Nuclear Power After Fukushima

Where is it Heading?

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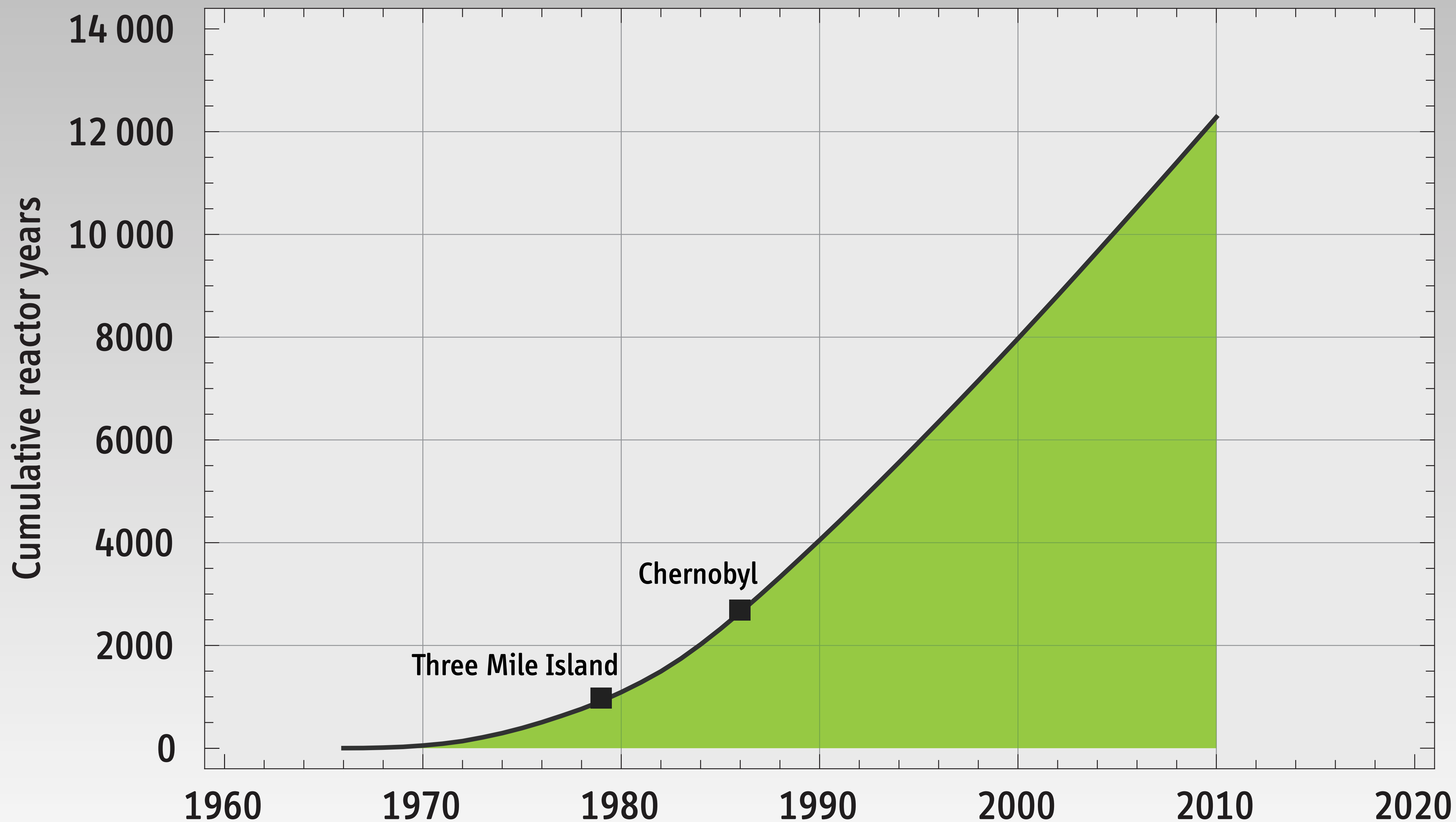
Princeton University

Fondazione Eni Enrico Mattei
Venice, May 31, 2012

Revision 2

Nuclear Power: Years of Boredom Interrupted by Moments of Sheer Terror?



Low estimate based on the age of reactors operating today, IAEA Power Reactor Information System
(actual value for 2010 closer to 14,000 reactor years)

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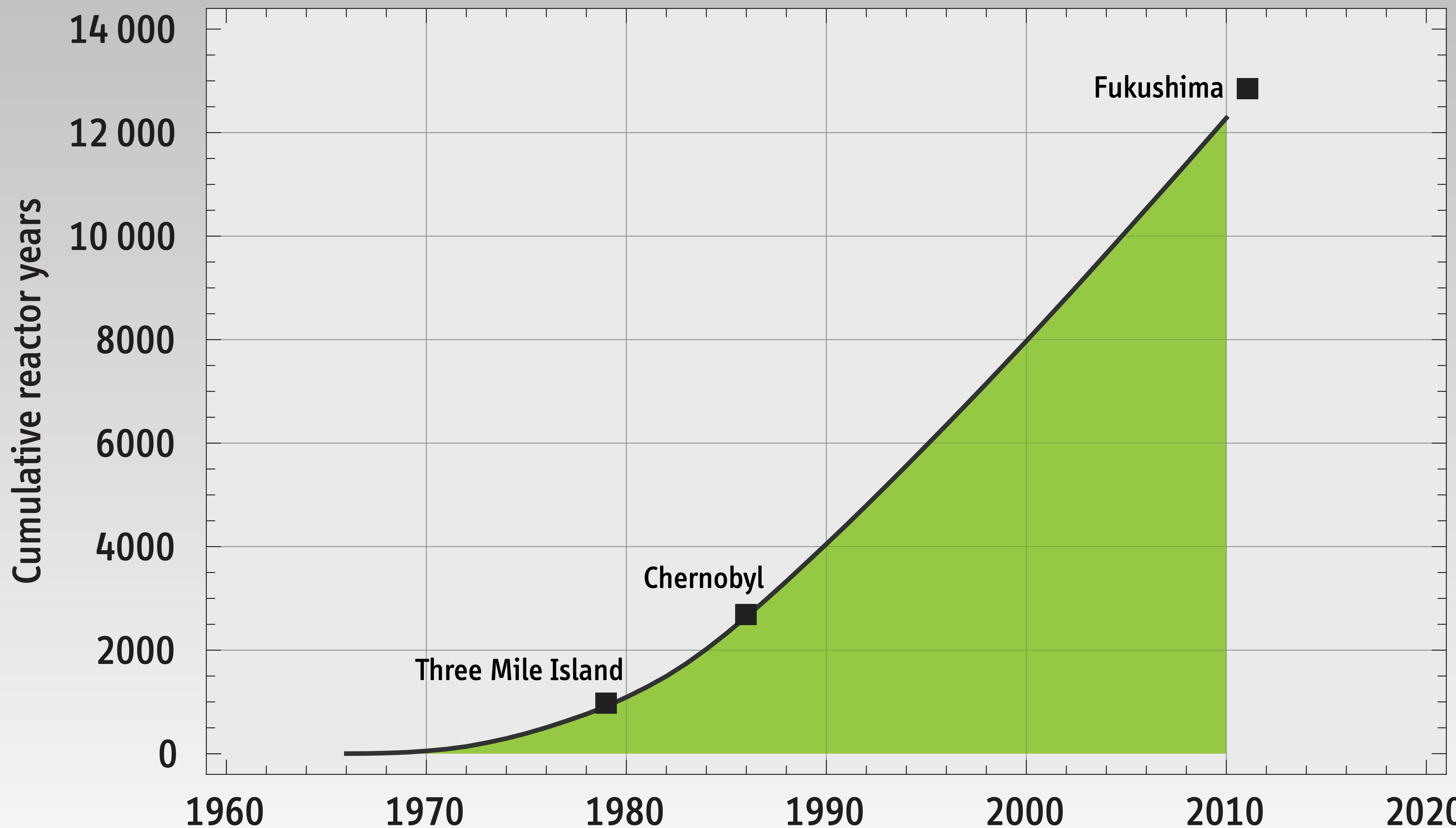

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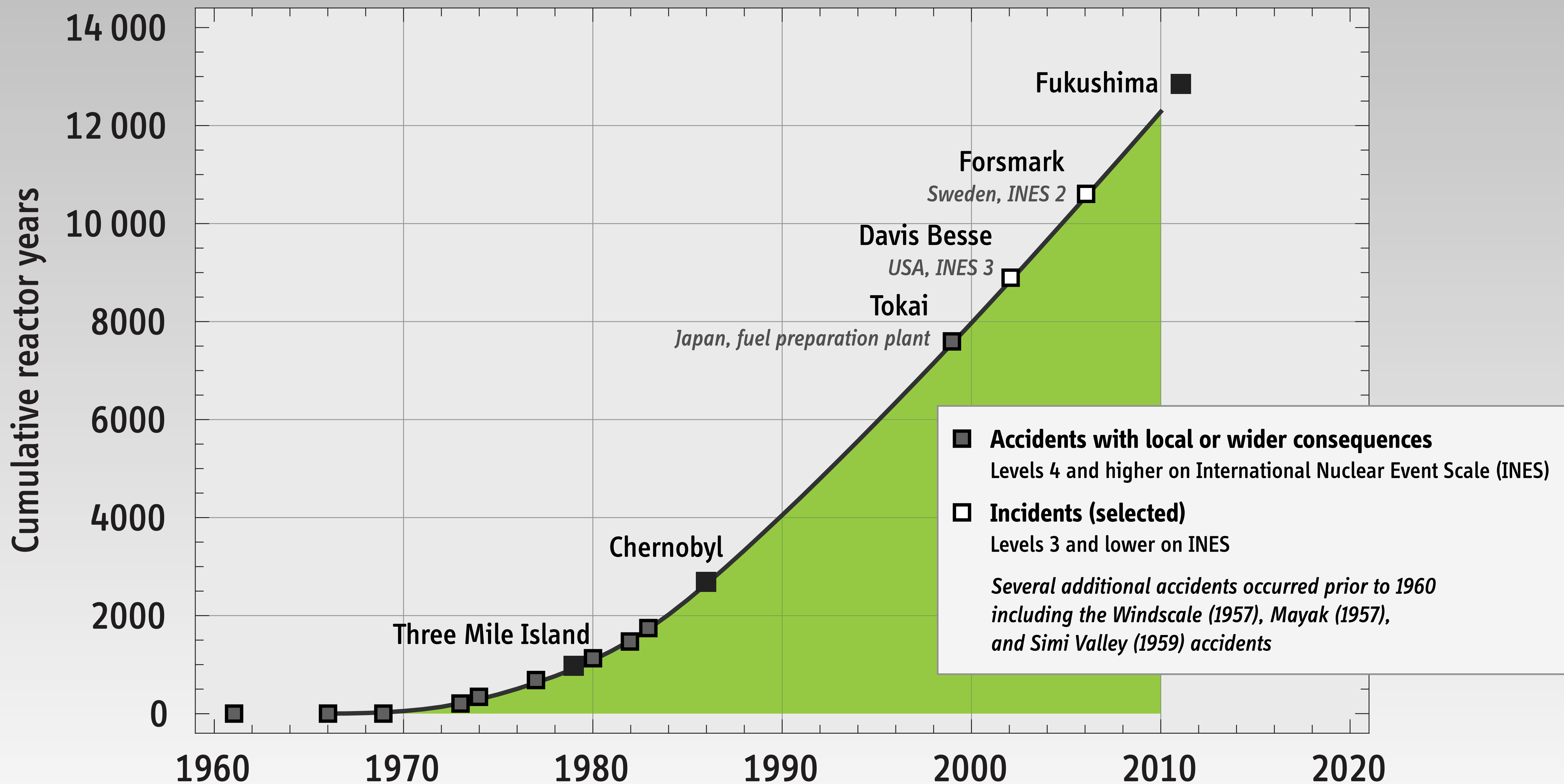

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1
2
3
4
5
6
Fukushima-Daiichi Plant
Source: TEPCO, undated

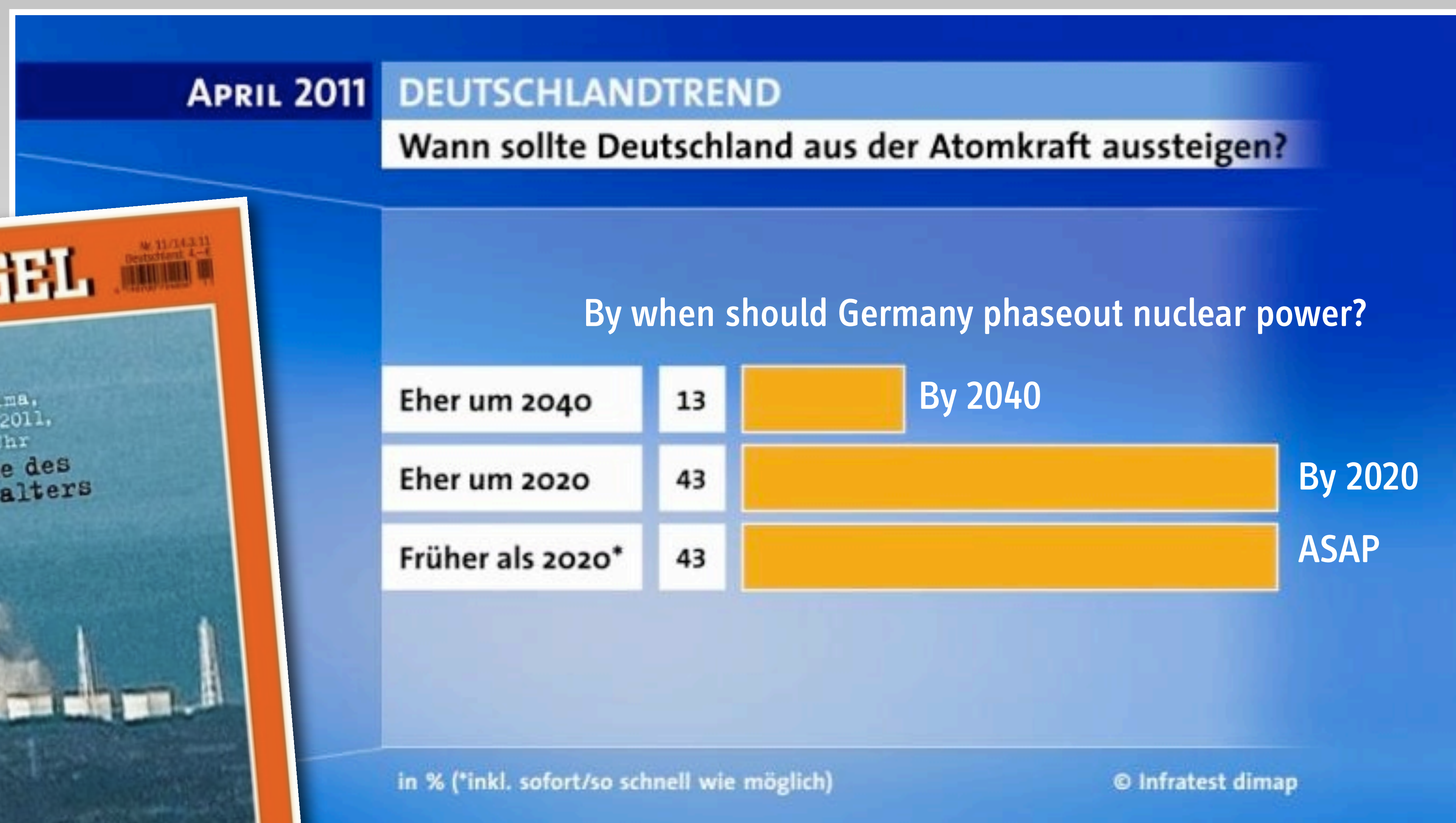

March 14, 2011 - DigitalGlobe

Watershed Moment or Storm in a Teacup?

International Responses To Fukushima

In Germany, the Fukushima Accidents Overnight Consolidated Support for Nuclear Phaseout

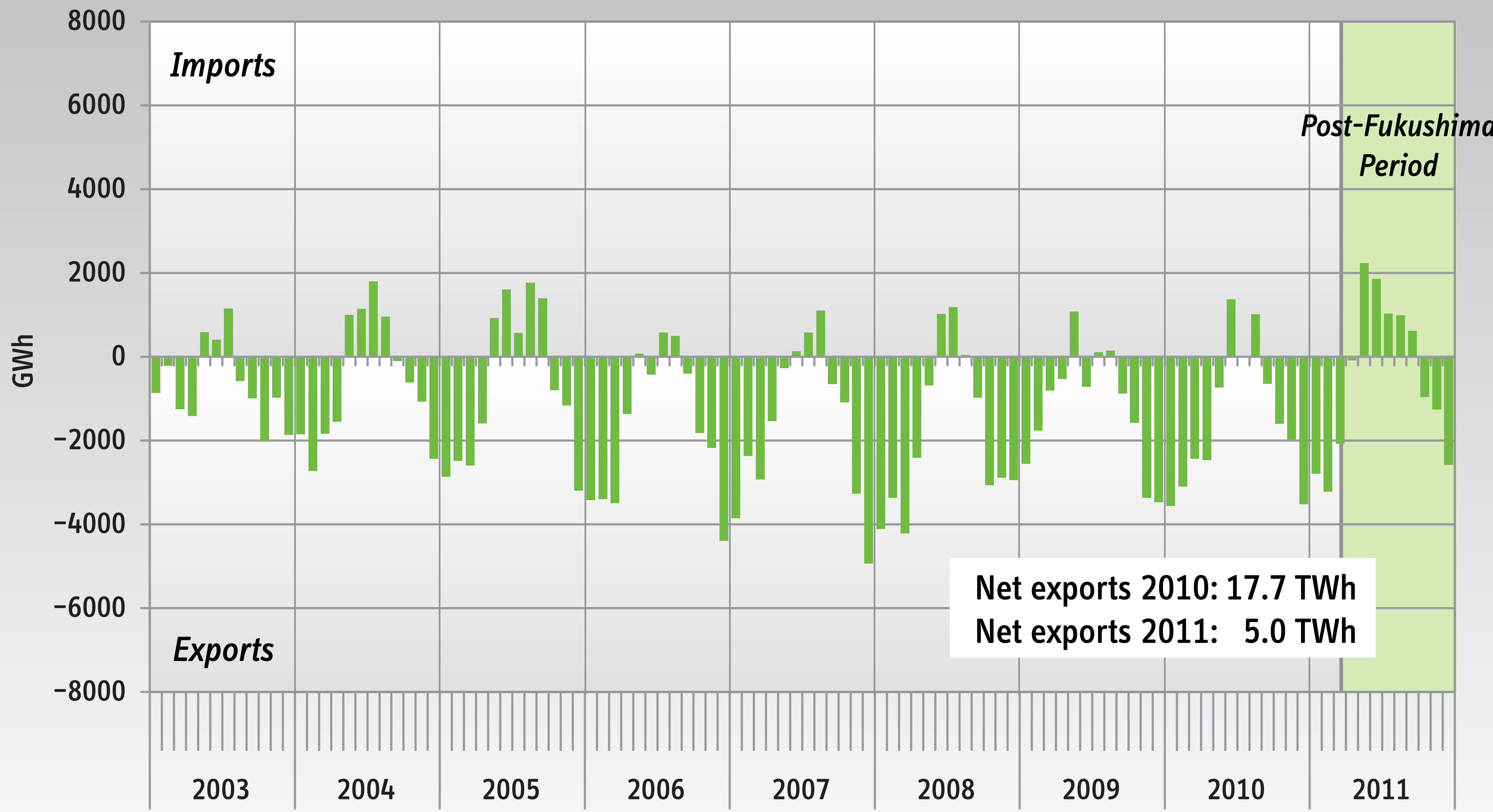
86% support nuclear phaseout by 2020 (Polling data from April 4–5, 2011)



Top: www.presseportal.de/pm/6694/2022635/ard_das_erste
Left: Spiegel Cover from March 14, 2011: The End of the Atomic Era

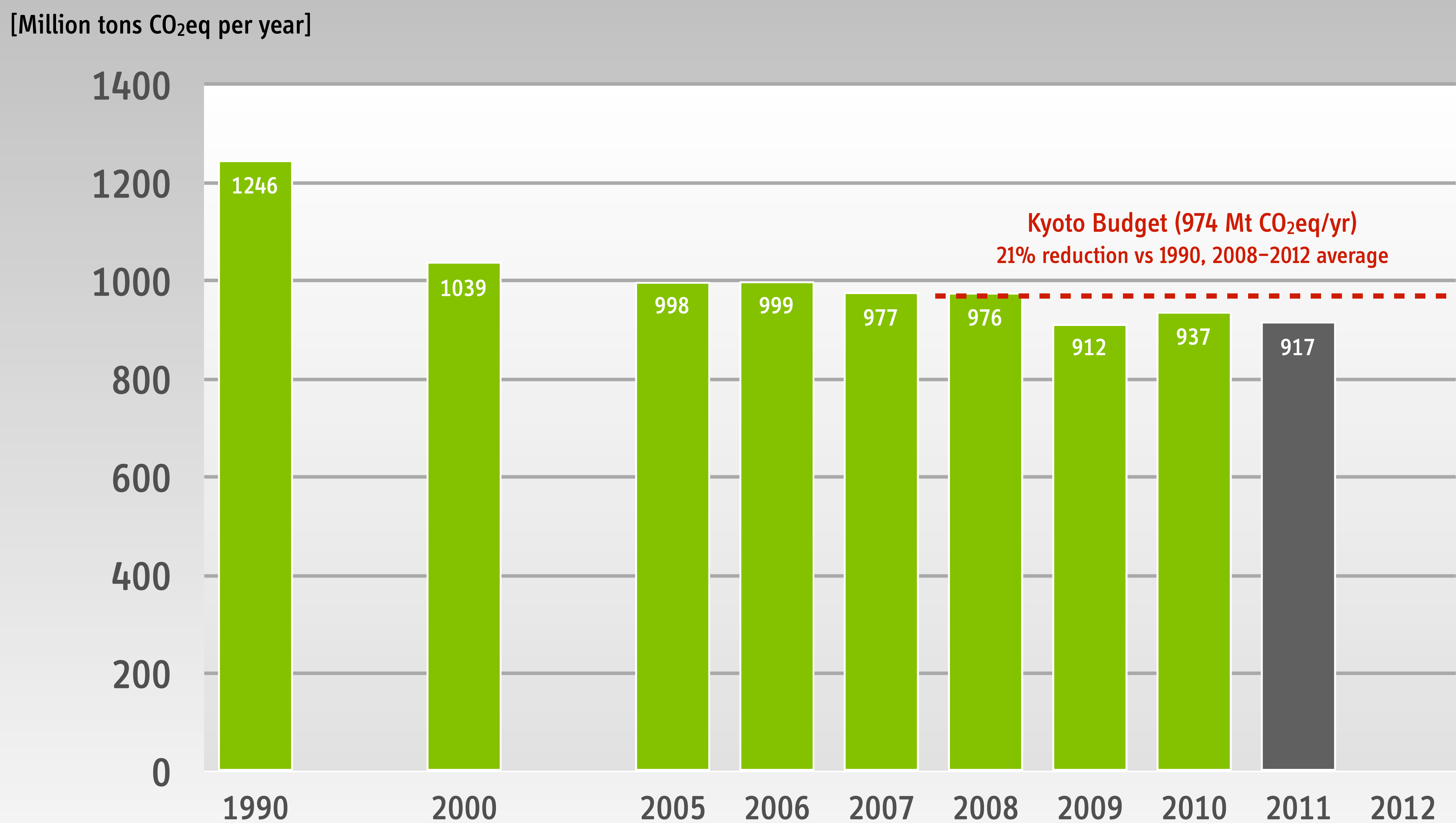
Germany's Electricity Imports/Exports

The Impact of Post-Fukushima Shutdowns is Visible but not Dramatic



Charlotte Loreck, *Atomausstieg in Deutschland*, Institute of Applied Technology, Darmstadt, March 2012

Germany's GHG Emissions Have Not Spiked Despite the Shutdown of Eight Reactors in March 2011



"Weniger Treibhausgase mit weniger Atomenergie," Press Release, 17/2012, Umweltbundesamt, April 12, 2012
See also European Central Data Reposoitory, cdr.eionet.europa.eu/de/eu/ghgmm/envtw7blw

The International Response to the Fukushima Accidents Has Been Very Uneven

Germany

Consolidating a national consensus on phaseout of nuclear power

- Immediate shutdown of eight oldest (out of a fleet of seventeen) reactors
- Complete phaseout by 2022

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Japan

Fundamental review of energy policy underway

- As of early May 2012, all 54 reactors shut down; several units are unlikely to come back online
- Strong public support for significantly reduced role of nuclear power in the future

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France

New government considers significant adjustments to French energy policy

- Planned reduction of nuclear electricity generation from almost 80% down to 50% by 2025–2030
- Major life-extension program underway: EUR 40 billion plus EUR 10 billion post Fukushima

The International Response to the Fukushima Accidents Has Been Very Uneven

several

Reconsidering a new or more important role of nuclear power

- Mostly relevant for non-committed “newcomer” countries
- Also includes countries with existing small programs (Belgium, Switzerland, the Netherlands, ...)

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China

Ambitious expansion plans largely unaffected

- Safety review of all current plants; possible new licensing requirements for future plants
- Target for 2020: add 35–45 GW to existing 12 GW (Share of nuclear electricity in 2011: 1.85%)

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USA

Continued commitment to nuclear power

but only few new construction projects moving forward despite government support

United States: The Market is Deciding

Federal Loan Guarantees

as part of the Energy Policy Act of 2005, up to $18.5 billion
Obama Administration has sought to increase amount to $54.5 billion

Most proposed construction projects have stalled

some before and some after the Fukushima Accidents

Vogtle-3 and -4 Project (Waynesboro, GA) moving forward

2 x Westinghouse AP-1000, 2200 MWe, expected for 2016 and 2017
Combined Construction and Operating License issued in February 2012
$14 billion investment; $8.3 billion in Federal loan guarantees

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"Let me state unequivocally that I've never met a nuclear plant I didn't like;
Having said that, let me also state unequivocally that new ones don't make any sense right now."

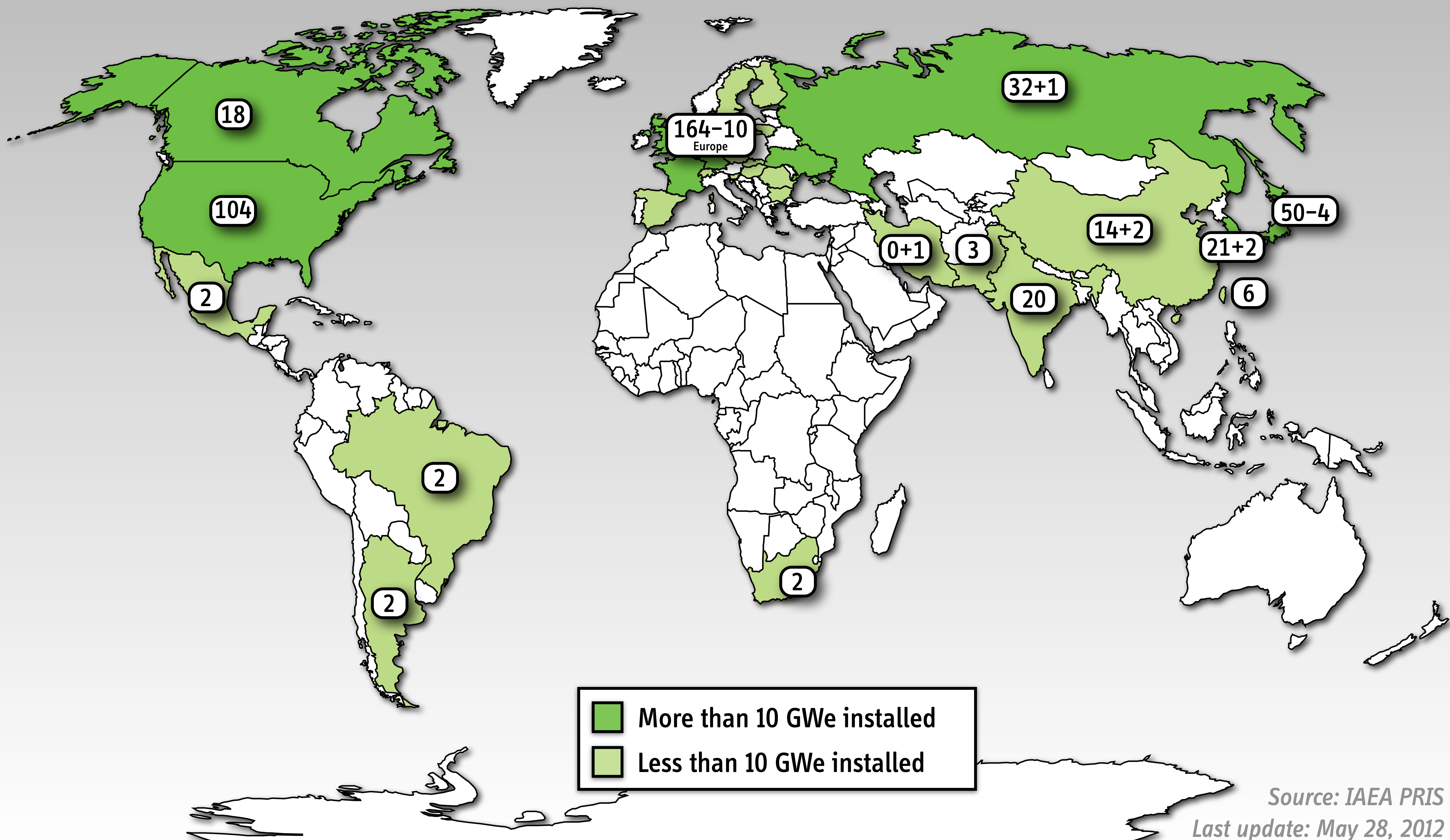
John Rowe, Former CEO Exelon, March 29, 2012

quoted in www.forbes.com/sites/jeffmcmahon/2012/03/29/exelons-nuclear-guy-no-new-nukes

Looking Forward

Nuclear Power Reactors in the World, 2012

436 operational reactors (8 less than 12 months ago) in 31 countries provide about 13% of global electricity

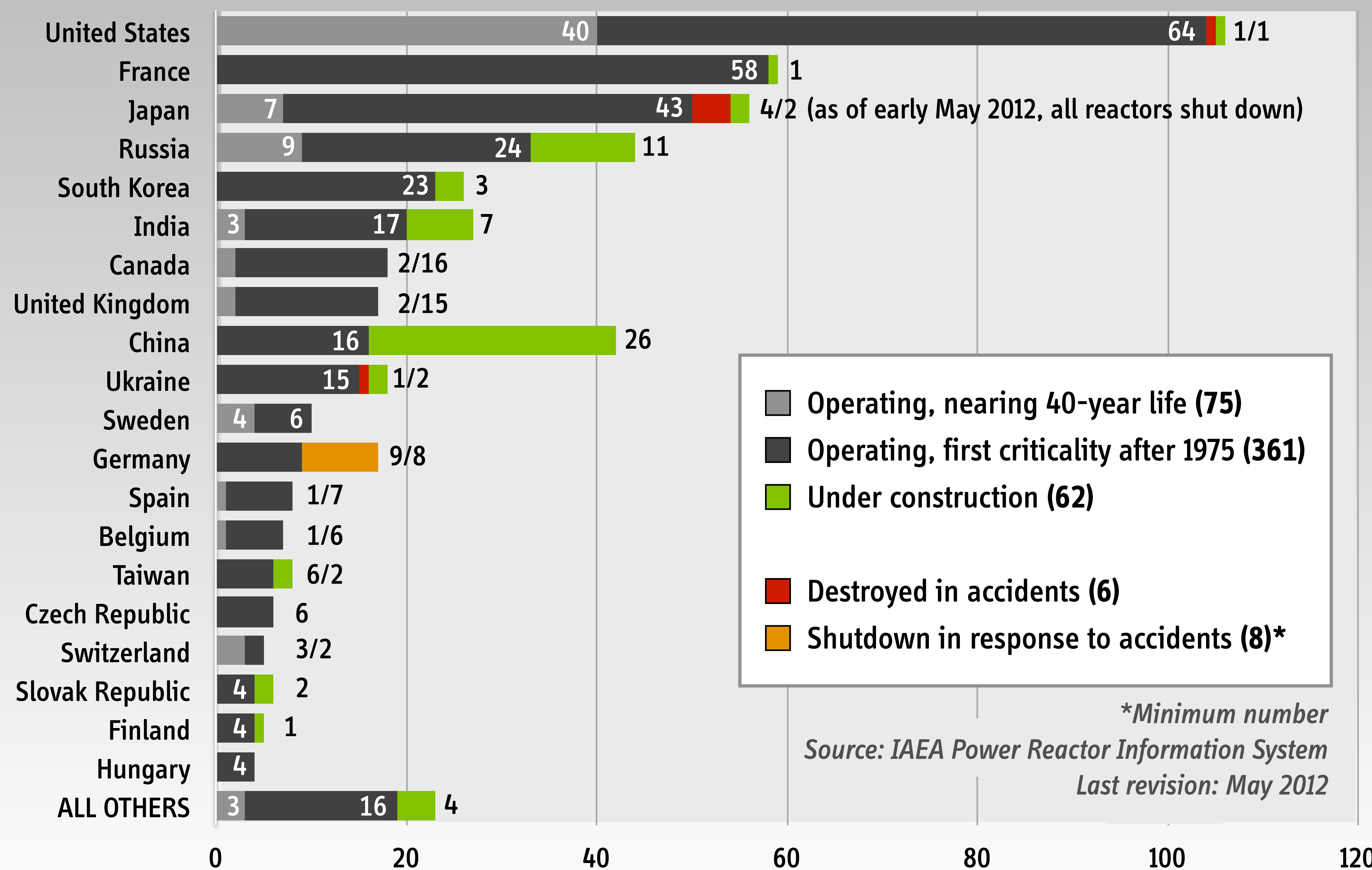


Source: IAEA PRIS

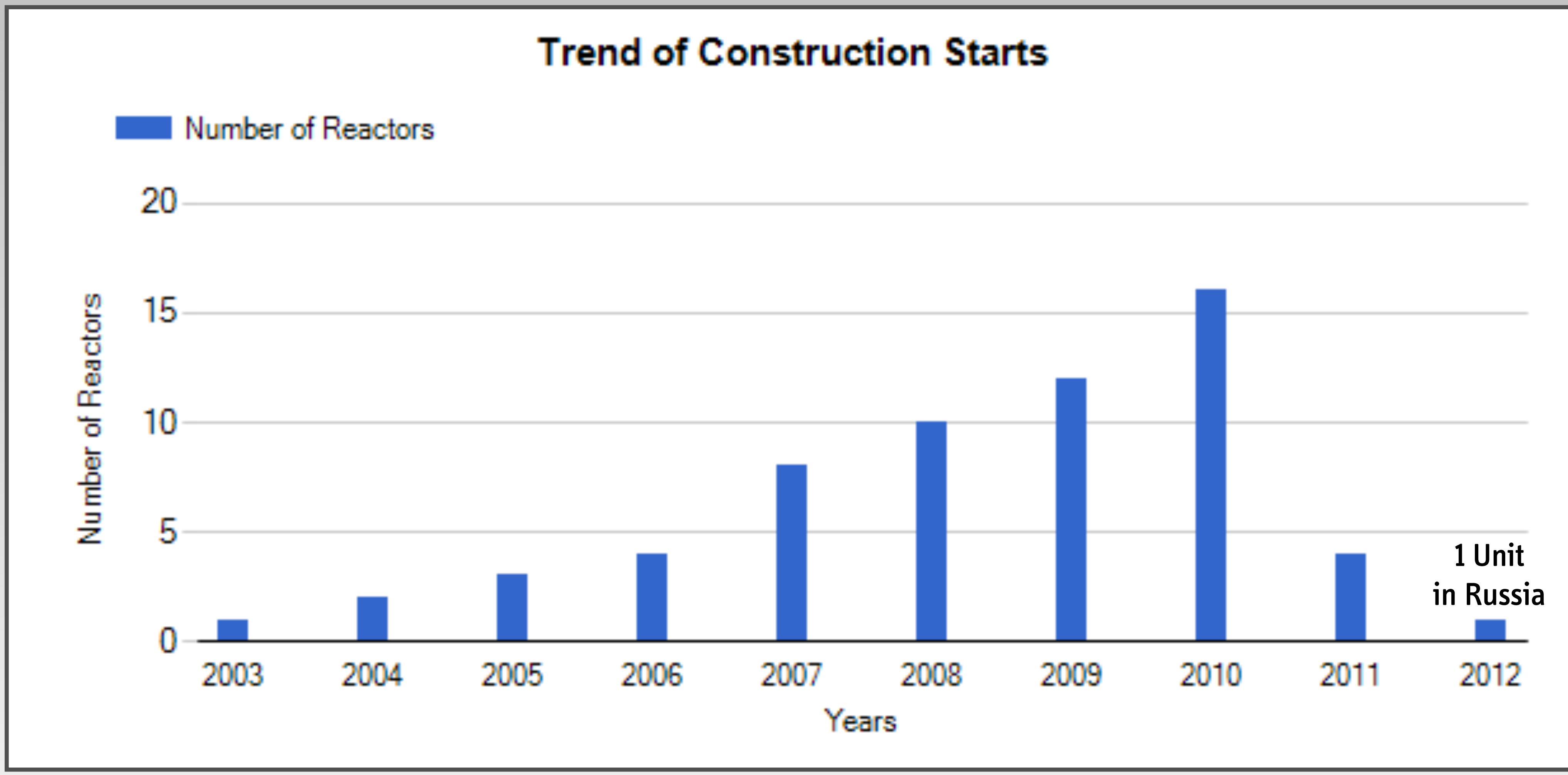
Last update: May 28, 2012

The Existing Fleet of Power Reactors is Aging

(20-year life-extensions have already been granted for most U.S. reactors)

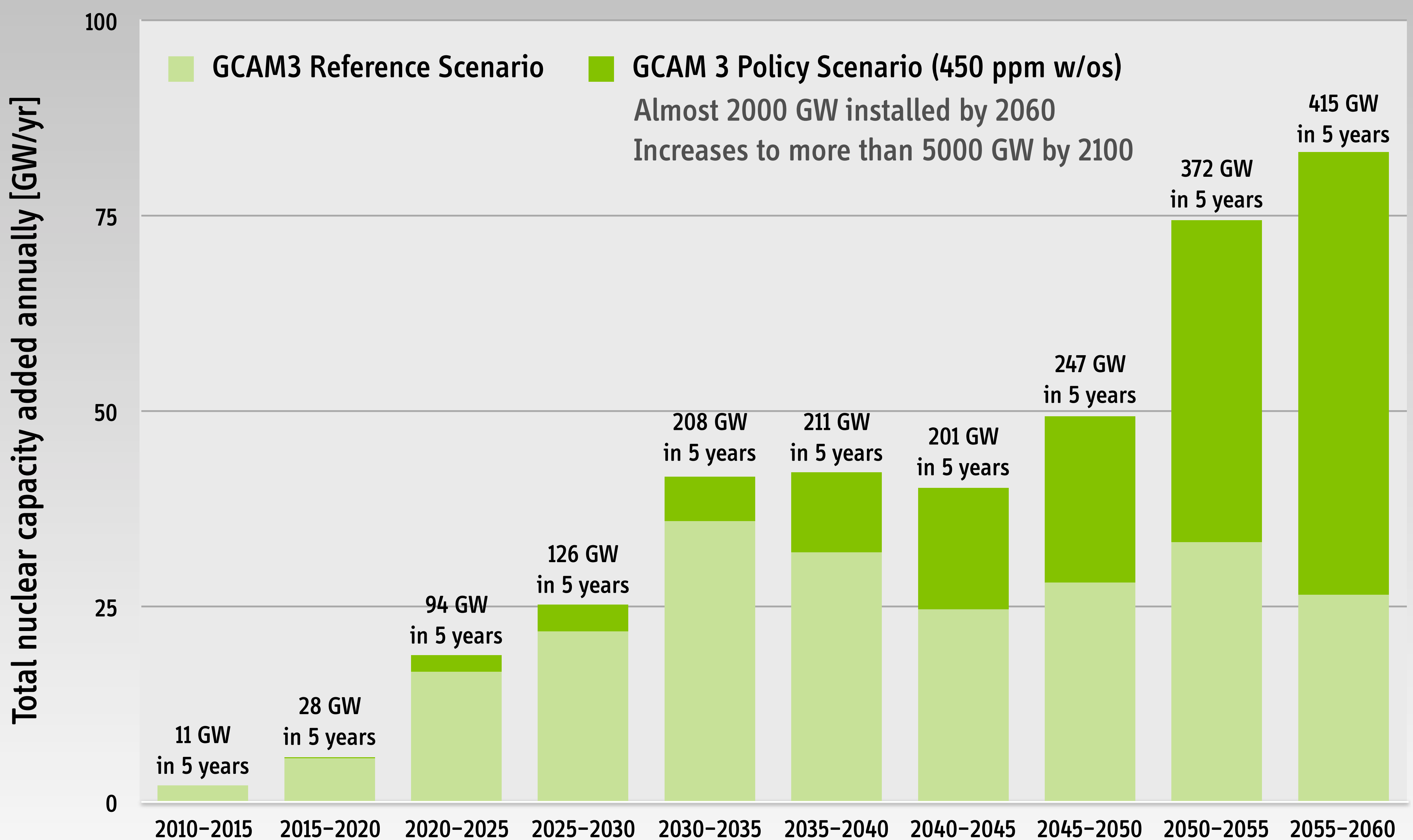


Construction Starts By Year



Source: Power Reactor Information System (PRIS), International Atomic Energy Agency, http://pris.iaea.org/public/
Information retrieved: May 24, 2012

Many Energy Scenarios (Still) Envision an Early Expansion of Nuclear Power



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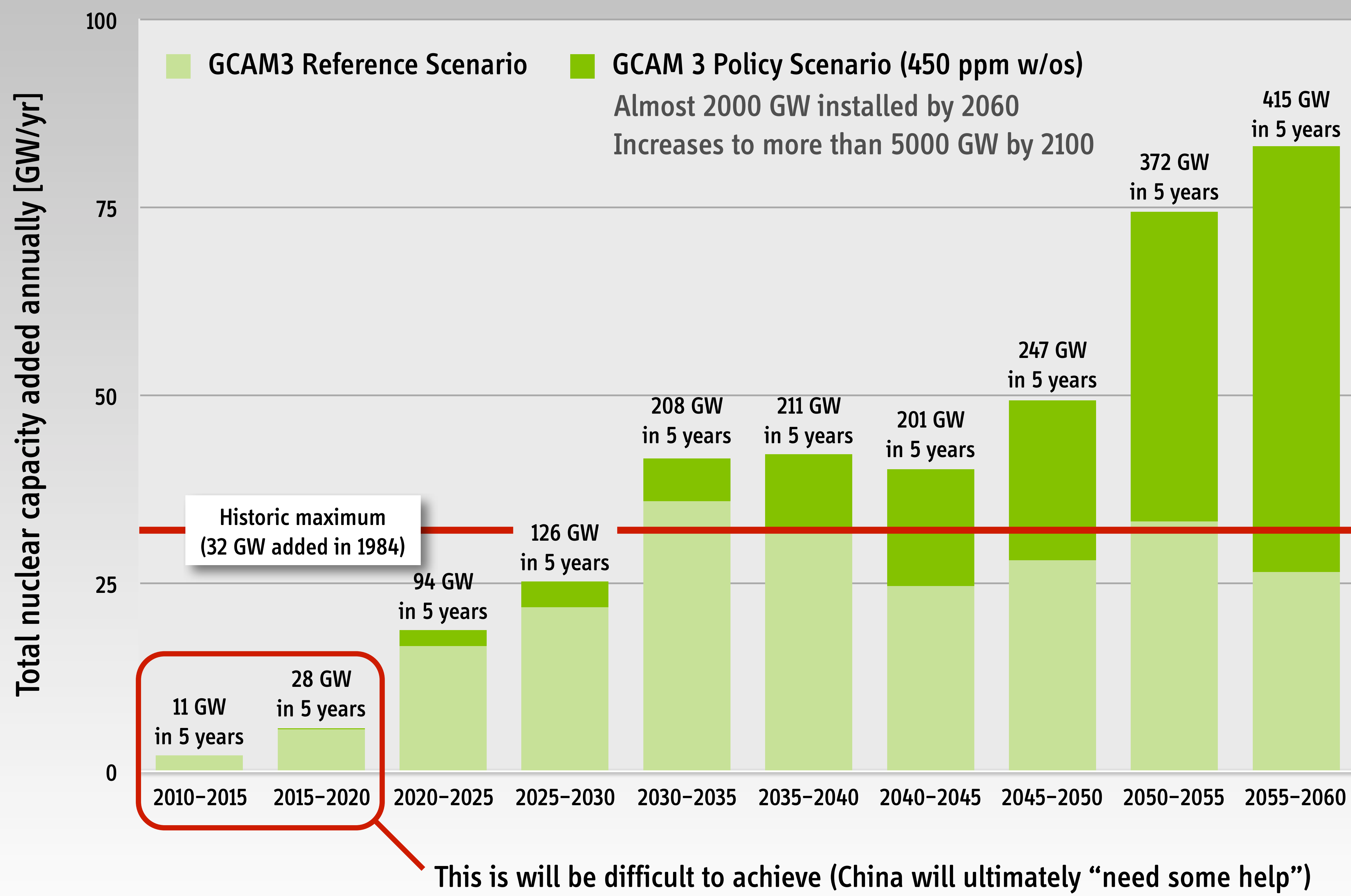
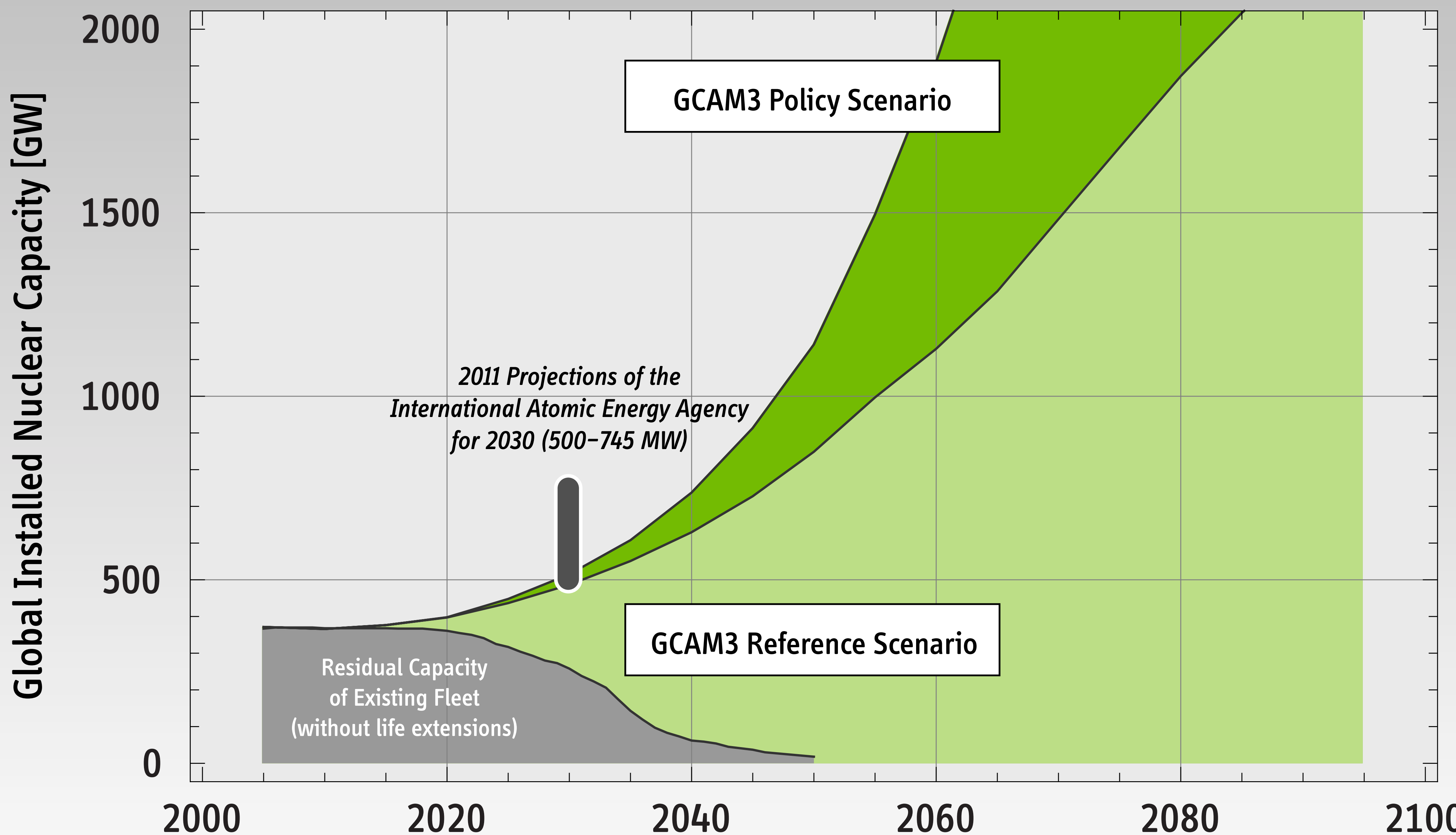


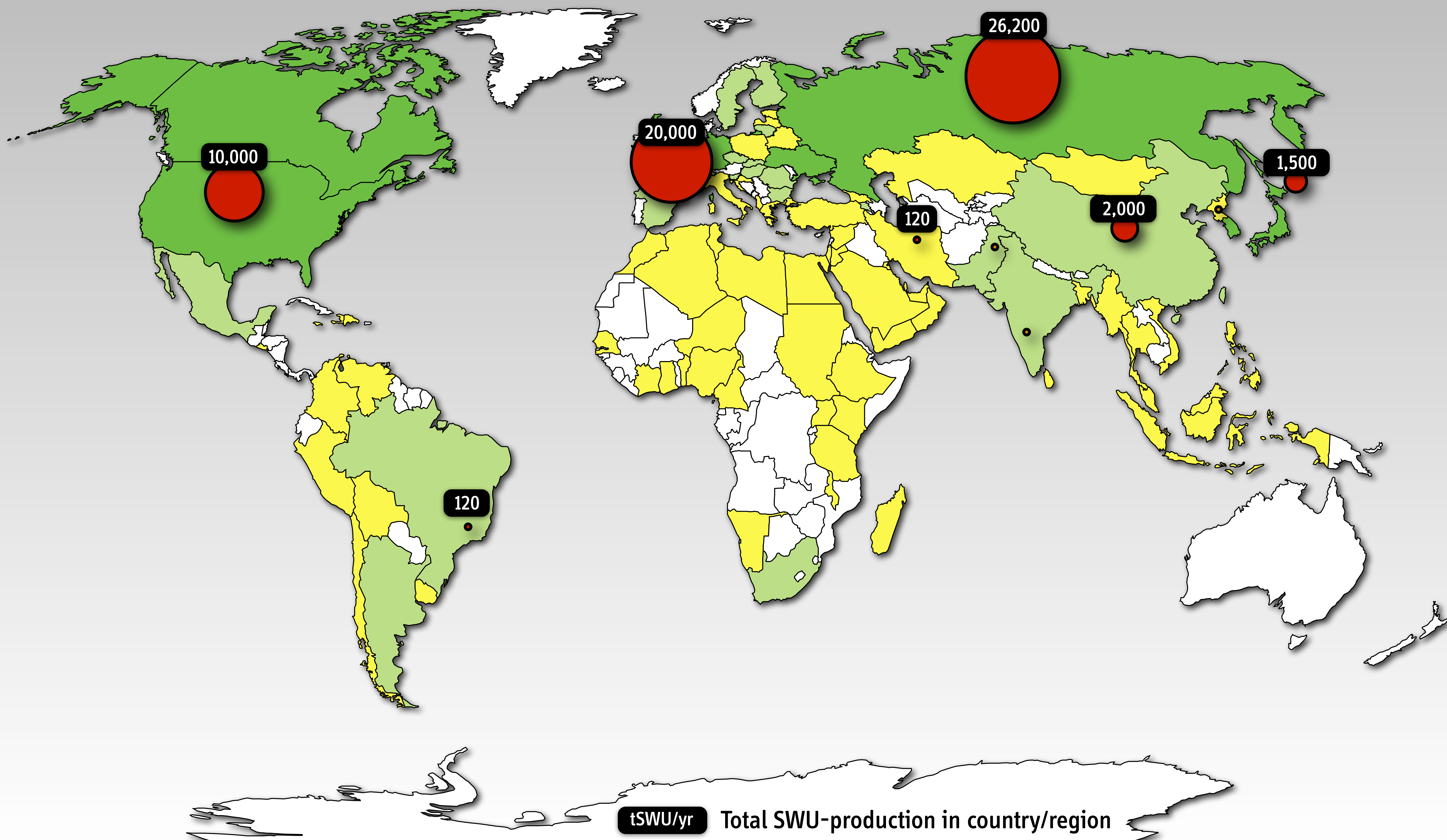
Many Energy Scenarios (Still) Envision an Early and Large Expansion of Nuclear Power



Global nuclear electricity under Policy Scenario (450 ppm w/os): 1910 GWe in 2060 (23% of total) and 5190 GWe in 2095 (34% of total)

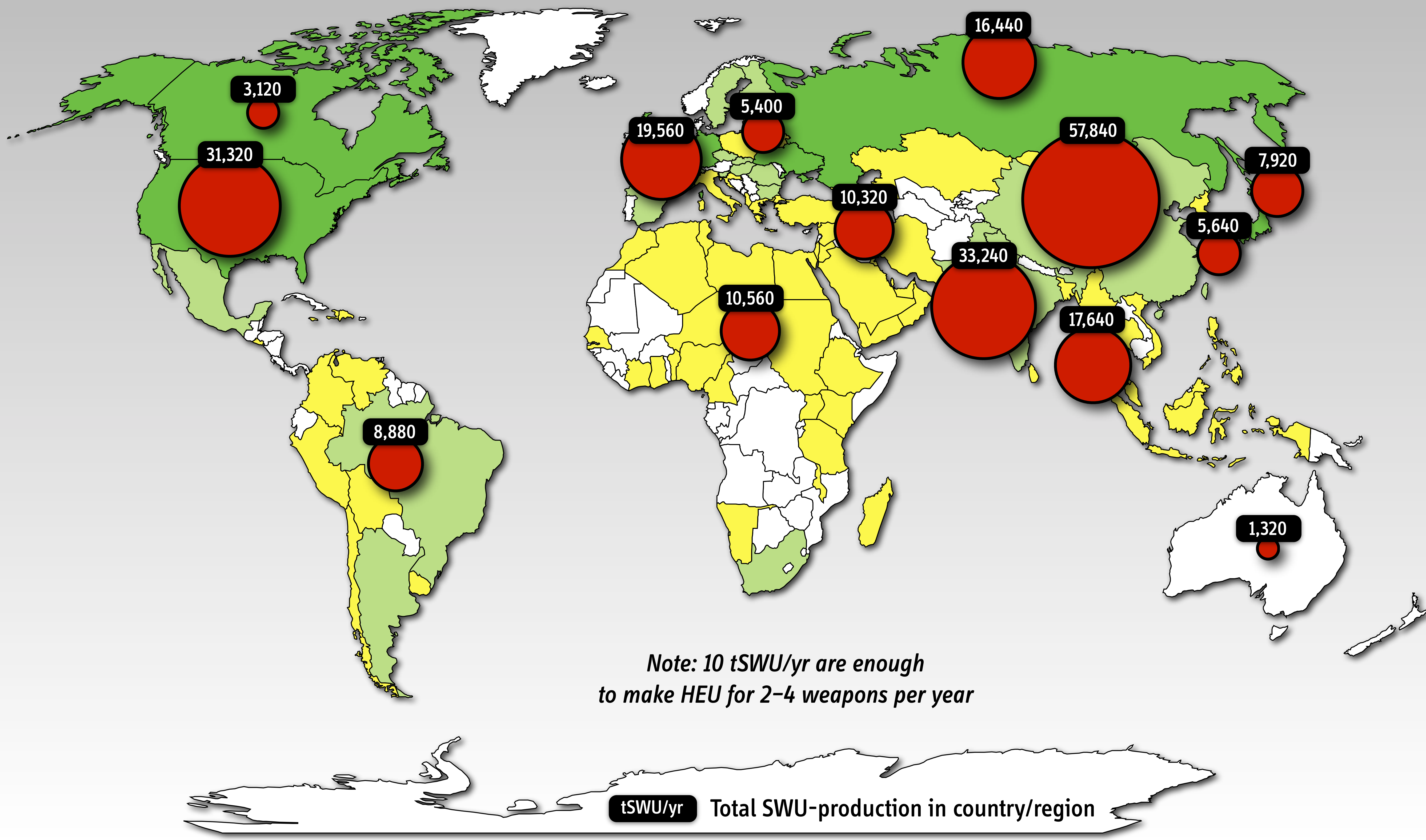
Global Uranium Enrichment Capacities, 2010

(14 operational plants in 10 countries, not including two military plants)



Global Uranium Enrichment Capacities, 2060

Based on the requirements for GCAM3 Policy Scenario in 14 World Regions



Are New Technologies on the Horizon?

The Case of Small Modular Reactors

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 enhanced safety and security**
  Almost all designs envision underground siting
- **Potential nonproliferation benefits**
  Long-lived cores

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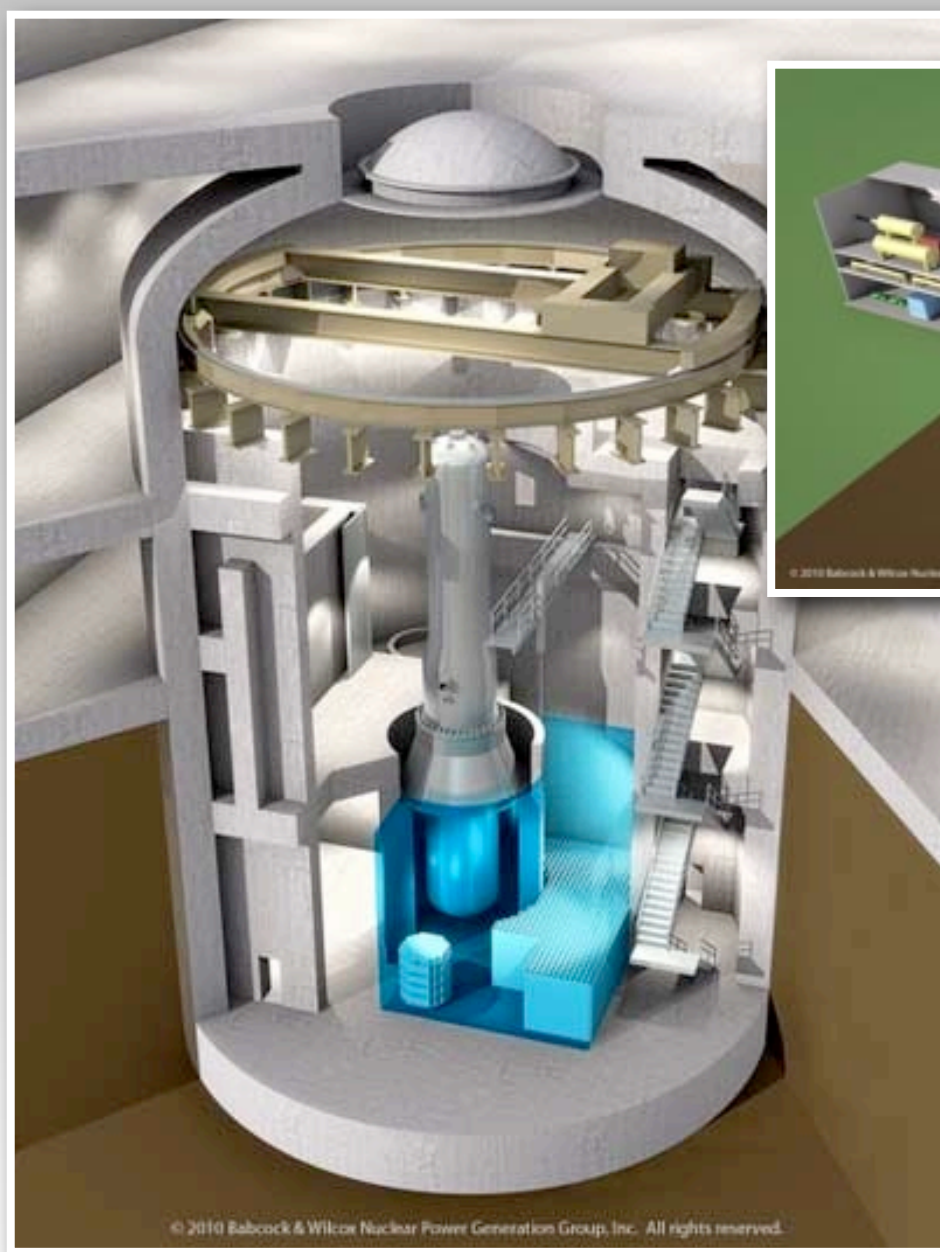
BUT: Ultimately, everything will hinge on the economics

In January 2012, 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

www.grants.gov/search/search.do?mode=VIEW&oppId=138813

Could Small Nuclear Reactors Play a Role?

Several designs are based on standard light-water reactor technology



Babcock & Wilcox mPower Concept

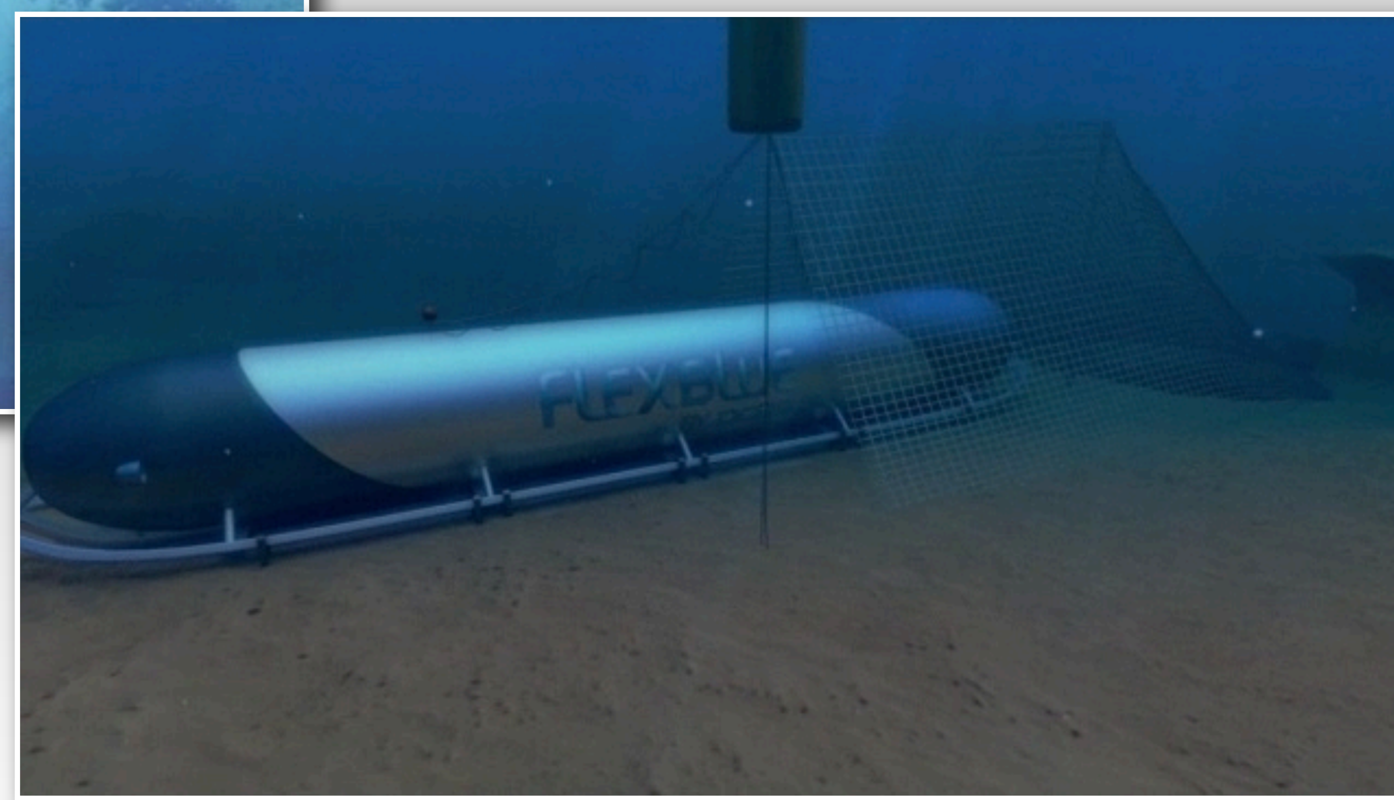
- Light-water cooled
- 125-750 MWe
- Underground construction
- 60-year spent fuel storage onsite
- Quasi-standard LWR fuel

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

Could Small Nuclear Reactors Play a Role?

Proposed new deployment options: underground, on barges, underwater

FlexBlue
DCNS (formerly *Direction des Constructions Navales*, DCN)
jointly with Areva, CEA, and EDF



Length:	about 100 m
Diameter:	12–15 m
Power:	50–250 MWe
Siting:	Seafloor mooring at a depth of 60 to 100 m a few kilometers off coast

http://en.dcnsgroup.com/energie/civil-nuclear-engineering/flexblue/

Whenever You Read About a “Stunning” New Reactor

It Most Likely is a Fast Neutron Reactor Design

“The Energy Multiplier Module (EM²) … 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.”

The design provides “the simplest possible fuel cycle, and it requires only one uranium enrichment plant per planet.”

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.”

Top: General Atomics, Technical Fact Sheet; Middle: C. Forsberg on Traveling Wave Reactor quoted in *Technology Review,* March/April 2009; Bottom: GE-Hitachi, ARC/PRISM Fact Sheet

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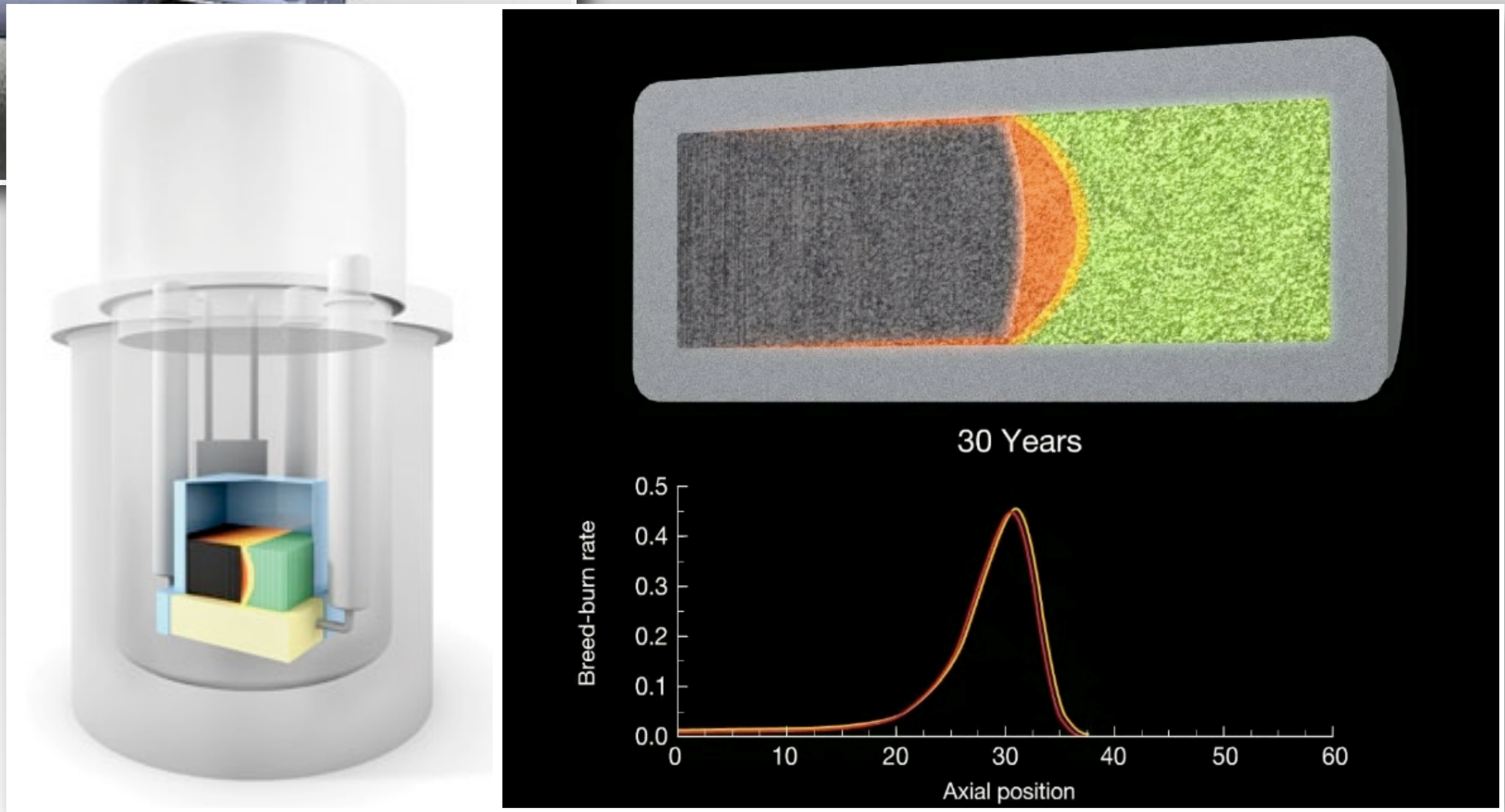
EM2: “Nuclear Waste to Energy”
www.ga.com/energy/em2/

Traveling Wave Reactor
www.terrapower.com



Princeton's "Re-Engineering the Nuclear Future" Project

Review and analyze proposed SMR designs and their associated nuclear fuel cycles

Research supported by extensive neutronics calculations for notional SMR's

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Examine the implications of a large-scale deployment of this technology with a particular focus on proliferation risk, nuclear waste generation, and economics

Research will include work with Integrated Assessment Models
(while seeking improvements in the characterization of nuclear power in these models)

Example

Notional Long-lived Small Modular Reactor in Once-through Mode

Fuel Inventory of a Long-lived Small Modular Reactor Operated in a Once-Through Mode

MCODE Simulations for Notional Design, 500 MW thermal, 30-year core life, 300 days per year

Resource and Fuel Cycle Requirements

500 MW thermal for 30 years (300 days per year; 9,000 effective full power days)

	Standard LWR (50 MWd/kg)
Fuel demand	90 tons (5%-enriched fuel)
Uranium requirements (to make fuel)	1040 tons (reference)
Enrichment	654,000 SWU (reference)
Plutonium inventory in spent fuel	1.1 tons (12 kg per ton of fuel)
Waste volume	90 tons (reference)

Resource and Fuel Cycle Requirements

500 MW thermal for 30 years (300 days per year; 9,000 effective full power days)

	Standard LWR (50 MWd/kg)	Small Modular LWR (30 MWd/kg)
Fuel demand	90 tons (5%-enriched fuel)	150 tons (5%-enriched fuel)
Uranium requirements (to make fuel)	1040 tons (reference)	1720 tons (65% increase)
Enrichment	654,000 SWU (reference)	1,080,000 SWU (65% increase)
Plutonium inventory in spent fuel	1.1 tons (12 kg per ton of fuel)	1.5 tons (10 kg per ton of fuel)
Waste volume	90 tons (reference)	150 tons (65% increase)

Resource and Fuel Cycle Requirements

500 MW thermal for 30 years (300 days per year; 9,000 effective full power days)

	Standard LWR (50 MWd/kg)	Small Modular LWR (30 MWd/kg)	SMR TYPE F2 (fast spectrum, once-through)
Fuel demand	90 tons (5%-enriched fuel)	150 tons (5%-enriched fuel)	20 tons* (12%-enriched starter fuel)
Uranium requirements (to make fuel)	1040 tons (reference)	1720 tons (65% increase)	570 tons (45% reduction)
Enrichment	654,000 SWU (reference)	1,080,000 SWU (65% increase)	430,000 SWU (35% reduction)
Plutonium inventory in spent fuel	1.1 tons (12 kg per ton of fuel)	1.5 tons (10 kg per ton of fuel)	2.8 tons (70 kg per ton of fuel)
Waste volume	90 tons (reference)	150 tons (65% increase)	40 tons (55% reduction)

*Does not include 20 additional tons of depleted uranium for blankets

In principle, some long-lived SMR concepts could be attractive for deployment in the 2020–2030 timeframe (but the "temptation" to reprocess the fuel from the used cores might be significant)

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 Economics & Possible Business Models”
2nd Annual Nuclear Energy Insider SMR Conference, Columbia, SC, April 24, 2012

Where Is Nuclear Power Heading?

Some Concluding Observations

Many countries remain committed to nuclear power
but deployment and role of nuclear power is likely to be more uneven

Germany’s phaseout will be a “game changer”

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SMR attract significant attention; many innovative features; some prototypes will be built

Small may be beautiful ... but it is small

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An early large-scale global nuclear expansion has become very unlikely

New thinking is needed about the potential (smaller) role of nuclear power in energy portfolios