Sector coupling via hydrogen to lower the cost of energy system decarbonization: Supplementary Information

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Supplementary Figures

Figure S1. Hourly hydrogen refuelling profile normalized based on the mean

Figure S2. Natural gas consumption breakdowns in H2 and power sectors.

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Figure S3. Total system cost and optimal generation and storage capacity mixes in the power and H\textsubscript{2} sectors with varying number of representative weeks, given $100/\text{tonne}$ carbon price, 1 million tonne/year hydrogen demand, and $300/\text{kW}$ electrolyzer cost. (a) Total system cost and H\textsubscript{2} generation capacity; (b) Power generation capacity. SMR: steam methane reformer; LH\textsubscript{2}: Liquid H\textsubscript{2}; GH\textsubscript{2}: Gaseous H\textsubscript{2}. 
Figure S4. The amounts of transported H₂ per year via different transport modes under different pipeline cost scenarios and pipeline pressures. (a) 100 bar inlet pressure; (b) 80 bar inlet pressure. The baseline 100 bar pipeline parameters are shown in Table 3 (corresponding to 100% pipeline cost factor). For 80 bar pipeline, the baseline unit capacity is 4.3 tonne/hour, and the baseline capital cost is 1.58 million $/unit. The H₂ demand is 1 million tonne/year. LH₂: Liquid H₂; GH₂: Gaseous H₂.
Figure S5. Differences in the optimal power system capacity mix and variable renewable energy (VRE) curtailment between energy systems with and without conversions between power to H\textsubscript{2} under various CO\textsubscript{2} price and FCEV penetration scenarios. (a) Differences in the optimal power system capacity mix; (b) Differences in the VRE curtailment. The carbon price varies from 0 to 1000 $/tonne (upper x label). The hydrogen demand varies from 1 to 4 million tonne/year (lower x label). The capital cost of electrolyzer is assumed to be $300/kW\textsubscript{e}. In (b), the VRE curtailment reductions are calculated as the differences in the curtailment percentages between energy systems with and without conversions between power to H\textsubscript{2} in each CO\textsubscript{2} price and FCEV penetration scenario.
Figure S6. Differences in the total system cost and CO2 emission between energy systems with and without conversions between power to H2 under various CO2 price and hydrogen demand scenarios. The hydrogen demand varies from 1 to 20 million tonne/year (upper x label). The carbon price varies from 0 to 1000 $/tonne (lower x label). The capital cost of electrolyzer is assumed to be $300/kW_e. The cost savings are shown as percentages of the total system costs in each CO2 price and hydrogen demand scenario, while the emission reductions are shown as percentages of the CO2 emission in the case with $0/tonne CO2 and respective hydrogen demand level.
Figure S7. Differences in the optimal power system generation mix, total system cost, and CO₂ emission between energy systems with and without conversions between power to H₂ under various CO₂ price and hydrogen demand scenarios, considering non-combustion GHG emissions from natural gas. (a) Differences in the optimal power system generation mix; (b) Differences in the total system cost and CO₂ emission. The carbon price varies from 0 to 1000 $/tonne (upper x label). The hydrogen demand varies from 1 to 4 million tonne/year (lower x label). The capital cost of electrolyzer is assumed to be $300/kWₑ. In (b), the cost savings are shown as percentages of the total system costs in each CO₂ price and hydrogen demand scenario, while the emission reductions are shown as percentages of the CO₂ emission in the case with $0/tonne CO₂, $300/kW electrolyzer, and 1 million tonne/year hydrogen demand.
Figure S8. Optimal generation and storage capacity mixes and CO$_2$ emissions in the power and H$_2$ sectors under various CO$_2$ price and electrolysis cost scenarios in U.S. Northeast, considering non-combustion GHG emissions from natural gas. Technologies that are not cost-competitive are not shown. (a) H$_2$ generation capacity; (b) Power generation capacity; (c) H$_2$ generation per year; (d) Electricity generation or electrical storage energy discharge per year; (e) Chemical/electrochemical energy storage capacity in power and H$_2$ sectors; (f) CO$_2$ emissions in power and H$_2$ sectors. The hydrogen demand is 1 million tonne/year. The carbon price varies from 0 to 1000 $/tonne (upper x label). The electrolyzer cost varies from $700/kW to $300/kW (lower x label). SMR: steam methane reformer; LH2: Liquid H$_2$; GH2: Gaseous H$_2$. 
Figure S9. Optimal generation and storage capacity mixes and CO\textsubscript{2} emissions in the power and H\textsubscript{2} sectors under various CO\textsubscript{2} price and electrolysis cost scenarios in U.S. Northeast, given the current cost of SMR with CCS. (a) H\textsubscript{2} generation capacity; (b) Power generation capacity; (c) H\textsubscript{2} generation per year; (d) Electricity generation or electrical storage energy discharge per year; (e) Chemical/electrochemical energy storage capacity in power and H\textsubscript{2} sectors; (f) CO\textsubscript{2} emissions in power and H\textsubscript{2} sectors. The hydrogen demand is 1 million tonne/year. The carbon price varies from 0 to 1000 S/tonne (upper x label). The electrolyzer cost varies from $700/kW to $300/kW (lower x label). The capital cost of SMR with CCS is $1680/kW\textsubscript{H2}. SMR: steam methane reformer; LH2: Liquid H\textsubscript{2}; GH2: Gaseous H\textsubscript{2}.
**Supplementary Tables**

**Table S1. Additional Parameters of the DOLPHYN model**

| Parameter                                | Value               |
|------------------------------------------|---------------------|
| Discount rate                            | 5.4%                |
| Power transmission expansion cost        | 1,600/MW-mile       |
| Power transmission loss                  | 1%/100 miles        |
| Value of lost load (electricity)         | $20,000/MWh         |
| Value of lost load (hydrogen)            | $1,000/kg           |
| Gas Price                                | $5.4/MMBTU          |
| CO₂ transportation and storage cost      | $20/tonne           |

**Table S2. Parameters of Existing power transfer capacity (High Voltage AC) between various model zones. Zone 7 represents Canada. For each line, transmission losses are computed based on 1% per 100 miles loss factor (Table S1) and the distance between the centroid of the two zones**

| Line     | Max Power Flow (MW) | Line Distance (km) | Transmission Loss Percentage |
|----------|----------------------|--------------------|------------------------------|
| Zone 1-2 | 2000                 | 317                | 3.17%                        |
| Zone 2-3 | 2950                 | 199                | 1.99%                        |
| Zone 3-4 | 760                  | 99                 | 0.99%                        |
| Zone 4-5 | 1528                 | 216                | 2.16%                        |
| Zone 3-5 | 600                  | 158                | 1.58%                        |
| Zone 2-5 | 800                  | 179                | 1.79%                        |
| Zone 5-6 | 5400                 | 186                | 1.86%                        |
| Zone 2-6 | 150                  | 340                | 3.40%                        |
| Zone 6-7 | 2600                 | 0                  | 2.40%                        |
| Zone 2-7 | 1650                 | 0                  | 2.40%                        |
| Zone 1-7 | 800                  | 0                  | 2.40%                        |

**Table S3. Inter-Zone Distances of the Six Zones in the U.S. Northeast for Trucks and Pipelines (mile).**

| Zone | 1   | 2   | 3   | 4   | 5   | 6   |
|------|-----|-----|-----|-----|-----|-----|
| 1    | 0   | 317 | 504 | 602 | 487 | 608 |
| 2    | 317 | 0   | 199 | 297 | 179 | 340 |
| 3    | 504 | 199 | 0   | 99  | 158 | 333 |
| 4    | 602 | 297 | 99  | 0   | 216 | 358 |
| 5    | 487 | 179 | 158 | 216 | 0   | 186 |
| 6    | 608 | 340 | 333 | 358 | 186 | 0   |
Table S4. Power capacities for the results of Figure 3. All capacity units are GW.

| Electrolyser Cost | Carbon Price | Pumped Hydro | Hydro | PV | Wind | Nuclear | CCGT | CCGT w/ CCS | OCGT | Li-ion Battery |
|-------------------|--------------|--------------|-------|----|------|---------|------|-------------|------|----------------|
| $700/kW           | 0 $/tonne    | 2.8          | 10.5  | 23.8 | 36.7 | 0       | 18.4 | 0           | 6.9  | 4.9            |
|                   | 50 $/tonne   | 2.8          | 10.5  | 30.5 | 41.8 | 0       | 15.9 | 0           | 5.6  | 7.3            |
|                   | 100 $/tonne  | 2.8          | 10.5  | 30.8 | 46.1 | 0       | 15.0 | 0           | 5.1  | 8.1            |
|                   | 1000 $/tonne | 2.8          | 10.5  | 44.6 | 58.6 | 0       | 4.8  | 0           | 12.5 |                |
| $500/kW           | 0 $/tonne    | 2.8          | 10.5  | 23.8 | 36.7 | 0       | 18.4 | 0           | 6.9  | 4.9            |
|                   | 50 $/tonne   | 2.8          | 10.5  | 30.5 | 43.2 | 0       | 15.9 | 0           | 5.8  | 6.8            |
|                   | 100 $/tonne  | 2.8          | 10.5  | 33.4 | 49.3 | 0       | 14.5 | 0           | 4.6  | 8.1            |
|                   | 1000 $/tonne | 2.8          | 10.5  | 44.9 | 58.2 | 0       | 4.7  | 0           | 12.3 |                |
| $300/kW           | 0 $/tonne    | 2.8          | 10.5  | 23.8 | 37.0 | 0       | 18.4 | 0           | 6.8  | 4.9            |
|                   | 50 $/tonne   | 2.8          | 10.5  | 32.2 | 45.8 | 0       | 15.7 | 0           | 5.3  | 7.0            |
|                   | 100 $/tonne  | 2.8          | 10.5  | 34.0 | 49.9 | 0       | 14.4 | 0           | 4.4  | 8.0            |
|                   | 1000 $/tonne | 2.8          | 10.5  | 44.5 | 57.9 | 0       | 4.8  | 0           | 11.8 |                |

Table S5. Capacity factors of power sector infrastructures for the results of Figure 3.

| Electrolyser Cost | Carbon Price | Pumped Hydro | Hydro | PV | Wind | Nuclear | CCGT | CCGT w/ CCS | OCGT | Li-ion Battery |
|-------------------|--------------|--------------|-------|----|------|---------|------|-------------|------|----------------|
| $700/kW           | 0 $/tonne    | 0.13         | 0.56  | 0.16 | 0.45 | 0       | 0.38 | 0           | 0.01 | 0.08           |
|                   | 50 $/tonne   | 0.16         | 0.56  | 0.17 | 0.44 | 0       | 0.27 | 0           | 0.01 | 0.13           |
|                   | 100 $/tonne  | 0.19         | 0.56  | 0.17 | 0.44 | 0       | 0.23 | 0           | 0.01 | 0.15           |
|                   | 1000 $/tonne | 0.25         | 0.55  | 0.17 | 0.42 | 0       | 0.02 | 0.15        | 0     | 0.20           |
| $500/kW           | 0 $/tonne    | 0.13         | 0.56  | 0.16 | 0.45 | 0       | 0.37 | 0           | 0.01 | 0.08           |
|                   | 50 $/tonne   | 0.17         | 0.56  | 0.17 | 0.45 | 0       | 0.26 | 0           | 0.01 | 0.12           |
|                   | 100 $/tonne  | 0.19         | 0.56  | 0.17 | 0.45 | 0       | 0.19 | 0           | 0.01 | 0.14           |
|                   | 1000 $/tonne | 0.25         | 0.55  | 0.18 | 0.43 | 0       | 0.02 | 0.15        | 0     | 0.20           |
| $300/kW           | 0 $/tonne    | 0.13         | 0.56  | 0.16 | 0.45 | 0       | 0.37 | 0           | 0.01 | 0.08           |
|                   | 50 $/tonne   | 0.15         | 0.56  | 0.17 | 0.45 | 0       | 0.25 | 0           | 0.01 | 0.10           |
|                   | 100 $/tonne  | 0.18         | 0.56  | 0.17 | 0.45 | 0       | 0.18 | 0           | 0.01 | 0.14           |
|                   | 1000 $/tonne | 0.26         | 0.55  | 0.18 | 0.43 | 0       | 0.02 | 0.15        | 0     | 0.21           |