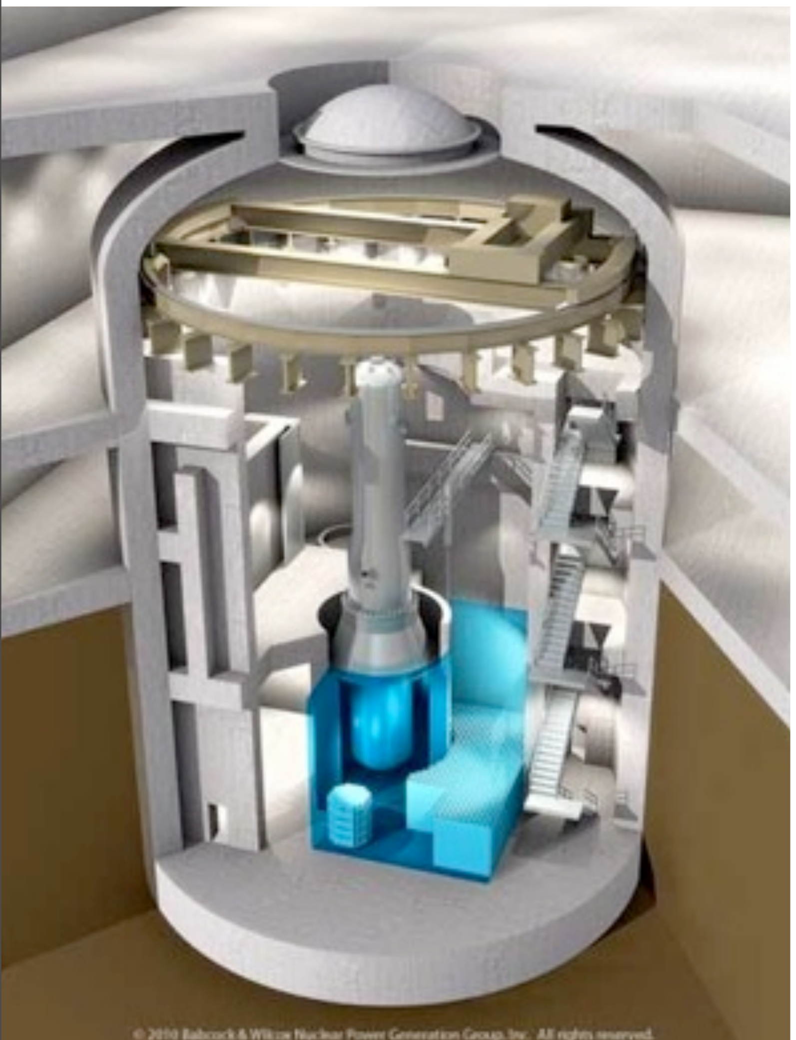


Small Modular Reactors

The State of Play, 2013

Alexander Glaser

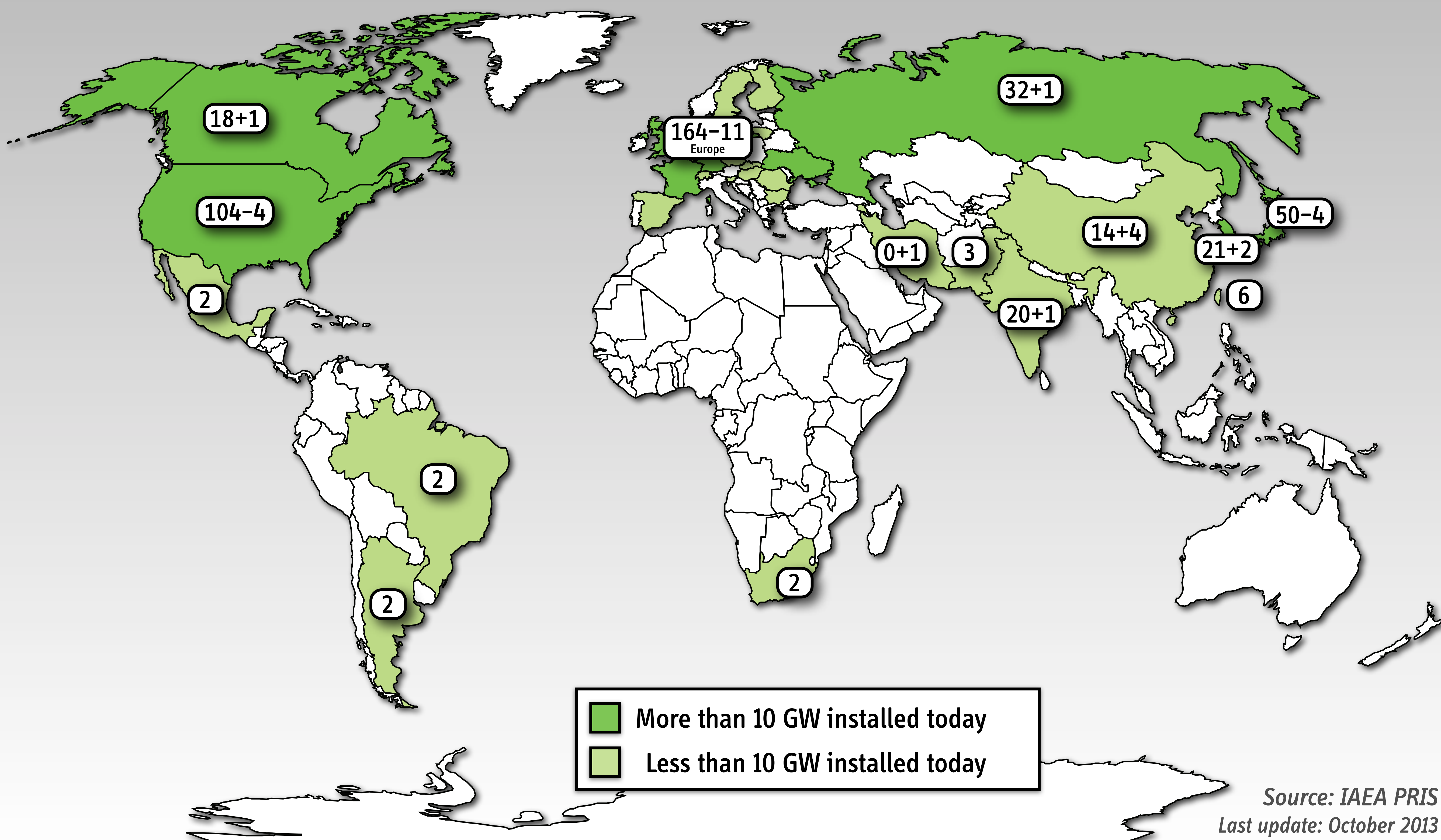
Georgetown University, Doha, Qatar

October 27, 2013

Revision 4

Nuclear Power Reactors in the World, 2013

435 operational reactors (9 fewer than in February 2011) in 31 countries provide about 13% of global electricity

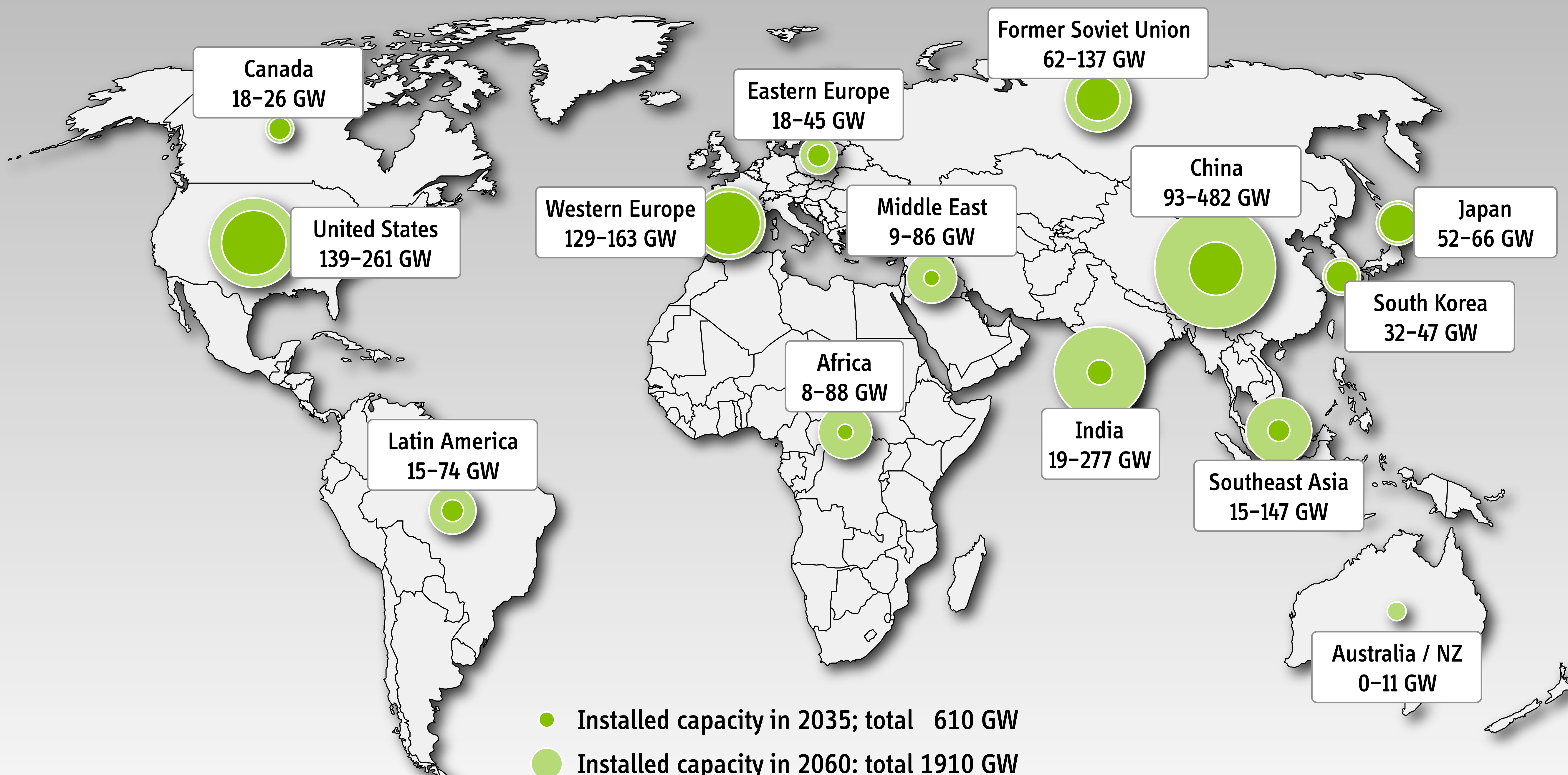


Source: IAEA PRIS

Last update: October 2013

Scenario for Global Nuclear Capacity, 2035–2060

GCAM policy scenario (450 ppm, stabilizes at dT = 2.25 °C by the end of the century)

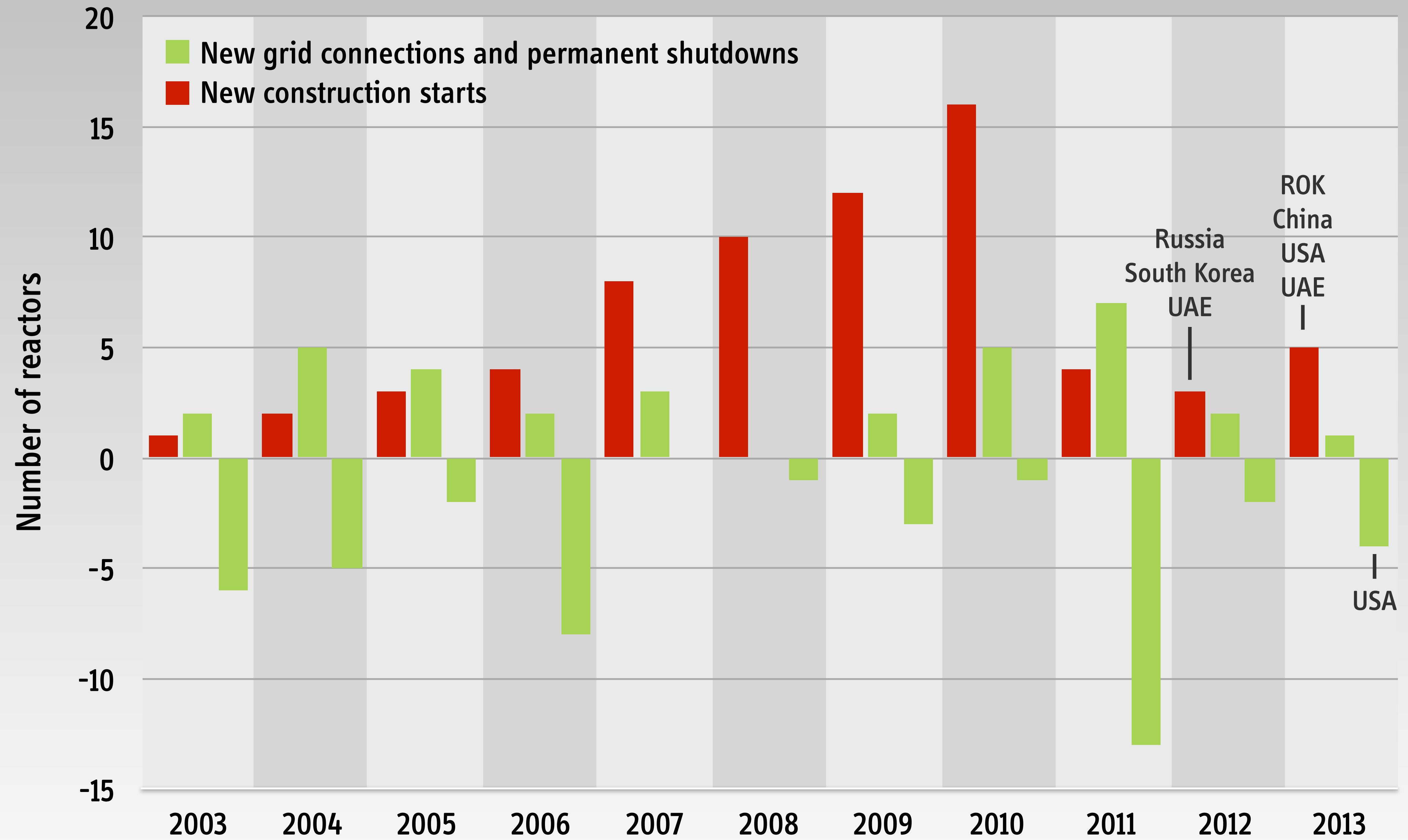


Global Change Assessment Model, www.globalchange.umd.edu/models/gcam/

What is Being Built Today?

Hitting the "Reset" Button in 2011?

New Grid Connections, Permanent Shutdowns, and New Construction Starts over the Past Decade



Source: International Atomic Energy Agency, Power Reactor Information System (PRIS), www.iaea.org/PRIS, October 2013


FOR SALE
LARGE REACTORS ?

Reactors Under Construction, 2013

By Type and Country: 70 units in 14 countries

Reactor / Design	China	India	Russia	South Korea	UAE	USA	Other	Total
GENERATION II								
CPR-1000	12	–	–	–	–	–	–	12.0 GW
CNP Series	8	–	–	–	–	–	2	7.8 GW
OPR-1000	–	–	–	1	–	–	–	1.0 GW
VVER	2	2	7	–	–	–	4	14.2 GW
Other	1	5	1 + 2	–	–	1	2	7.1 GW
GENERATION III								
APR-1400	–	–	–	4	2	–	–	8.0 GW
ABWR	–	–	–	–	–	–	4	5.2 GW
GENERATION III+								
AP-1000	4	–	–	–	–	2	–	6.2 GW
EPR	2	–	–	–	–	–	2	6.5 GW
TOTAL	29	7	10	5	2	3	14	68.0 GW

Reactors available for export market (dark shading: VVER in China, India, Other; APR-1400 in UAE; AP-1000 in China, USA; EPR in China, Other)

GE Hitachi's ABWR (Taiwan) and Russia's KLT-40s (light shading: Other reactors in Russia "1 + 2"; ABWR in Other)

GEN-III Reactors Have Proven (Very) Expensive

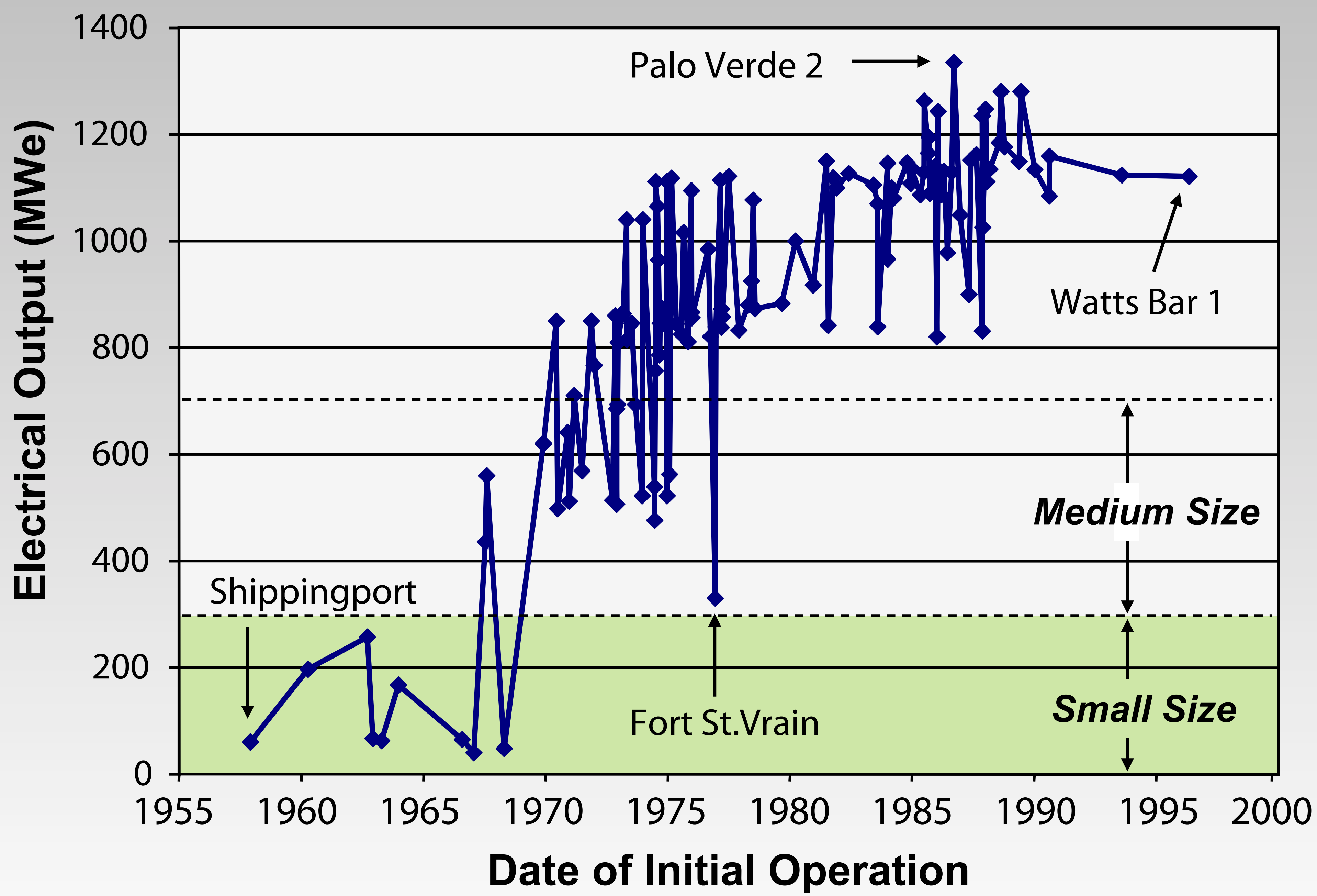
Olkiluoto 3 (Finland, 1650 MWe, built by Areva): Seven years behind schedule (2016 vs 2009)
Turnkey agreement ($4.3 billion), currently estimated loss for Areva: $7.2 billion

Source: www.bloomberg.com/news/2013-10-21/u-k-nuclear-future-relies-on-reactor-plagued-by-delays-energy.html (October 22, 2013)


FOR SALE
SMALL REACTORS ?

Capacities Have Been Increasing Over Time

Example: Electrical output of U.S. commercial nuclear power plants



Source: D. T. Ingersoll, "Deliberately Small Reactors and the Second Nuclear Era," *Progress in Nuclear Energy,* 51 (2009), 589–603

Why Consider Small Modular Reactors?

- **Substantially lower investment risks**
  $1 billion vs $10 billion projects; combined with shorter construction times
- **Better suited for electricity markets with low growth rates**
  Modules can be added to existing facilities "on demand"
- **Promise of meeting emerging (or niche) market needs**
  Replacement of aging coal/oil-fired plants, non-electricity applications, etc.
- **Promise of enhanced safety and security**
  Almost all designs envision underground siting
- **Potential nonproliferation benefits**
  Long-lived cores

- **BUT: Ultimately, most will hinge on the economics**

Proposed New Deployment Options for SMRs

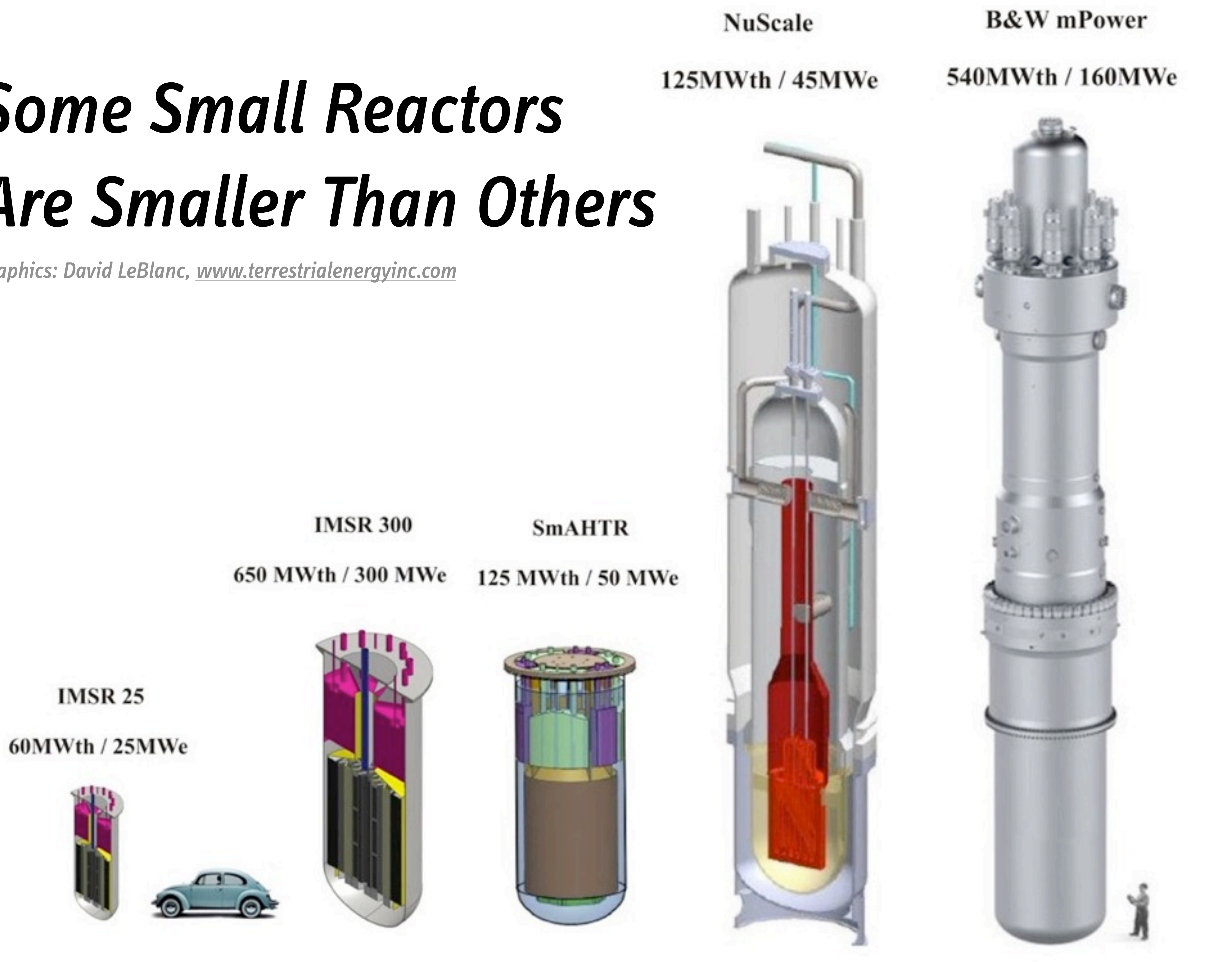
underground, underwater, on barges

FlexBlue
proposed by DCNS (formerly *Direction des Constructions Navales,* DCN) jointly with Areva, CEA, and EDF
http://en.dcnsgroup.com/energie/civil-nuclear-engineering/flexblue/

Floating Nuclear Power Plant
proposed by Rosatom
Akademik Lomonosov (2 x 32 MWe) under construction

Some Small Reactors Are Smaller Than Others

Graphics: David LeBlanc, www.terrestrialenergyinc.com



A Plethora of SMR Designs has been Proposed

Numerous concepts under development in the United States, Russia, South Korea, China, Japan, Argentina, France, and others

A good overview of proposed designs is: *Status of Small and Medium Sized Reactor Designs*, International Atomic Energy Agency, Vienna, September 2012
www.iaea.org/NuclearPower/Downloadable/SMR/files/smr-status-sep-2012.pdf

Comparing the Essential Design Options

Here, introduce four different "families" of SMRs
emphasizing primary drivers and objectives, NOT technology choices per se

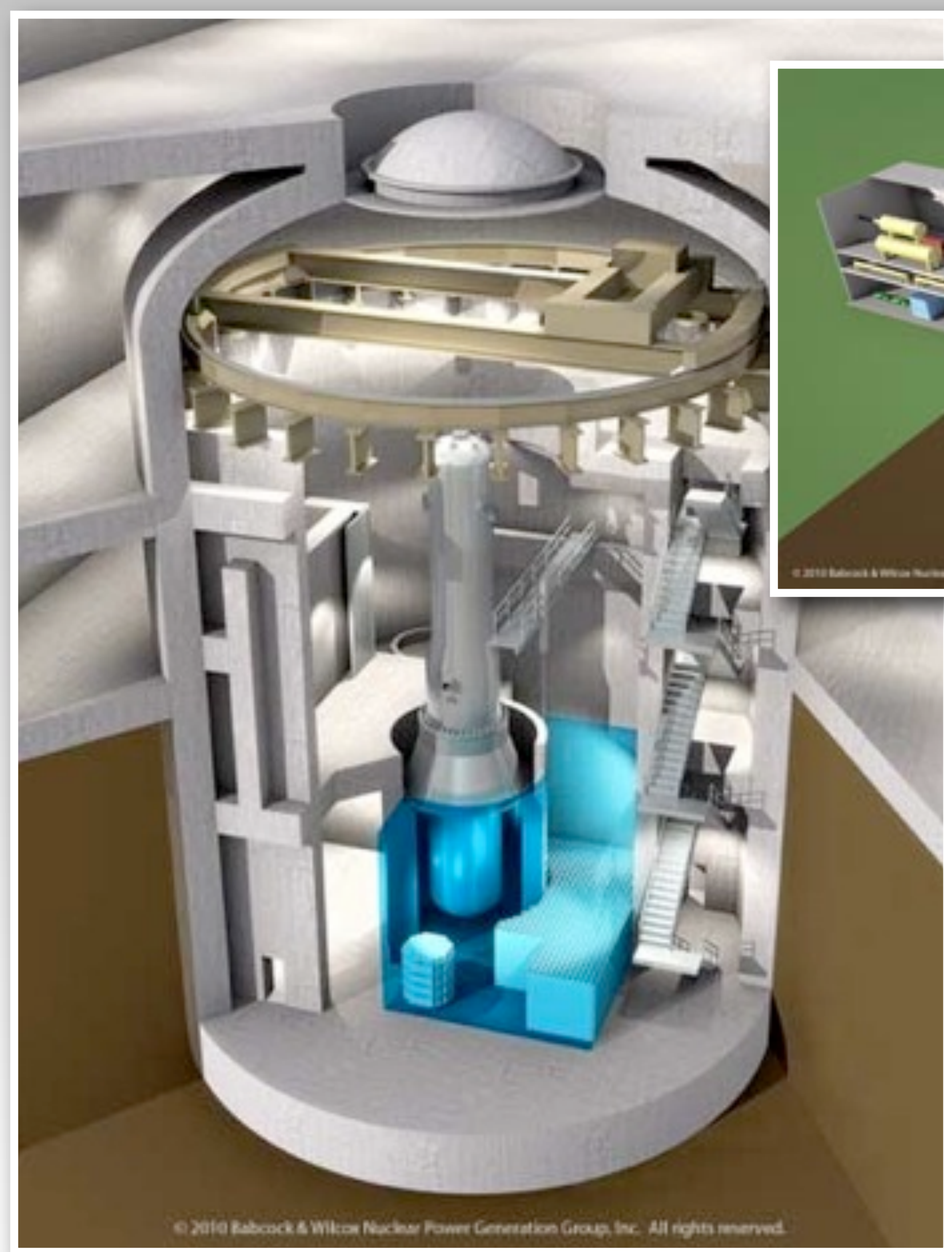
Alexander Glaser, Laura Berzak Hopkins, and M. V. Ramana, "Resource Requirements and Proliferation Risks Associated with Small Modular Reactors," *Nuclear Technology*, 184 (1), October 2013, pp. 121–129

SMR Family 1

"Getting Into the Game Early"

"We believe that SMRs have to be demonstrated as soon as possible;
Our design is therefore based on established light-water reactor technologies"

Most Candidate Designs Are Based on Standard Light-water Reactor Technology



Babcock & Wilcox mPower Concept

- Light-water cooled
- 180-720 MWe (i.e., up to 4 modules)
- Underground construction
- 60-year spent fuel storage onsite
- Quasi-standard LWR fuel

Source: www.babcock.com/products/modular_nuclear/

Most Candidate Designs Are Based on Standard Light-water Reactor Technology

Design	Company	Power	Status
mPower	Babock & Wilcox	2 x 180 MWe	Detailed design
NuScale	NuScale Power	12 x 45 MWe	Detailed design
W-SMR	Westinghouse	225 MWe	Basic design
HI-SMUR (SMR-160)	Holtec	145 MWe	Basic design
SMART	KAERI	100 MWe	Licensed
CAREM	CNEA	25 MWe	Under construction
KLT-40S	OKBM, Russia	2 x 32 MWe	Under construction
VBER-300	OKBM, Russia	295 MWe	Detailed design

In January 2012, the U.S. DOE announced a 5-year $452 million cost-sharing program to support engineering, design certification, and licensing for up to two first-of-a-kind SMR designs

Babcock & Wilcox' mPower emerged as sole winner; second round now underway

SMR Family 1

"Getting into the Game Early"

Characteristics compared to existing gigawatt-scale light-water reactor

Significantly higher uranium/fuel demand (up to 50–60%)
(and respective increase in volume of spent fuel)

Significantly higher demand for enrichment capacities

Comparable attractiveness of spent fuel for reprocessing or diversion
(i.e., slightly increased total plutonium production but lower concentration in spent fuel)

Deployment Timing

Prototypes within 5–10 years possible/likely

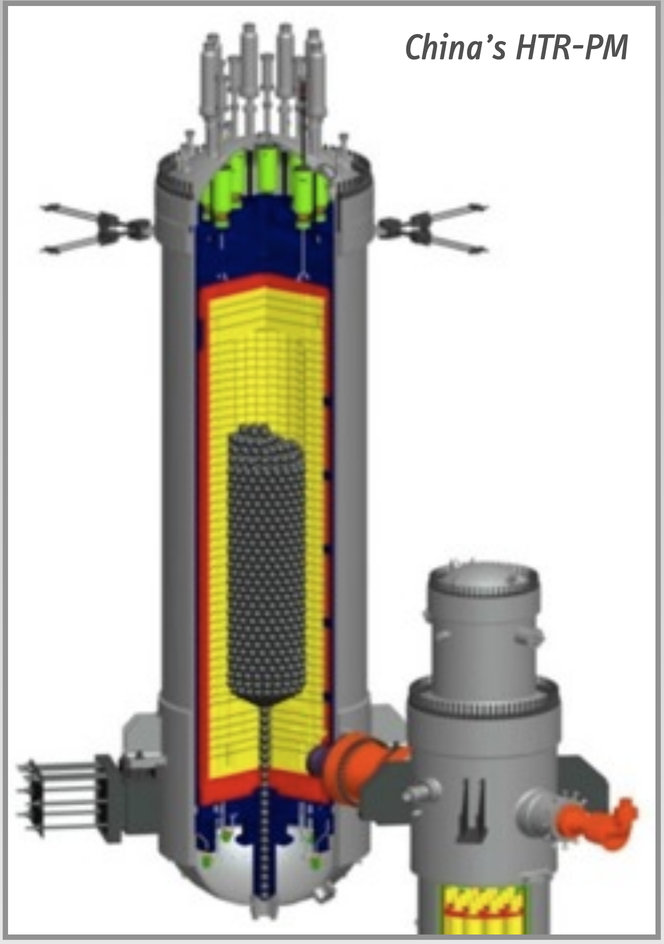
Russia's *Akademik Lomonosov* (2 x 32 MWe) under construction
mPower (USA, 2021/22) and SMART (South Korea) projects moving forward

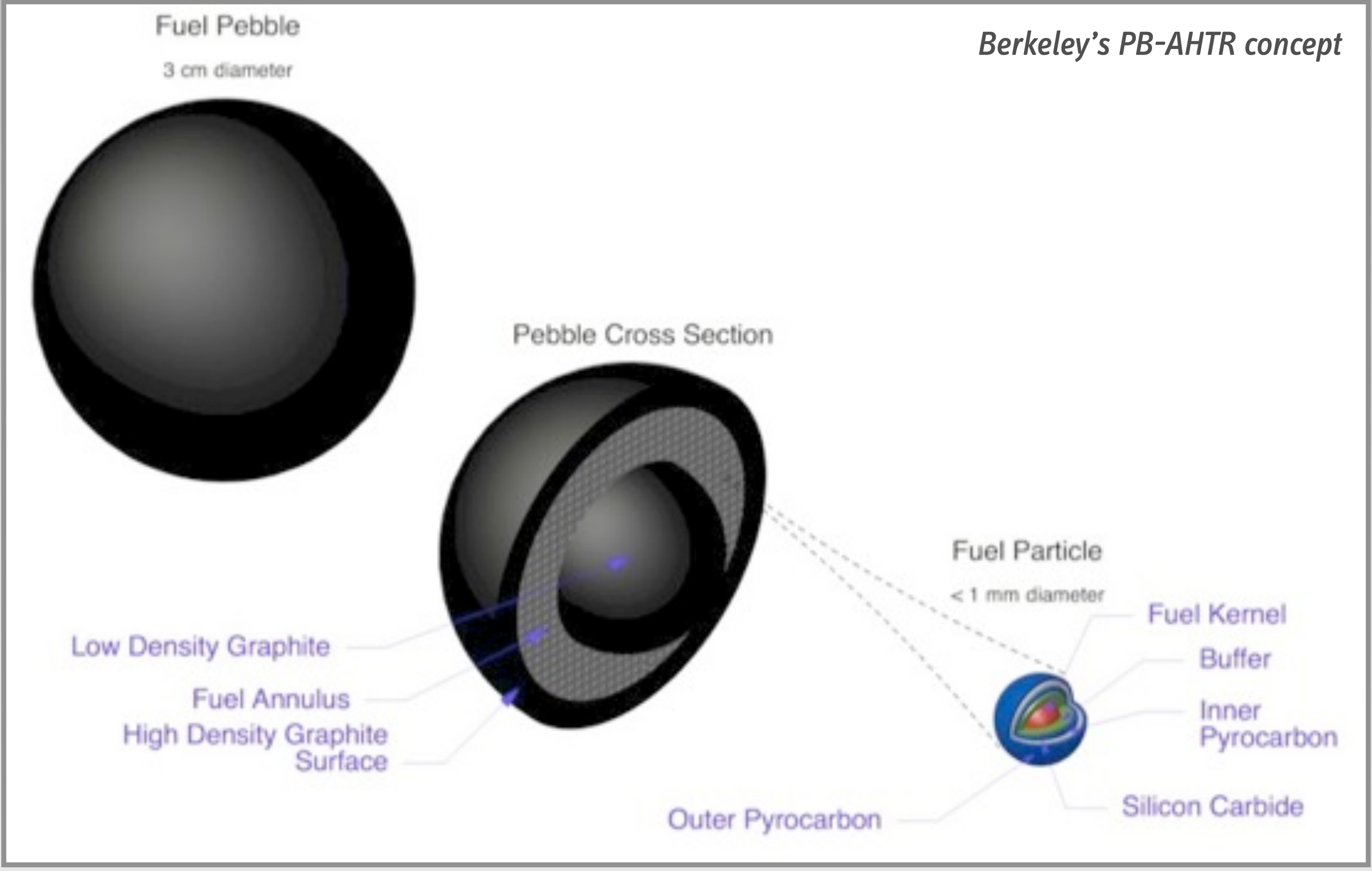
SMR Family 2

“Succeeding the Second Time Around”

“We believe that SMRs have to take advantage of their small size and qualitatively improve on safety; Our design is based on innovative (and previously demonstrated) concepts”

Gas-Cooled High-Temperature Reactor





Radically different reactor and fuel concept, but continued interest in some countries
(building on experience with earlier prototype reactors, i.e., Germany's AVR and THTR)

HTR-PM (Pebble-bed Modules), 200 MWe (2 x 250 MWt)
Shidao Bay 1, under construction since December 2012

SMR Family 2

"Succeeding the Second Time Around"

Characteristics compared to existing gigawatt-scale light-water reactor

Comparable demands for uranium resources and enrichment capacities

Potential for improved safety and (high-temperature) non-electricity applications

Net changes of proliferation risks unclear; has both advantages and disadvantages
(fuel not attractive for reprocessing, new challenges for safeguards)

Deployment Timing

Some technology gaps, but prototypes within next 10–15 years possible

First grid connection of China's HTR-PM expected for 2018
Broader potential for export market and/or large-scale deployment unclear

SMR Family 3

“Dealing with the Waste Legacy”

“We believe that unresolved nuclear waste issues impede the future of nuclear power;
Our design is therefore optimized for use of spent nuclear fuel”

Whenever You Read About a "Stunning" New Reactor

It Most Likely is a Fast Neutron Reactor Design

26 Advanced Recycling Centers "are capable of consuming the entire 120,000 tons of SNF. Additionally, they are capable of producing 50,000 MWe and avoiding the emission of 400,000,000 tons of CO_2 every year."

"The Energy Multiplier Module (EM^2) ... turns nuclear waste into energy."

"The current amount of used nuclear fuel waste in storage at U.S. nuclear plants is sufficient for 3,000 modules."

Top: GE-Hitachi, ARC/PRISM Fact Sheet; Bottom: General Atomics, Technical Fact Sheet

SMR Family 3

“Dealing with the Waste Legacy”

Characteristics compared to existing gigawatt-scale light-water reactor

Significantly decreased demands for uranium resources and enrichment capacities

Based on premise of large-scale reprocessing of existing spent fuel
(and generally also continued processing of fuel in new reactors)

Introducing qualitatively new proliferation risks with large flows of fissile materials

Deployment Timing

Prototypes within next 10–15 years unlikely

Technology gaps, persistent policy and licensing issues
Broader potential for export market and/or large-scale deployment unclear

SMR Family 4

“Offering Nuclear Batteries”

“We believe that customers want ‘worry-free’ energy solutions;
Our design therefore avoids on-site refueling and (typically) has a lifetime core”

Early Interest in SMRs was Often Motivated by this Objective

2007 IAEA report discusses 30 reactor concepts

Status of Small Reactor Designs Without On-Site Refuelling, IAEA-TECDOC-1536, International Atomic Energy Agency, January 2007

Today very few projects in this category seem to retain some momentum

Design	Company	Power	Status
Gen4 Module (G4M)	Gen4 Energy (USA)	25 MWe	Conceptual design
4S	Toshiba (Japan)	10 MWe	Detailed design

Systems with long-lived cores (typically break-even breeders with fast-neutron spectrum)

Design	Company	Power	Status
FNPP	OKBM (Russia)	2 x 32 MWe	Under construction
Flexblue	DCNS (France)	160 MWe	Conceptual design

Mobile systems based on standard light-water reactor technology

Selling the Vision of the “Nuclear Battery”

Source: www.okbm.nnov.ru/english/lomonosov

Source: Gen4 Energy (Hyperion)

SMR Family 4

“Offering Nuclear Batteries”

Characteristics compared to existing gigawatt-scale light-water reactor

Significantly decreased resource demand
(especially when combined with fast-neutron spectrum)

In principle, compatible with once-through operation
(but large plutonium inventory in spent fuel making it “attractive” for reprocessing)

Overall proliferation risk strongly depends on deployment modes

Deployment Timing

Prototypes within next 10–15 years (very) unlikely

Possible exception will be Russia’s FNPP based on light-water reactor technology
Large technology gaps, especially with regard to irradiation performance of fuels and materials

Economics

SMR Cost Estimates Are Highly Uncertain

(and are typically higher for the more mature projects)

Design	Company	Power	Overnight Cost	Total Capital Cost
mPower	Babock & Wilcox	2 x 180 MW	$5,000/kWe	$1,800 million
NuScale	NuScale Power	12 x 45 MW	$4,630/kWe	$2,500 million
W-SMR	Westinghouse	225 MW	$4,500/kWe	$1,010 million
HI-SMUR	Holtec	145 MW	$5,000/kWe	$725 million
SMART	KAERI	100 MW	$5,000/kWe	$500 million
CAREM	CNEA	25 MW	$4,000/kWe	$100 million
KLT-40S	OKBM, Russia	70 MW	$3,750/kWe	$260 million
VBER-300	OKBM, Russia	295 MW	$3,500/kWe	$1,030 million
PBMR	PBMR Ltd.	165 MW	$2,120/kWe	$350 million
HTR-PM	Tsinghua	210 MW	$2,000/kWe	$420 million
4S	Toshiba	10 MW	$3,000/kWe	$30 million
HPM	Gen4/Hyperion	25 MW	$4,000/kWe	$100 million
PRISM	GE-Hitachi	4 x 310 MW	$2,570/kWe	$3,200 million

Data adapted from Jonathan Hinze (Ux Consulting), “SMR Market Outlook and Deployment Prospects”
4th Annual Platts SMR Conference, Washington, DC, May 29, 2013

What Does It All Mean?

Some Concluding Observations

SMRs attract significant attention; demonstration of some prototypes very likely

Small may be beautiful, but it is small

Even under most optimistic assumptions, little generating capacity based on SMR technologies could be deployed by 2030

Some concepts are innovative, but many are not

Risk of technology lock-in by giving preference to short-term demonstrations

A world with many small modular reactors has both similarities and differences from one that is dominated by standard light-water reactors

To a large extent, "missions" determine resource requirements and proliferation risks

Enduring Challenges for SMRs

as an alternative to gigawatt-scale reactors

Economics

Currently highly uncertain and typically higher for more mature projects

$4000–5000/kWe for Western vendors

Highly dependent on learning rates (LEAD/FOAK vs NOAK)
Some studies assume a rate on the order of 10%; requires about 50 modules for break-even

"We Can't Rob Peter to Pay Paul"

Ongoing discussions between regulatory agencies and SMR applicants about "trade-offs"
Staffing (control room and security), emergency planning, fees, insurance and liability

Internationally, is there a Demand for the Technology?