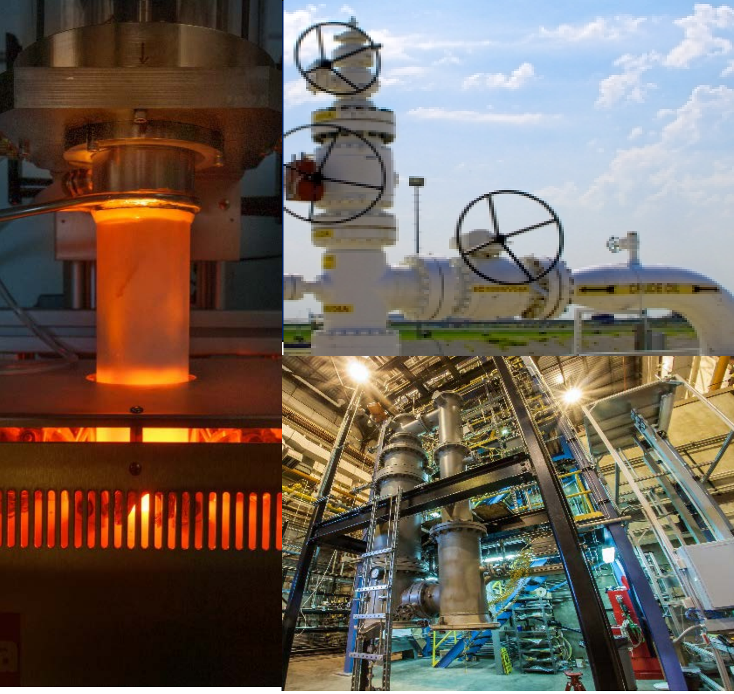


U.S. DEPARTMENT OF ENERGY | Office of Fossil Energy

# Worldwide A-USC Developments
## Opportunities and Threats to Domestic Supply Chain

**DOE Crosscutting Workshop on Developing a Domestic Supply Chain for High-Temperature Steam Cycles**
**Pittsburgh, PA**
**14 November 2018**


**Scott M. Smouse**

Senior Advisor, Office of Clean Coal and Carbon Management

Acting Director
Office of Strategic Engagement
Office Strategic Planning, Analysis & Engagement

# Critical materials and advanced power systems – global opportunities



- Improved efficiency, flexibility, and reliability of coal-based power systems are of paramount importance to coal's future
- China, India, Japan, the European Union, and United States developing materials critical to advanced A-USC cycles and other advanced power systems, such as sCO2
- U.S. success could represent substantial competitive advantage in foreign markets for new high-performance power systems and retrofits
- Differing levels of interest exist on RD&D cooperation among nations on material development and testing and system design
  - At IEA Clean Coal Centre's 3rd A-USC Workshop (Dec. 2017), India and China indicated that they would benefit from international cooperation
  - Materials available on global markets being tested in China and its program has sought outside help on characterization tests
  - India interested in partnerships for material development and testing, but also appears to prioritize limiting reliance on foreign resources

# Critical materials and advanced power systems – threats to domestic supply chain

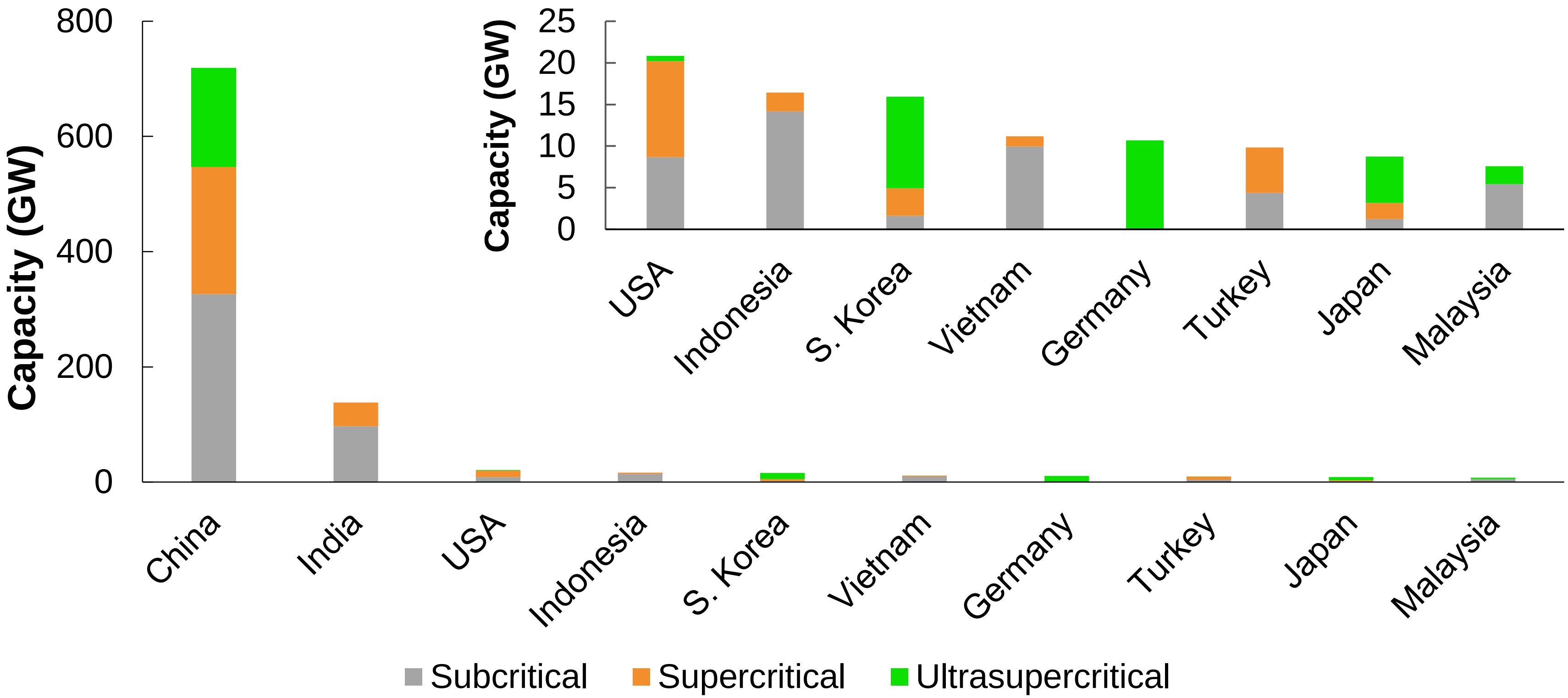


- U.S. domestic market has become challenging for testing materials that are critical to advanced coal-based power cycles
- Substantial deployment of state-of-the-art coal power cycles is occurring mainly in Asia
- Competitive global supply for power plant equipment
  - Licensing, joint ventures, local fabrication, etc.
- Countries developing A-USC concepts balance performance with cost when selecting highest operating temperature and pressure (for example, single reheat vs double reheat)

# Higher efficiency coal-based power generation technologies have been deployed mainly in Asia

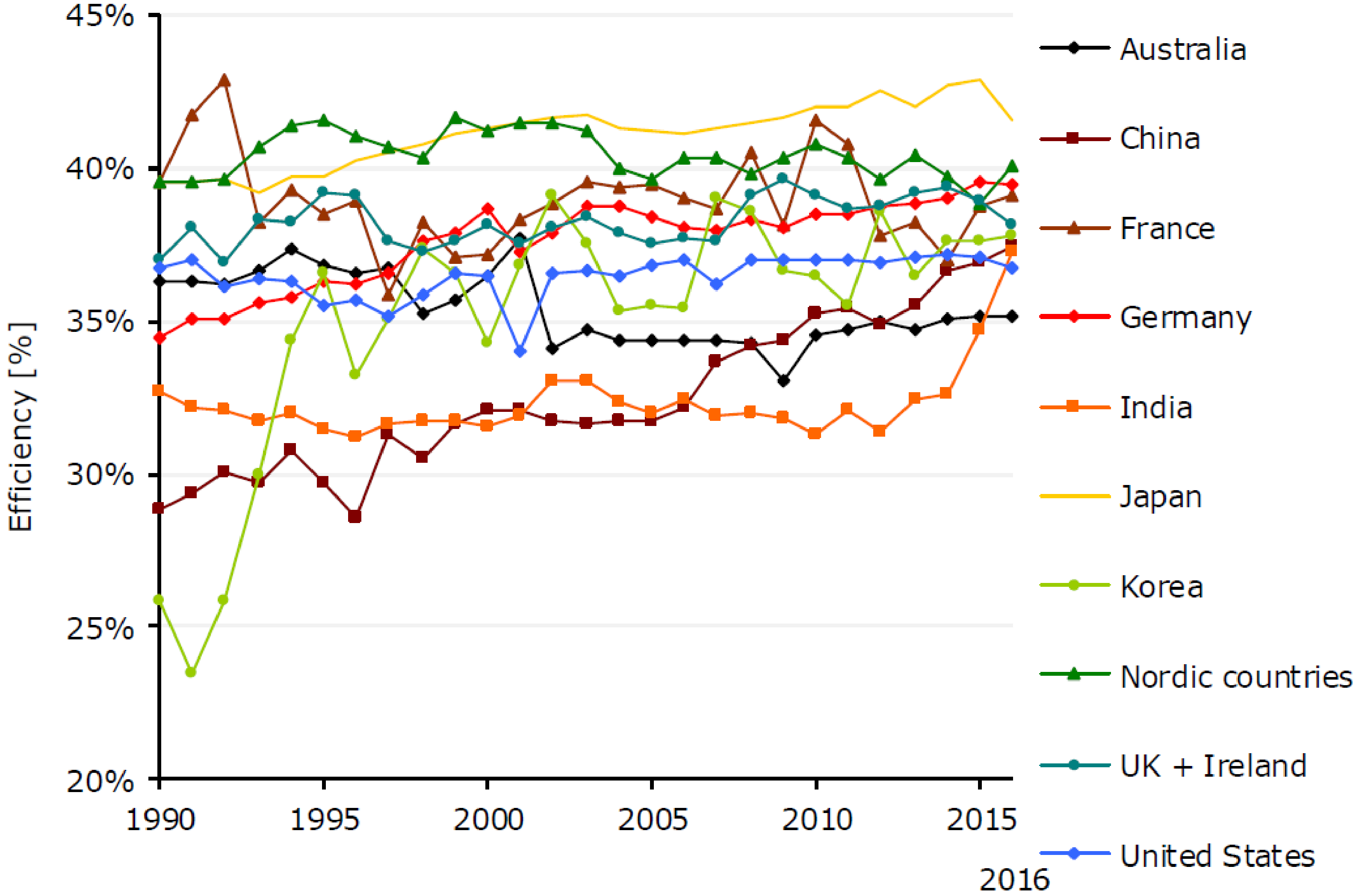


**Total new coal power capacity added from 2003 to 2016, by technology type**



# Operating efficiency of coal-fired power generation varies greatly around the world






*International Comparison of Fossil Power Efficiency and CO2 Intensity – Update 2018, Ecofys, September 2018*

# Goals for countries developing A-USC coal-fired power technologies



| Program | Steam Temp. (°C) | Target Efficiency (%, LHV, net) | Program Start | Demonstration Plant Date and Capacity (MW) | Program Includes |
|---|---|---|---|---|---|
| EU | 700 | 50 | 1998 | 2021 / 500 | Coatings, biomass cofiring |
| United States | 760 | 45-47 (HHV) | 2000 | 2021 / 600 | Oxyfuel, coatings |
| Japan | 700 | >50 | 2008 | 2021 / 600 | Biomass cofiring |
| China | 700 | 46-50 | 2011 | 2021 / 660 | |
| India | 700 | >50 | 2011 | -- / 800 | |

* Minchener, IEA Clean Coal Centre, A-USC Workshop, December 2017

Note: NTPC's annual report for the year ended March 31, 2018 states that India's target steam temperature is 710/720°C and target efficiency is 46%

# International A-USC material programs



- Japan developed basic technologies for materials and manufacturing of boilers, turbines, and valves for 700°C class A-USC; continues to test failure modes for Ni-based components with complex shapes
- China continues to evaluate materials and costs; has not reached conclusions on highest-temperature and -pressure conditions
- India has selected In617 for highest-temperature and -pressure applications in their conceptual design, largely due to cost
- EU materials assessment recommended ASME Grade 92 ferritic steel alloy

# Advanced coal power technology in China – I



China's 1,320-MW Pingshan Power Plant Phase II – only coal unit reported under development that would achieve both highest steam temperature (630°C or 1166°F) and highest steam pressure (330 bar or 4,786 psi)

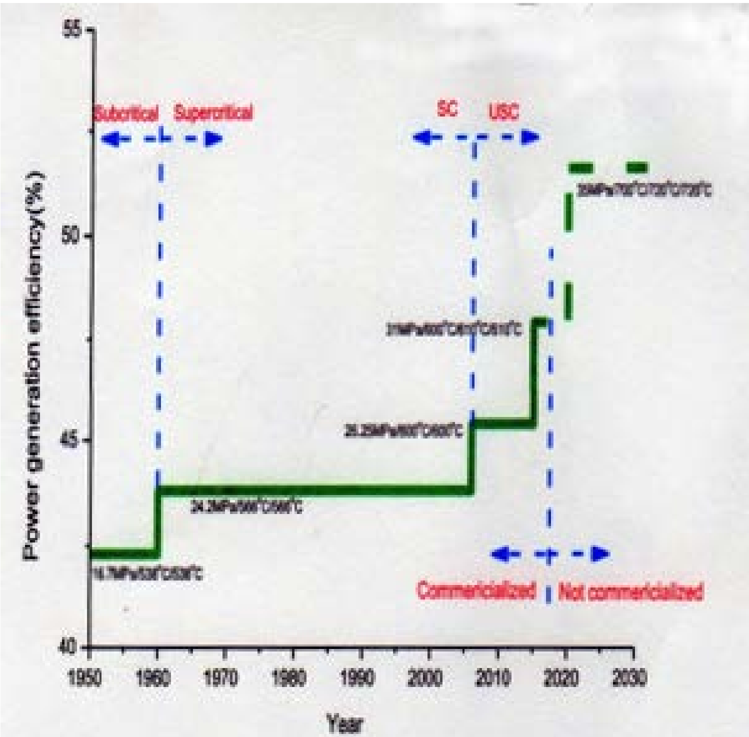
| Technology[1] | Net Efficiency (LHV, %) | $CO_2$ Emissions (g/kWh, gross) |
|---|---|---|
| Subcritical | <38 | 798.6 - 807.3 |
| Supercritical | <42 | 726.5 - 734.4 |
| 600°C USC | <45 | 681.7 - 689.1 |
| 700°C USC | 45.0 – 50.0 | 623.5 - 692.8 |
| Pingshan (1320 $MW_e$, 600°C USC) | 49.8 | 622.7 |
| Pingshan (700°C USC) | 53.0 | 588.2 |

1. Minchener, loc. Cit.
2. Excerpted from Thermal Science and Engineering Progress 5 (2018) 364–371

- Preliminary target was to establish large demonstration unit (35 to 36 MPa and 700°C/720°C) with efficiency >50%
  - Planned demonstration unit 660 MW at 36 MPa and 700°C/720°C
- Component testing conducted, similar to European COMTES 700 [23], with steam parameters (26.8 MPa, 725°C, 10.8 t/h) in two-pass 320-MW boiler
  - First 700°C testing
    - Materials for waterwall, superheater, header, and high-temperature piping tested
    - Used both domestic materials (e.g., GH984G, C-HRA-1, and C-HRA-3) and imported materials (e.g., In617B, In740H, and H282)
- China has basic understanding needed to design and manufacture 700°C A-USC units
- High-temperature material production and supply poses major bottleneck
- Performance tests of high-strength nickel-based alloys conducted; no satisfactory results

# Advanced coal power technology in China – II

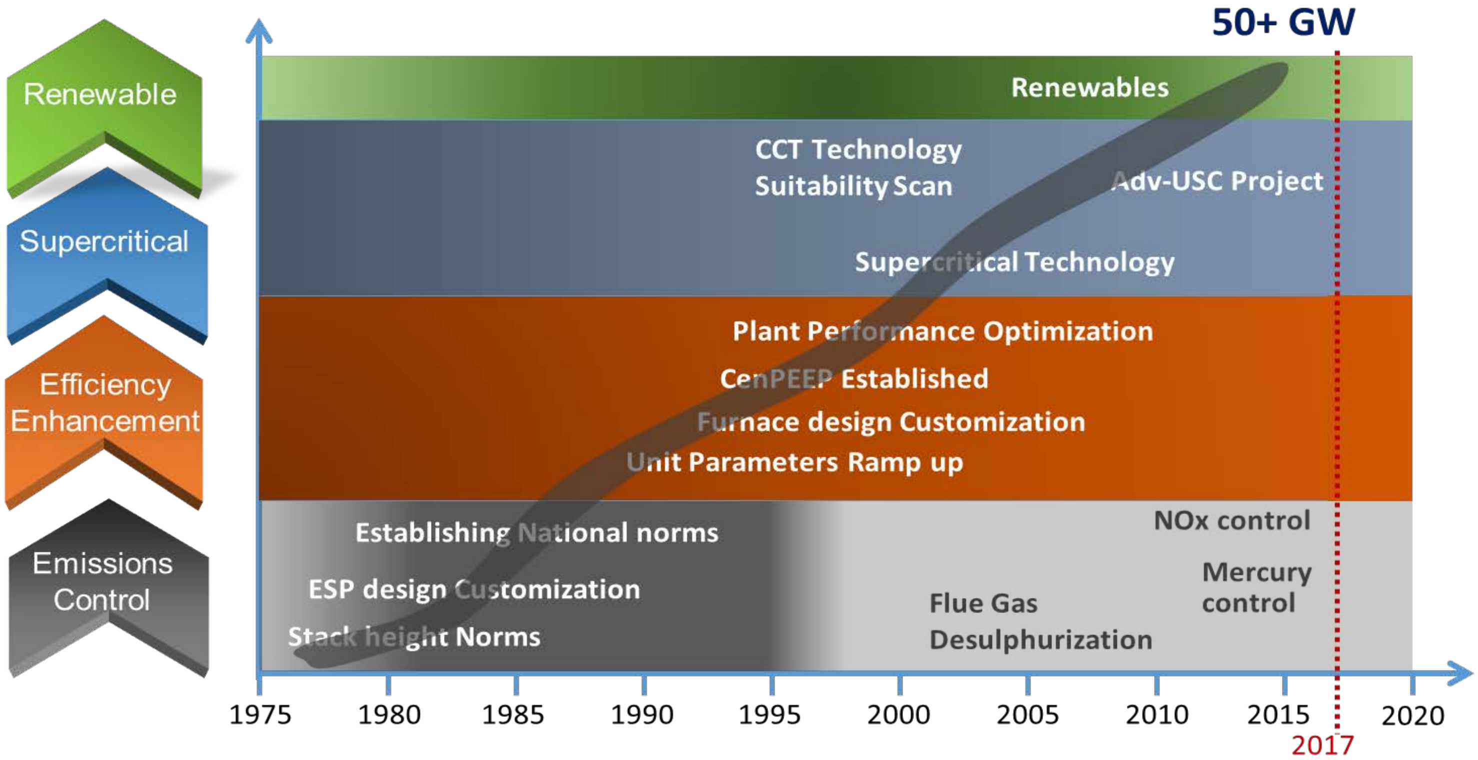





China currently has 600°C units in operation. Ultimate goal is to develop 35 MPa, 700°C, 720°C,720°C units with net efficiencies >50%

| Boiler parameter | 700°C USC (BMCR) | 600°C USC (BMCR) |
|---|---|---|
| SH steam flow, t/h | 1760 | 1960 |
| SH steam pressure, MPa.g* | 37.37 | 27.46 |
| Superheat steam temp., °C | 705 | 605 |
| Feedwater temp., °C | 313 | 297 |
| Reheat steam flow, t/h | 1266 | 1760 |
| Reheat steam inlet pressure, MPag | 10.07 | 5.97 |
| RH steam inlet temp., °C | 427 | 373 |
| RH steam outlet pressure, MPag | 9.87 | 5.77 |
| RH steam outlet temp.,°C | 723 | 603 |

# Advanced coal power in India – II




From 3rd AUSC Workshop, Setty., et al. NTPC

- Focus shifting from improving performance and reliability of existing power plants to emissions control and new power plants based on SC and USC power cycles
- A-USC mission plans development of indigenous technology for steam parameters

# Advanced coal power in India – I

## *A-USC mission development plans for indigenous AUSC technology*

| Parameter[1] | Value | Unit |
|---|---|---|
| Main Steam Temperature | 710 | °C |
| Main Steam Pressure | 30.5 | MPa |
| Main Steam Flow | 1850 | TPH |
| RH Steam Temperature (Single Reheat) | 720 | °C |
| Reheat Pressure | 6.3 | MPa |
| Cooling Water Temperature | 32 | °C |
| Temperature Rise across Condenser | 6.5 | °C |
| Final Feed Water Temperature | 305 | °C |
| HHV Efficiency | 46 | % |

1. From 3rd AUSC Workshop, Edkie and Chetal: Indian AUSC Programme

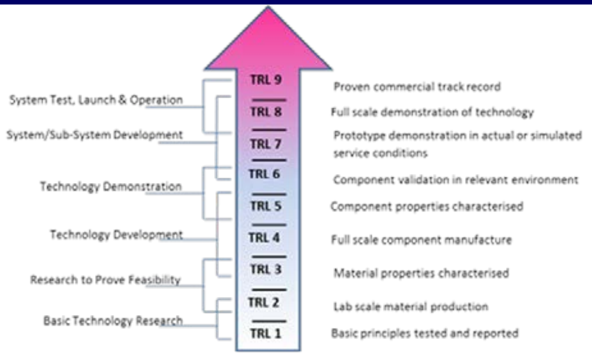
### Materials for Indian AUSC - Boiler

| Component | | Material |
|---|---|---|
| Header inlet | Superheater 1, 2, 3 and 4 | P91, Alloy 617 AND Alloy 617 |
| | Reheater 1.1 and 1.2 | P22, alloy 617 |
| Header outlet | Superheater 1, 2, 3 and 4 | Alloy 617 |
| | Reheater 1.1 and 1.2 | Alloy 617 |
| Pipes | Superheater 1 | P91, Alloy 617 |
| | Superheater 2 | Alloy 617 |
| | Superheater 3 | Alloy 617 |
| | Reheater 1.1 | Alloy 617 |
| | Reheater 1.2 | Alloy 617 |

These choices can be compared to those in other programs through work at TU-Graz

# A-USC development status

## TRL data summarizes state of testing and evaluation




| | T23 | T/P92 | MarBN | 347HFG | S304H | Sanicro25 | 310HNbN | HR6W | Nim 263 | IN617B | Ha282 | IN740H |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Microstructural Understanding | 8,8,8 [1] | 7,8,7 | 6,-,7 | 8,8,8 | 8,8,8 | 7,7,- | 8,8,8 | 5,6,7 | 6,7,- | 8,8,6 | 6,8,- | 6,8,- |
| Thermophysical Properties | 8,8,8 | 7,7,7 | 5,-,6 | 8,8,8 | 8,8,8 | 6,6,- | 8,8,8 | 6,7,7 | 6,7,- | 8,8,7 | 6,8,- | 6,8,- |
| Mechanical Properties | 8,8,8 | 7,8,7 | 4,-,6 | 8,8,8 | 8,8,8 | 7,7,- | 8,8,8 | 6,7,7 | 5,6,- | 7,7,6 | 6,7,- | 5,7,- |
| Corrosion/Oxidation | 8,8,8 | 7,8,7 | 4,-,5 | 7,7,7 | 7,7,7 | 7,7,- | 7,7,8 | 6,6,6 | 4,4,- | 6,6,5 | 6,6,- | 5,6,- |
| Welding Similar | 8,8,8 | 8,8,8 | 5,-,6 | 8,8,7 | 8,8,8 | 7,7,- | 8,8,8 | 6,6,6 | 4,6,- | 7,7,5 | 6,7,- | 6,7,- |
| Welding Dis-Similar | 8,8,8 | 7,7,7 | 3,-,- | 6,7,- | 6,7,6 | -,-,- | -,-,- | 5,5,6 | 4,5,- | 6,6,5 | 5,6,- | 6,6,- |
| Inspection/NDT | 8,8,8 | 8,8,8 | 4,-,6 | 8,8,8 | 8,8,8 | 6,-,- | 8,8,8 | 5,6,6 | 4,6,- | 6,6,- | 5,6,- | 6,6,- |
| Cold Work | 8,8,8 | 7,7,7 | -,-,- | 7,6,6 | 7,8,- | 6,5,- | 7,6,- | 5,5,6 | n/a | 6,6,6 | 5,7,- | 4,5,- |
| Induction Bending | n/a | 7,7,7 | 0,0,0 | n/a | n/a | n/a | n/a | 0,0,5 | 0,-,- | -,-,- | n/a | 0,4,- |
| Repair | 8,8,8 | 7,7,7 | -,-,- | 7,-,- | 7,-,- | 6,-,- | 7,-,- | 5,5,5 | 3,5,- | 6,6,- | 5,6,- | 5,5,- |
| SCC in SCW | 8,8,8 | 7,7,7 | -,-,- | 7,7,- | 7,7,7 | 5,-,- | 7,7,7 | 5,5,5 | 3,-,- | 5,5,- | 5,6,- | 5,5,- |

Barnard, Doosan Babcock, presented at IEA CCC 3rd AUSC Workshop

# Differences in material standards, codes, and specifications complicate technology exports



***Meeting U.S. standards alone***
***do not guarantee entry into a foreign market***

- In United States, ASTM and ASME both set related standards
- Other countries developing A-USC materials have own National Standards Bodies that set their own standards and specifications
- Significant differences in national regulations on pressure equipment are acknowledged by International Organization for Standardization (ISO)
  - ISO formed Technical Committee (TC11 – Boilers and Pressure Vessels) based on expressions of interest from a number of countries
  - Committee created to acknowledge the significant differences in compliance with specific national standard(s), limiting source or specification of materials, use of specific inspection bodies, etc.
  - Participants include France, Germany, Hungary, Italy, UK, Sweden from Europe, USA, Canada. Australia, China, Korea and Japan. Another 35 countries hold observer status.

# Countries "exporting" coal-fired boilers and steam turbines

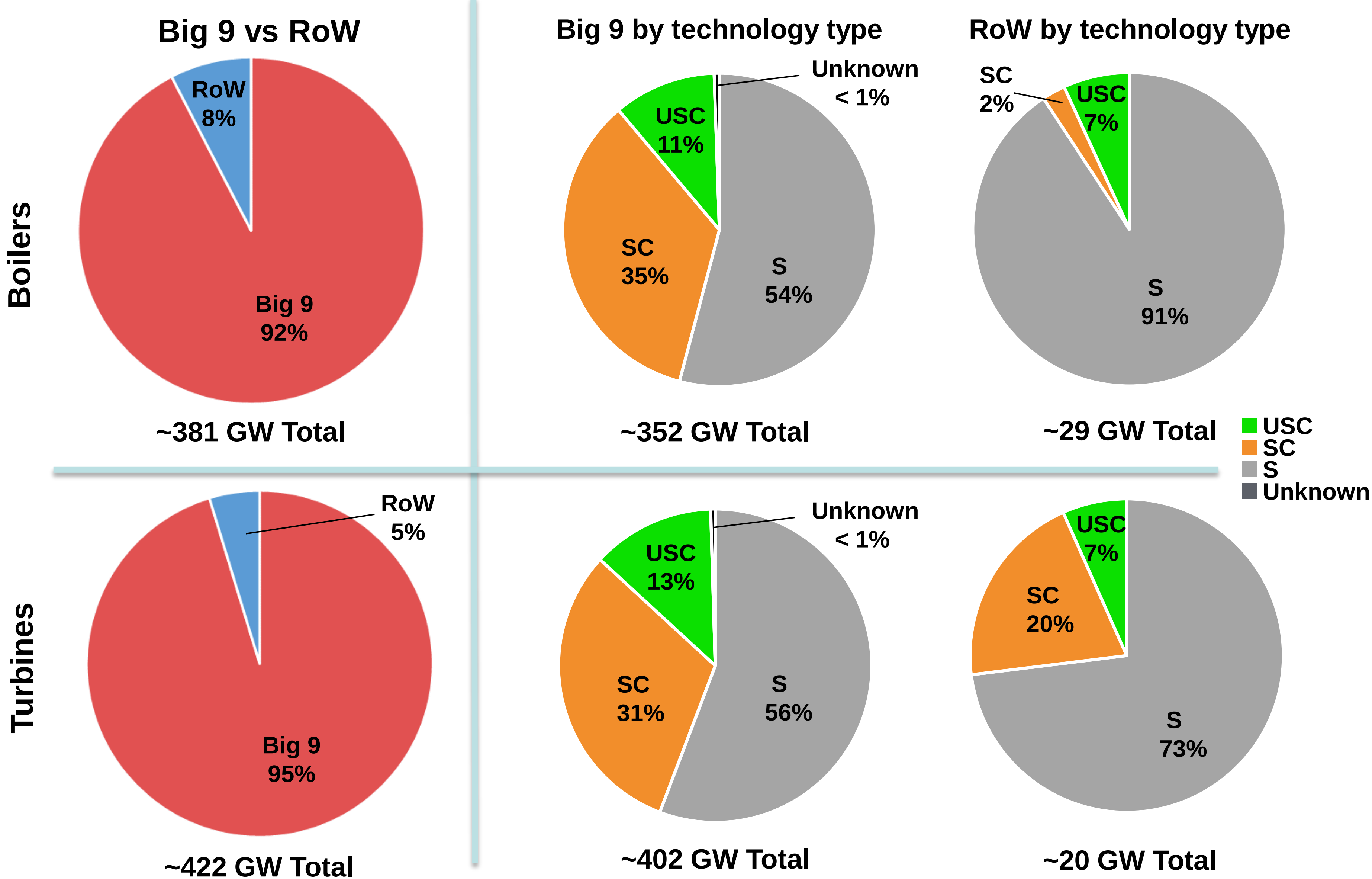


| "Big 9" | | Rest of the World (RoW) | |
|---|---|---|---|
| Boilers | Turbines | Boilers | Turbines |
| China | China | Austria | Czech Republic |
| France | France | Canada | India |
| Germany | Germany | Czech Republic | Italy |
| Japan | Japan | Denmark | Poland |
| Russia | Russia | Finland | Romania |
| South Korea | South Korea | Hungary | Sweden |
| Switzerland | Switzerland | India | Ukraine |
| United Kingdom | United Kingdom | Italy | Yugoslavia |
| United States | United States | Poland | |
| | | Romania | |
| | | Slovakia | |
| | | Spain | |
| | | Taiwan | |

*Data source: WEPP Database December 2017 release*
*Note: "Big 9" = Top 9 countries in boiler and turbine exports by capacity since 1988*

# Big 9 dominate export markets and export more efficient technologies

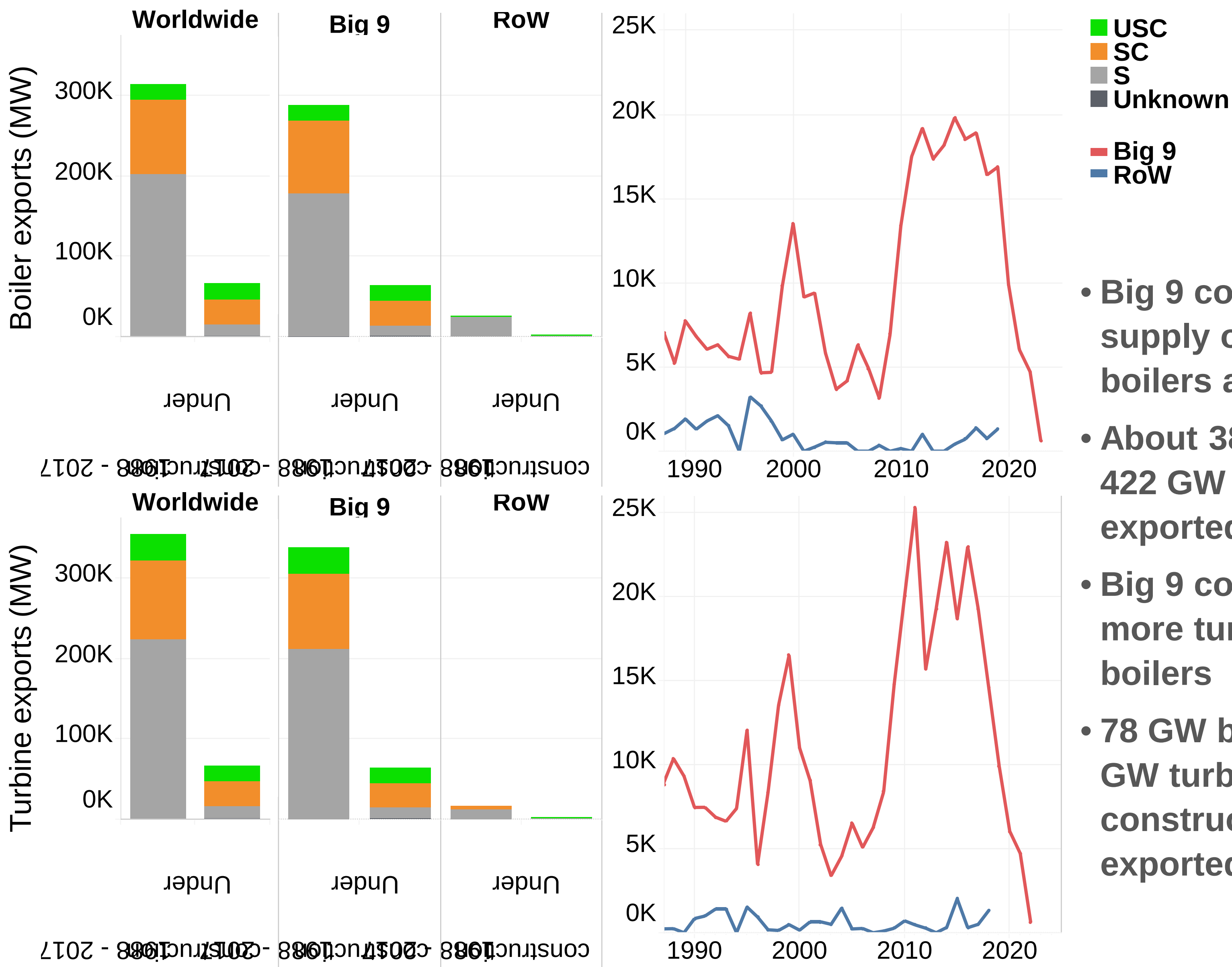





*Data source: Platts McGraw Hill Utility Data Institute's World Electric Power Plants Database (December 2017)*
*Note: Including capacities operating or under construction as indicated in the December 2017 database noted above*

# Big 9 dominate boiler and turbine exports since 1988



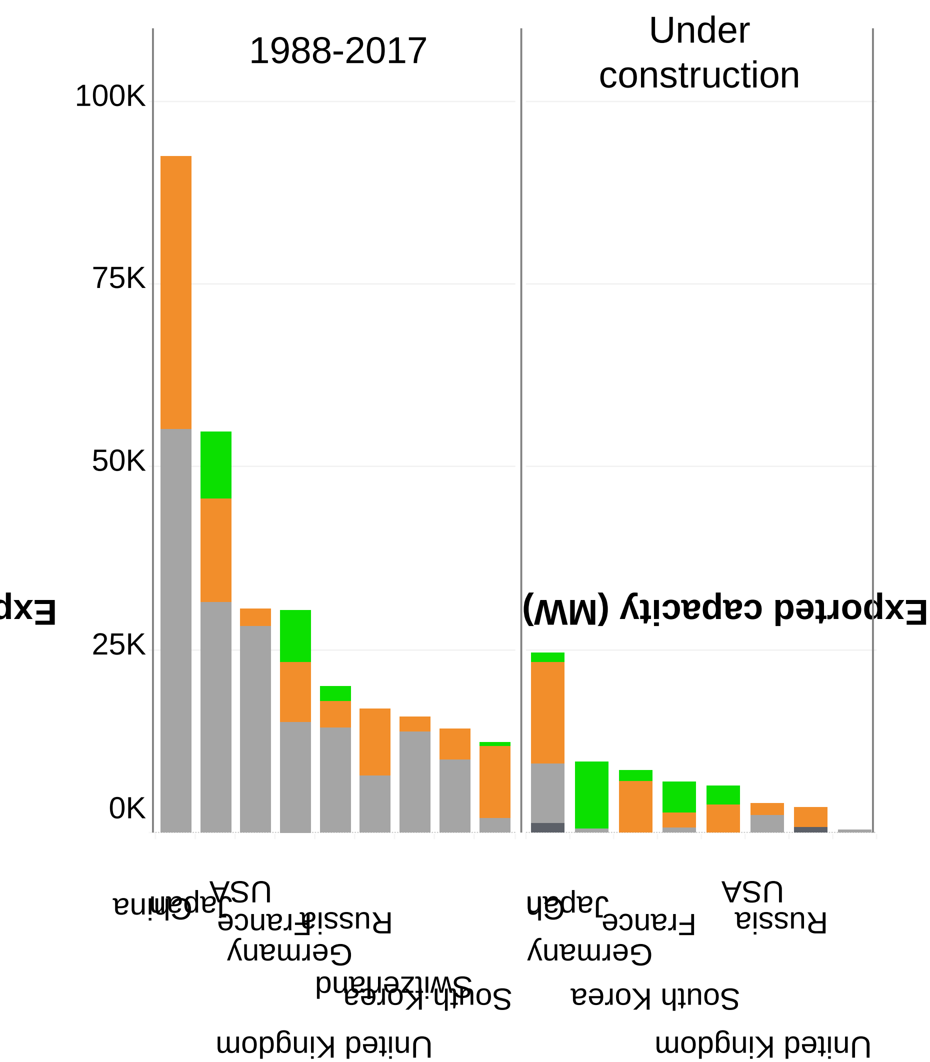



- **Big 9 countries dominate supply of S, SC, and USC boilers and turbines**
- **About 381 GW of boilers 422 GW of turbines exported since 1988**
- **Big 9 countries exported more turbines than boilers**
- **78 GW boilers and 80 GW turbines under construction with exported equipment**

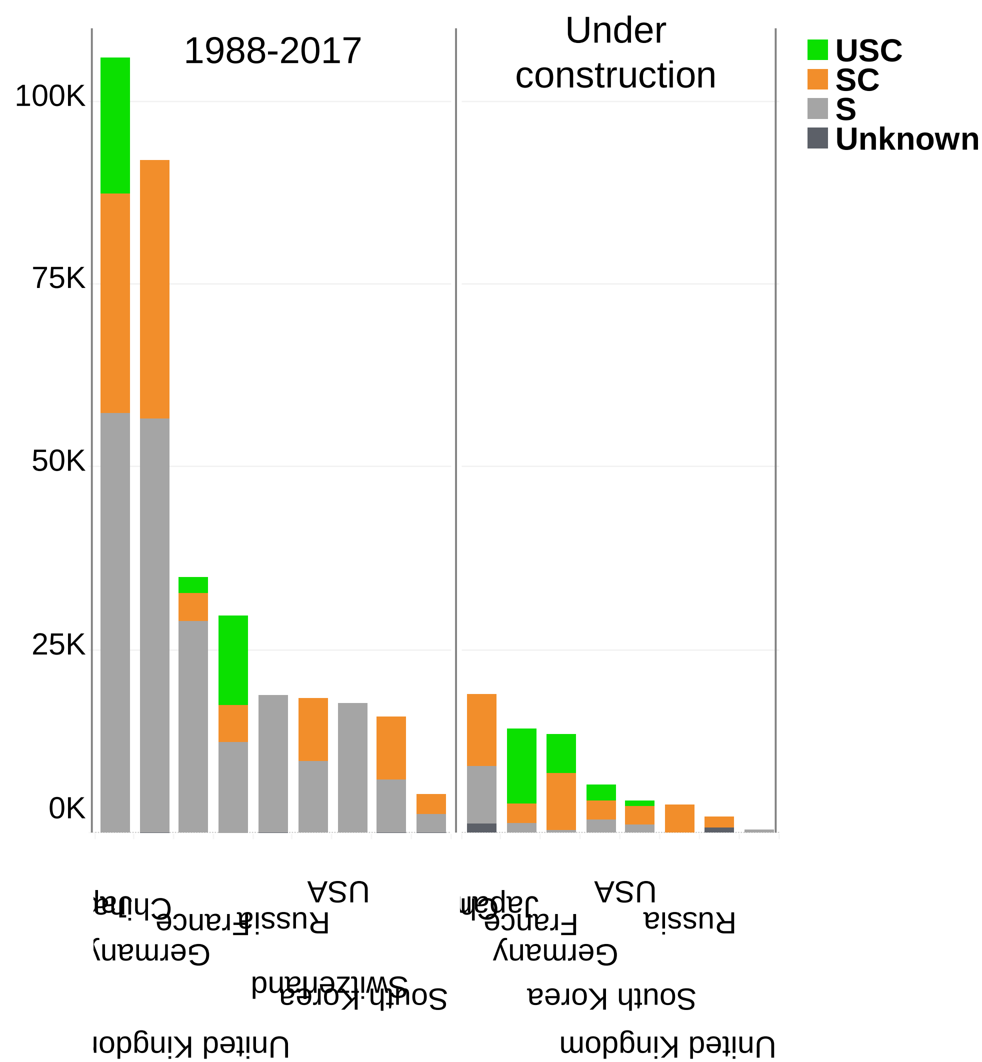
*Data source: WEPP database December 2017 release*

# China and Japan are world's largest exporters

Office of
Fossil Energy




**Boiler exports**

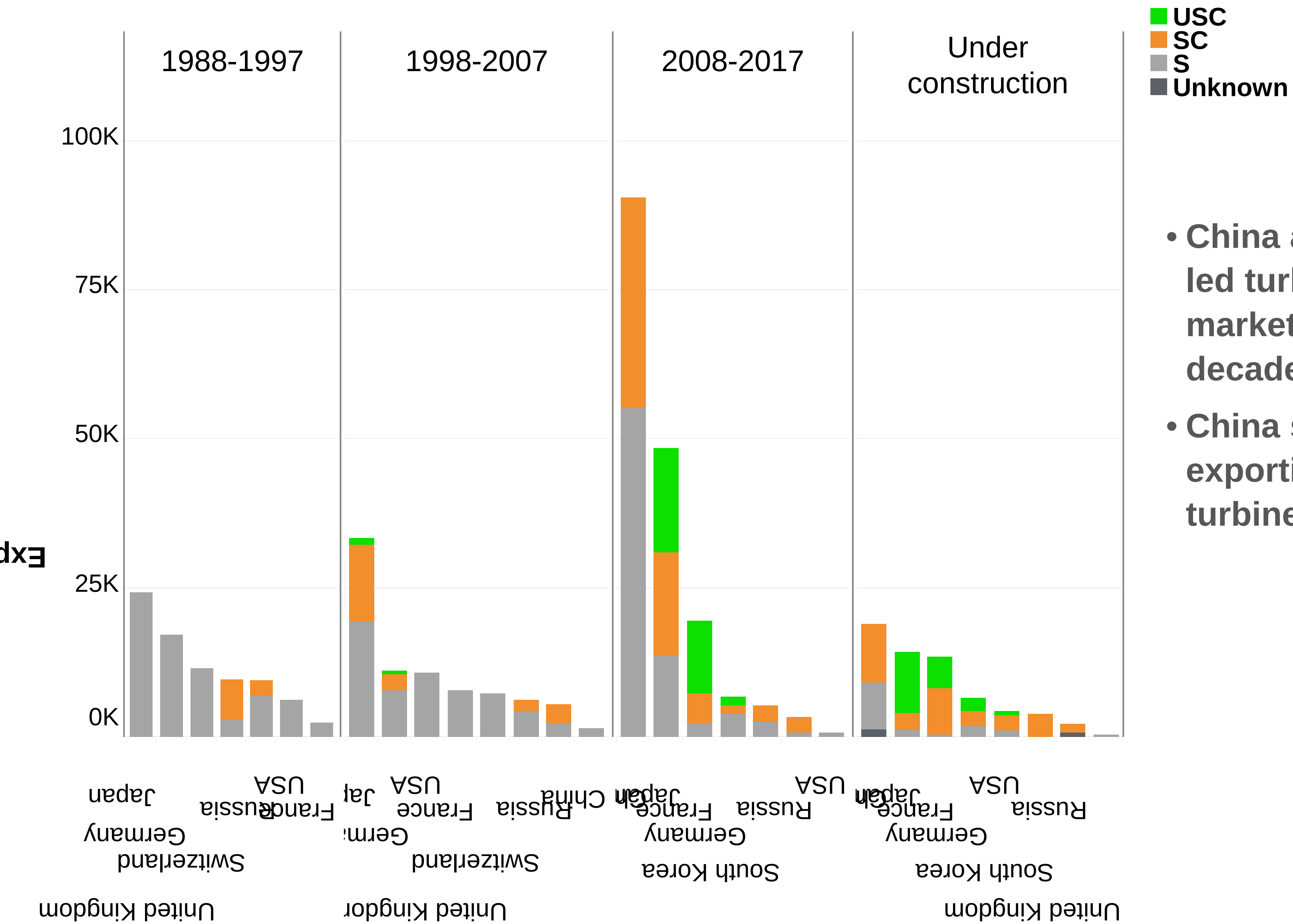



**Steam turbine exports**

*Data source: WEPP database December 2017 release*

# China became dominant exporter of steam turbines in less than a decade






- **China and Japan led turbine export market over last decade**
- **China started exporting USC turbines**

*Data source: WEPP database December 2017 release*

# Summary



- Center of coal power plant construction has dramatically shifted to Asia
- United States is small exporter in global coal power equipment markets:
  - In less than decade since 2005, China overtook Japan as world's leading exporter of subcritical and supercritical boilers and turbines
  - Although with regional differences, higher-efficiency coal power generation technologies increasingly deployed worldwide and gaining share in equipment export markets
  - Japan is world's leading exporter of supercritical and USC equipment, but China could emerge based on domestic world-class construction
- A-USC development activities
  - A number of national programs on-going to develop A-USC and other power systems
  - Programs focused on main steam temperature between 700°C and 760°C and main pressure ranging from ~30 to ~36 MPa
  - Extensive material evaluation programs on-going and variety of strategies guide material selection. Some countries may adjust cycle conditions (T, P) to allow lower-cost materials to be used. Many candidate materials being testing in several programs
  - Individual national programs are seeking to develop new materials, sometimes based on enhancements of existing materials (for example, addition of N to manage scaling)
  - China, India, and EU see value in cooperation on materials development, sub-scale testing, and a-priori evaluation for end use
  - India also values the potential of advanced materials to support increased cycling of coal power plants