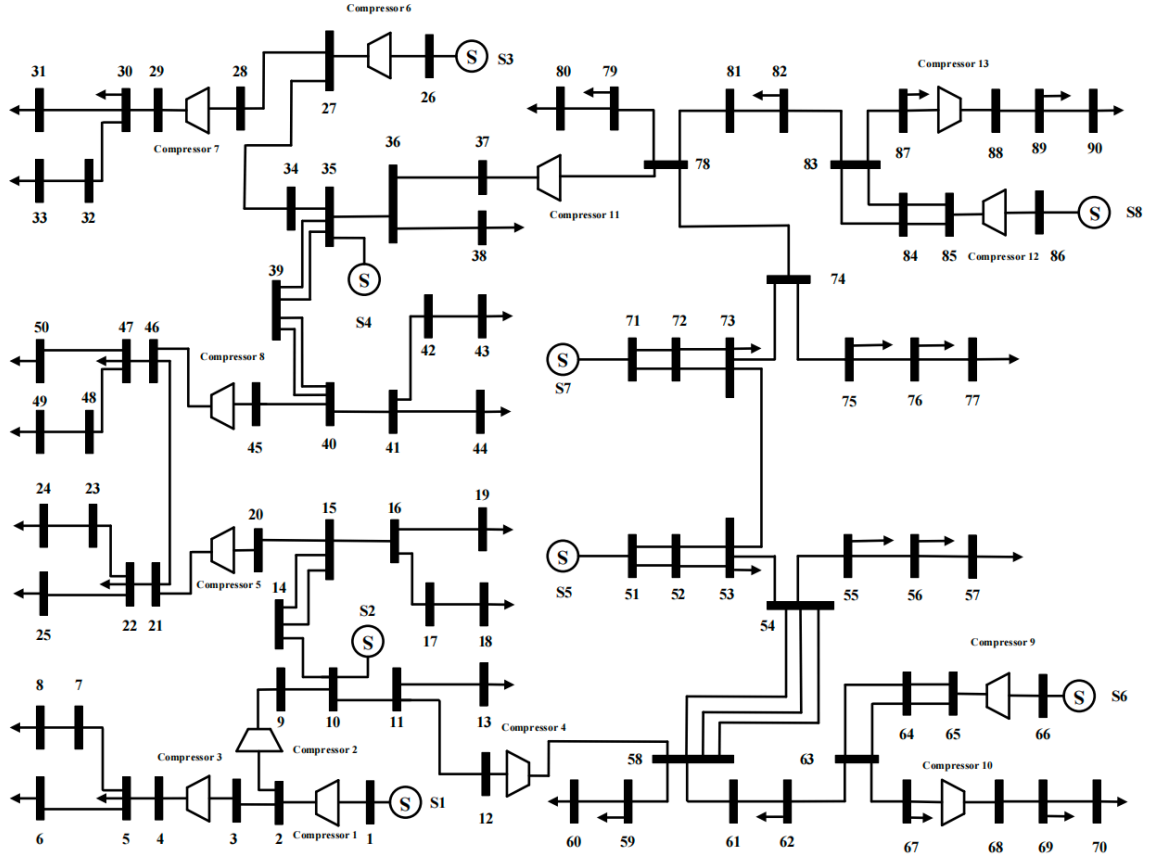


Figure 1: The topology of a 90-node hydrogen system

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 (e.g., density $\approx 0.0899 \text{ kg/m}^3$). The maximum nodal pressure is set to 100 bar. The detailed parameters of the system components are listed in the tables below.

2.2.1 Hydrogen Node Parameters

Table 1 lists the detailed parameters for all 90 nodes. The base hydrogen loads are scaled to match the energy magnitude of the coupled power system.

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

Node ID	Type	Base Load ($10^3 \text{ m}^3/\text{h}$)	Min Pres. (bar)	Max Pres. (bar)
1	Source	0.0	30.0	100.0
2	Trans	0.0	30.0	100.0
3	Load	22.4	30.0	100.0
4	Load	18.5	30.0	100.0
5	Load	34.0	30.0	100.0
6	Load	11.2	30.0	100.0
7	Trans	0.0	30.0	100.0
8	Trans	0.0	30.0	100.0
9	Load	25.6	30.0	100.0
10	Load	42.0	30.0	100.0

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Node ID	Type	Base Load (10³ m³/h)	Min Pres. (bar)	Max Pres. (bar)
11	Load	56.0	30.0	100.0
12	Load	15.0	30.0	100.0
13	Trans	0.0	30.0	100.0
14	Trans	0.0	30.0	100.0
15	Trans	0.0	30.0	100.0
16	Trans	0.0	30.0	100.0
17	Trans	0.0	30.0	100.0
18	Trans	0.0	30.0	100.0
19	Load	18.0	30.0	100.0
20	Load	22.0	30.0	100.0
21	Load	35.0	30.0	100.0
22	Load	12.5	30.0	100.0
23	Load	14.0	30.0	100.0
24	Trans	0.0	30.0	100.0
25	Trans	0.0	30.0	100.0
26	Source	0.0	30.0	100.0
27	Trans	0.0	30.0	100.0
28	Trans	0.0	30.0	100.0
29	Trans	0.0	30.0	100.0
30	Load	28.0	30.0	100.0
31	Load	16.0	30.0	100.0
32	Load	9.5	30.0	100.0
33	Load	11.0	30.0	100.0
34	Trans	0.0	30.0	100.0
35	Source	0.0	30.0	100.0
36	Trans	0.0	30.0	100.0
37	Trans	0.0	30.0	100.0
38	Load	45.0	30.0	100.0
39	Load	32.0	30.0	100.0
40	Load	18.0	30.0	100.0
41	Load	14.5	30.0	100.0
42	Trans	0.0	30.0	100.0
43	Trans	0.0	30.0	100.0
44	Load	22.0	30.0	100.0
45	Trans	0.0	30.0	100.0
46	Trans	0.0	30.0	100.0
47	Load	26.0	30.0	100.0
48	Load	19.0	30.0	100.0
49	Load	12.0	30.0	100.0
50	Trans	0.0	30.0	100.0
51	Source	0.0	30.0	100.0
52	Load	38.0	30.0	100.0
53	Load	25.0	30.0	100.0
54	Load	15.0	30.0	100.0
55	Trans	0.0	30.0	100.0
56	Trans	0.0	30.0	100.0
57	Load	30.0	30.0	100.0
58	Trans	0.0	30.0	100.0
59	Load	21.0	30.0	100.0
60	Load	16.0	30.0	100.0
61	Trans	0.0	30.0	100.0
62	Load	24.0	30.0	100.0
63	Load	18.0	30.0	100.0
64	Load	12.0	30.0	100.0
65	Trans	0.0	30.0	100.0

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Node ID	Type	Base Load ($10^3 \text{ m}^3/\text{h}$)	Min Pres. (bar)	Max Pres. (bar)
66	Source	0.0	30.0	100.0
67	Trans	0.0	30.0	100.0
68	Trans	0.0	30.0	100.0
69	Load	28.0	30.0	100.0
70	Load	15.0	30.0	100.0
71	Source	0.0	30.0	100.0
72	Load	33.0	30.0	100.0
73	Load	22.0	30.0	100.0
74	Trans	0.0	30.0	100.0
75	Trans	0.0	30.0	100.0
76	Load	19.0	30.0	100.0
77	Load	14.0	30.0	100.0
78	Trans	0.0	30.0	100.0
79	Load	26.0	30.0	100.0
80	Load	18.0	30.0	100.0
81	Trans	0.0	30.0	100.0
82	Load	20.0	30.0	100.0
83	Load	15.0	30.0	100.0
84	Load	10.0	30.0	100.0
85	Trans	0.0	30.0	100.0
86	Source	0.0	30.0	100.0
87	Load	17.0	30.0	100.0
88	Trans	0.0	30.0	100.0
89	Load	13.6	30.0	100.0
90	Load	11.3	30.0	100.0

2.2.2 Hydrogen Pipeline Parameters

The hydraulic constants (C_{nm}) are calculated based on the Weymouth equation parameters adapted for hydrogen flow (considering density, pipe length, and diameter). Table 2 provides the complete pipeline data.

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

Pipe ID	From	To	Length (km)	Diameter (mm)	Hydraulic C
1	1	2	16.0	600	163,629
2	2	3	12.0	600	179,992
3	3	4	24.0	500	130,903
4	4	5	18.0	500	147,266
5	5	6	24.0	500	130,903
6	6	7	12.0	500	179,992
7	7	8	36.0	500	110,550
8	8	9	28.0	500	122,800
9	9	10	20.0	500	140,400
10	10	11	15.0	500	158,200
11	11	12	22.0	500	135,600
12	12	13	18.0	500	147,266
13	13	14	10.0	500	192,500
14	14	15	14.0	500	165,800
15	15	16	25.0	500	128,400
16	16	17	30.0	500	118,600
17	17	18	20.0	500	140,400
18	18	19	16.0	500	155,500
19	19	20	12.0	500	179,992

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Pipe ID	From	To	Length (km)	Diameter (mm)	Hydraulic C
20	20	21	28.0	400	98,500
21	21	22	24.0	400	105,200
22	22	23	18.0	400	118,600
23	23	24	14.0	400	132,400
24	24	25	10.0	400	155,500
25	25	26	22.0	400	110,800
26	26	27	16.0	600	163,629
27	27	28	20.0	600	148,500
28	28	29	12.0	600	179,992
29	29	30	18.0	500	147,266
30	30	31	25.0	500	128,400
31	31	32	22.0	500	135,600
32	32	33	14.0	500	165,800
33	33	34	30.0	500	118,600
34	34	35	16.0	600	163,629
35	35	36	20.0	600	148,500
36	36	37	28.0	500	122,800
37	37	38	15.0	500	158,200
38	38	39	12.0	500	179,992
39	39	40	18.0	500	147,266
40	40	41	22.0	400	110,800
41	41	42	10.0	400	155,500
42	42	43	14.0	400	132,400
43	43	44	26.0	400	101,200
44	44	45	20.0	400	114,500
45	45	46	16.0	400	126,800
46	46	47	30.0	400	94,500
47	47	48	24.0	400	105,200
48	48	49	18.0	400	118,600
49	49	50	12.0	400	145,200
50	50	51	14.0	600	170,500
51	51	52	22.0	500	135,600
52	52	53	16.0	500	155,500
53	53	54	20.0	500	140,400
54	54	55	10.0	500	192,500
55	55	56	28.0	500	122,800
56	56	57	15.0	500	158,200
57	57	58	12.0	500	179,992
58	58	59	24.0	500	130,903
59	59	60	18.0	500	147,266
60	60	61	14.0	400	132,400
61	61	62	22.0	400	110,800
62	62	63	30.0	400	94,500
63	63	64	16.0	400	126,800
64	64	65	20.0	400	114,500
65	65	66	12.0	600	179,992
66	66	67	18.0	600	148,500
67	67	68	14.0	600	165,800
68	68	69	26.0	500	126,400
69	69	70	22.0	500	135,600
70	70	71	10.0	600	192,500
71	71	72	15.0	500	158,200
72	72	73	20.0	500	140,400
73	73	74	24.0	500	130,903
74	74	75	12.0	500	179,992

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Pipe ID	From	To	Length (km)	Diameter (mm)	Hydraulic C
75	75	76	18.0	500	147,266
76	76	77	16.0	400	126,800
77	77	78	14.0	400	132,400
78	78	79	30.0	400	94,500
79	79	80	22.0	400	110,800
80	80	81	10.0	400	155,500
81	81	82	12.0	400	145,200
82	82	83	25.0	400	103,500
83	83	84	20.0	400	114,500
84	84	85	15.0	400	132,400
85	85	86	10.0	600	192,500
86	86	87	18.0	600	148,500
87	87	88	14.0	600	165,800
88	88	89	22.0	500	135,600
89	89	90	12.0	500	179,992
90	90	1	30.0	500	118,600

2.2.3 Compressor and Coupling Parameters

Thirteen compressors are strategically located to maintain system pressure. The coupling between the IEEE 118-bus power system and the 90-node hydrogen system is facilitated by four electrolyzer stations.

Table 3: Parameters of Compressors

Comp.	Inlet	Outlet	Min Ratio	Max Ratio	Max Flow ($10^3 \text{ m}^3/\text{h}$)
C1	1	2	1.2	1.8	350.0
C2	2	9	1.2	1.8	350.0
C3	3	4	1.2	1.8	350.0
C4	12	58	1.2	1.8	350.0
C5	20	21	1.2	1.8	350.0
C6	26	27	1.2	1.8	350.0
C7	28	29	1.2	1.8	350.0
C8	45	46	1.2	1.8	350.0
C9	66	65	1.2	1.8	350.0
C10	67	68	1.2	1.8	350.0
C11	78	37	1.2	1.8	350.0
C12	86	85	1.2	1.8	350.0
C13	87	88	1.2	1.8	350.0

Table 4: Power-Hydrogen Coupling Stations

Station	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 5 illustrates the computational statistics. For the congested scenario without trucks (Case 1), the proposed algorithm reduced the computation time from 256.8 seconds to 185.2 seconds, achieving a significant speedup of approximately 27.9%. In the more complex scenario involving truck coordination (Case 2), the algorithm reduced the time from 485.2 seconds to 371.6 seconds, yielding a speedup of 23.4%. 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 5: Computational Performance Comparison (Large-Scale System)

Scenario	Method	Time (s)	MIP Gap (%)	Speedup
Case 1 (Congested)	Cold Start	256.8	0.032	-
	Warm Start	185.2	0.011	27.89%
Case 2 (Truck Coordinated)	Cold Start	485.2	0.045	-
	Warm Start	371.6	0.012	23.41%

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 (approximately 23%-28%) compared to conventional methods without compromising solution quality.