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## Supplemental information

# Achieving an 80% carbon-free electricity system in China by 2035

**Nikit Abhyankar, Jiang Lin, Fritz Kahrl, Shengfei Yin, Umed Paliwal, Xu Liu, Nina Khanna, Qian Luo, David Wooley, Mike O'Boyle, Olivia Ashmoore, Robbie Orvis, Michelle Solomon, and Amol Phadke**

**Supplemental Information**

**Figure S1: Overall modeling approach, Related to STAR Method**

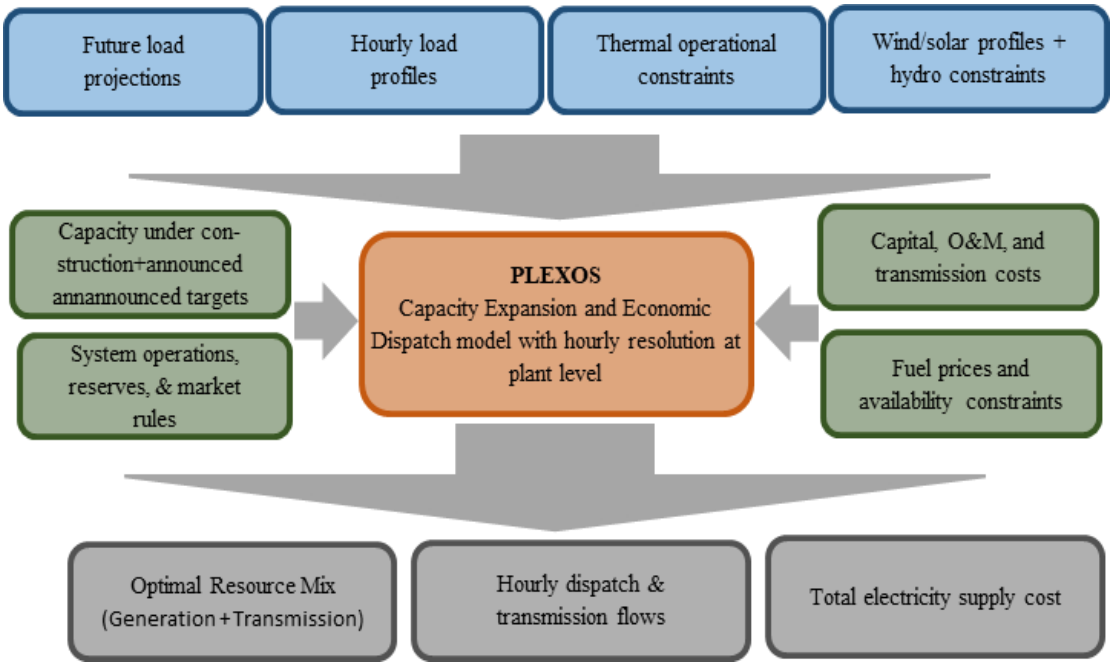


**Figure S2: Average heat rate of a coal unit (660 MW supercritical) as a function of unit loading, Related to STAR Method**

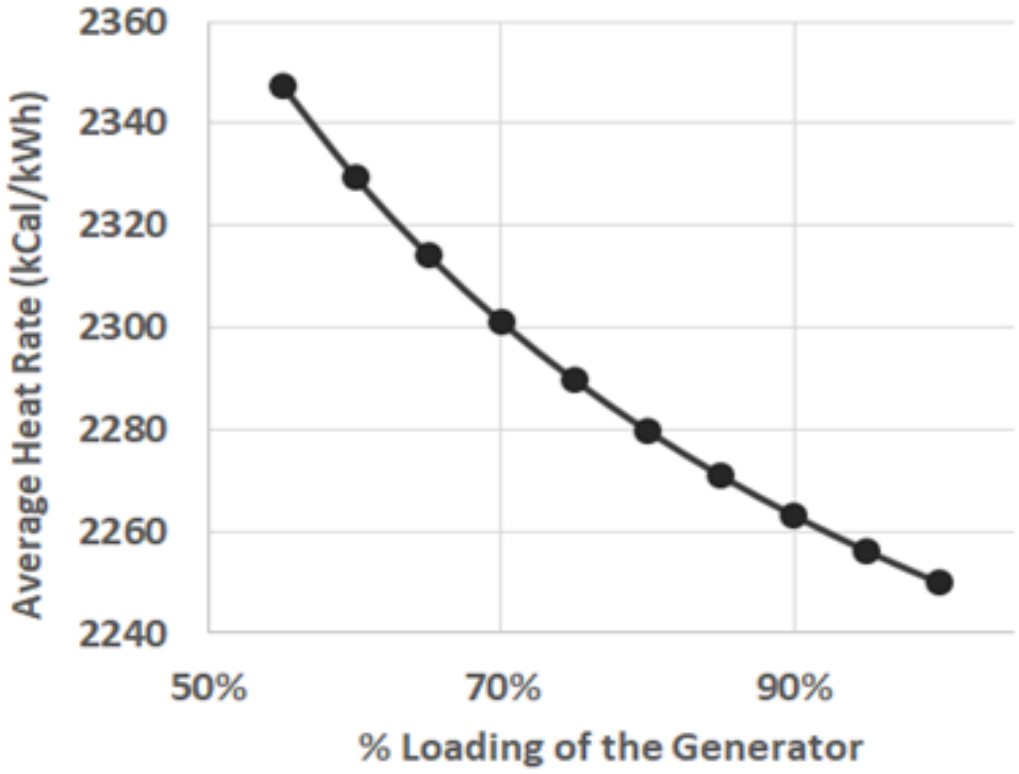


**Figure S3. Spatial distribution of PM concentration reductions (left) and avoided mortalities (right) caused by power plant emissions under the Clean Energy scenario when compared with the Reference scenario in 2035, Related to STAR Method**

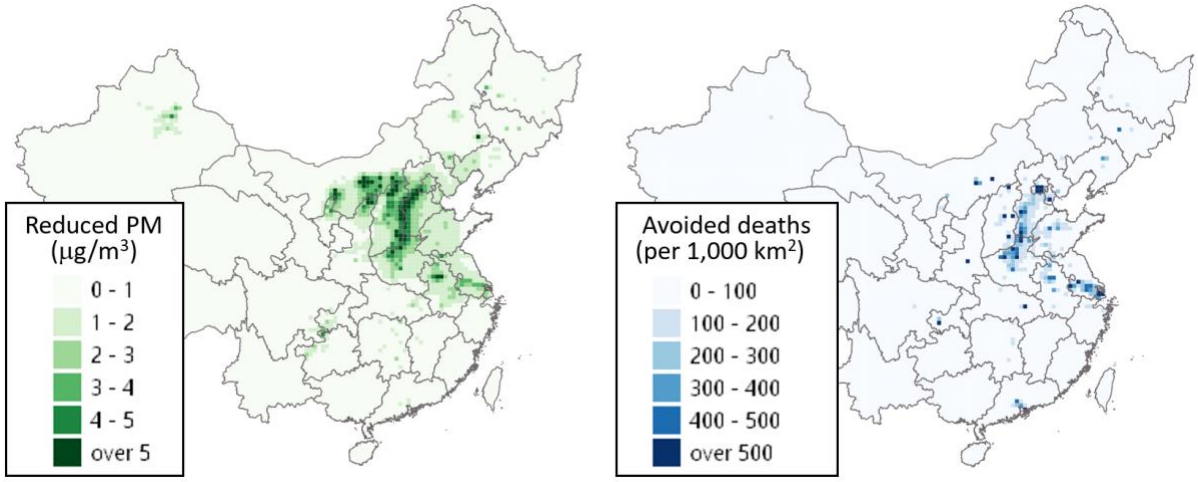


**Figure S4. Historical labor productivity growth rate index by sector in China, Related to STAR Method**

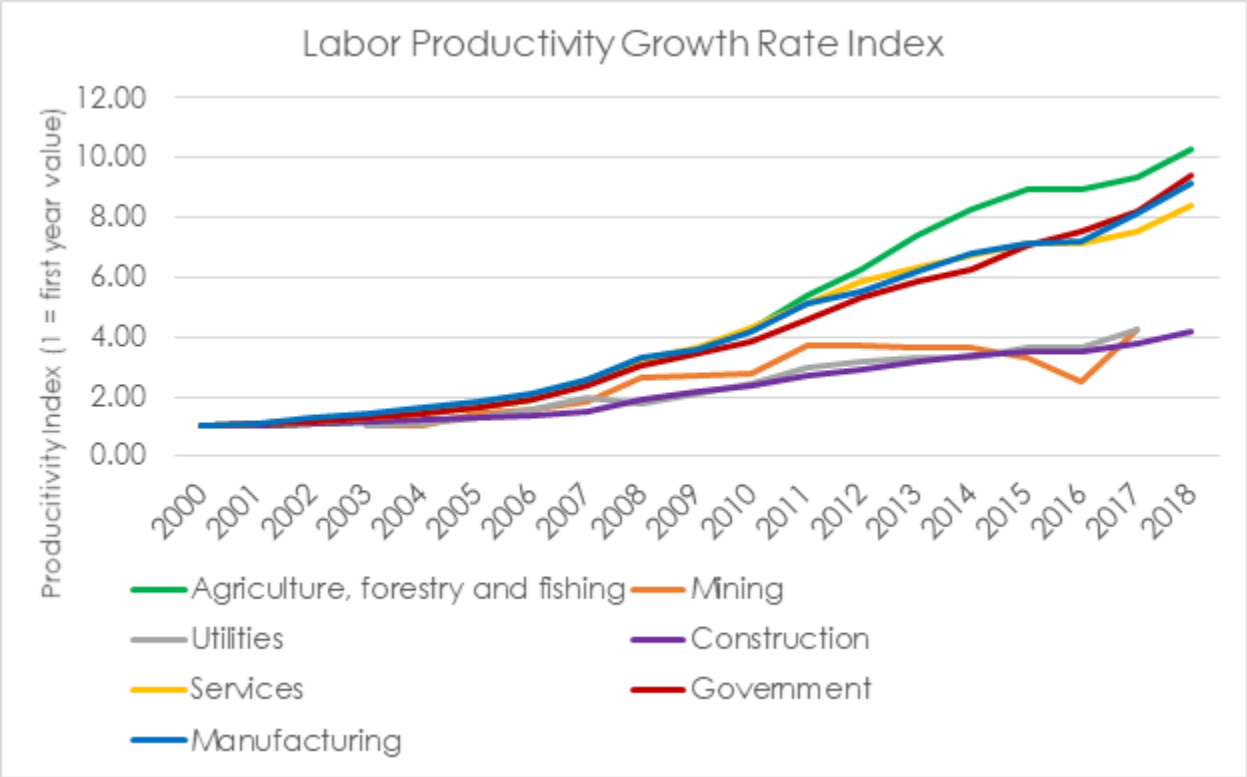


**Figure S5. Historical labor productivity growth rate index by manufacturing industry in China, Related to STAR Method**

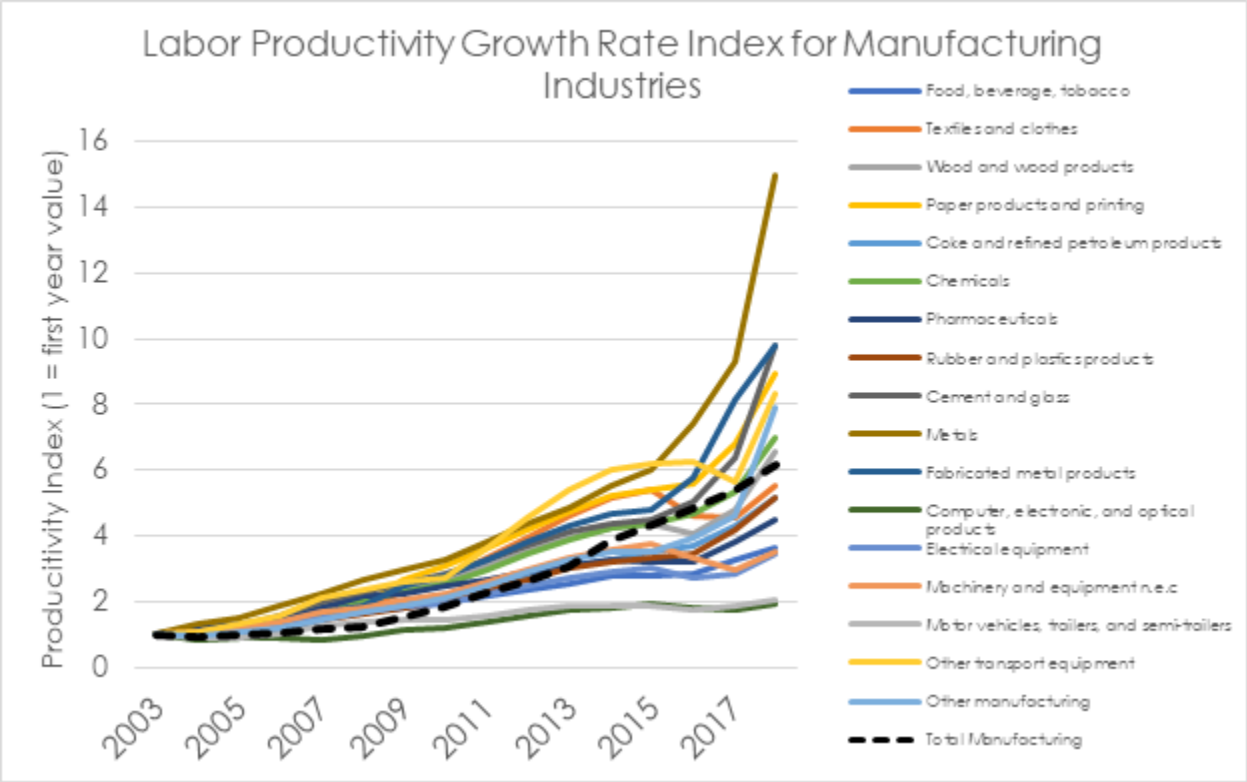


**Figure S6. Cumulative change in job-years when assuming no incremental growth in productivity. This is an upper bound on employment changes, Related to STAR Method**

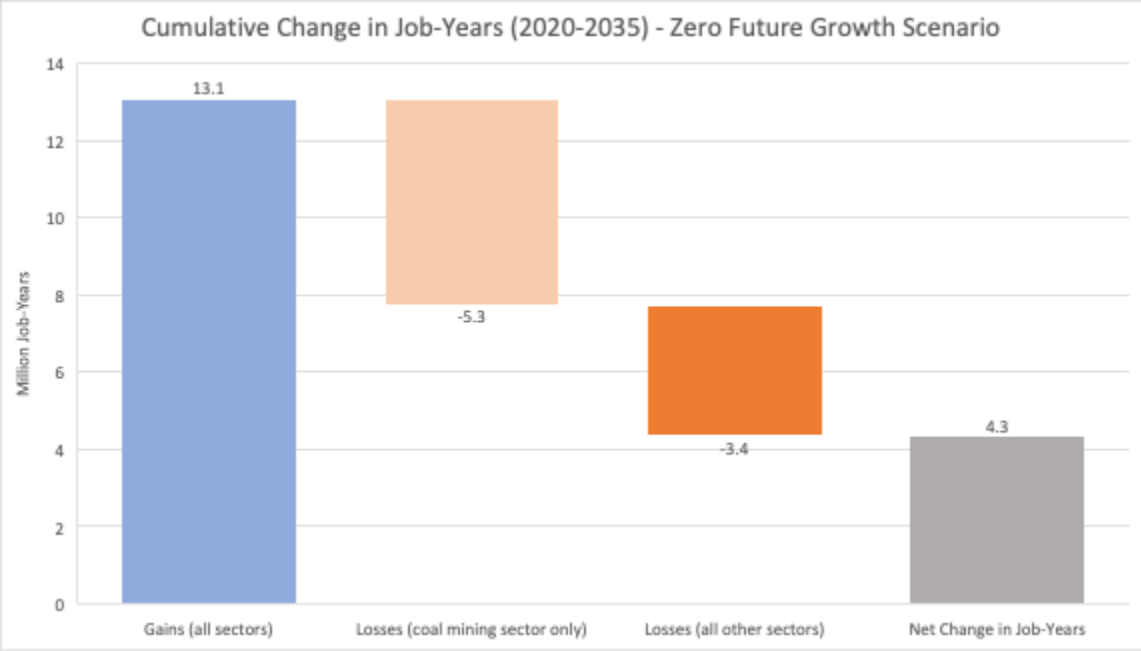


**Figure S7. Cumulative change in job-years using sector-by-sector labor productivity growth rate index estimates based on historical data, Related to STAR Method**

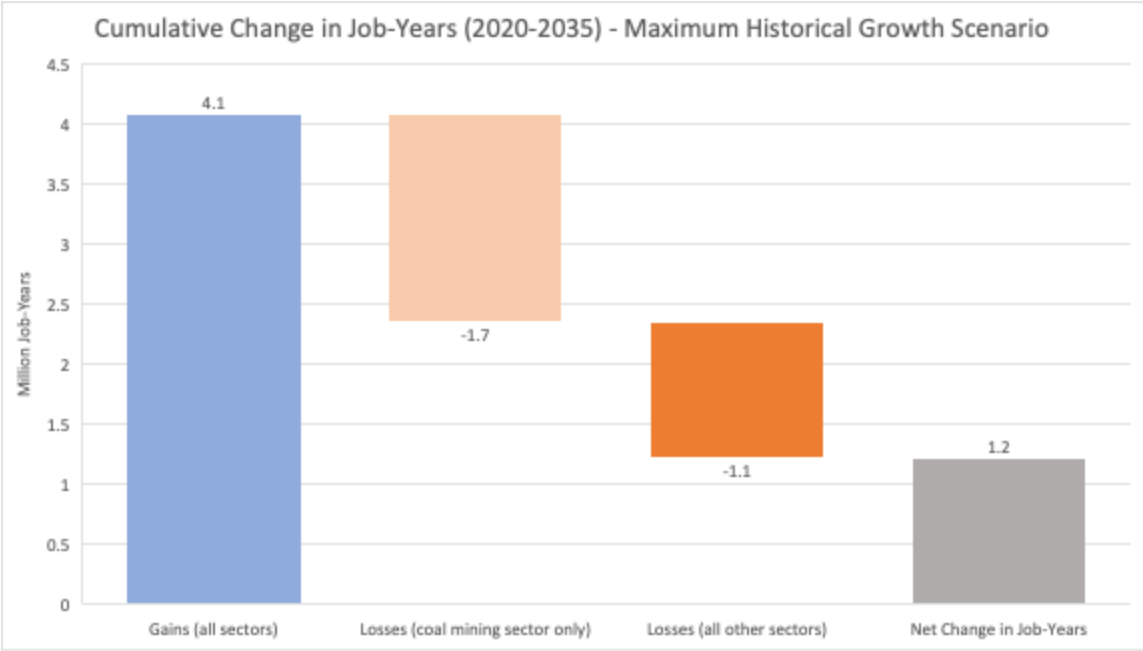
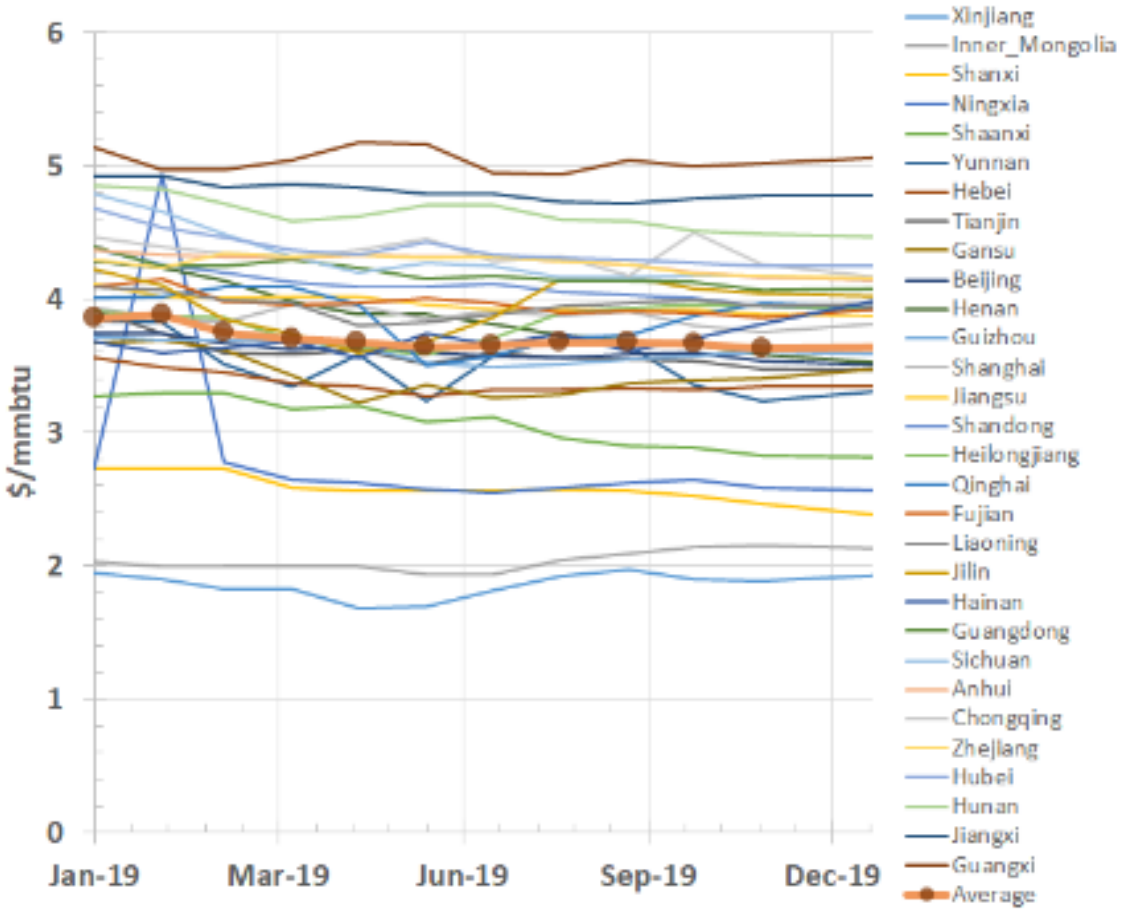


**Figure S8: Province level coal prices, Related to STAR Method**




Source: http://www.imcec.cn/zgdm_2019.

**Figure S9. Estimated solar capacity factors in China, Related to STAR Method**

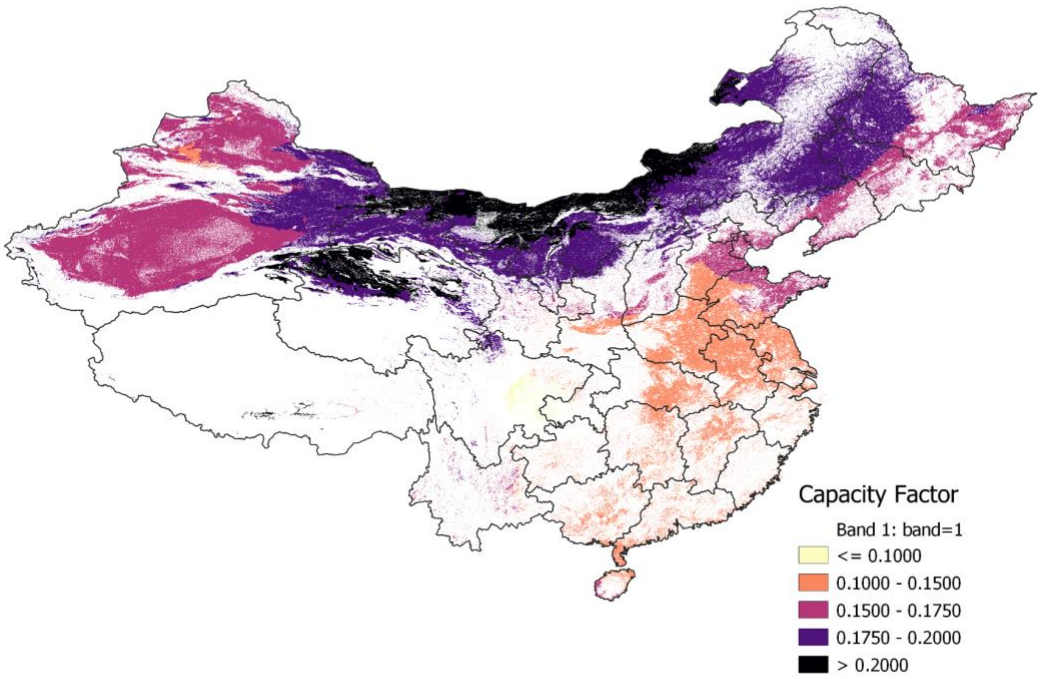


**Figure S10. Estimated Wind Capacity Factors in China, Related to STAR Method**

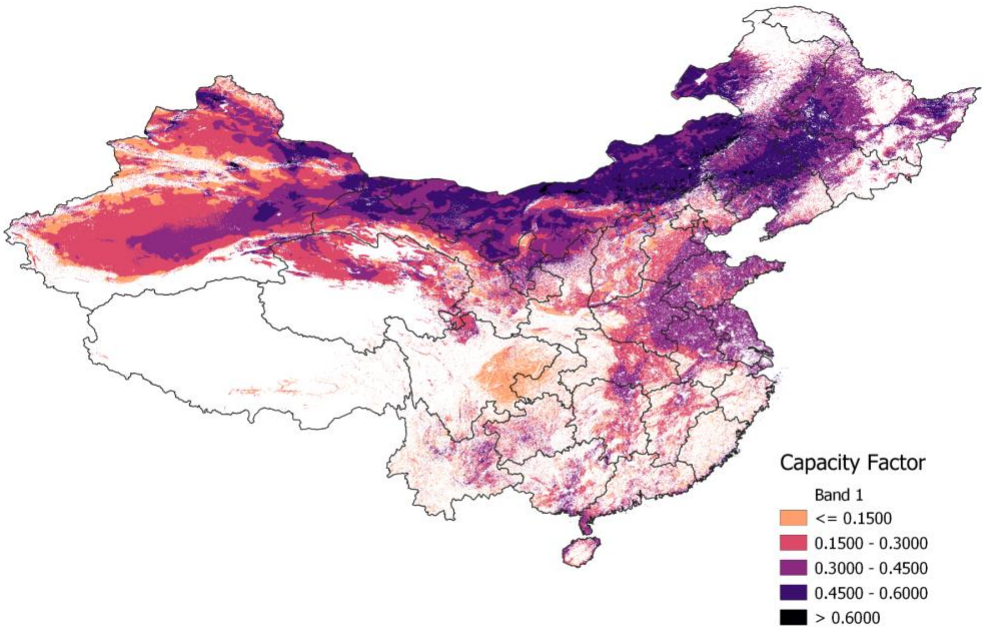


**Figure S11. Estimated offshore wind capacity factors in China, Related to STAR Method**

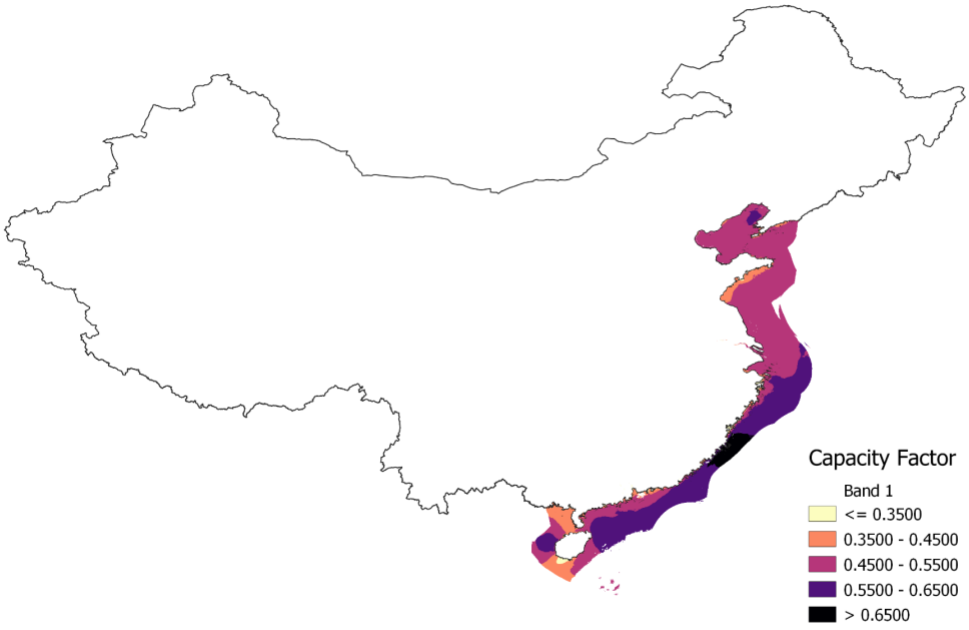


**Figure S12. Current Policy Scenario (Installed Capacity in GW), Related to STAR Method**

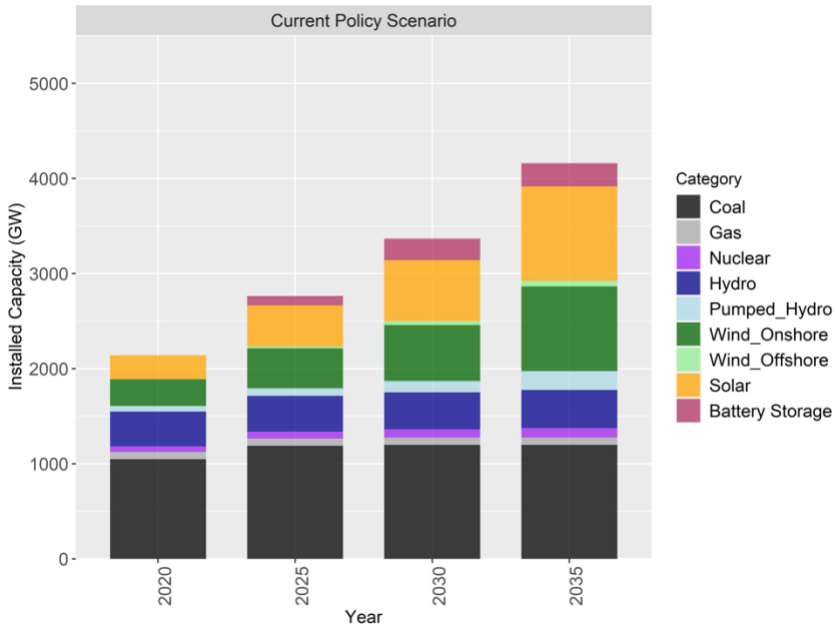


**Figure S13. Current Policy Scenario (Annual Generation in TWh/yr), Related to STAR Method**

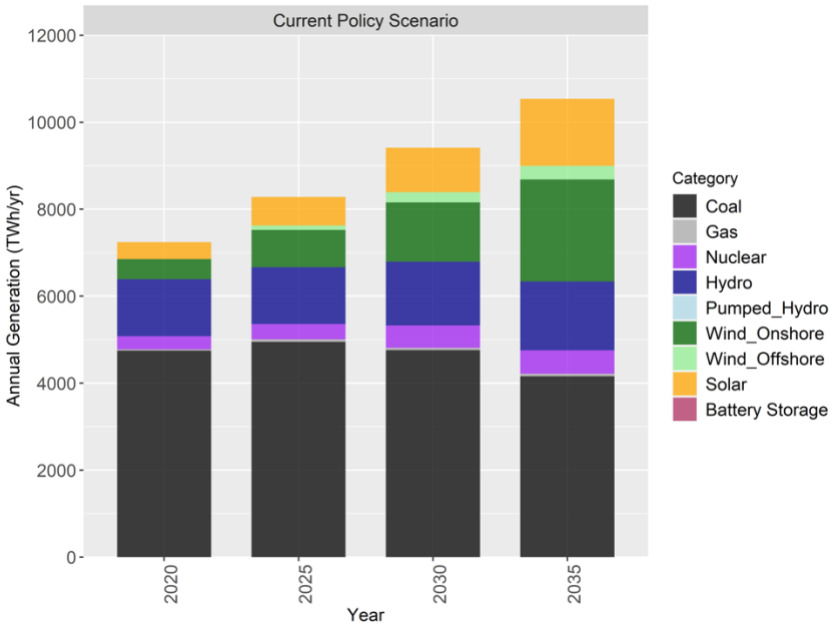


**Figure S14. Clean Energy Scenario (Installed Capacity in GW), Related to STAR Method**

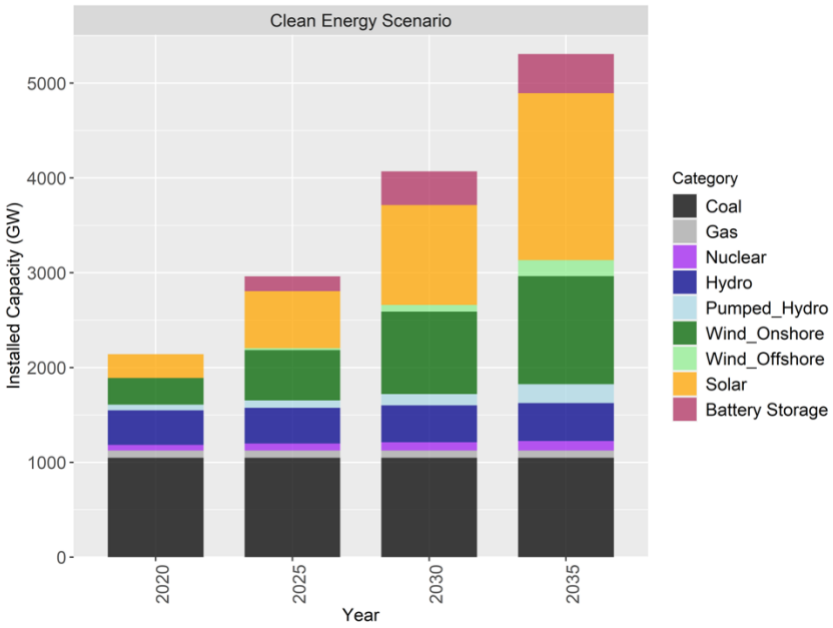


**Figure S15. Clean Energy Scenario (Annual Generation in TWh/yr), Related to STAR Method**

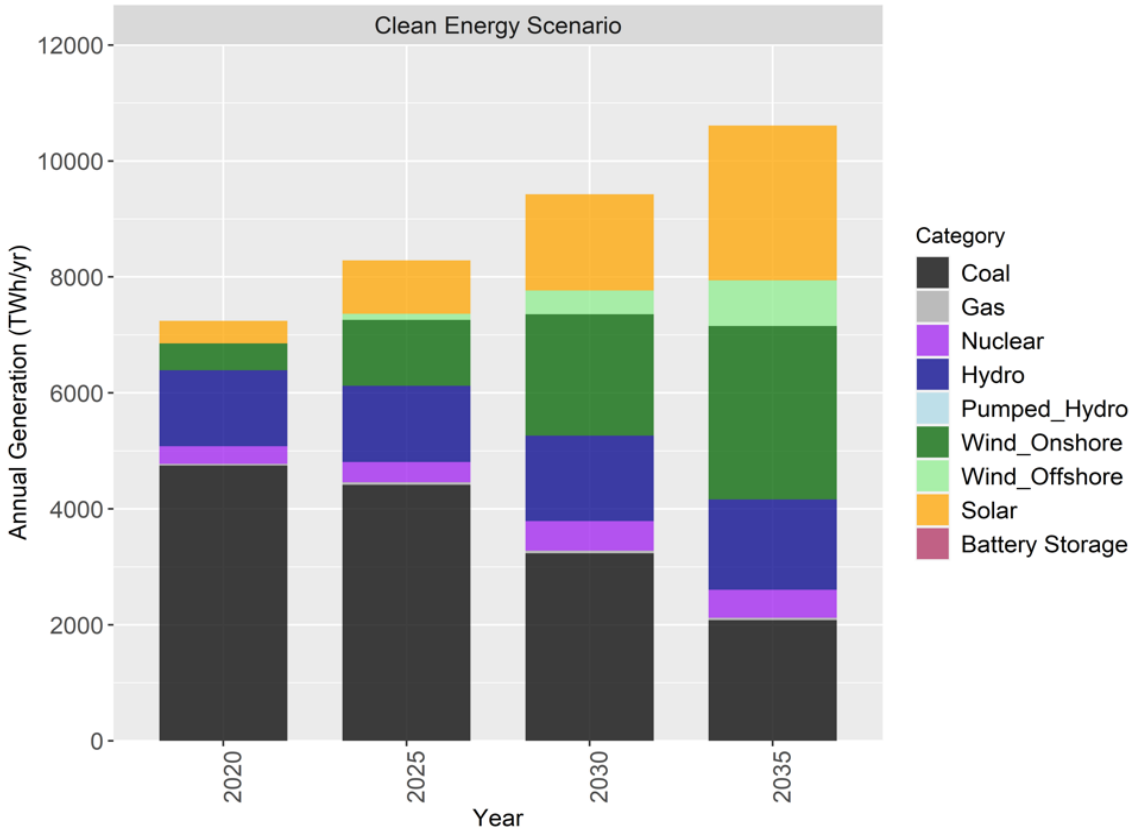


**Figure S16. Offshore Sensitivity Case (Installed Capacity in GW), Related to STAR Method**

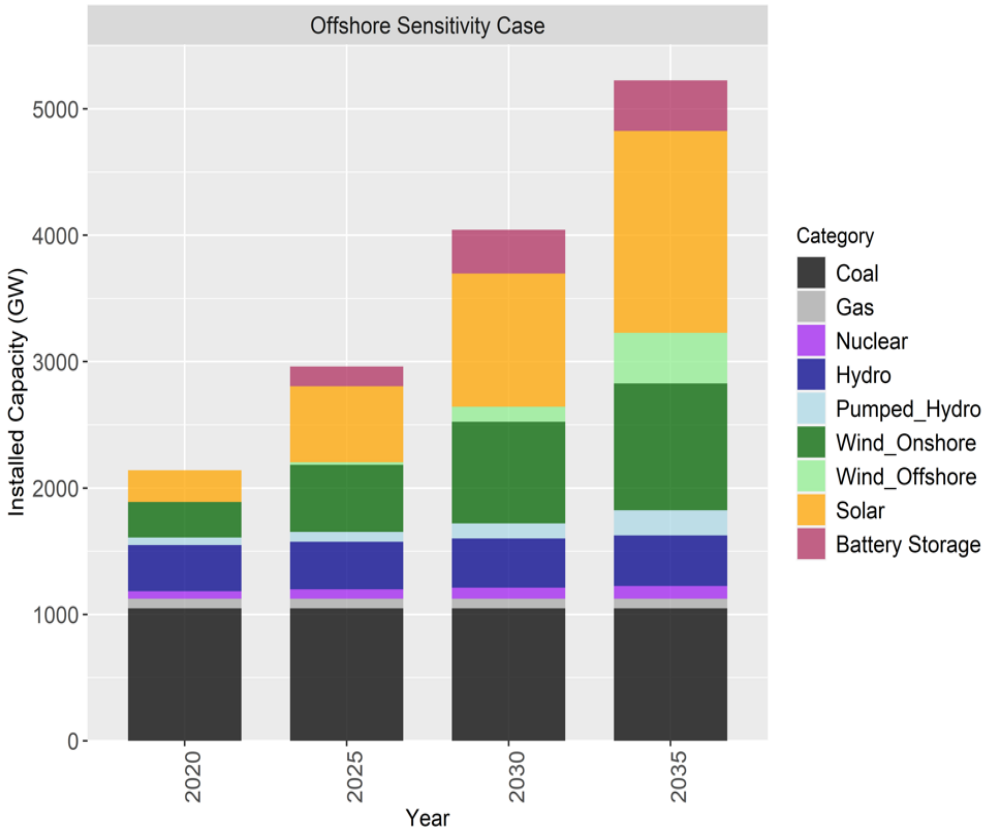


**Figure S17. Offshore Sensitivity Case (Annual Generation in TWh/yr), Related to STAR Method**

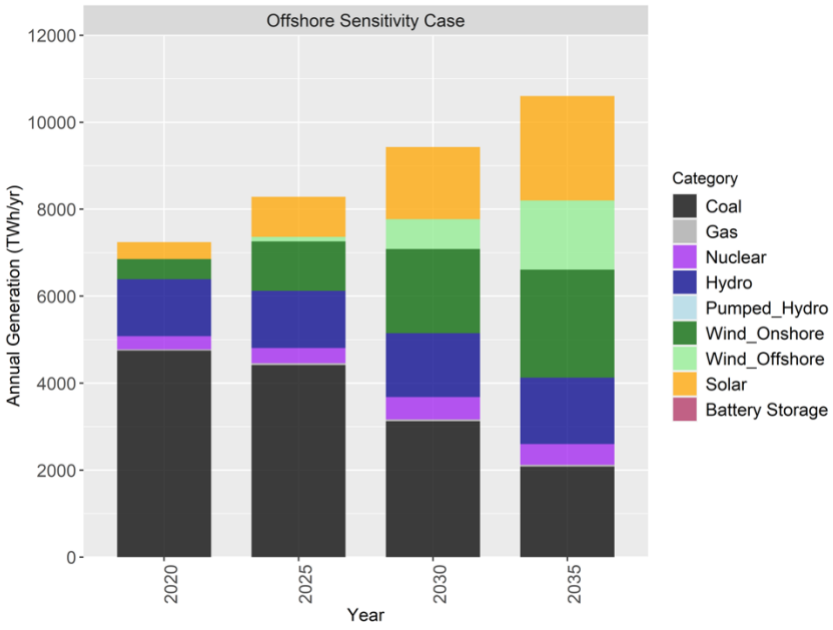


**Table S1: Assumptions on Operational Parameters of Power Plants, Related to STAR Method**

| | Coal (new) | Gas CCGT | Gas CT | Hydro | Nuclear | Battery | Pumped Hydro |
|---|---|---|---|---|---|---|---|
| **Planned Outage rate** | 5% | 5% | 5% | 5% | 10% | 1% | 5% |
| **Forced Outage rate** | 5% | 5% | 5% | 5% | 10% | 1% | 5% |
| **Technical Minimum Level %** | 40% | 30% | 20% | 0% | 90% | 0% | 0% |
| **Cold-start time (hours)** | 24 | 12 | 1 | #N/A | 96 | 0 | #N/A |
| **Minimum up-time (hours)** | 12 | 6 | 1 | 0 | 96 | 0 | 0 |
| **Minimum down-time (hours)** | 6 | 3 | 1 | 0 | 96 | 0 | 0 |
| **Cold-start Cost ($/MW)** | 100 | 30 | 1 | #N/A | #N/A | #N/A | #N/A |
| **Ramping (% of installed capacity per minute)** | 1% | 2% | 10% | 100% | #N/A | 100% | 100% |
| **Auxiliary Consumption** | 7% | 5% | 2% | 1% | 10% | 0.5% | 1% |
| **Roundtrip Efficiency** | #N/A | #N/A | #N/A | #N/A | #N/A | 90% | 80% |

**Table S2. Premature deaths associated with power plant emissions in China in 2020, 2025, and 2035 under Current Policy and Clean Energy scenarios. (Percentages are the mortality reductions compared with the Current Policy case.), Related to STAR Method**

| | 2020 | 2025 | 2035 |
|---|---|---|---|
| Current Policy | 118,430 | 130,060 | 104,720 |
| Clean Energy | | 115,380 (12%) | 50,560 (52%) |

**Table S3. Electricity Demand Projections Used in this Study and in Other Recent Studies, Related to Figure 13 and STAR Method**

| Study / Scenario | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| **This study** | **7300** | **8350** | **9400** | **10745** | **12090** | **13435** | **14780** |
| ICCSD (2020) / 1.5°C | 7300 | | 9400 | | | | 14780 |
| ICCSD (2020) / 2°C | 7300 | | 9400 | | | | 13100 |
| CNREC (2021) / Below 2°C | 7736 | | 11387 | 12740 | 13809 | 14889 | 15527 |
| SGCC (2020) / Low range | | | | 11500 | | | 12400 |
| SGCC (2020) / High range | | | | 12900 | | | 14700 |
| EFC () / 1.5°C high | 7285 | | 10021 | 11228 | 12180 | 13913 | 15773 |
| IEA (2020) / Stated policies | | 8891 | 9952 | | 12023 | | |
| IEA (2020) / Sustainable dev. | | 8607 | 9317 | | 10951 | | |
| Jiang (2018) / 2°C | 7000 | 8500 | 9000 | | 11000 | | 12000 |
| Jiang (2018) / 1.5°C | 8000 | 9000 | 10000 | | 13000 | | 14000 |
| CEC (2020) | 7521 | 9500 | | | | | |

**Table S4. Base and Projected Shares of National Electricity Demand, Related to STAR Method**

| Province | 2019 | 2035 | Province | 2019 | 2035 |
|---|---|---|---|---|---|
| Beijing | 1.61% | 1.53% | Hubei | 3.05% | 3.04% |
| Tianjin | 1.21% | 1.15% | Hunan | 2.57% | 2.55% |
| Hebei | 5.32% | 5.29% | Guangdong | 9.24% | 9.57% |
| Shanxi | 3.12% | 3.12% | Guangxi | 2.63% | 2.84% |
| Inner Mongolia | 5.04% | 5.01% | Hainan | 0.49% | 0.56% |
| Liaoning | 3.31% | 3.18% | Chongqing | 1.60% | 1.45% |
| Jilin | 1.08% | 1.02% | Sichuan | 3.64% | 3.33% |
| Heilongjiang | 1.37% | 1.29% | Guizhou | 2.13% | 2.34% |
| Shanghai | 2.16% | 2.07% | Yunnan | 2.50% | 2.56% |
| Jiangsu | 8.64% | 8.42% | Tibet | 0.11% | 0.10% |
| Zhejiang | 6.49% | 6.29% | Shaanxi | 2.64% | 2.57% |
| Anhui | 3.17% | 3.10% | Gansu | 1.78% | 1.80% |
| Fujian | 3.31% | 3.31% | Qinghai | 0.99% | 0.99% |
| Jiangxi | 2.12% | 2.20% | Ningxia | 1.50% | 1.62% |
| Shandong | 8.58% | 8.21% | Xinjiang | 3.96% | 4.49% |
| Henan | 4.64% | 5.00% | | | |

**Table S5. Estimated Provincial and National SLFs in 2019 and 2035, Related to STAR Method**

| Province | 2019 | 2035 | Province | 2019 | 2035 |
|---|---|---|---|---|---|
| Beijing | 0.55 | 0.50 | Hubei | 0.72 | 0.57 |
| Tianjin | 0.71 | 0.58 | Hunan | 0.77 | 0.58 |
| Hebei | 0.78 | 0.66 | Guangdong | 0.55 | 0.51 |
| Shanxi | 0.87 | 0.68 | Guangxi | 0.85 | 0.62 |
| Inner Mongolia | 0.95 | 0.72 | Hainan | 0.73 | 0.65 |
| Liaoning | 0.88 | 0.69 | Chongqing | 0.61 | 0.52 |
| Jilin | 0.82 | 0.65 | Sichuan | 0.78 | 0.56 |
| Heilongjiang | 0.85 | 0.66 | Guizhou | 0.74 | 0.63 |
| Shanghai | 0.66 | 0.57 | Yunnan | 0.96 | 0.67 |
| Jiangsu | 0.73 | 0.56 | Tibet | 0.75 | 0.65 |
| Zhejiang | 0.65 | 0.51 | Shaanxi | 0.89 | 0.59 |
| Anhui | 0.72 | 0.56 | Gansu | 0.94 | 0.72 |
| Fujian | 0.68 | 0.61 | Qinghai | 0.94 | 0.76 |
| Jiangxi | 0.74 | 0.58 | Ningxia | 0.93 | 0.72 |
| Shandong | 0.88 | 0.65 | Xinjiang | 0.88 | 0.71 |
| Henan | 0.67 | 0.59 | National | 0.78 | 0.62 |

**Table S6. Wind, Solar and Battery Storage Capital Cost Assumptions, Related to STAR Method and Figure 14**

| | **2025** | **2030** | **2035** |
|---|---|---|---|
| Onshore Wind (2020 yuan/kW) | 5338 | 5135 | 4914 |
| Offshore Wind (2020 yuan/kW) | 14582 | 13885 | 13314 |
| Solar PV (2020 yuan/kW) | 2599 | 2282 | 2029 |
| Battery storage (4 hour, 2020 yuan/kWh) | 406 | 311 | 267 |

**Table S7: Assumptions on Fixed Costs of Conventional Technologies, Related to STAR Method**

| Technology | Capital Cost of New Capacity (2020 yuan/kW) | Fixed O&M Cost (2020 yuan/kW-yr) |
|---|---|---|
| **Coal (Ultra supercritical)** | 3170 | 95 |
| **Gas (CCGT)** | 1965 | 114 |
| **Hydro** | 9510 | 171 |
| **Nuclear** | 13314 | 628 |

Note: costs converted to 2020 yuan using exchange rate of 6.34 yuan/USD

**Table S8: Summary of Key Assumptions and Variables, Related to STAR Method**

| Parameter | Assumption | Source |
|---|---|---|
| **Geographic Scope** | 32 interconnected provinces | |
| **Clean Technology Cost** | BNEF projections | BNEF 2020 |
| **Operations & Maintenance (O&M)** | Fixed and variable O&M costs of all non-retired power plants are included. | |
| **Weighted Average Cost of Capital (WACC)** | 5% | Expert consultations |
| **Energy Demand** | National load forecasts based on Tsinghua's 2020 1.5C scenario, provincial shares of national demand, and monthly provincial generation shares | Tsinghua ICCSD, 2020 |
| **Extreme Events Analysis (Performed in PLEXOS)** | Modeled highest net load (load minus wind and solar generation) week in the summer and winter in 2035, using 35 years of wind and solar data for China | |
| **Technical Lifespan** | Wind: 30 years<br>Solar PV: 30 years<br>Hydropower: 100 years<br>Battery: 15 years<br>Nuclear: 60-80 years<br>Gas CT: 50 years<br>Gas CCGT: 60 years | Expert consultations, He et al (2020) |
| **Coal Retirements** | Coal plants assumed to retire in 30 years in the coal retirement sensitivity | Expert consultations |

| | | |
|---|---|---|
| **Economic Lifespan** | Standard amortization is 30 years, batteries are 15 years.<br><br>No forced retirement of gas assets. | Expert consultations, He et al (2020) |
| **Electrification of Buildings, Industry and Transport** | Assumes growing reliance on electric vehicles, heating, and industry, per national load forecasts | Tsinghua ICCSD, 2020 |
| **Coal and Natural Gas Prices** | Assume 2019 actual price remains constant through 2035 | |
| **Energy Policy** | ***Current Policy scenario:*** annual deployment of wind and solar limited to current government goals; 150 GW of net coal generation currently under construction is built.<br><br>***Clean Energy scenario:*** no new net coal generation capacity additions after 2020; non-fossil share of generation rises to 80% in 2035. | |

**Table S9. Current Policy Scenario (Installed Capacity in GW,) Related to STAR Method**

| | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| **Coal** | 1,049 | 1,189 | 1,199 | 1,199 |
| **Gas** | 76 | 76 | 76 | 76 |
| **Nuclear** | 59 | 73 | 87 | 100 |
| **Hydro** | 365 | 376 | 389 | 400 |
| **Pumped_Hydro** | 60 | 79 | 119 | 199 |
| **Wind_Onshore** | 280 | 420 | 590 | 890 |
| **Wind_Offshore** | - | 20 | 40 | 60 |
| **Solar** | 253 | 433 | 643 | 993 |
| **Battery Storage** | - | 98 | 225 | 244 |
| **Total** | **2,142** | **2,765** | **3,368** | **4,161** |

**Table S10. Current Policy Scenario (Annual Generation in TWh/yr), Related to STAR Method**

| | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| **Coal** | 4,747 | 4,951 | 4,758 | 4,160 |
| **Gas** | 31 | 58 | 55 | 55 |
| **Nuclear** | 303 | 350 | 514 | 539 |
| **Hydro** | 1,312 | 1,306 | 1,466 | 1,582 |
| **Wind_Onshore** | 462 | 857 | 1,362 | 2,349 |
| **Wind_Offshore** | - | 104 | 236 | 312 |
| **Solar** | 391 | 658 | 1,022 | 1,540 |
| **Total** | **7,245** | **8,283** | **9,413** | **10,538** |

**Table S11. Clean Energy Scenario (Installed Capacity in GW), Related to STAR Method**

| | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| **Coal** | 1,049 | 1,049 | 1,049 | 1,049 |
| **Gas** | 76 | 76 | 76 | 76 |
| **Nuclear** | 59 | 73 | 87 | 100 |
| **Hydro** | 365 | 376 | 389 | 400 |
| **Pumped_Hydro** | 60 | 79 | 119 | 199 |
| **Wind_Onshore** | 280 | 530 | 870 | 1,138 |
| **Wind_Offshore** | - | 20 | 70 | 170 |
| **Solar** | 253 | 603 | 1,053 | 1,761 |
| **Battery Storage** | - | 155 | 356 | 414 |
| **Total** | **2,142** | **2,961** | **4,069** | **5,308** |

**Table S12. Clean Energy Scenario (Annual Generation in TWh/yr), Related to STAR Method**

| | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| **Coal** | 4,747 | 4,414 | 3,233 | 2,083 |
| **Gas** | 31 | 45 | 46 | 39 |
| **Nuclear** | 303 | 349 | 512 | 484 |
| **Hydro** | 1,312 | 1,315 | 1,471 | 1,558 |
| **Wind_Onshore** | 462 | 1,137 | 2,093 | 2,991 |
| **Wind_Offshore** | - | 104 | 414 | 786 |
| **Solar** | 391 | 921 | 1,658 | 2,672 |
| **Total** | **7,245** | **8,284** | **9,426** | **10,613** |

**Table S13. Offshore Sensitivity Case (Installed Capacity in GW), Related to STAR Method**

| | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| **Coal** | 1,049 | 1,049 | 1,049 | 1,049 |
| **Gas** | 76 | 76 | 76 | 76 |
| **Nuclear** | 59 | 73 | 87 | 100 |
| **Hydro** | 365 | 376 | 389 | 400 |
| **Pumped_Hydro** | 60 | 79 | 119 | 199 |
| **Wind_Onshore** | 280 | 530 | 805 | 1,004 |
| **Wind_Offshore** | - | 20 | 120 | 400 |
| **Solar** | 253 | 603 | 1,053 | 1,597 |
| **Battery Storage** | - | 155 | 346 | 400 |
| **Total** | **2,142** | **2,961** | **4,043** | **5,226** |

**Table S14. Offshore Sensitivity Case (Annual Generation in TWh/yr), Related to STAR Method**

| | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| **Coal** | 4,747 | 4,414 | 3,123 | 2,082 |
| **Gas** | 31 | 45 | 42 | 39 |
| **Nuclear** | 303 | 349 | 513 | 480 |
| **Hydro** | 1,312 | 1,315 | 1,471 | 1,527 |
| **Wind_Onshore** | 462 | 1,137 | 1,937 | 2,484 |
| **Wind_Offshore** | - | 104 | 683 | 1,587 |
| **Solar** | 391 | 921 | 1,659 | 2,404 |
| **Total** | **7,245** | **8,284** | **9,428** | **10,603** |