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**Supplementary information**

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# **Breaking the hard-to-abate bottleneck in China's path to carbon neutrality with clean hydrogen**

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## The supplementary information

# Breaking the “hard-to-abate” bottleneck in China’s path to carbon neutrality with clean hydrogen

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**Supplementary Table 1.** Key mitigation technologies in the iron and steel industry with carbon mitigation potential and abatement costs

| Type                | No. | Technology name                                                                                                                                 | CO <sub>2</sub> abatement cost | Carbon emission abatement | TRL scale                 | TRL type |
|---------------------|-----|-------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|---------------------------|---------------------------|----------|
|                     |     |                                                                                                                                                 | \$/ton                         | kgCO <sub>2</sub> /t      | See Supplementary Table 3 |          |
| Material efficiency | 1   | Coke dry quenching device of high temperature and high pressure                                                                                 | 24                             | 2.3                       | Mature                    | TRL 11   |
|                     | 2   | Sintering waste heat power generation technology in the iron and steel industry                                                                 | 126                            | 0.7                       | Mature                    | TRL 11   |
|                     | 3   | Dry recovery technology of converter gas                                                                                                        | 92                             | 1.2                       | Mature                    | TRL 11   |
|                     | 4   | Moisture control and air separation technology for coking coal                                                                                  | 90                             | 9.6                       | Mature                    | TRL 11   |
|                     | 5   | Waste heat utilization technology of flue gas in mineral furnace                                                                                | 121                            | 5.0                       | Mature                    | TRL 11   |
|                     | 6   | Unsteady waste heat recovery and saturated steam power generation technology                                                                    | 29                             | 1.4                       | Mature                    | TRL 11   |
|                     | 7   | High-temperature flue gas dry purification and recycling technology of fully enclosed submerged arc furnace                                     | 20                             | 6.2                       | Mature                    | TRL 11   |
|                     | 8   | Sintering waste heat recycling technology                                                                                                       | 66                             | 1.7                       | Mature                    | TRL 11   |
|                     | 9   | Recovery and utilization of sensible heat of coke oven waste gas                                                                                | 31                             | 8.9                       | Mature                    | TRL 11   |
|                     | 10  | Regenerative combustion technology: Regenerative rotary hearth furnace treatment of metallurgical dust and recovery of iron and zinc technology | 260                            | 1.1                       | Mature                    | TRL 11   |
|                     | 11  | Energy saving technology of rotary cutting type high air temperature top burning hot blast stove                                                | 105                            | 5.7                       | Mature                    | TRL 11   |
|                     | 12  | New energy-saving technology of high thermal conductivity and high-density silica bricks for large coke ovens                                   | 43                             | 4.6                       | Mature                    | TRL 11   |
|                     | 13  | Integral optimization of cold ramming and paste forming furnace energy saving technology                                                        | 3                              | 3.8                       | Mature                    | TRL 11   |
|                     | 14  | High-emissivity coating technology                                                                                                              | 5                              | 5.3                       | Mature                    | TRL 11   |
|                     | 15  | Energy-saving technology of heat storage combustion without induced draft fan and directional valve                                             | 8                              | 4.5                       | Mature                    | TRL 11   |

**Supplementary Table 1 (continued).** Key mitigation technologies in the iron and steel industry with carbon mitigation potential and abatement costs

| Type                   | No. | Technology name                                                                                              | CO <sub>2</sub> abatement cost | Carbon emission abatement | TRL scale                 | TRL type |
|------------------------|-----|--------------------------------------------------------------------------------------------------------------|--------------------------------|---------------------------|---------------------------|----------|
|                        |     |                                                                                                              | \$/ton                         | kgCO <sub>2</sub> /t      | See Supplementary Table 3 |          |
| Technology performance | 16  | Screw expansion power drive energy-saving technology                                                         | 43                             | 3                         | Mature                    | TRL 11   |
|                        | 17  | Application technology of coaxial unit for energy recovery of metallurgical waste heat and pressure          | 11                             | 5                         | Mature                    | TRL 11   |
|                        | 18  | Recovering waste heat by direct heat exchange with blast furnace slagging water                              | 21                             | 7                         | Mature                    | TRL 11   |
|                        | 19  | Blast furnace blast dehumidification and energy-saving technology                                            | 25                             | 3                         | Mature                    | TRL 11   |
|                        | 20  | Liquid sealing technology of annular cooler                                                                  | 117                            | 0                         | Mature                    | TRL 11   |
|                        | 21  | Technology of waste gas recovery and pressure automatic regulation in coke oven carbonization chamber        | 76                             | 0                         | Mature                    | TRL 11   |
|                        | 22  | Intelligent energy-saving technology for large-scale blast furnace based on optimization of gas volume index | 121                            | 16                        | Mature                    | TRL 11   |
|                        | 23  | Energy management and control technology in the iron and steel industry                                      | 4                              | 13                        | Mature                    | TRL 11   |
|                        | 24  | Energy saving technology of blackbody enhanced radiation in heating furnace                                  | 6                              | 11                        | Mature                    | TRL 11   |
|                        | 25  | Intermediate and low temperature solar energy industrial thermal application system technology               | 81                             | 3                         | Mature                    | TRL 11   |
| Electrification        | 26  | BF-BOF (H <sub>2</sub> +Zero-C electricity)                                                                  | 120                            | 640                       | Large prototype           | TRL 5    |
|                        | 27  | BF-BOF (Zero-C electricity)                                                                                  | 118                            | 164                       | Large prototype           | TRL 5    |
|                        | 28  | EAF-scrap (Zero-C electricity)                                                                               | 118                            | 421                       | Large prototype           | TRL 5    |
|                        | 29  | DRI-coal (Zero-C electricity)                                                                                | 118                            | 793                       | Large prototype           | TRL 5    |
|                        | 30  | DRI-gas (Zero-C electricity)                                                                                 | 118                            | 427                       | Large prototype           | TRL 5    |
|                        | 31  | DRI-gas (H <sub>2</sub> +Zero-C electricity)                                                                 | 235                            | 1088                      | Large prototype           | TRL 5    |

**Supplementary Table 1 (continued).** Key mitigation technologies in the iron and steel industry with carbon mitigation potential and abatement costs

| Type     | No. | Technology name                                                            | CO <sub>2</sub> abatement cost | Carbon emission abatement | TRL scale                    | TRL type |
|----------|-----|----------------------------------------------------------------------------|--------------------------------|---------------------------|------------------------------|----------|
|          |     |                                                                            | \$/ton                         | kgCO <sub>2</sub> /t      | See Supplementary Table 3    |          |
| Hydrogen | 32  | DRI-NG H2: Green H2-30% injection                                          | 147                            | 150                       | Pre-commercial demonstration | TRL 7    |
|          | 33  | DRI-NG H2: Green H2-90% injection                                          | 147                            | 449                       | Large prototype              | TRL 5    |
|          | 34  | DRI-NG H2: Green H2-100% injection                                         | 147                            | 498                       | Large prototype              | TRL 5    |
|          | 35  | Hydrogen as auxiliary reduction (BF-BOF)-Hydrogen green                    | 62                             | 1380                      | Pre-commercial demonstration | TRL 7    |
|          | 36  | HYBRIT- carbon abatement 1575kg/ton-large scale 60Mt/yr-hydrogen green     | 128                            | 1575                      | Full prototype at scale      | TRL 6    |
|          | 37  | HYBRIT- carbon abatement 1575kg/ton-medium scale 23Mt/yr-hydrogen green    | 173                            | 1024                      | Full prototype at scale      | TRL 6    |
|          | 38  | HYBRIT- carbon abatement 1575kg/ton-small scale 7Mt/yr-hydrogen green      | 211                            | 551                       | Pre-commercial demonstration | TRL 7    |
|          | 39  | GrInHy2.0- carbon abatement 1600kg/ton-large scale 60Mt/yr-hydrogen green  | 130                            | 1600                      | Full prototype at scale      | TRL 6    |
|          | 40  | GrInHy2.0- carbon abatement 1600kg/ton-medium scale 23Mt/yr-hydrogen green | 176                            | 1040                      | Full prototype at scale      | TRL 6    |
|          | 41  | GrInHy2.0- carbon abatement 1600kg/ton-small scale 7Mt/yr-hydrogen green   | 290                            | 560                       | Pre-commercial demonstration | TRL 7    |
|          | 42  | GrInHy2.0- carbon abatement 1200kg/ton-large scale 60Mt/yr-hydrogen green  | 98                             | 1200                      | Full prototype at scale      | TRL 6    |
|          | 43  | GrInHy2.0- carbon abatement 1200kg/ton-medium scale 23Mt/yr-hydrogen green | 132                            | 780                       | Full prototype at scale      | TRL 6    |
|          | 44  | GrInHy2.0- carbon abatement 1200kg/ton-small scale 7Mt/yr-hydrogen green   | 217                            | 420                       | Pre-commercial demonstration | TRL 7    |
| CCUS     | 45  | SR-BOF with CCUS                                                           | 36                             | 1470                      | Pre-commercial demonstration | TRL 7    |
|          | 46  | DRI-gas (CCUS)                                                             | 25                             | 670                       | Early adoption               | TRL 10   |
|          | 47  | DRI-coal (CCUS)                                                            | 25                             | 742                       | Early adoption               | TRL 10   |

**Supplementary Table 1 (continued).** Key mitigation technologies in the iron and steel industry with carbon mitigation potential and abatement costs

| Type           | No. | Technology name                                                                        | CO <sub>2</sub> abatement cost | Carbon emission abatement | TRL scale     | TRL type |
|----------------|-----|----------------------------------------------------------------------------------------|--------------------------------|---------------------------|---------------|----------|
| CCUS+ Hydrogen | 48  | DRI-NG H2: Blue H2(SMR+89%CCUS)-30% injection                                          | 294                            | 131                       | Demonstration | TRL 8    |
|                | 49  | DRI-NG H2: Blue H2(SMR+89%CCUS)-90% injection                                          | 294                            | 394                       | Demonstration | TRL 8    |
|                | 50  | DRI-NG H2: Blue H2(SMR+89%CCUS)-100% injection                                         | 294                            | 437                       | Demonstration | TRL 8    |
|                | 51  | Hydrogen as auxiliary reduction (BF-BOF)-hydrogen blue: SMR89% CCUS                    | 123                            | 1200                      | Demonstration | TRL 8    |
|                | 52  | HYBRIT- carbon abatement 1575kg/ton-large scale 60Mt/yr-hydrogen blue                  | 256                            | 1382                      | Demonstration | TRL 8    |
|                | 53  | HYBRIT- carbon abatement 1575kg/ton-medium scale 23Mt/yr-hydrogen blue: SMR89% CCUS    | 346                            | 898                       | Demonstration | TRL 8    |
|                | 54  | HYBRIT- carbon abatement 1575kg/ton-small scale 7Mt/yr-hydrogen blue: SMR89% CCUS      | 422                            | 484                       | Demonstration | TRL 8    |
|                | 55  | GrInHy2.0- carbon abatement 1600kg/ton-large scale 60Mt/yr-hydrogen blue: SMR89% CCUS  | 260                            | 1404                      | Demonstration | TRL 8    |
|                | 56  | GrInHy2.0- carbon abatement 1600kg/ton-medium scale 23Mt/yr-hydrogen blue: SMR89% CCUS | 351                            | 912                       | Demonstration | TRL 8    |
|                | 57  | GrInHy2.0- carbon abatement 1600kg/ton-small scale 7Mt/yr-hydrogen blue: SMR89% CCUS   | 579                            | 491                       | Demonstration | TRL 8    |
|                | 58  | GrInHy2.0- carbon abatement 1200kg/ton-large scale 60Mt/yr-hydrogen blue: SMR89% CCUS  | 195                            | 1053                      | Demonstration | TRL 8    |
|                | 59  | GrInHy2.0- carbon abatement 1200kg/ton-medium scale 23Mt/yr-hydrogen blue: SMR89% CCUS | 263                            | 684                       | Demonstration | TRL 8    |
|                | 60  | GrInHy2.0- carbon abatement 1200kg/ton-small scale 7Mt/yr hydrogen blue: SMR89% CCUS   | 434                            | 368                       | Demonstration | TRL 8    |

**Supplementary Table 2.** Key mitigation technologies in the cement industry with carbon mitigation potential and abatement costs

| Type              | No. | Technology name                                            | Carbon emission abatement | CO <sub>2</sub> abatement cost | TRL scale                 | TRL type |
|-------------------|-----|------------------------------------------------------------|---------------------------|--------------------------------|---------------------------|----------|
|                   |     |                                                            | kg /t CO <sub>2</sub>     | \$/t CO <sub>2</sub>           | See Supplementary Table 3 |          |
| Energy efficiency | 1   | Mining optimization                                        | 1.6                       | 233                            | Mature                    | TRL 11   |
|                   | 2   | Power system of ore transportation                         | 1.0                       | 78                             | Mature                    | TRL 11   |
|                   | 3   | New steel tape hoist                                       | 1.3                       | 119                            | Mature                    | TRL 11   |
|                   | 4   | Efficient pre-calciner pre-heater system                   | 13.0                      | 46                             | Mature                    | TRL 11   |
|                   | 5   | Increase in pre-heater stages                              | 8.6                       | 5                              | Mature                    | TRL 11   |
|                   | 6   | New efficient burner                                       | 2.6                       | 48                             | Mature                    | TRL 11   |
|                   | 7   | Oxy-fuel technology for cement clinker                     | 7.8                       | 15                             | Mature                    | TRL 11   |
|                   | 8   | Fan inverter technology with high temperature              | 1.8                       | 45                             | Mature                    | TRL 11   |
|                   | 9   | The fourth-generation grate cooler technology              | 13.0                      | 52                             | Mature                    | TRL 11   |
|                   | 10  | New efficient drying technology                            | 2.6                       | 42                             | Mature                    | TRL 11   |
|                   | 11  | Vertical mill for raw material grinding                    | 9.6                       | 94                             | Mature                    | TRL 11   |
|                   | 12  | Roller press for raw material grinding                     | 11.9                      | 84                             | Mature                    | TRL 11   |
|                   | 13  | Co-grinding system                                         | 7.7                       | 63                             | Mature                    | TRL 11   |
|                   | 14  | Pure low-temperature waste heat cogeneration technology    | 25                        | 75                             | Early adoption            | TRL 10   |
|                   | 15  | Pentane media pure low temperature cogeneration technology | 4                         | 36                             | Early adoption            | TRL 10   |
| Alternative fuels | 16  | Fuel switching (coal/oil/gas/biomass)                      | 50                        | 19                             | Early adoption            | TRL 10   |
|                   | 17  | Pre-treatment of alternative fuel (grinding, drying)       | 8                         | 0.4                            | Early adoption            | TRL 10   |
|                   | 18  | Gasification or pre-combustion of alternative fuels        | 41                        | 2                              | Early adoption            | TRL 10   |
|                   | 19  | Alternative fuel technology for cement production          | 87                        | 17                             | Early adoption            | TRL 10   |

**Supplementary Table 2 (continued).** Key mitigation technologies in the cement industry with carbon mitigation potential and abatement costs

| Type                                 | No. | Technology name                                                                                            | Carbon emission abatement | CO <sub>2</sub> abatement cost | TRL scale       | TRL type |
|--------------------------------------|-----|------------------------------------------------------------------------------------------------------------|---------------------------|--------------------------------|-----------------|----------|
|                                      |     |                                                                                                            | kg /t CO <sub>2</sub>     | \$/t CO <sub>2</sub>           |                 |          |
| Reducing the clinker to cement ratio | 20  | Electrolyzer-based process for decarbonating CaCO <sub>3</sub>                                             | 979                       | 65                             | Concept         | TRL 3    |
|                                      | 21  | Non-carbonated raw material for cement production–use of calcium carbide residue (CCR)                     | 374                       | 20                             | Mature          | TRL 11   |
|                                      | 22  | Alternative decarbonated raw materials for clinker production-10%-15% granulated blast furnace slag (GBFS) | 100                       | 5                              | Mature          | TRL 11   |
|                                      | 23  | Further reduction of clinker content in cement by use of fly ash                                           | 98                        | 1                              | Mature          | TRL 11   |
|                                      | 24  | Further reduction of clinker content in cement by use of natural pozzolanas                                | 92                        | 4                              | Mature          | TRL 11   |
| CCUS                                 | 25  | Carbon capture and storage (CCUS)                                                                          | 933                       | 6                              | Demonstration   | TRL 8    |
|                                      | 26  | Post-combustion capture using absorption technologies                                                      | 800                       | 60                             | Demonstration   | TRL 7    |
|                                      | 27  | Post-combustion capture using membrane processes                                                           | 955                       | 30                             | Small prototype | TRL 4    |
| Green Hydrogen                       | 28  | Green H <sub>2</sub> heating-30% injection-average                                                         | 150                       | 28                             | Large prototype | TRL 5    |
|                                      | 29  | Green H <sub>2</sub> heating-30% injection-large NSP kiln                                                  | 225                       | 20                             | Large prototype | TRL 5    |
|                                      | 30  | Green H <sub>2</sub> heating-90% injection-average                                                         | 449                       | 28                             | Large prototype | TRL 5    |
|                                      | 31  | Green H <sub>2</sub> heating-90% injection-small NSP kiln                                                  | 236                       | 56                             | Large prototype | TRL 5    |
|                                      | 32  | Green H <sub>2</sub> heating-90% injection-medium NSP kiln                                                 | 438                       | 36                             | Large prototype | TRL 5    |
|                                      | 33  | Green H <sub>2</sub> heating-90% injection-large NSP kiln                                                  | 674                       | 20                             | Large prototype | TRL 5    |
|                                      | 34  | Green H <sub>2</sub> heating-100% injection-average                                                        | 498                       | 28                             | Large prototype | TRL 5    |
|                                      | 35  | Green H <sub>2</sub> heating-100% injection-small NSP kiln                                                 | 262                       | 56                             | Large prototype | TRL 5    |
|                                      | 36  | Green H <sub>2</sub> heating-100% injection-medium NSP kiln                                                | 486                       | 36                             | Large prototype | TRL 5    |
|                                      | 37  | Green H <sub>2</sub> heating-100% injection-large NSP kiln                                                 | 747                       | 20                             | Large prototype | TRL 5    |

**Supplementary Table 2 (continued).** Key mitigation technologies in the cement industry with carbon mitigation potential and abatement costs

| Type                    | No. | Technology name                                              | Carbon emission abatement | CO <sub>2</sub> abatement cost | TRL scale                    | TRL type |
|-------------------------|-----|--------------------------------------------------------------|---------------------------|--------------------------------|------------------------------|----------|
|                         |     |                                                              | kg /t CO <sub>2</sub>     | \$/t CO <sub>2</sub>           |                              |          |
| Blue hydrogen with CCUS | 38  | Blue H2 (SMR+89%CCUS) heating-30% injection-average          | 131                       | 32                             | Demonstration                | TRL 8    |
|                         | 39  | Blue H2 (SMR+89%CCUS) heating-30% injection-large NSP kiln   | 197                       | 17                             | Demonstration                | TRL 8    |
|                         | 40  | Blue H2 (SMR+89%CCUS) heating-90% injection-average          | 394                       | 32                             | Pre-commercial demonstration | TRL 7    |
|                         | 41  | Blue H2 (SMR+89%CCUS) heating-90% injection-small NSP kiln   | 207                       | 48                             | Pre-commercial demonstration | TRL 7    |
|                         | 42  | Blue H2 (SMR+89%CCUS) heating-90% injection-medium NSP kiln  | 384                       | 32                             | Pre-commercial demonstration | TRL 7    |
|                         | 43  | Blue H2 (SMR+89%CCUS) heating-90% injection-large NSP kiln   | 591                       | 17                             | Pre-commercial demonstration | TRL 7    |
|                         | 44  | Blue H2 (SMR+89%CCUS) heating-100% injection-average         | 437                       | 32                             | Pre-commercial demonstration | TRL 7    |
|                         | 45  | Blue H2 (SMR+89%CCUS) heating-100% injection-small NSP kiln  | 229                       | 48                             | Pre-commercial demonstration | TRL 7    |
|                         | 46  | Blue H2 (SMR+89%CCUS) heating-100% injection-medium NSP kiln | 426                       | 32                             | Pre-commercial demonstration | TRL 7    |
|                         | 47  | Blue H2 (SMR+89%CCUS) heating-100% injection-large NSP kiln  | 656                       | 17                             | Pre-commercial demonstration | TRL 7    |

**Supplementary Table 3.** Technology readiness level (TRL) classifications applied to all technologies of the study

| TRL scale       | TRL level | Detail                                       | Description                                                                             |
|-----------------|-----------|----------------------------------------------|-----------------------------------------------------------------------------------------|
| Concept         | 1         | Initial idea                                 | Basic principles have been defined                                                      |
|                 | 2         | Application formulated                       | Concept and application of solution have been formulated                                |
|                 | 3         | Concept needs validation                     | Solution needs to be prototyped and applied                                             |
| Small prototype | 4         | Early prototype                              | Prototype proven in test conditions                                                     |
| Large prototype | 5         | Large prototype                              | Components proven in conditions to be deployed                                          |
|                 | 6         | Full prototype at scale                      | Prototype proven at scale in conditions to be deployed                                  |
| Demonstration   | 7         | Pre-commercial demonstration                 | Solution working in expected conditions                                                 |
|                 | 8         | First-of-a-kind commercial                   | Commercial demonstration, full scale deployment in final form                           |
| Early adoption  | 9         | Commercial operation in relevant environment | Solution in commercially available, needs evolutionary improvement to stay competitive. |
|                 | 10        | Integration needed at scale                  | Solution is commercial and competitive but needs further integration efforts            |
| Mature          | 11        | Proof of stability reached                   | Predictable growth                                                                      |

Note: Supplementary Tables 1 and 2 according to IEA ETP Clean Energy Technology Guide (<https://www.iea.org/articles/etp-clean-energy-technology-guide>).

**Supplementary Table 4.** Technology penetration in typically hard-to-abate sectors in the BAU, NDC, ZERO-NH, and ZERO-H scenarios (2020-2060)

| Industry       |                           |      |      |      |      |      |      |      |      |      |      |         |      |      |      |      |        |      |      |      |      |
|----------------|---------------------------|------|------|------|------|------|------|------|------|------|------|---------|------|------|------|------|--------|------|------|------|------|
| Sub-sector     | Technology                | BAU  |      |      |      |      | NDC  |      |      |      |      | ZERO-NH |      |      |      |      | ZERO-H |      |      |      |      |
|                |                           | 2020 | 2030 | 2040 | 2050 | 2060 | 2020 | 2030 | 2040 | 2050 | 2060 | 2020    | 2030 | 2040 | 2050 | 2060 | 2020   | 2030 | 2040 | 2050 | 2060 |
| Iron and Steel | BOF-BF                    | 87%  | 84%  | 80%  | 76%  | 72%  | 87%  | 77%  | 70%  | 64%  | 55%  | 87%     | 73%  | 64%  | 51%  | 37%  | 87%    | 72%  | 56%  | 43%  | 25%  |
|                | EAF                       | 13%  | 16%  | 20%  | 24%  | 28%  | 13%  | 23%  | 30%  | 36%  | 45%  | 13%     | 27%  | 36%  | 49%  | 63%  | 13%    | 25%  | 35%  | 39%  | 44%  |
|                | Hydrogen-DRI              | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 3%   | 9%   | 18%  | 31%  |
| Cement         | Shaft kiln                | 12%  | 7%   | 4%   | 2%   | 0%   | 12%  | 4%   | 1%   | 0%   | 0%   | 12%     | 1%   | 0%   | 0%   | 0%   | 12%    | 1%   | 0%   | 0%   | 0%   |
|                | Mid-/Small NSP kiln       | 48%  | 37%  | 28%  | 22%  | 16%  | 48%  | 32%  | 22%  | 17%  | 12%  | 48%     | 24%  | 15%  | 9%   | 0%   | 48%    | 22%  | 11%  | 7%   | 0%   |
|                | Large NSP kiln with CCUS  | 37%  | 48%  | 56%  | 60%  | 61%  | 37%  | 53%  | 54%  | 47%  | 43%  | 37%     | 57%  | 51%  | 32%  | 15%  | 37%    | 52%  | 42%  | 23%  | 5%   |
|                | NSP with WHR and CCUS     | 3%   | 8%   | 12%  | 17%  | 23%  | 3%   | 11%  | 23%  | 36%  | 45%  | 3%      | 18%  | 34%  | 59%  | 85%  | 3%     | 20%  | 35%  | 52%  | 71%  |
|                | NSP with hydrogen heat    | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 5%   | 12%  | 18%  | 24%  |
| Ammonia        | Coal-based                | 72%  | 73%  | 71%  | 72%  | 70%  | 72%  | 63%  | 52%  | 41%  | 32%  | 72%     | 48%  | 26%  | 12%  | 0%   | 72%    | 45%  | 23%  | 9%   | 0%   |
|                | Gas-based                 | 28%  | 27%  | 29%  | 28%  | 30%  | 28%  | 37%  | 48%  | 59%  | 68%  | 28%     | 52%  | 74%  | 88%  | 100% | 28%    | 50%  | 66%  | 74%  | 57%  |
|                | Electrochemical Synthesis | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 5%   | 11%  | 17%  | 43%  |
| Methanol       | CTM                       | 56%  | 57%  | 59%  | 62%  | 67%  | 56%  | 43%  | 38%  | 34%  | 31%  | 56%     | 33%  | 20%  | 11%  | 0%   | 56%    | 30%  | 17%  | 8%   | 0%   |
|                | CGTM                      | 21%  | 20%  | 19%  | 18%  | 17%  | 21%  | 18%  | 15%  | 12%  | 11%  | 21%     | 14%  | 9%   | 6%   | 5%   | 21%    | 12%  | 7%   | 4%   | 0%   |
|                | NTM                       | 23%  | 23%  | 22%  | 20%  | 16%  | 23%  | 39%  | 47%  | 54%  | 58%  | 23%     | 53%  | 71%  | 83%  | 95%  | 23%    | 52%  | 62%  | 69%  | 79%  |
|                | CGTM/NTM                  | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 6%   | 14%  | 19%  | 21%  |

**Supplementary Table 4 (continued).** Technology penetration in typically hard-to-abate sectors in the BAU, NDC, ZERO-NH, and ZERO-H scenarios (2020-2060)

| Transport    |                               |      |      |      |      |      |      |      |      |      |      |         |      |      |      |      |        |      |      |      |      |
|--------------|-------------------------------|------|------|------|------|------|------|------|------|------|------|---------|------|------|------|------|--------|------|------|------|------|
| Sub-sector   | Technology                    | BAU  |      |      |      |      | NDC  |      |      |      |      | ZERO-NH |      |      |      |      | ZERO-H |      |      |      |      |
|              |                               | 2020 | 2030 | 2040 | 2050 | 2060 | 2020 | 2030 | 2040 | 2050 | 2060 | 2020    | 2030 | 2040 | 2050 | 2060 | 2020   | 2030 | 2040 | 2050 | 2060 |
| LDV          | Gasoline LDVs                 | 92%  | 93%  | 95%  | 96%  | 97%  | 92%  | 76%  | 56%  | 44%  | 38%  | 92%     | 62%  | 34%  | 18%  | 0%   | 92%    | 59%  | 31%  | 16%  | 0%   |
|              | Gasoline-electric hybrid LDVs | 7%   | 6%   | 4%   | 3%   | 2%   | 7%   | 16%  | 28%  | 36%  | 37%  | 7%      | 22%  | 24%  | 3%   | 0%   | 7%     | 25%  | 28%  | 9%   | 0%   |
|              | Electric LDVs                 | 1%   | 1%   | 1%   | 1%   | 1%   | 1%   | 8%   | 16%  | 20%  | 25%  | 1%      | 16%  | 42%  | 79%  | 100% | 1%     | 15%  | 39%  | 71%  | 95%  |
|              | Hydrogen fuel cell LDVs       | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 1%   | 2%   | 4%   | 5%   |
| Buses        | Gasoline/Diesel Buses         | 48%  | 49%  | 51%  | 53%  | 55%  | 48%  | 20%  | 9%   | 4%   | 0%   | 48%     | 13%  | 7%   | 3%   | 0%   | 48%    | 12%  | 3%   | 1%   | 0%   |
|              | CNG/CPG buses                 | 37%  | 36%  | 33%  | 31%  | 29%  | 37%  | 47%  | 40%  | 32%  | 17%  | 37%     | 45%  | 22%  | 8%   | 0%   | 37%    | 50%  | 36%  | 20%  | 0%   |
|              | Electric buses                | 15%  | 15%  | 16%  | 16%  | 16%  | 15%  | 33%  | 51%  | 64%  | 83%  | 15%     | 42%  | 71%  | 89%  | 100% | 15%    | 24%  | 32%  | 36%  | 39%  |
|              | Hydrogen fuel cell buses      | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 14%  | 29%  | 43%  | 61%  |
| Light Trucks | Diesel/Gasoline LDTs          | 71%  | 69%  | 67%  | 65%  | 64%  | 71%  | 56%  | 52%  | 49%  | 48%  | 71%     | 42%  | 24%  | 13%  | 0%   | 71%    | 39%  | 19%  | 7%   | 0%   |
|              | CNG/Ethanol LDTs              | 29%  | 31%  | 33%  | 35%  | 36%  | 29%  | 44%  | 47%  | 48%  | 47%  | 29%     | 55%  | 49%  | 28%  | 0%   | 29%    | 50%  | 48%  | 26%  | 0%   |
|              | Electric LDTs                 | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 1%   | 3%   | 5%   | 0%      | 3%   | 27%  | 59%  | 100% | 0%     | 2%   | 12%  | 29%  | 47%  |
|              | Hydrogen fuel cell LDTs       | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 9%   | 21%  | 38%  | 53%  |

**Supplementary Table 4 (continued).** Technology penetration in typically hard-to-abate sectors in the BAU, NDC, ZERO-NH, and ZERO-H scenarios (2020-2060)

| Transport and Other |                         |      |      |      |      |      |      |      |      |      |      |         |      |      |      |      |        |      |      |      |      |
|---------------------|-------------------------|------|------|------|------|------|------|------|------|------|------|---------|------|------|------|------|--------|------|------|------|------|
| Sub-sector          | Technology              | BAU  |      |      |      |      | NDC  |      |      |      |      | ZERO-NH |      |      |      |      | ZERO-H |      |      |      |      |
|                     |                         | 2020 | 2030 | 2040 | 2050 | 2060 | 2020 | 2030 | 2040 | 2050 | 2060 | 2020    | 2030 | 2040 | 2050 | 2060 | 2020   | 2030 | 2040 | 2050 | 2060 |
| Heavy Trucks        | Diesel HDTs             | 96%  | 95%  | 93%  | 90%  | 87%  | 96%  | 91%  | 82%  | 71%  | 59%  | 96%     | 71%  | 43%  | 21%  | 0%   | 96%    | 68%  | 39%  | 16%  | 0%   |
|                     | Bio diesel/CNG HDTs     | 4%   | 5%   | 7%   | 10%  | 13%  | 4%   | 9%   | 17%  | 27%  | 39%  | 4%      | 22%  | 30%  | 21%  | 0%   | 4%     | 26%  | 31%  | 26%  | 0%   |
|                     | Electric HDTs           | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 1%   | 2%   | 2%   | 0%      | 7%   | 27%  | 58%  | 100% | 0%     | 4%   | 15%  | 22%  | 34%  |
|                     | Hydrogen fuel cell HDTs | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 2%   | 15%  | 36%  | 66%  |
| Shipping            | Fuel Oil Ships          | 90%  | 91%  | 91%  | 90%  | 88%  | 90%  | 67%  | 58%  | 54%  | 49%  | 90%     | 57%  | 29%  | 12%  | 0%   | 90%    | 55%  | 26%  | 11%  | 0%   |
|                     | LNG/Duofuel Ships       | 10%  | 9%   | 9%   | 10%  | 12%  | 10%  | 33%  | 42%  | 46%  | 51%  | 10%     | 42%  | 66%  | 77%  | 80%  | 10%    | 35%  | 45%  | 38%  | 23%  |
|                     | Ammonia Ships           | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 1%   | 5%   | 11%  | 20%  | 0%     | 9%   | 24%  | 43%  | 65%  |
|                     | Hydrogen ships          | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 1%   | 5%   | 8%   | 12%  |
| Residential Heating | Coal-based              | 68%  | 67%  | 65%  | 64%  | 64%  | 68%  | 63%  | 57%  | 50%  | 41%  | 68%     | 43%  | 29%  | 13%  | 0%   | 68%    | 40%  | 26%  | 11%  | 0%   |
|                     | Gas-based               | 24%  | 23%  | 23%  | 22%  | 21%  | 24%  | 25%  | 27%  | 31%  | 39%  | 24%     | 42%  | 32%  | 15%  | 3%   | 24%    | 48%  | 37%  | 27%  | 9%   |
|                     | Electricity-based       | 8%   | 10%  | 12%  | 14%  | 15%  | 8%   | 12%  | 16%  | 19%  | 20%  | 8%      | 15%  | 39%  | 72%  | 97%  | 8%     | 12%  | 29%  | 45%  | 64%  |
|                     | Hydrogen-based          | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%      | 0%   | 0%   | 0%   | 0%   | 0%     | 0%   | 8%   | 17%  | 25%  |

**Supplementary Table 5. Hydrogen production technologies and costs**

| Technology description                                | Efficiency (LHV) [%] |       |       |       | Investment cost [\$/kW] |        |       |       | Fixed O&M cost [\$/kW] |       |       |       | Lifetime |
|-------------------------------------------------------|----------------------|-------|-------|-------|-------------------------|--------|-------|-------|------------------------|-------|-------|-------|----------|
|                                                       | 2015                 | 2020  | 2030  | 2050  | 2015                    | 2020   | 2030  | 2050  | 2015                   | 2020  | 2030  | 2050  | Years    |
| AEC electrolysis, centralized                         | 61.2%                | 63.6% | 65.9% | 69.2% | 1281.86                 | 718.8  | 658.9 | 599   | 64.09                  | 35.94 | 32.95 | 29.95 | 25       |
| PEMEC electrolysis, centralized                       | 54%                  | 58%   | 62%   | 67%   | 2276.2                  | 1317.8 | 718.8 | 479.2 | 113.81                 | 65.89 | 35.94 | 23.96 | 15       |
| SOEC electrolysis, centralized                        | 68%                  | 76%   | 79%   | 79%   | 4552.4                  | 2635.6 | 718.8 | 479.2 | 227.62                 | 79.07 | 21.56 | 14.38 | 20       |
| Biomass gasification, medium-large scale, centralized | 56%                  | 60%   | 63%   | 70%   | 3168                    | 2497   | 1550  | 997   | 158.3                  | 124.6 | 77.5  | 49.7  | 20       |
| Coal gasification, medium size, centralized           | 55%                  | 60%   | 60%   | 60%   | 689                     | 689    | 689   | 689   | 17.2                   | 17.2  | 17.2  | 17.2  | 25       |
| Coal gasification, large size, centralized            | 40%                  | 45%   | 50%   | 55%   | 556                     | 507    | 422   | 271   | 33.0                   | 30.4  | 26.9  | 16.3  | 25       |
| Coal gasification + CCUS, medium scale, centralized   | 55%                  | 58%   | 58%   | 58%   | 794                     | 794    | 794   | 794   | 33.0                   | 33.0  | 33.0  | 33.0  | 25       |
| Coal gasification + CCUS, large scale, centralized    | 40%                  | 43%   | 48%   | 48%   | 686                     | 590    | 436   | 281   | 49.3                   | 41.3  | 27.3  | 19.6  | 25       |
| Natural gas reforming, small size, centralized        | 76%                  | 76%   | 76%   | 76%   | 519                     | 481    | 414   | 266   | 19.7                   | 19.2  | 15.3  | 10.6  | 25       |
| Natural gas reforming, large size, centralized        | 62%                  | 66%   | 66%   | 66%   | 242                     | 223    | 190   | 122   | 11.8                   | 11.2  | 9.2   | 6.1   | 25       |
| Natural gas reforming + CCUS, small size, centralized | 69%                  | 69%   | 69%   | 69%   | 709                     | 648    | 541   | 348   | 35.5                   | 32.4  | 28.6  | 17.4  | 25       |
| Natural gas reforming + CCUS, large size, centralized | 57%                  | 57%   | 57%   | 57%   | 342                     | 300    | 230   | 148   | 17.1                   | 15.0  | 13.8  | 7.4   | 25       |

Note: Data sources<sup>1-4</sup>.

**Supplementary Table 6.** Assumptions for sensitivity analyses.

**(A)** GDP growth rate assumptions

| Scenario                                             | 2020-2030 | 2030-2040 | 2040-2050 | Description                                                                                                                                                                                                                                                                                      |
|------------------------------------------------------|-----------|-----------|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Central GDP growth case                              | 5.1%      | 2.9%      | 2.9%      | The GDP growth assumption for the central case is the same as that used in the scenarios in the IEA “World Energy Outlook 2021” report <sup>5</sup> .                                                                                                                                            |
| High GDP growth case - Comprehensive economic reform | 5.1%      | 4.1%      | 3.0%      | The high-GDP growth scenario uses the growth rate of the comprehensive reform scenario of a recent report on Chinese GDP by the World Bank Group (WBG) and Development Research Center of the State Council, China (DRCSC) <sup>6</sup> . Details of the assumptions can be found in the report. |
| Low GDP growth case - Limited economic reform        | 4.0%      | 1.7%      | 2.3%      | The low-GDP scenario uses the growth rate of the limited reform scenario of the WBG and DRCSC report. <sup>6</sup>                                                                                                                                                                               |

**(B)** Hydrogen production cost assumptions

| Scenario                                        | Description                                                                                                                                                                                                                  |
|-------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Central cost case                               | Assumes all of the changes in production efficiency and costs listed in Supplementary Table 5.                                                                                                                               |
| High H <sub>2</sub> cost (4 cases)              | Assumes +10%, +30%, +50%, or +100% technology cost increase over central case for each milestone year (2020, 2030, 2050).                                                                                                    |
| Low H <sub>2</sub> cost (4 cases)               | Assumes -10%, -30%, -50%, or -60% technology cost decrease over central case for each milestone year (2020, 2030, 2050).                                                                                                     |
| Incremental high H <sub>2</sub> cost (49 cases) | Assumes +51%, +52%, ... or +99% technology cost increase over central case for each milestone year, to identify the rate of increase above which the ZERO-H scenario would be more cost effective than the ZERO-NH scenario. |

**Supplementary Table 7.** Hydrogen penetration in total final energy consumption (TFEC) at the provincial level (2060)

| No. | Province       | Hydrogen TFEC penetration in 2060 |
|-----|----------------|-----------------------------------|
| 1   | Hebei          | 29.30%                            |
| 2   | Beijing        | 27.60%                            |
| 3   | Guangdong      | 24.60%                            |
| 4   | Shanghai       | 22.40%                            |
| 5   | Tianjin        | 21.40%                            |
| 6   | Jiangsu        | 21.30%                            |
| 7   | Fujian         | 18.50%                            |
| 8   | Zhejiang       | 17.90%                            |
| 9   | Sichuan        | 16.60%                            |
| 10  | Liaoning       | 15.60%                            |
| 11  | Inner Mongolia | 14.90%                            |
| 12  | Henan          | 13.50%                            |
| 13  | Hubei          | 12.80%                            |
| 14  | Guizhou        | 12.80%                            |
| 15  | Shandong       | 12.60%                            |
| 16  | Shanxi         | 11.70%                            |
| 17  | Chongqing      | 11.70%                            |
| 18  | Yunnan         | 11.30%                            |
| 19  | Heilongjiang   | 10.60%                            |
| 20  | Ningxia        | 10.50%                            |
| 21  | Anhui          | 10.20%                            |
| 22  | Hunan          | 10.10%                            |
| 23  | Guangxi        | 9.80%                             |
| 24  | Gansu          | 9.80%                             |
| 25  | Jiangxi        | 9.40%                             |
| 26  | Jilin          | 9.20%                             |
| 27  | Qinghai        | 8.30%                             |
| 28  | Hainan         | 7.40%                             |
| 29  | Shaanxi        | 7.40%                             |
| 30  | Xinjiang       | 6.70%                             |
| 31  | Tibet          | 3.70%                             |

## Supplementary Note 1: Description of the MAPLE model

The MAPLE model was developed based on the IEA-ETSAP modeling tool TIMES-VEDA (<https://iea-etsap.org/index.php/etsap-tools>). This model has been applied in the past decade to analyze China's mitigation pathway in the DDPP project led by IDDRI<sup>7</sup>, a World Bank Group energy policy project,<sup>8</sup> and others. The analysis framework is based on the European Commission Horizon Project 2020 Paris Reinforce Project for Innovative Scenarios in the Future ([https://paris-reinforce.epu.ntua.gr/detailed\\_model\\_doc/](https://paris-reinforce.epu.ntua.gr/detailed_model_doc/)). We further updated the MAPLE model in this paper by adding more detailed technological processes to the hard-to-abate sectors and hydrogen applications (see Supplementary Notes 3 and 4). The MAPLE model includes hundreds of parameters and functions, which are listed in the IEA-ETSAP TIMES tool documents ([https://iea-etsap.org/docs/Documentation\\_for\\_the\\_TIMES\\_Model-PartII.pdf](https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-PartII.pdf)). Briefly, it simulates the investment in, and operation of, major energy technologies under emissions reduction constraints in China. The model can project and simulate future energy use trends under multiple scenarios and varying degrees of mitigation. The model's objective is to find the minimum total cost of the energy system given the energy demand and any other major constraints on the energy system (e.g., technology availability and growth rates).

The objective functions take the form:

$$C = \sum_t [(CINV_t + CFOM_t + CFU_t + CD_t) / (1 + d_t)^{t-2020}] \quad (1)$$

$$CINV_t = CP_{p,t} + CNP_{p,t} + CS_{p,t} \quad (2)$$

In equation (1),  $t$  is the year or time period,  $p$  denotes the technological process, and the variables  $C$ ,  $CINV$ ,  $CFOM$ ,  $CFU$ ,  $CD$ , and  $d_t$  represent total cost, investment cost, fixed O&M cost, fuel cost, delivery cost and discount rate, respectively. In the investment cost formula (2),  $CP$ ,  $CNP$ ,  $CS$  refer to production capacity cost, new pipeline infrastructure cost, and storage cost, respectively. Note that most current bottom-up models in China do not consider hydrogen and associated technologies, and most existing hydrogen studies for China do not consider blue hydrogen.

The constraints in this paper include resource and emission constraints (see equations (3)-(5)). In these constraints, TE denotes total emissions. Other constraints in the model include those related

to inter-period capacity transfer, technical activity, and the flow balance equation. MAPLE-China follows the integrated MARKAL/EFOM system (TIMES) energy planning modeling platform principles, and detailed instructions and functions can be found in the documentation for the TIMES Model.

$$RS_t \geq \sum_p DF_{t,p} \quad (3)$$

$$TE_t = \sum_{p,i} (DF_{p,t,i} \times ef_{i,p}), i = [coal; oil; gas] \quad (4)$$

$$\begin{cases} TE_{2030} \geq TE_t \text{ (if } t \geq 2030) \\ TE_{2060} \leq 0 \end{cases} \quad (5)$$

The model performs calculations from 2015/2020 to 2060. The base year calibration mainly includes the following aspects: (1) total energy consumption and the category-based energy consumptions of various sectors and sub-sectors; (2) energy consumption per unit of end-use demand of major divisions; and (3) CO<sub>2</sub> emissions. The main data sources for the MAPLE-China model are the energy balance tables found in China's Energy Statistical Yearbook<sup>9-14</sup>. For energy consumption in the industrial sub-sectors and technologies, we used several sources, including the China Statistical Yearbook<sup>15-21</sup>, Industrial Statistical Yearbook<sup>22-26</sup>, China Steel Statistics<sup>27-32</sup>, China Chemical Industry Yearbook<sup>33-35</sup>, China Nonferrous Metals Industry Yearbook<sup>36-40</sup>, and China Energy Statistical Yearbook<sup>9-14</sup>. The data sources also include China Transportation Yearbook<sup>41-46</sup>, China Building Energy Efficiency Annual Development Research Report<sup>47-53</sup>, and the China Electric Power (Statistical) Yearbook<sup>54-60</sup>.

### **Supplementary Note 2: Final energy demand drivers and elasticities**

The economic, population, and sectoral growth (e.g., physical production of industrial activities) in the MAPLE model for Chinese regions are used as specific drivers for the growth in energy demand, as in the TIMES-MARKAL (MARKet ALlocation) series models (<https://iea-etsap.org/index.php/etsaptool/model-generators/markal>), such as MARKAL-India ([https://paris-reinforce.epu.ntua.gr/detailed\\_model\\_doc/markal\\_india](https://paris-reinforce.epu.ntua.gr/detailed_model_doc/markal_india)), TIMES-CAC (TIMES-Central Asian Caspian Model; [https://www.i2am-paris.eu/detailed\\_model\\_doc/times\\_cac](https://www.i2am-paris.eu/detailed_model_doc/times_cac)), and the NATEM

model (North American TIMES Energy Model; [https://www.i2am-paris.eu/detailed\\_model\\_doc/natem](https://www.i2am-paris.eu/detailed_model_doc/natem)). The detailed demand functions can be found in the documentation for the TIMES model-Part I ([https://iea-etsap.org/docs/Documentation\\_for\\_the\\_TIMES\\_Model-Part-I.pdf](https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I.pdf); see chapter 4).

Unlike the typical methods for forecasting future terminal service demand involving econometric regression, statistical analysis of historical data, and elasticity coefficients, the final energy demand forecasts are differentiated by sector in this paper. The predictions of the transport sector's future passenger and freight turnover and the construction sector's future residential and public building area are based on elasticity equations.

The transportation sector is divided into road, railway, shipping, and other transport modes and is further classified into freight and passenger transportation. The passenger final service demand unit is MPKM (million person-kilometers), and the freight service demand unit is MTKM (million ton-kilometers). The construction sector in the model is divided into urban residential, rural residential, large commercial, and general commercial buildings. The main factors affecting the demand for energy services in the transportation sector are population, GDP growth rate, and final service prices, which are classified according to the passenger and freight transportation modes. The influential factors for construction energy service demand mainly include population, urbanization rate, and per capita income. A driving factor is a variable that is added to the demand for different final services and used to predict the final service demand in the model calculation year.

$$Demand_t = Demand_{t-1} \times k \times driver^{elasticity}, \quad (6)$$

where  $k$  is a constant that is used for adjustment. The driving factor acts on the final service demand changes through demand elasticity, as shown in equation (6). The driving factors are different for the various sectoral energy service demands. The driving factors for passenger transportation service demand are per capita income, energy service price, and population; for freight service demand, they are income and energy service price; for construction service demand, they are GDP growth, urbanization rate, population, and changes in energy intensity. In the industrial sector, the predictions are modeled and analyzed separately according to the final industrial product.

Combined model comparisons and expert surveys are used to determine future energy service demands. For example, the raw steel demand prediction function is shown in equation (7):

$$DM_{steel} = RF_1 \times c_1 + RF_2 \times c_2 + CF \times c_3 + \sum_i T_i \times c_{4i} + AP \times c_5 + E_x, \quad (7)$$

where  $DM_{steel}$  is the demand for steel;  $RF_1$  and  $RF_2$  represent the increases in the building areas of urban and rural residential buildings, respectively;  $CF$  defines the increase in commercial building area;  $T$  denotes the increase in transportation products, including passenger cars, buses, trucks, and ships;  $AP$  represents the increase in the number of household electrical appliances;  $E_x$  refers to other steel demands (exports and imports are considered);  $c$  represents the steel intensities of products in construction of the three different building types, transportation, and household appliances, with units  $t$  steel/ $m^2$ ,  $t$  steel/vehicle, and  $t$  steel/appliance, respectively; and  $i$  denotes vehicle type, including passenger car, bus, truck, ship, and others.

### **Supplementary Note 3:** Updates to the MAPLE model compared to other models

The MAPLE model has been updated to version 4.0. In version 1.0, the model was able to answer questions pertaining to national-level system optimization solutions. Different from other models with detailed supply curves for coal, oil, and gas mining from different fields at varying costs, it helped to avoid the overestimation of fuel substitution with a single price assumption. In version 2.0, local pollutant emissions were added to the MAPLE model, an important innovation at that time. Instead of setting simplified emission coefficients for  $SO_x$ ,  $NO_x$ , and primary PM-based emissions for each sector/fuel, we set emission coefficients based on processes. This was important, especially for the industrial sector, due to the complex emission processes and the different end-of-pipe control measures applied in these processes. Doing so helped avoid bias in environmental impact analysis results. In addition, for the residential and industrial sectors, the geographic granularity of the model was updated to 31 provinces<sup>61,62</sup> because the residential sector accounts for a large amount of particulate matter ( $PM_{2.5}$ ) emissions, and MAPLE aims to analyze the co-benefits of emission reductions for air quality. Based on this version, we found that even with the best-available technology (BAT) of end-of-pipe control measures, China's local pollutant

emission target could not be met in 2030 and that further deep decarbonization efforts would be needed to reduce local pollutants before they are emitted<sup>63,64</sup>.

For the most recent version, more improvements have been introduced. First, hydrogen applications have been added, especially for final-use demand processes, something that has not been fully addressed in most models as of yet. Second, the HTA sectors have been expanded to include more detailed processes. This version enhances the explanation of the actual energy system and therefore allows the model to analyze the heterogeneity of different HTA processes with hydrogen applications. More detailed information on these technological processes can be found in Supplementary Notes 4 and 5.

#### **Supplementary Note 4: Model description of technology processes in the HTA sectors**

The model includes 579 HTA sector technological processes. The specific technologies are defined by their technical and economic parameters ([https://iea-etsap.org/docs/Documentation\\_for\\_the\\_TIMES\\_Model-PartII.pdf](https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-PartII.pdf)). The HTA sectors included in this study include industrial production of cement, iron, steel, and key chemicals (including ammonia, soda, and caustic soda), as well as heavy-duty transport, such as trucking and shipping. The descriptions of the iron and steel technological processes include coking, sintering, pelleting, blast furnaces, electric furnaces, and hydrogen-DRI furnaces at different scales and efficiencies. The mitigation technologies for the iron and steel sector include material efficiency, technology performance, electrification, and the CCUS and hydrogen requirements for 60 mitigation technological processes, see Supplementary Table 1. In the cement sector, the clinker production and cement production processes are analyzed separately, with both dry and wet processes at different scales considered for clinker production. The mitigation technologies in the cement sector include energy efficiency, such as an efficient pre-calciner pre-heater system; alternative fuels, such as the gasification or pre-combustion of these fuels; reducing the clinker to cement ratio measures; CCUS; and blue and green hydrogen. The 47 cement mitigation technologies are listed in Supplementary Table 2.

In addition to detailed descriptions of the ferrous metal and cement industries, the industrial sector also includes descriptions of production of non-metallic materials (glass, paper, and brick), chemicals (ammonia, methanol, ethylene, soda, caustic soda, yellow phosphorus, and other chemicals), and petroleum-based chemical products<sup>61</sup>. All the industrial products have detailed process descriptions. These processes include those for non-ferrous metals (copper, aluminum, zinc, and lead products with multiple processes), non-metallic materials (glass, paper, and brick), chemicals [Haber-Bosch-produced ammonia (both thermochemical and electrochemical processes), methanol, ethylene, soda, caustic soda, yellow phosphorus, and other chemicals) and petroleum-based chemical products. For example, for the glass industry, we consider horizon pull for glass methods with different efficiencies, vertical pull for glass methods with different efficiencies, and float glass processes with different efficiencies. As another example, for the brick industry, we consider different scales of tunnel plants, hollow brick, internal combustion brick, and brick made from other materials.

For the transportation sector, different transport modes are considered, including road transport (two- and three-wheelers, light-duty vehicles, buses, and trucks), shipping, pipelines, and railways. Light-duty vehicles are further differentiated by fuel (gasoline, CNG, electricity, hydrogen, hybrid, and others), body design (passenger car, SUV, and others)<sup>65</sup>, and China's emission standards (IV, V, VI, and others). Trucks are classified by fuel (diesel, CNG, electricity, hybrid, hydrogen), emission standards, and load rate (light, medium, and heavy). In the residential sector, different energy consumption modes are considered (heating, cooling, hot water, cooking, lighting, appliances). Each of the modes are evaluated for both urban residential and rural residential dwellings due to differing energy consumption intensities. Space heating is further classified by region, considering the regional differences in heating appliances and fuels<sup>62</sup>.

The model describes the HTAs in detail, whereas other models tend to simplify them, especially in the industrial sector (<https://www.enerdata.net/solutions/poles-model.html>). It finds energy market partial equilibria and determines an optimal configuration of the energy systems to satisfy service demands at minimum cost over a long-term horizon while adhering to greenhouse gas emission constraints ([https://iea-etsap.org/docs/Documentation for the TIMES Model-Part-I.pdf](https://iea-etsap.org/docs/Documentation%20for%20the%20TIMES%20Model-Part-I.pdf)).

We consider the CCS technology cost to be 62-110 \$/ton CO<sub>2</sub> in 2020 and 42-92 \$/ton CO<sub>2</sub> in 2040<sup>66</sup>. Between 2020 and 2050, the investment cost of CCS technology is expected to decrease by 1.3-1.9% annually, according to BP<sup>67</sup>. Multiple negative emission technologies (NETs) are considered, including BECCS, with a cost of 100-200 \$/ton CO<sub>2</sub><sup>66</sup>, and DAC, with a cost assumed to be 200-300 \$/ton CO<sub>2</sub><sup>68</sup>.

#### **Supplementary Note 5: Model description of hydrogen technologies in the HTA sectors**

The hydrogen production technologies analyzed in this study include centralized electrolysis using AEC, PEMEC, and SOEC electrolyzers, biomass gasification, coal gasification with CCS, and natural gas reforming with and without CCS (Supplementary Table 5). Technology improvements are assumed by referring to IRENA<sup>3</sup> and DEA<sup>2</sup> for 2020 to 2050; note that the levels for 2060 are assumed the same as that for 2050. When it comes to the hydrogen demand in final end-use sectors, our model considers hydrogen technologies applied in the HTA sectors in detail, an advance over more simplified treatments of demand in other studies. The hydrogen technologies applied in the iron and steel sector include hydrogen injection in blast furnaces and hydrogen-DRI processes to provide both heat and a reductant (see Supplementary Table 1), and the hydrogen technologies in the cement sector include green hydrogen heating in large NSP (preheater drying process) kilns at different hydrogen injection rates, and blue hydrogen heating at different hydrogen injection rates (see Supplementary Table 2). The hydrogen applications in other sectors mainly include hydrogen used as feedstock for key chemical products, such as ammonia and methanol, and heating sources with different injection rates for use in multiple industrial processes. In the transportation sector, hydrogen is applied in all transport modes, including fuel cell light-duty vehicles, fuel cell fleet buses, fuel cell trucks (light, mid, and heavy), and shipping with hydrogen and ammonia as fuel. In the residential sector, we consider hydrogen use for space heating. Note that not all hydrogen applications are utilized in the future. Usage depends on the whole system optimization under varying carbon emission and other constraints, during which all hydrogen-consuming processes compete with other technologies to meet energy service and chemical feedstock demand.

### **Supplementary Note 6: Results on residential heating**

Besides the key applications of hydrogen in HTA industries and heavy-duty transport, we also modeled hydrogen use in residential heating and energy storage. North China has huge heat demands in winter. In the 2017-2018 winter, policies to encourage “coal-to-gas” and “coal-to-electricity” transitions in residential heating were vigorously promoted in 28 cities of north China (the so-called “26+2” program), to achieve both carbon mitigation and air quality targets. In the carbon neutral future, however, neither coal nor gas will provide residential heating. The ZERO-NH scenario results in a very high share of electrification (97%). Enormous expansion of electrified heating demand will create strong pressures on power balancing in regional grids in the winter, putting heating systems at risk due to unanticipated power outages. A larger share of hydrogen-fueled heating could help to reduce this risk, although modeling this benefit would require a power system model and is beyond the scope of the current study. In the ZERO-H scenario, electricity would still account for the largest proportion (72%) of the final energy demand for residential heating in 2060, but with a notable share of hydrogen-based heating (25%). To avoid shortages of heating supply, the energy efficiency of the housing stock in north China should be improved and neighborhood and regional power distribution networks would need to be upgraded to handle sharply growing demand for electricity.

### **Supplementary Note 7: Sensitivity analysis**

As represented in Supplementary Table 6A, the GDP growth rate of our central case was obtained from the IEA Energy Outlook Report 2021 (Table 2.1 of the report)<sup>5</sup>. The assumptions for higher and lower GDP growth rates come from the recent report on China’s economic growth by the World Bank Group (WBG) and Development Research Center of the State Council (DRCSC) of China cited earlier<sup>6</sup>. The higher GDP growth assumes aggressive economic reform in China, and the lower GDP growth assumes slower reform<sup>6</sup>. A moderate GDP growth scenario of the WBG and DRCSC report is consistent with our central case and thus is not separately assessed in the sensitivity analysis.

Because the future cost of clean hydrogen is uncertain, we carry out sensitivity analyses based on the 12 hydrogen production technologies listed in Supplementary Table 5. In the central case for ZERO-H, we have already considered the efficiency improvements and cost reductions for the future referring to DEA and IRENA studies<sup>2,3</sup>. For the sensitivity analyses, we set four scenarios of higher hydrogen costs (+10%, +30%, +50%, and +100%) and four scenarios of lower hydrogen costs (-10%, -30%, -50%, and -60%) for all hydrogen production technologies in each milestone year after the base year (Supplementary Table 6B). Chinese alkaline electrolysis systems of one producer cost \$300 per kW in 2021 according to BNEF<sup>69</sup>. The 300 \$/kW cost is equivalent to a 60% reduction compared to the level assumed in the central case, the rationale for a -60% scenario to test the national impacts of such low cost to the energy system and HTA sectors.

In addition, scenarios were tested with incremental 1% rates of cost increase between 50% and 100% to identify at the rate at which the ZERO-H scenario would require the same aggregate investment as the ZERO-NH scenario. The result, +87%, helps to reconfirm the considerable cost-competitiveness of clean hydrogen use demonstrated by the current analysis unless its production cost projections are significantly underestimated.

### **Supplementary Note 8: Sensitivity analysis results at sector and sub-sector levels**

In the following, sensitivity is defined as the percentage change in the rate of clean hydrogen penetration per unit percentage change in clean hydrogen production costs. Comparing HTA sectors, clean hydrogen penetration into the iron & steel industry is more sensitive to hydrogen production costs than in the cement and chemical industries. The hydrogen-DRI technology share would increase significantly when the hydrogen production costs decline more than 30%. The introduction of hydrogen-DRI still has a long way to go in China, but clean hydrogen injection in blast furnaces is less sensitive to hydrogen costs and would continue to be feasible in the near term. In the cement industry, NSP clinker production with clean hydrogen used as a heat source is highly sensitive to changes of hydrogen costs between plus or minus 10-30%. Ammonia production using green hydrogen is most sensitive to hydrogen cost when it declines by 30-50%. When production costs increase more than 30% above the current level, the penetration of hydrogen-based residential heating would shrink significantly by 2060 and electricity-based heating measures

would dominate. Given that hydrogen residential heating technologies require a significant upfront investment that likely includes customer subsidies, it is hard to envisage their widespread adoption compared to hydrogen technologies in HTA sectors. It seems unlikely that delivery of clean hydrogen via re-purposed gas mains will be economically feasible in the foreseeable future, according to analysis in the UK<sup>70</sup>. In the transport sector, hydrogen penetration in road passenger transport is less sensitive than freight transport to hydrogen production cost. The light-duty vehicle (LDV) market will remain dominated by electric vehicles even if hydrogen costs decline sharply. This results also from strong subsidy-based promotion of electric vehicles in China, which is effectively locking in this mode for LDVs and making the prospects for fuel-cell LDVs doubtful. As an example of the comparative effects of cost on different transportation modes, hydrogen fuel-cell long-distance fleet buses would be more sensitive than light trucks to clean hydrogen cost declines. With cost declines of more than 30%, heavy trucks and ships fueled by hydrogen and ammonia would dominate their markets, reaching penetration shares above 75%. In sum, declines in costs of clean hydrogen production indicate huge potential expansions of hydrogen use, especially in the iron & steel industry, heavy trucks, and shipping.

#### **Supplementary Note 9:** Additional discussion on the cost of hydrogen

Recent studies from IEA, IRENA, and BNEF concluded that the LCOH for green hydrogen will decline to competitive levels with fossil-derived hydrogen by 2030 in the US (under 2.0 \$/kg), EU (under 2.8 \$/kg), and Japan (under 3.3 \$/kg)<sup>71,72</sup>. Others suggest that despite this projected low LCOH in richer countries, countries such as China and India are not on the same cost trajectory. In these countries, the new investments needed for clean hydrogen production facilities and transport and storage infrastructure imply higher levelized costs. We thus consider all the processes required for clean hydrogen production and use in China, from original input data. Our results do not support the latter conclusion; instead, they show that a net \$1.72 trillion new investment cost could be avoided by exploiting clean hydrogen by 2060 instead of following a no-hydrogen scenario.

Although clean hydrogen has a promising future, incentives should not only focus on the supply side but also on demand sectors. Hydrogen-DRI technology in the iron and steel sector is still at a research and experimental stage and cannot currently be used in a commercially competitive

application. China has issued a hydrogen development strategy for 2023-2035, which mainly declared its determination to enhance hydrogen development rather than provided a detailed technology and policy roadmap to achieve it. Therefore, a realistic development pathway is needed. Incentives, including subsidies on steel products, and introducing a carbon trading system to the iron and steel sector, will help to bring large-scale hydrogen applications to fruition.

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