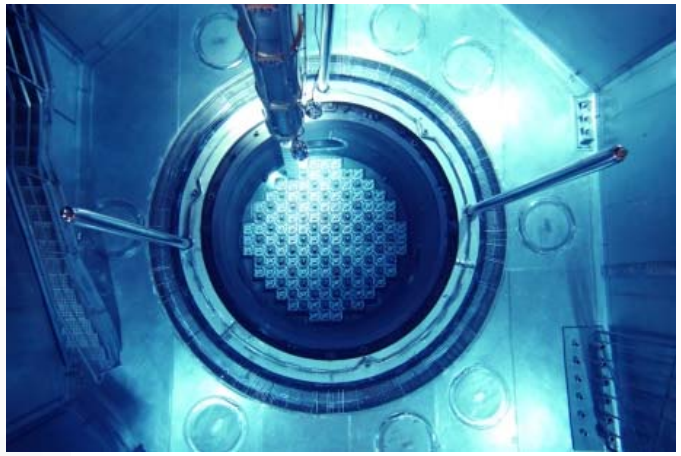

Nuclear Power Plants – Design and Safe Operation

- August 2018 -

Dr.- Ing. L. Mohrbach

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- Nuclear Energy and Climate
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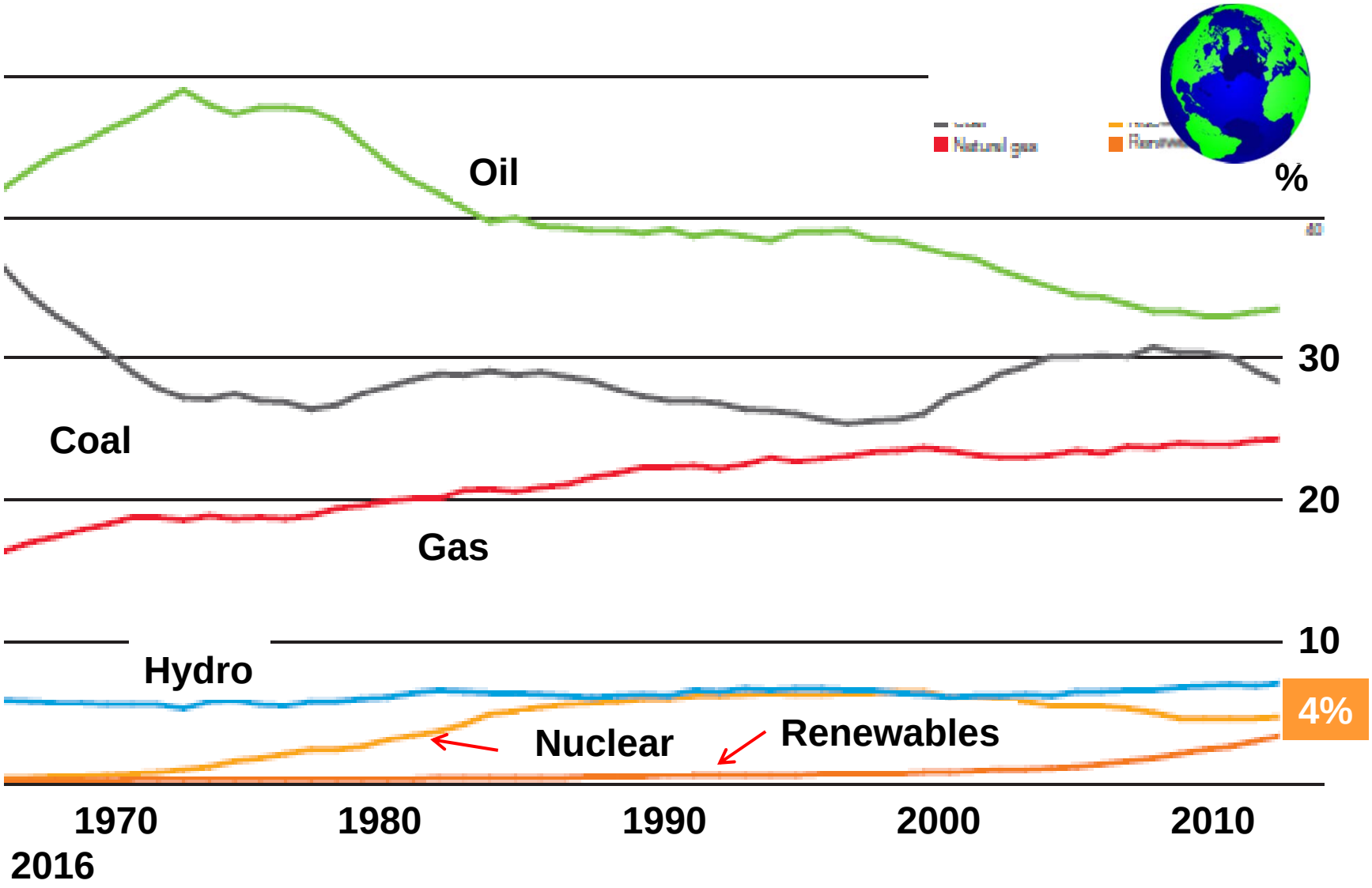
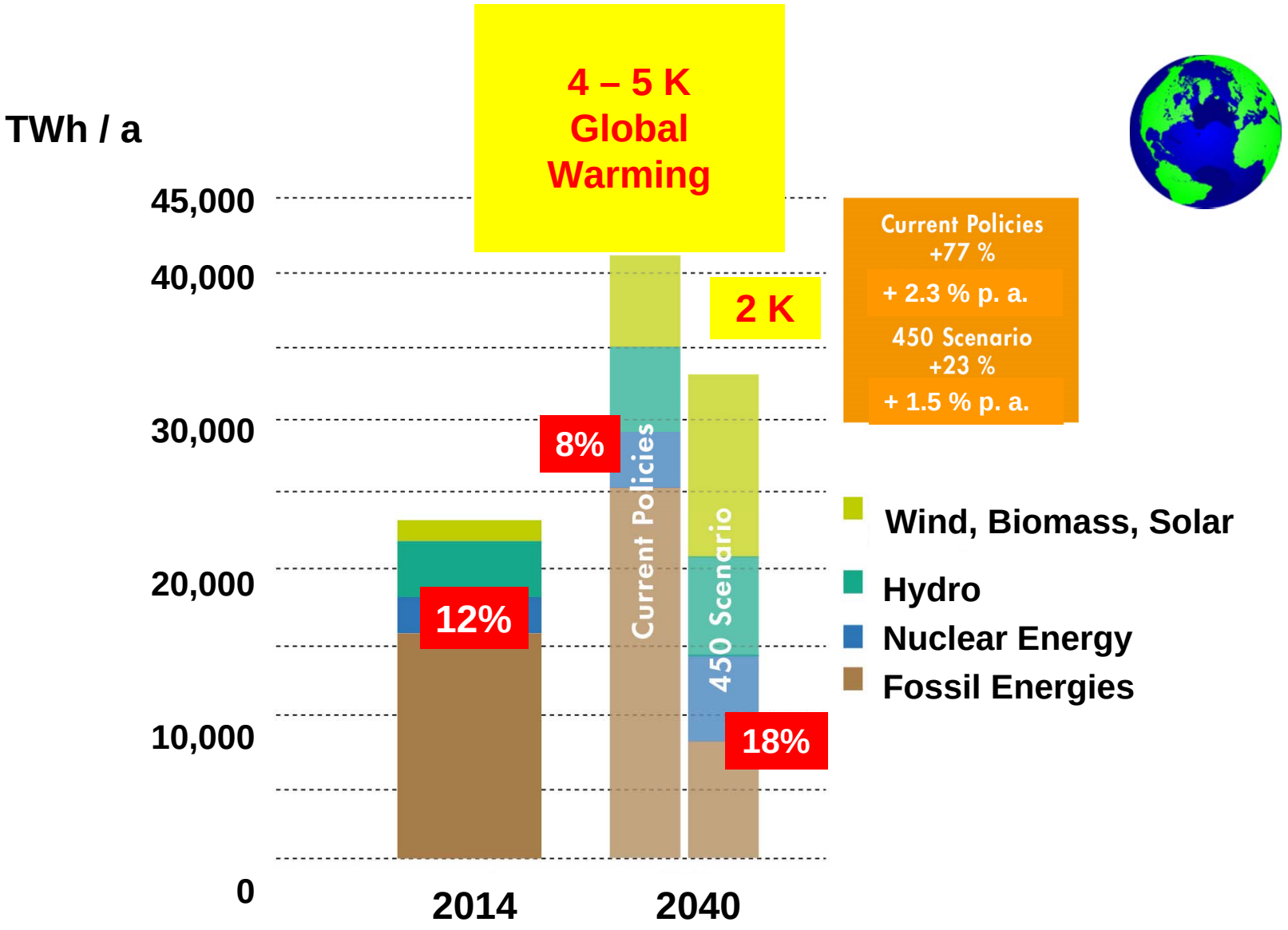
Breakdown of Primary Energy Sources Worldwide



www.bp.com/.../energy...2017/bp-statistical-review-of-world-energy-2017-full-re...

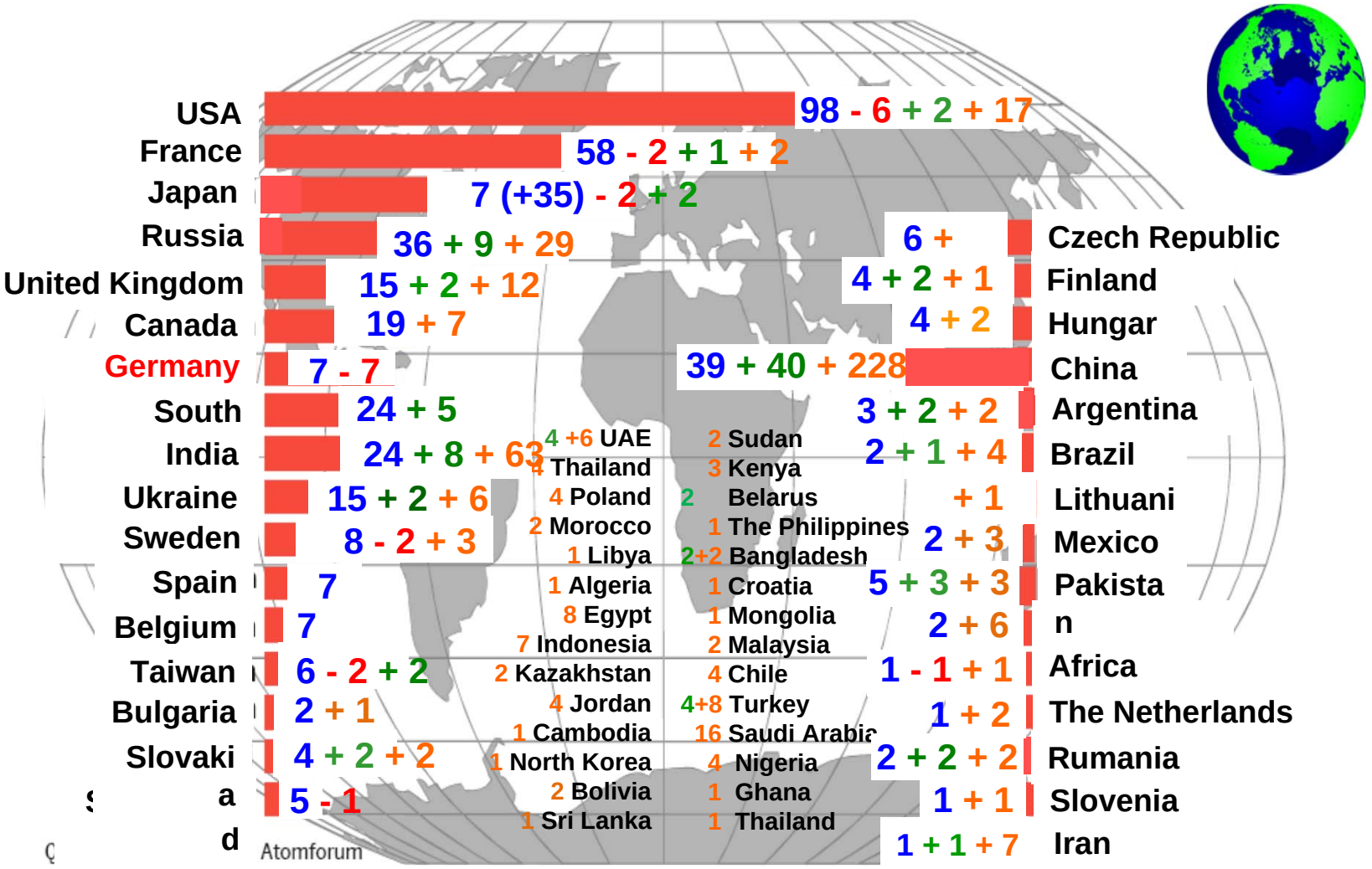
Power Generation Worldwide: Climate Agreement of Paris in 2017



Nuclear Energy Effectively Reduces CO_2 Emissions

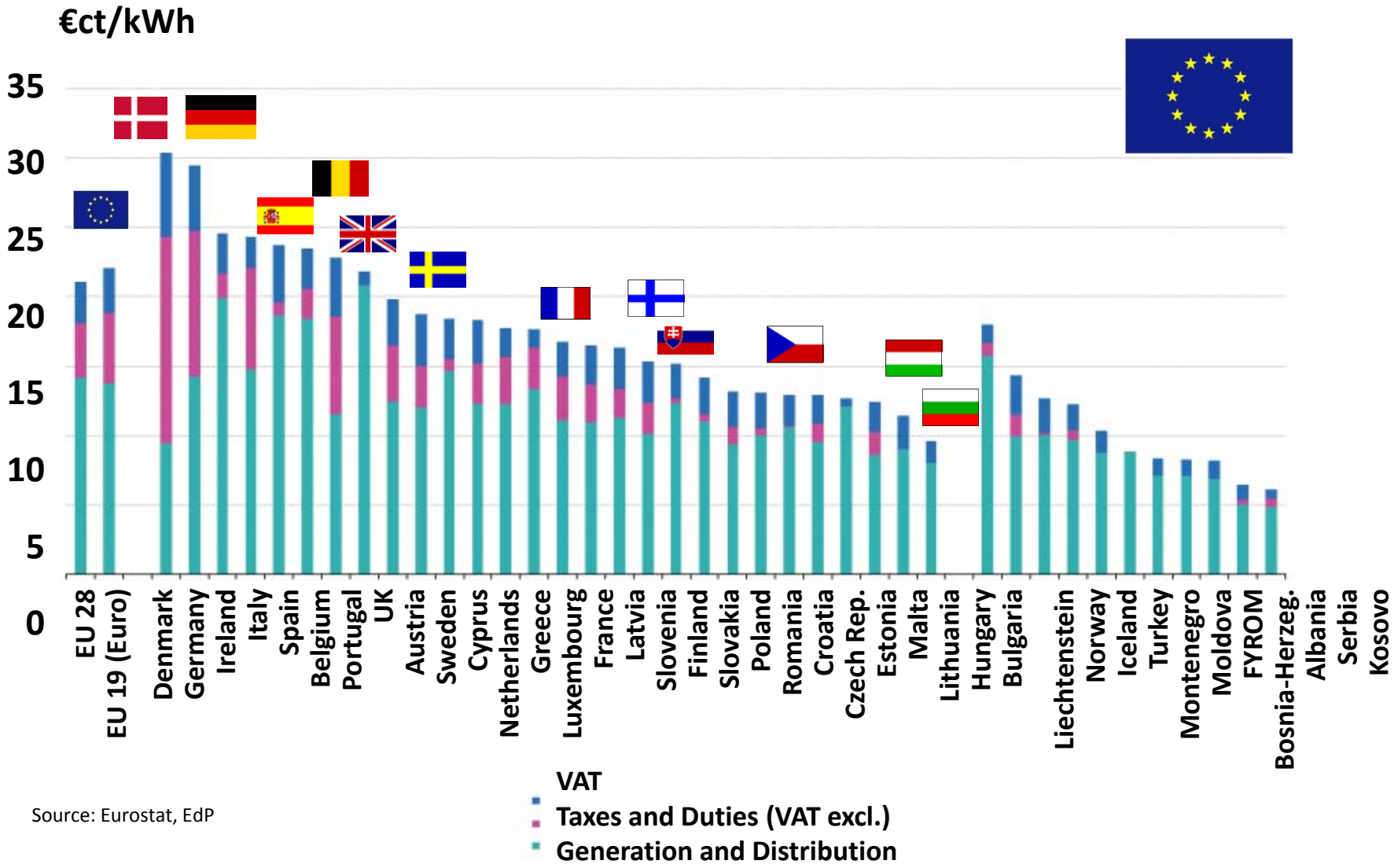
- **450 nuclear power plants provide about 12% of the worldwide electric energy supply.**
- **They save around 2 Gt CO_2 emissions p. a.**
- **This corresponds to approx. 6% of all anthropogenic CO_2 emissions**

450 Nuclear Power Plants in 31 Countries (4/2018)



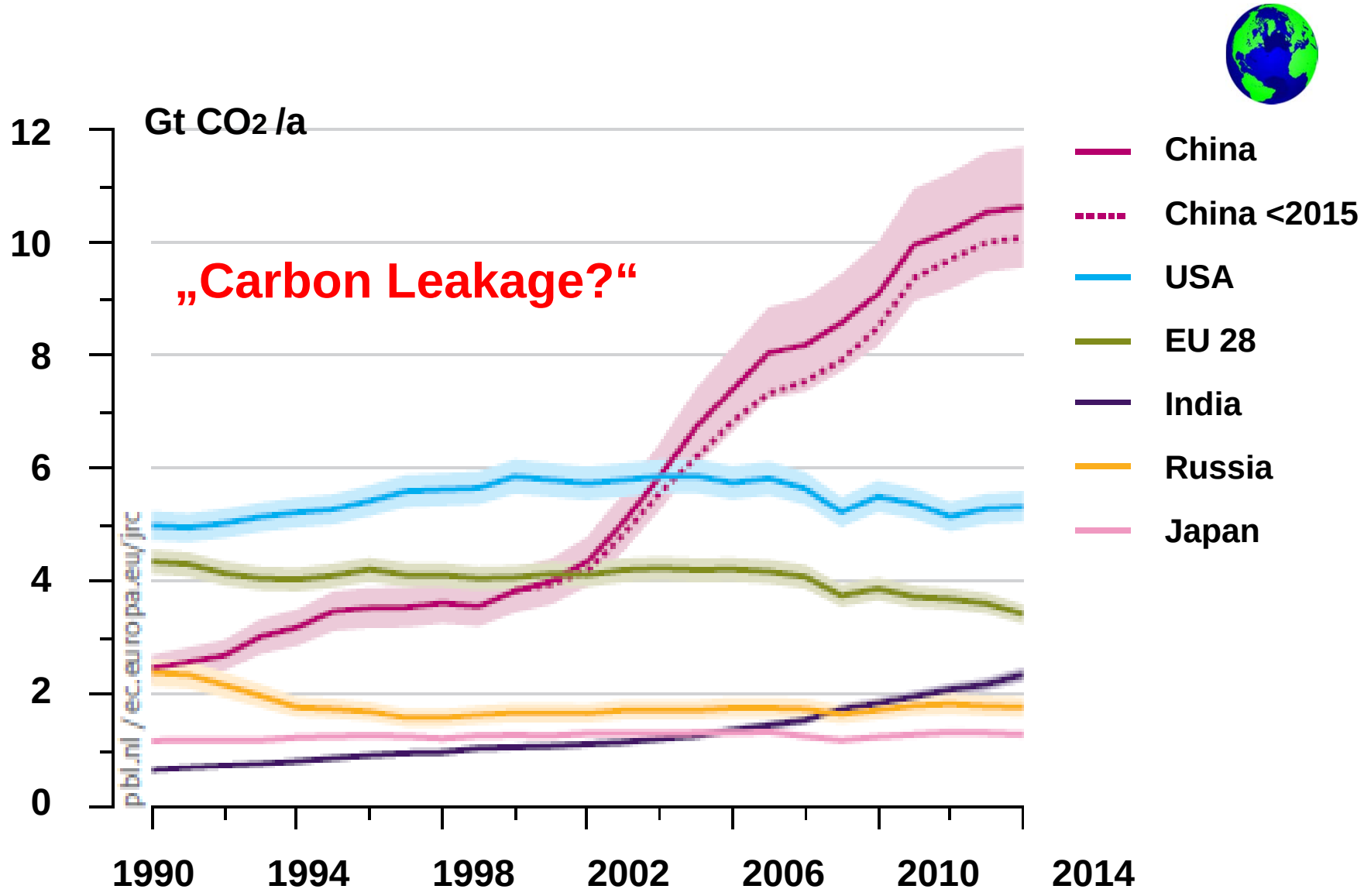
Decommissioning Planned: 21 Under Construction: 89 (IAEA: 57) Projects: 414 + 90

Household Electricity Prices in Europe in 2015 (2nd Half)

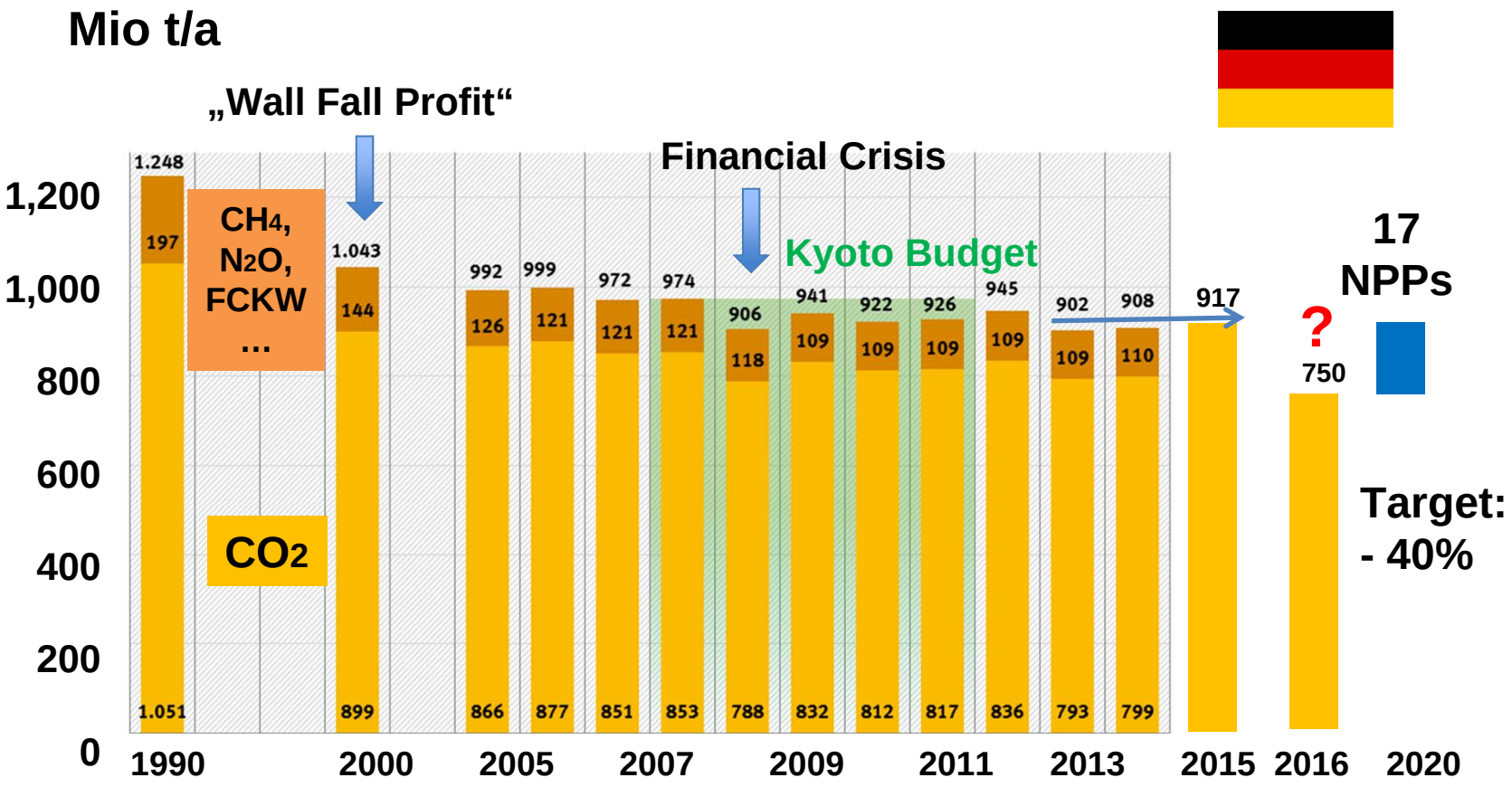


Source: Eurostat, EdP

CO_2 Emissions from Combustion plus Cement Production



Greenhouse Gas Emissions (CO_2 Equivalents)



Source: Umweltbundesamt Emissionssituation 2016, Energie-Infodienst 2017

Quelle: UBA Emissionssituation; Stand: 11.02.2016

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Classification of Advanced Developments

Westinghouse 4-Loop

Siemens-KWU Pre- Convoy

Framatome EPR

INVAP (Arg) CAREM

1965 **1995** **2010** **2030**

Generation I **Generation II** **Generation III** **Generation III+** **Generation IV**

Early Prototypes	Commercial Power Reactors	Evolutionary Plants	Further Increase of Efficiency	Improvement of efficiency, safety, waste economics
(~100 MW) PWR, BWR, Magnox	(600 – 1200 MW) CANDU, AGR, RBMK	(<1300 MW)	(1150 – 1650 MW)	Breeders, High-Temperature Reactors, Liquid Fuel Reactors, Steam Superheating

Small Modular Reactors („SMR“)

Reactors for the World Market in 2018 (Predecessor Types)

	Name	MWel	Developer	In Oper.	U. Con.	Planned
PWR	EPR	1650	Framatome/ EdF	-	6	10
	Atmea 1	1150	Framatome/ Mitsubishi	-	-	4
	AP-1000	1100	Brookfield (CAN)/ Westinghouse	-	2	-
	CAP-1000	1100	CNNC (China)/ Westinghouse	-	8	18
	CAP-1400	1300	CNNC	-	-	2
	ACPR-1000	1000	China GN/ CNPC	24	6	-
	Hualong- 1	1150	China GN/ CNNC	-	6	4
	WWER- 1000	1000	Atomenergoprojekt, OKB Gidropress	36	5	-
	MIR- 1200	1200	Atomenergoprojekt, OKB Gidropress	2	13	13
	TOI 1300	1300	Atomenergoprojekt, OKB Gidropress	-	2	-
	APR	1400	Korea Electric	1	9	3
BWR	ABWR	1380	General Electric, Hitachi (Toshiba)	5	2	4
	ESBWR	1600	General Electric	-	-	2
CANDU	E-CANDU-6	600	SNC Lavalin/ China GN	2	-	1
	IPHWR-700	700	Nuclear Power India	-	6	8
GEN IV	HTR-PM200	200	China NEC	-	2	2
	CFR-600	600	TerraPower/ CNNC	-	-	2
SMR	CAREM	27-100	CNEA (Arg.)/ INVAP	-	1	1
	KLT-40	35	Atomenergoprojekt	-	1x2	4
	Linglong 1	100	CNNC-CNEC New Energy/ NPIC	-	-	2

Summary: World Market for Nuclear Power Plants

8 Pressurised Water Reactors (5 Manufacturers)
2 Boiled Water Reactors (1 Manufacturer)
2 Heavy Water Reactors (2 Manufacturers)

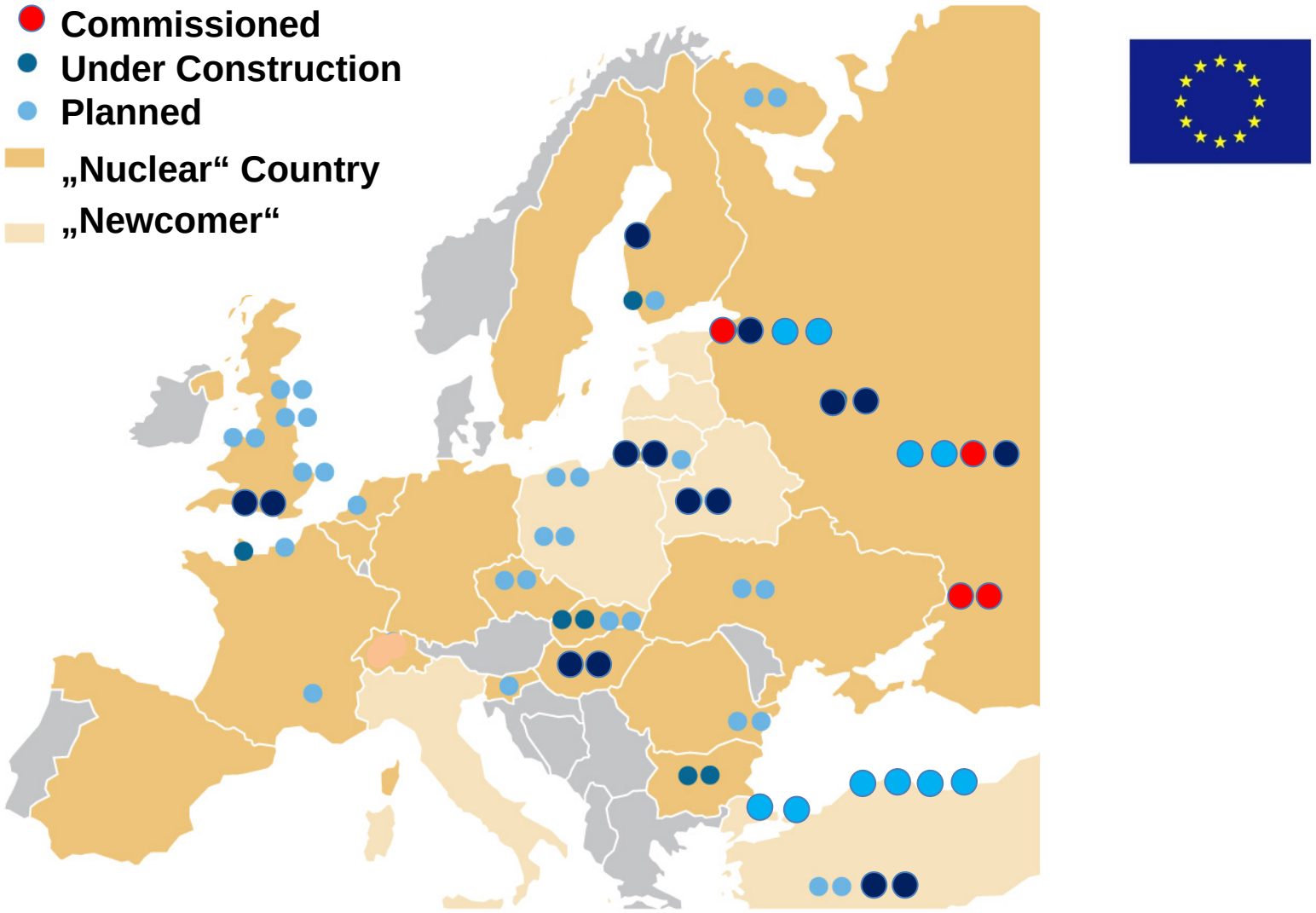
GENERATION- IV- Programme GIF (US Ministry of Energy 2002)

Six advanced reactor types with improved
- **safety,**
- **efficiency,**
- **risk of proliferation**

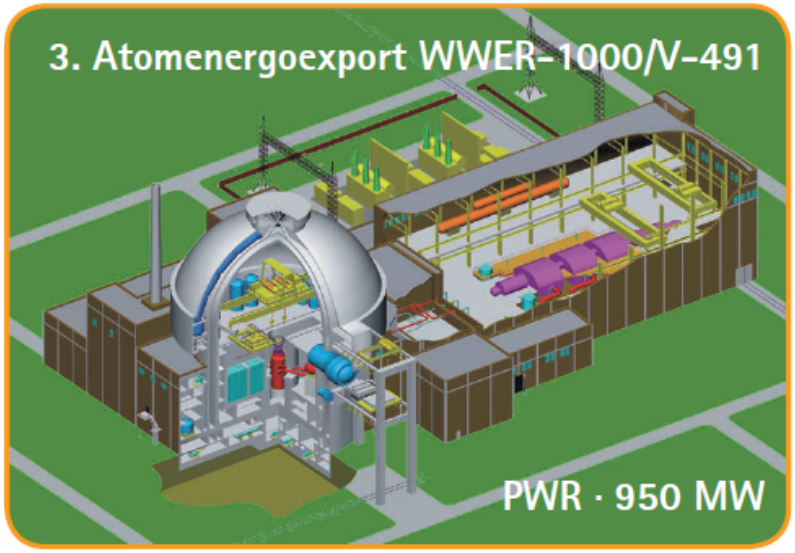
Small Modular Reactors:

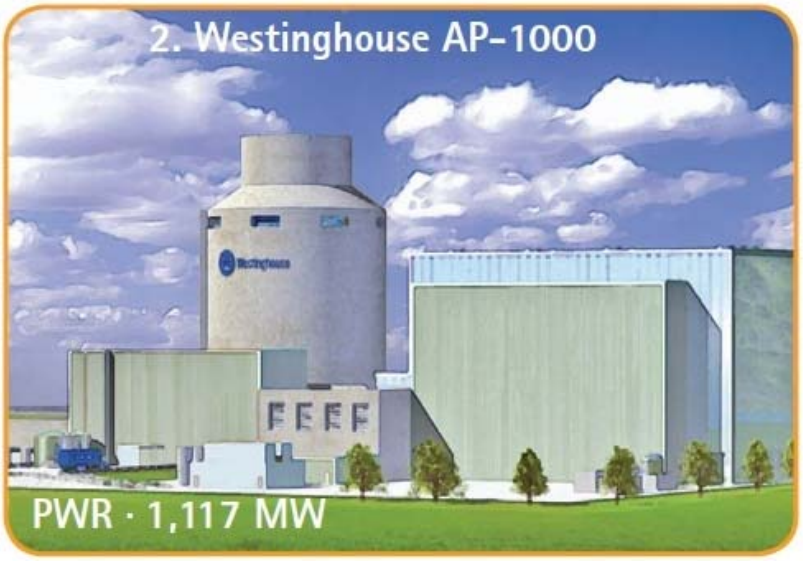
About 20 pressurised water reactors
About 5 light water reactors with supercritical steam parameters
About 10 high-temperature reactors
About 10 liquid metal cooled (fast) reactors (incl. breeders)
About 10 molten salt reactors

Nuclear Power Plant Projects in Europe



Nuclear Power Worldwide





Hinkley Point C (EdF Energy)

2 x 1650 MWe AREVA- EPR (4th-of-a-Kind)

First privately financed nuclear project in UK
2012: EPR Design Certification („GDA“)
2012: „Contract for Difference“:

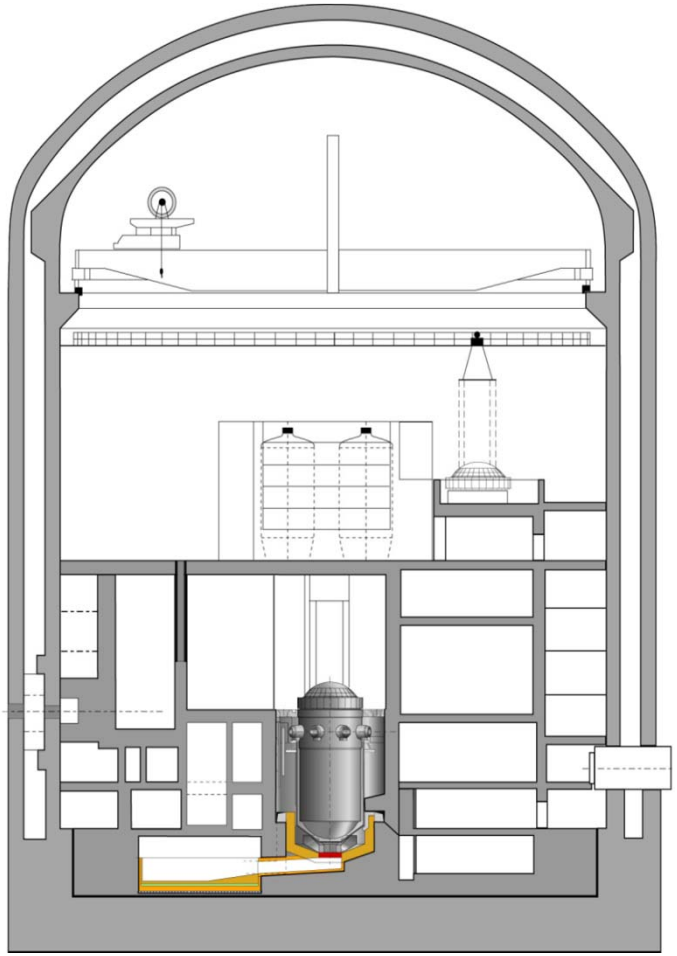
- Strike Price: 92.50 £/MWh (35a)
  (less expensive than gas, wind, coal...)
- (-3 £/MWh if Sizewell C follows)
- Inflation-indexed
- Incl. fuel, disposal, demolition
- Plant lifetime 60a +
- Costs of construction 16 G£ (in 2016)
- Calculated **payback time** (24 TWh/a): **7.2 a**
- Investors: EdF (66.5%) + CGN China General Nuclear (33.5%)
- 900 permanent jobs, + 5,600 during construction (57% UK)

Oct. 2014: Approval by European Commission (today: Brexit?)
Oct. 2015: Site licence
28 July 2016: EdF decision for investment (delayed by French worker councils, start of construction)
15 Sept. 2016: Re- evaluation by new government Theresa May („Brain Drain to China?“)
2023 - 25: In Operation (7% of UK´s power generation)

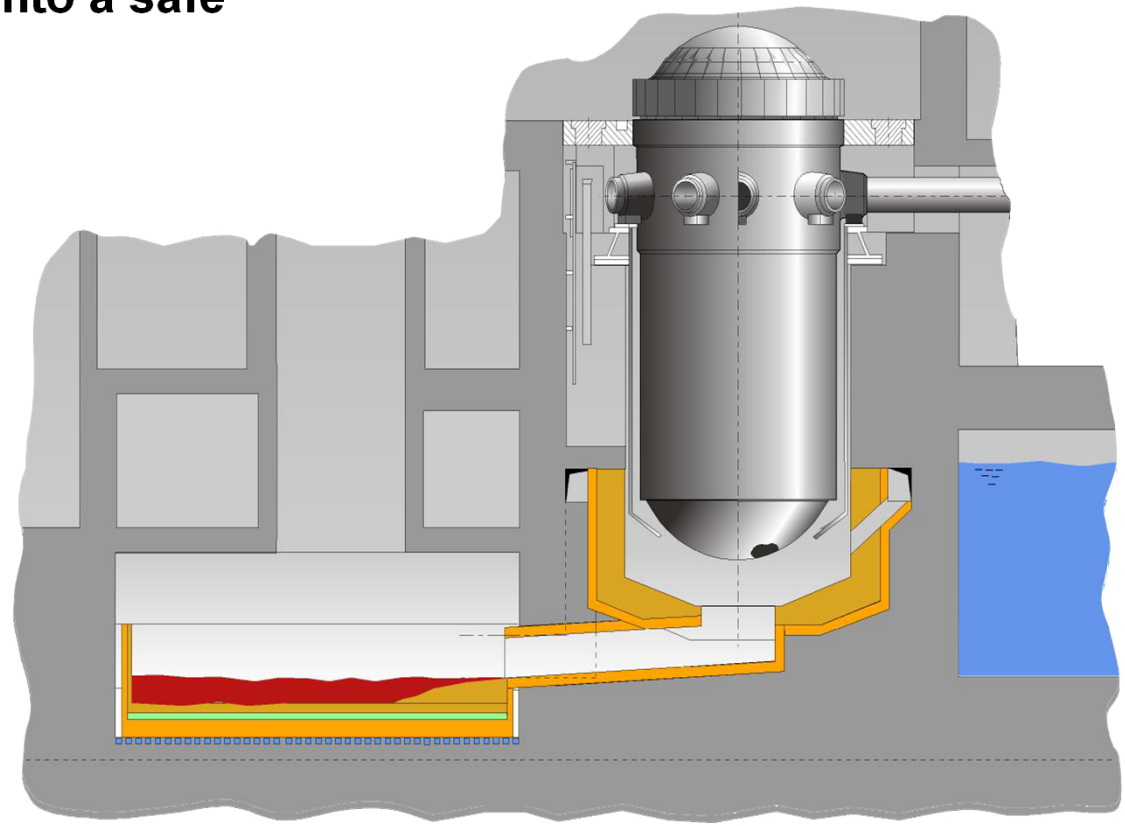
10 in Planning: 2 APR Moorside, 2 EPR Sizewell, 4 ABWR Wylfa+Oldbury, 2 Hualong Bradwell

Gen III+: EPR

- Evolutionary development of a German convoy and the French N4 construction line
- Design philosophy:
  - Further improvement of failure avoidance
  - Incident rates for meltdowns $<1 \cdot 10^{-7}/a$
  - Designed for severe, extremely improbable incidents. Limitation of impacts on the plant itself
  - Economically competitive



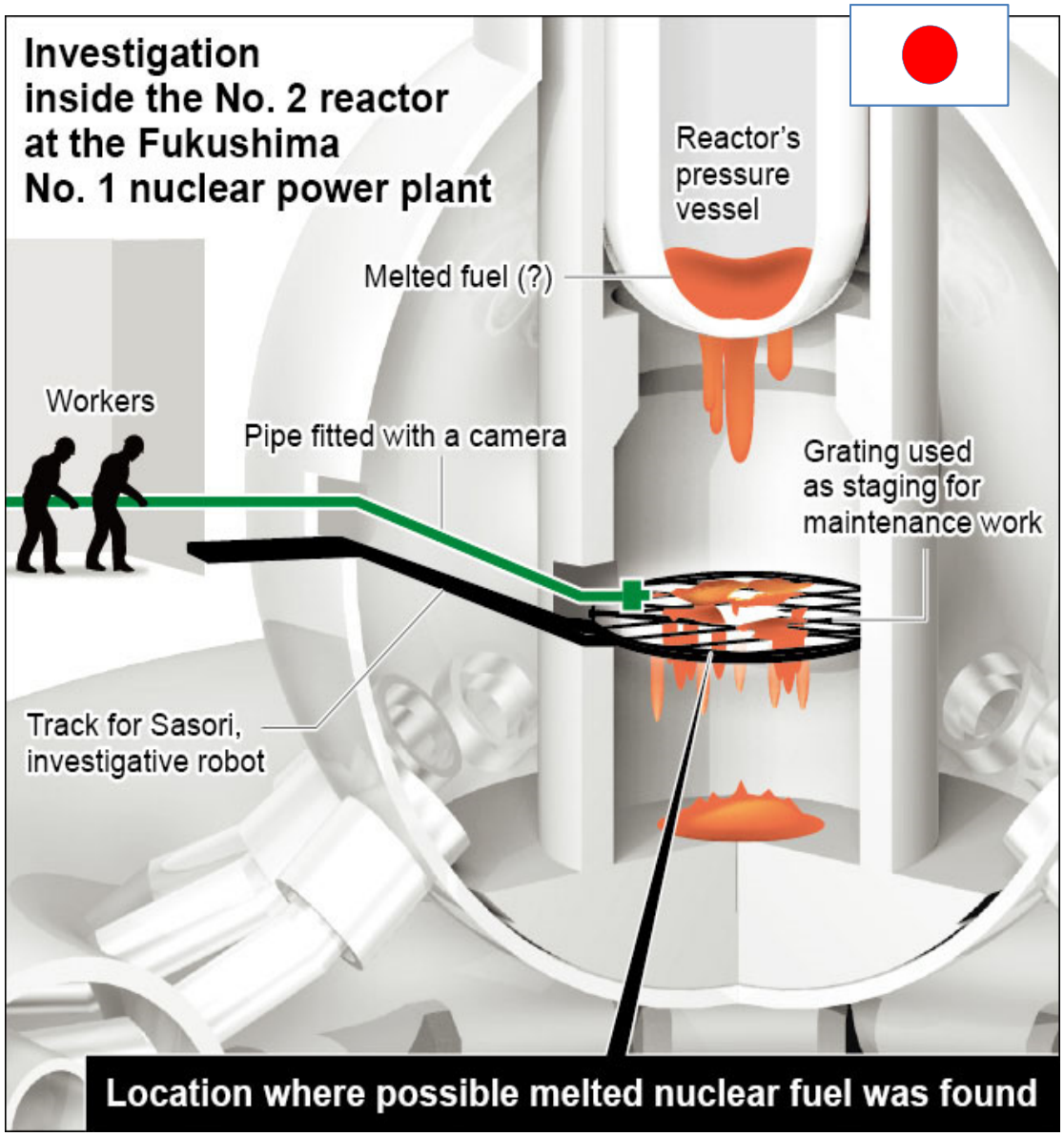
- Core catcher concept
- Transfer of corium into a safe condition
- Multilayer spreading area
- Long-term cooling from below and
- flooding from above from the IRWST.



Unit 2: Control Rod Drive Mechanism Room (below the reactor) in 2017

Finely fragmented corium (failure of the reactor pressure vessel under overpressure?)

Crashed floor grating

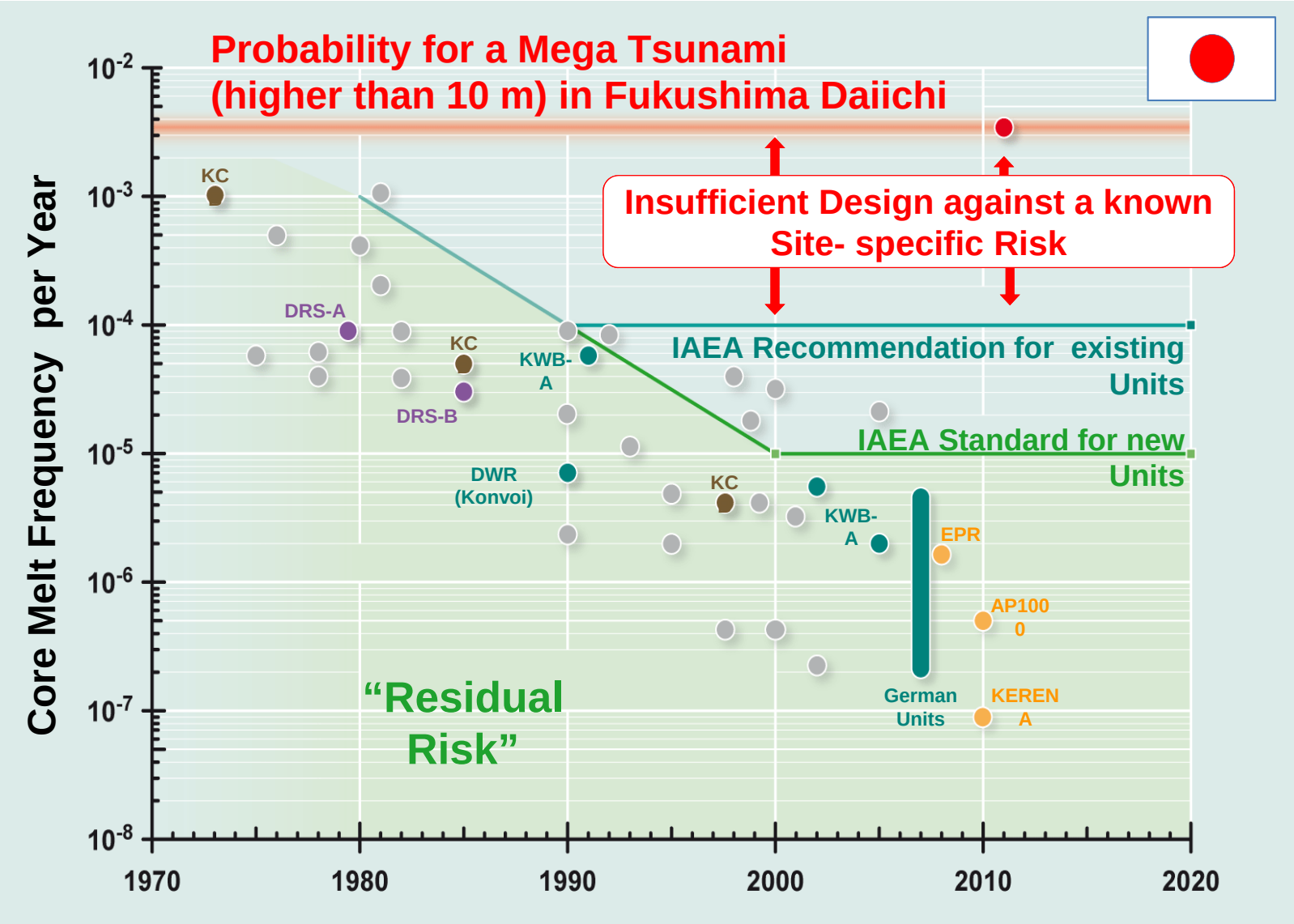


Source: Asahi Shimbun

Unit 2: Control Rod Drive Mechanism Room (floor) in 2018

Undamaged fuel assembly head

Results of Probabilistic Safety Analyses



IAEA: International Atomic Energy Agency Sources: IAEA, VGB

Gen III+: Light Water- (PWR) Concepts: AP-600/ AP-1000

- Westinghouse: Manufacturer of about ¾ of all PWRs worldwide.
- **Evolutionary**
- **Consequent simplification**
- **Expanded passive systems**
  - (e.g. no „nuclear“ diesel necessary)
- **1999: AP-600 certified by US-NRC**
  - Operators: Capacity too low
- **2005: AP-1000 certified (UK: 2011)**
  - Licence for China, 4 units
- **2012: 4 units in USA**
- **2016: USA: Delays**
- **2017: Insolvency of Westinghouse, abandonment of VC Summer 2-3**
- **2018: Commissioning of Sanmen-1**
- **2023: Commissioning of Vogtle-3**

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USA 2001: Generation IV International Forum (GIF)

Generation III („Evolutionary“):

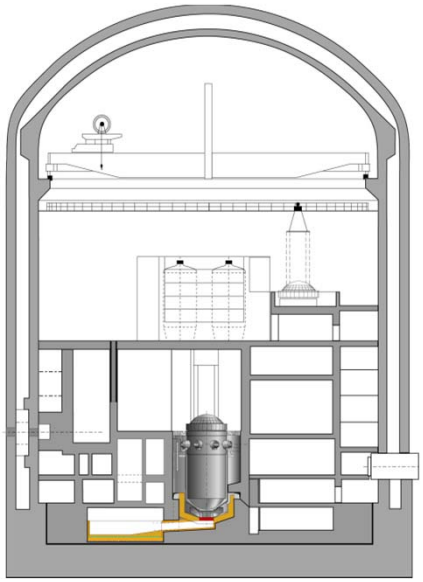
PWR – Pressurized Water Reactor

BWR – Boiling Water Reactor

CANDU – Heavy Water Reactor

Generation IV (Revolutionary“):

VHTR – Very-High-Temperature Reactor
GFR – Gas-Cooled Fast Reactor
SFR – Sodium-Cooled Fast Reactor
LFR – Lead-Cooled Fast Reactor
SCWR – Supercritical Water-Cooled Reactor
MSR – Molten Salt Reactor



Partly also for H_2 and process heat generation

VHTR	◆	◆	◆	◆	◆	◆	◆	◆	◆
GFR		◆	◆	◆	◆	◆	◆	◆	◆
SFR			◆	◆	◆			◆	◆
LFR		◆		◆	◆				◆
SCWR	◆	◆		◆	◆				◆
MSR		◆	◆						◆

http://gen-iv.ne.doe.gov

◆ Co-Chair im Steering Committee 🕮 Roland Schenkel,EC, 23.11.2005, Berlin

Targets of the „Generation IV International Forum“ after 2030

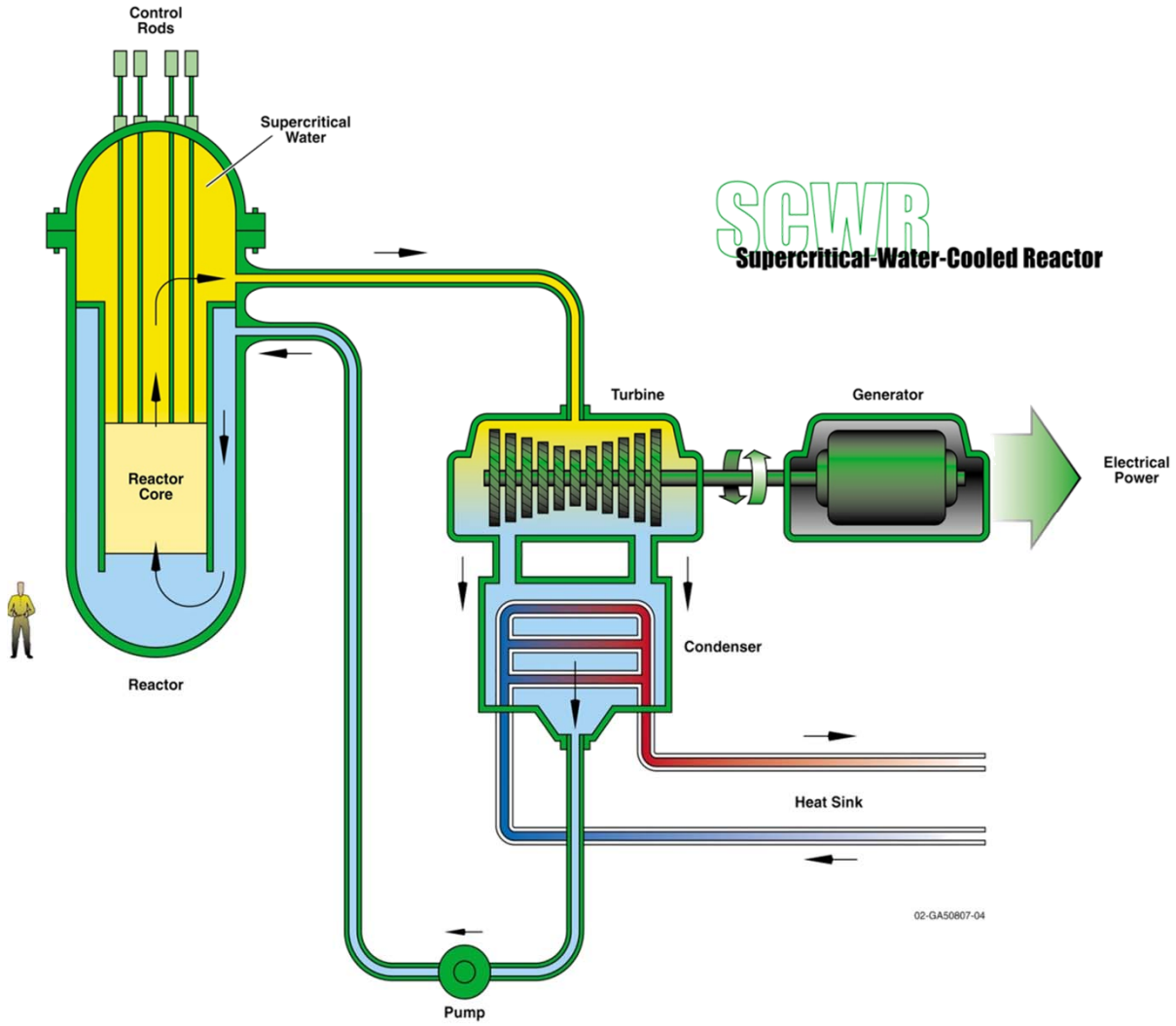
Further development (after GEN III):

- Profitability (cost-effectivness/efficency)
- Safety and reliability
- Minimisation of residues (partitioning + transmutation)
- Enlargement (expansion) of the fuel basis (U, Pu recycling, Th)
- Safeguards (stability of proliferation)

Further applications:

- Production of electrolytic hydrogen
- Seawater desalination
- Process heat

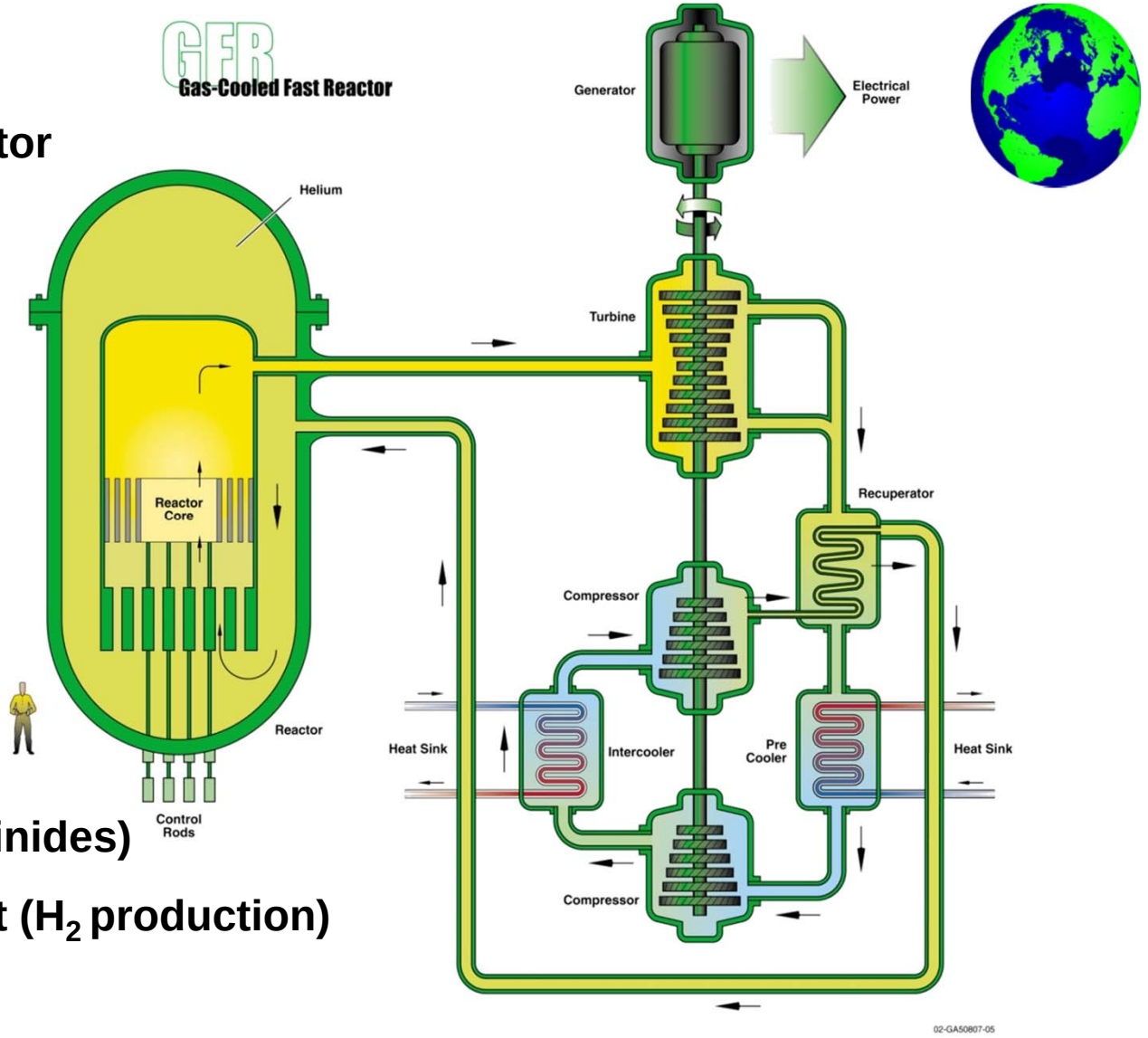
Gen IV (1): Supercritical- Water- Cooled Reactor = HPLWR



Gen IV (2) : Gas- Cooled Fast Reactor

GFR
Gas-cooled fast reactor

- **600 MWth,**
- **efficiency of 48%**
- **ceramic fuel, U/ Pu (20%)**
- **Helium-cooled (Brayton Cycle)**
- **closed fuel cycle (combustion of actinides)**
- **850 °C process heat (H_2 production)**

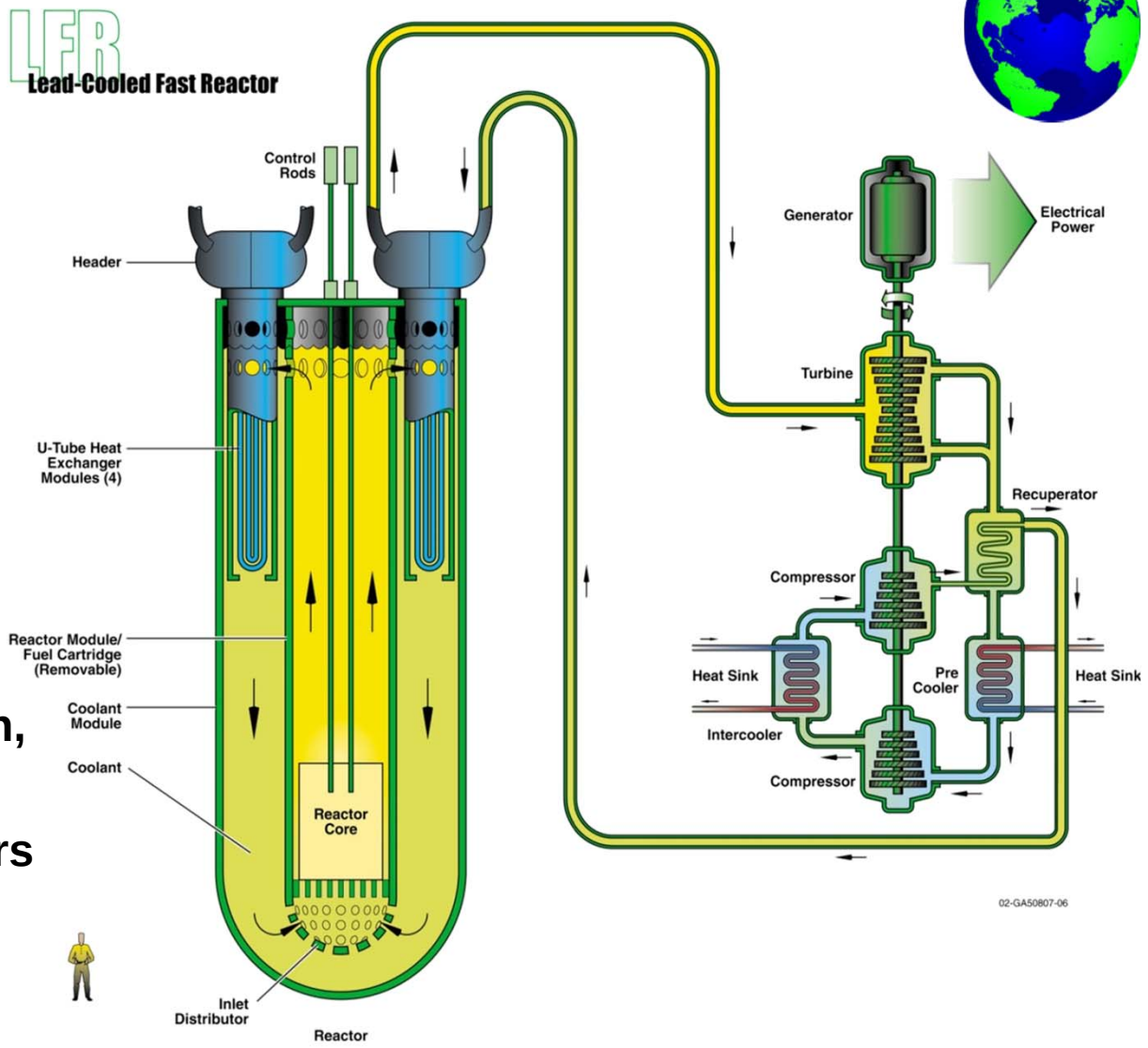


Gen IV (3): Lead- Cooled Fast Reactor

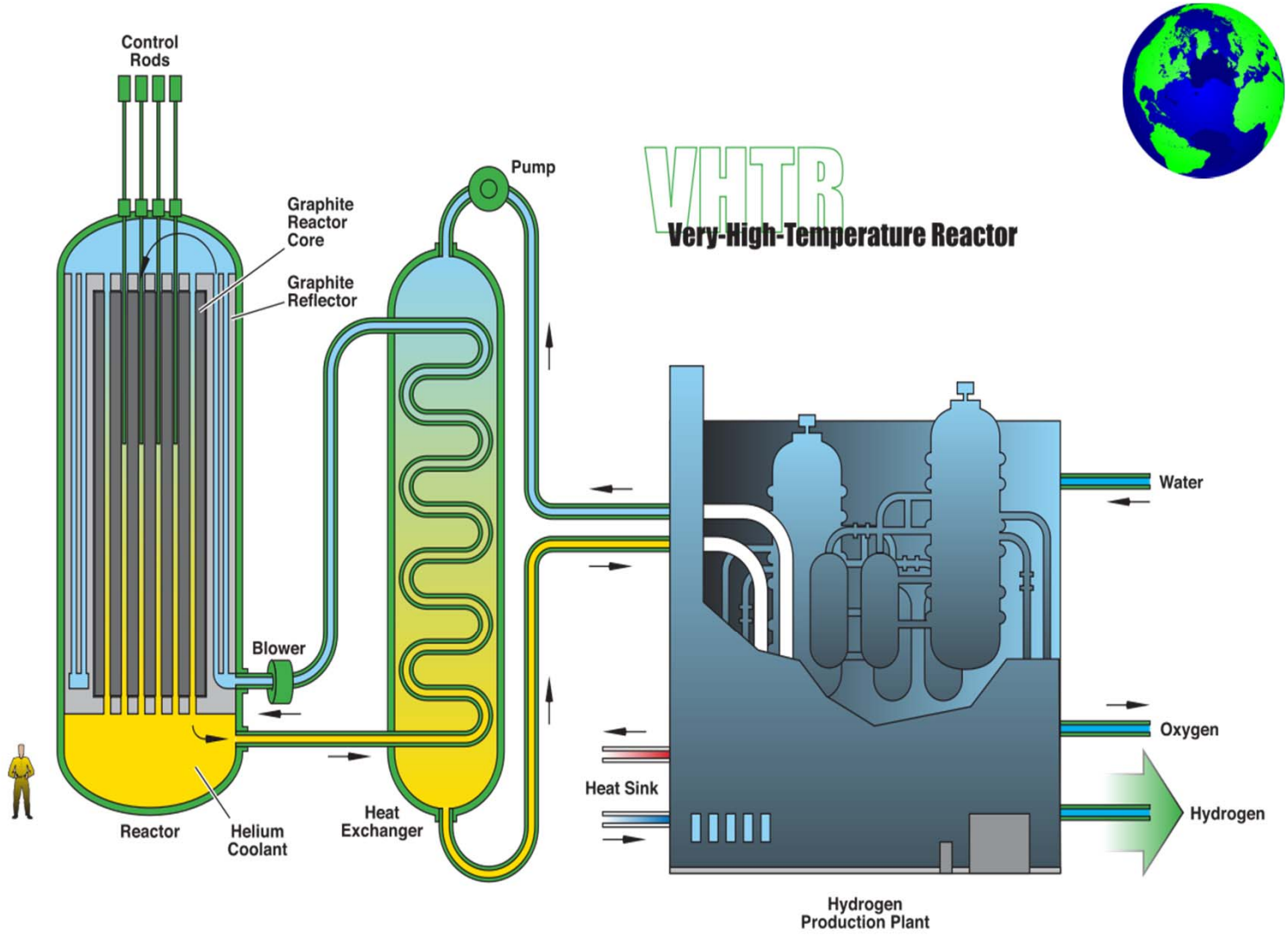
LFR

50 - 1200 MWe,

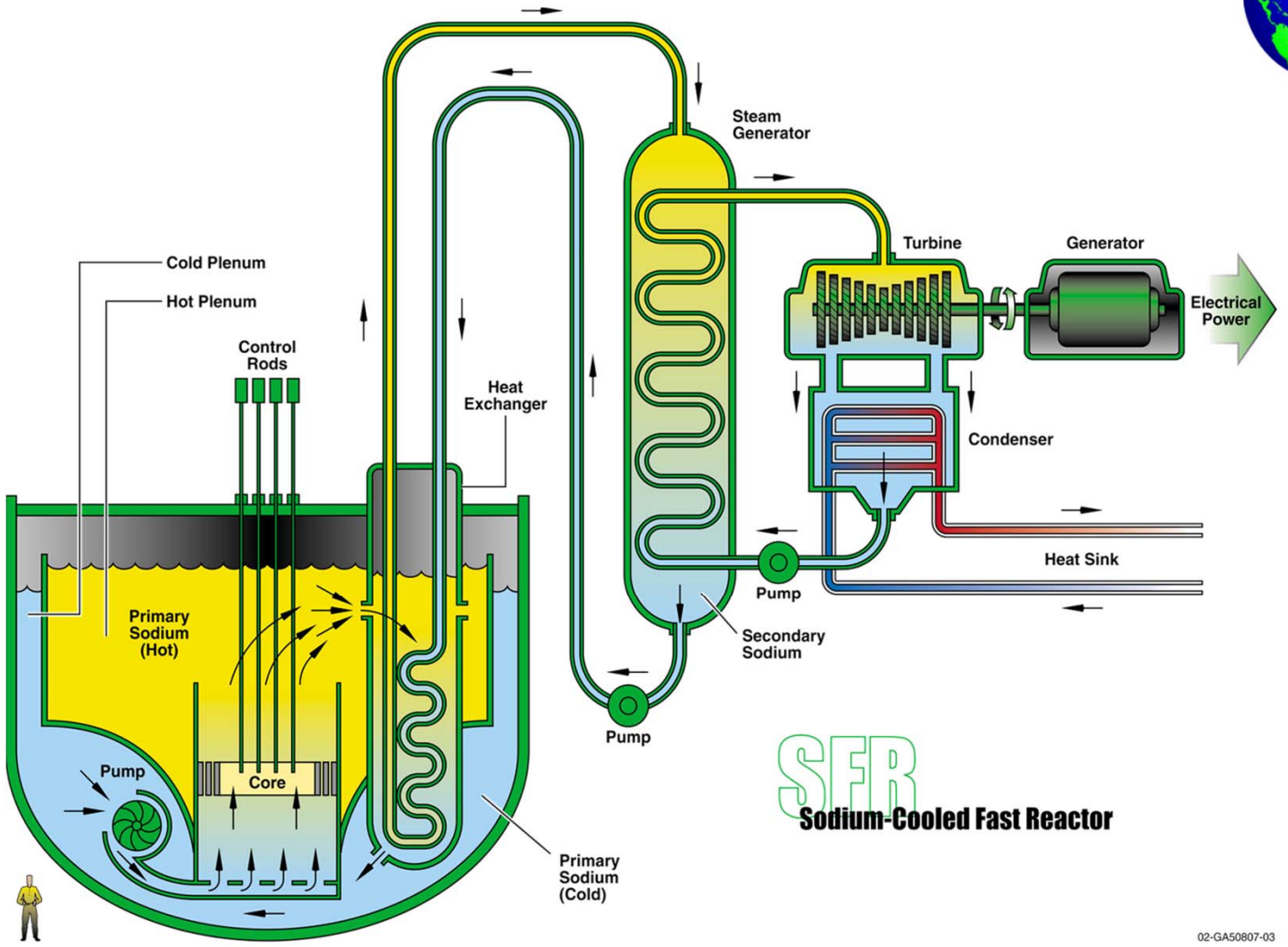
- **Unpressurised**
- **Natural circulation**
- **Metallic or nitrite fuel, U/ Pu**
- **Pb- or Pb/Bi- cooling for 550 °C**
- **Closed fuel cycle**
- **Seawater desalination, H_2 production**
- **Cycles of 15 – 20 years**



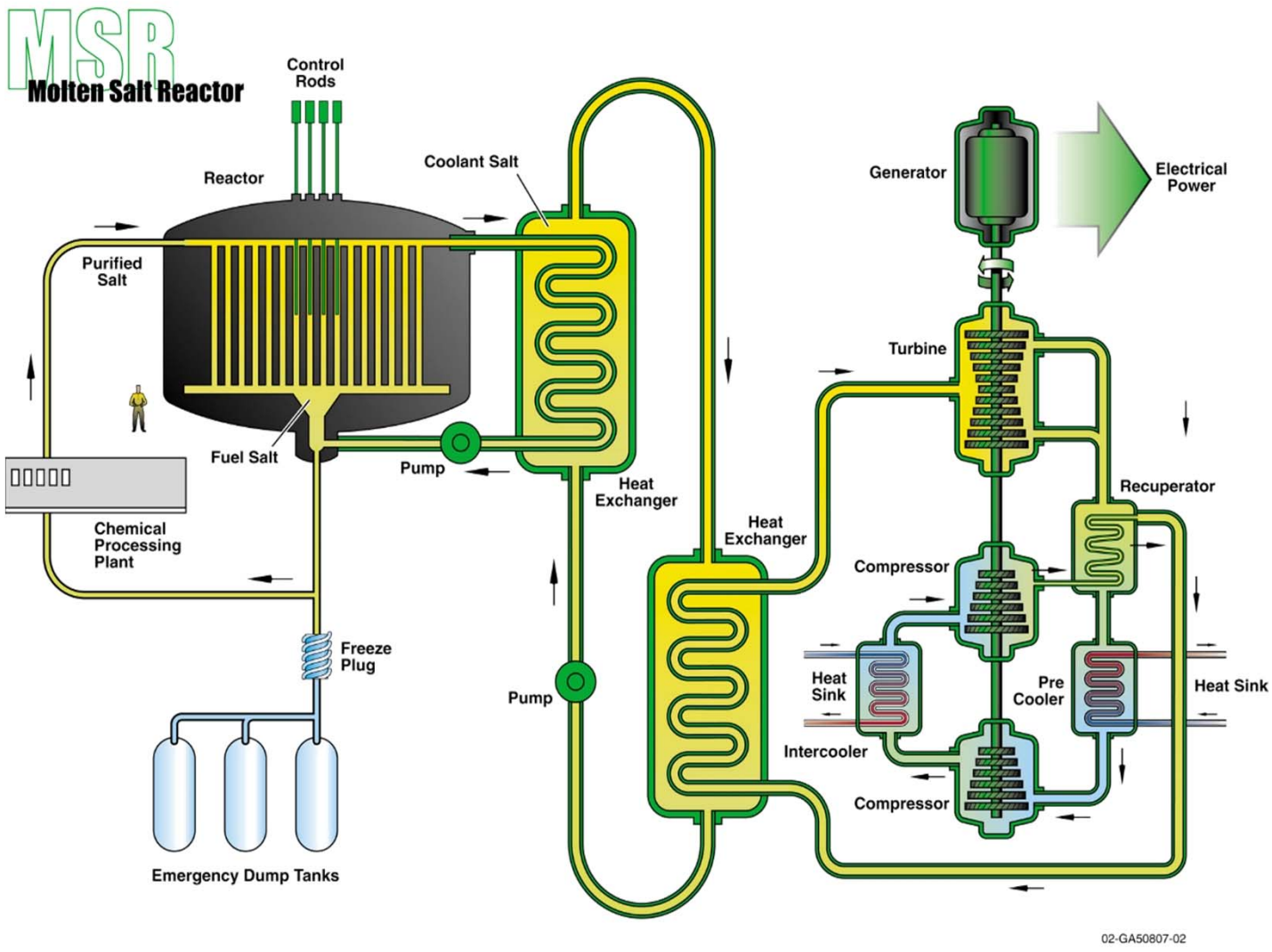
Gen IV (4): Very High- Temperature Reactor



Gen IV (5): Sodium- Cooled Fast Reactor



Gen IV (6): Molten Salt Reactor



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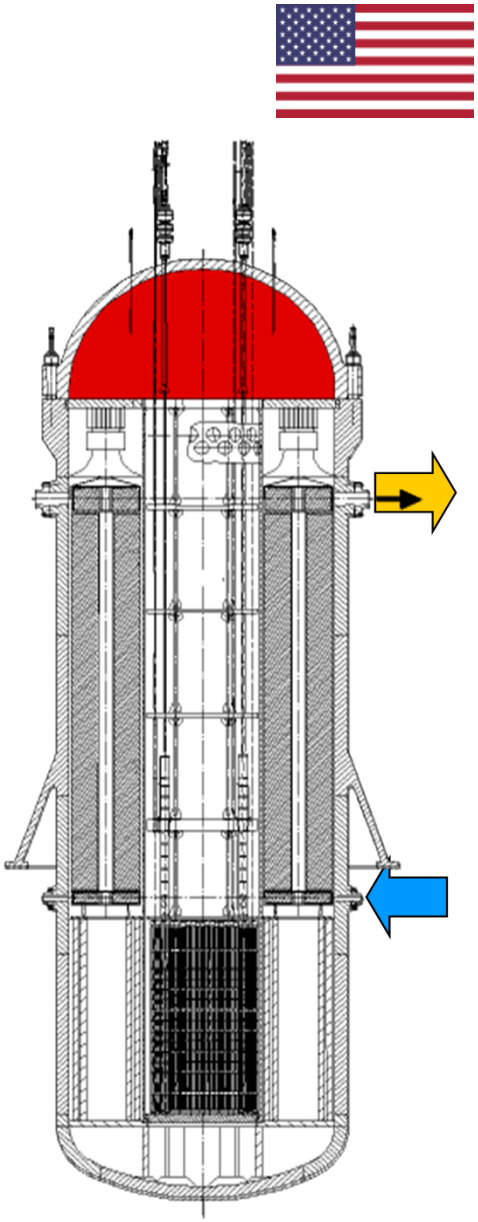
Gen III: Innovative Concepts – IRIS (Westinghouse)

International Reactor Innovative and Secure

- Development since 1999,
  Consortium under management of Westinghouse.
- Review within NERI- Generation IV
  (US-DOE).
- Modular system with 100-300 MW_{el}.
- PWR with integral pressure vessel:
  - core
  - control rods
  - coolant pumps (4)
  - steam generators (8 in pair design)
  - pressuriser



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- Modular system with 100-300 MW_{el}.
- PWR with integral pressure vessel:
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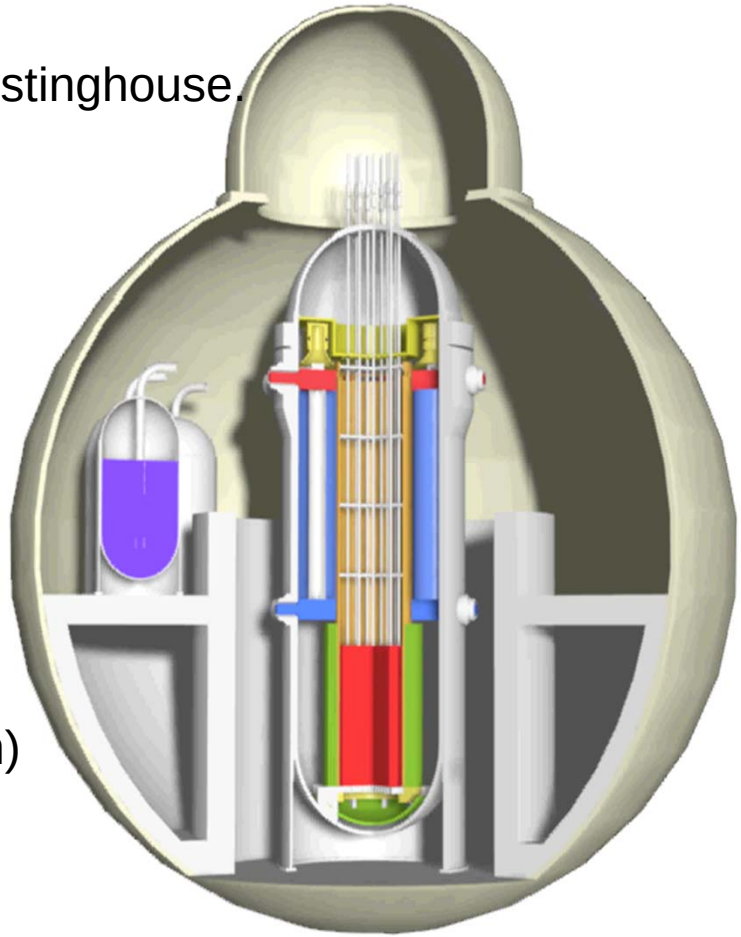
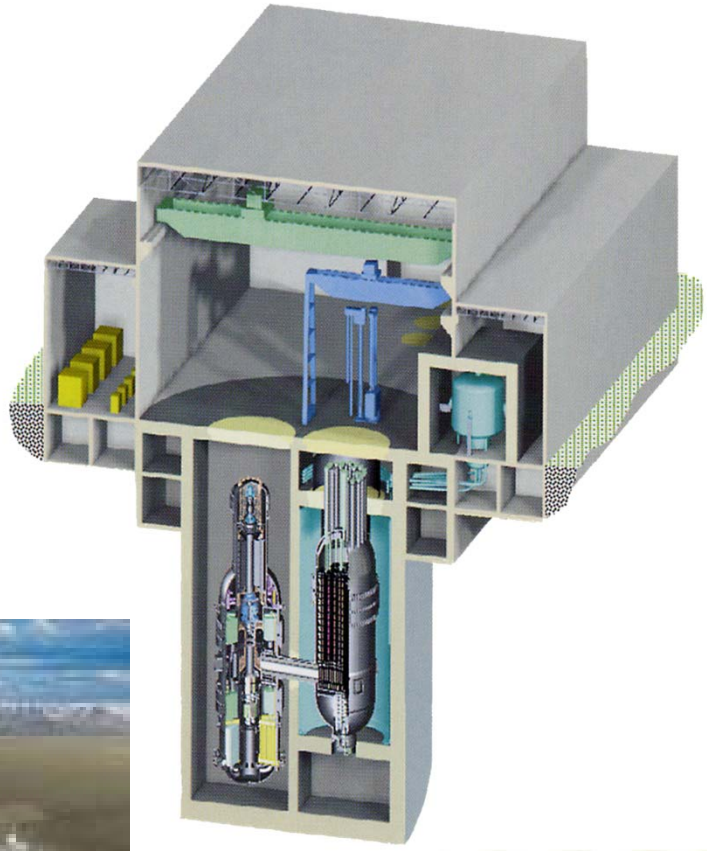
  - control rods
  - coolant pumps (4)
  - steam generator (8 in pair design)
  - pressuriser
- Full- pressure containment.



General Atomics Gas Turbine/ Modular Helium Reactor GT-MHR

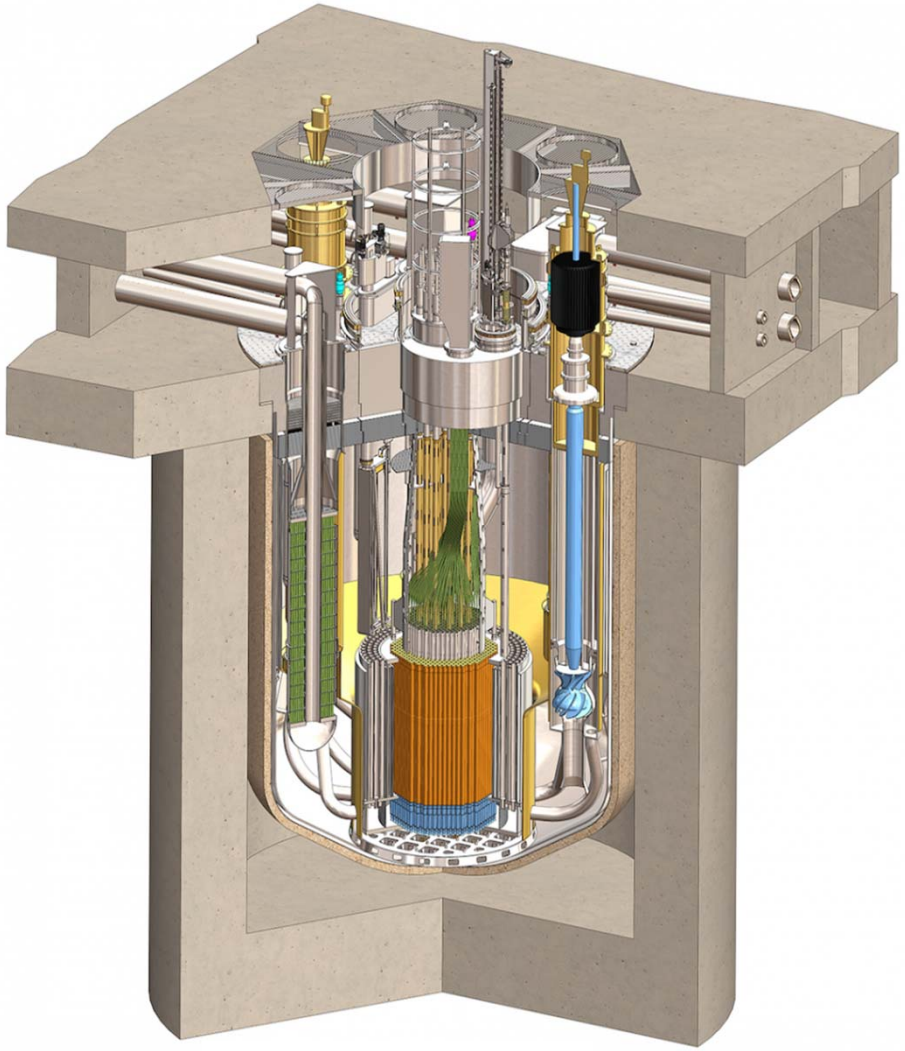
- **He- cooled, graphite- moderated high- temperature reactor**
- **Underground**
- **Development since 1985 by**
  - General Atomics,
  - Framatome,
  - Fuji Electric,
  - OKBM/ MINATOM (Russia)
- **Helium high- temperature turbine**
  - Brayton Cycle
- **Meltdown- resistant:**

  Residual heat removal by thermal radiation



Framatome, Frankreich

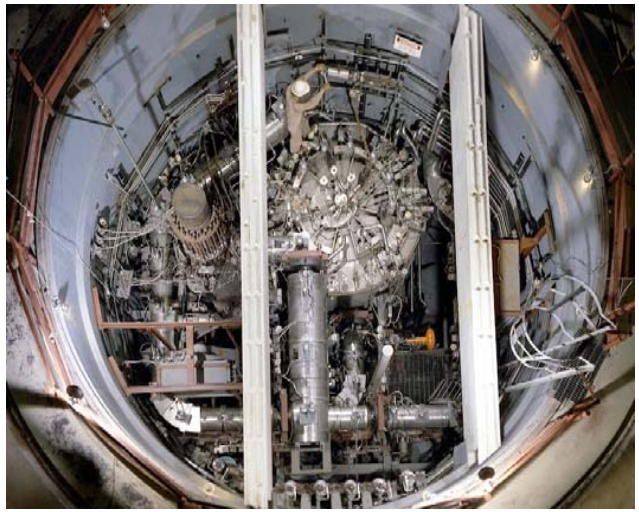
Terrapower Travelling Wave Reactor (Bill Gates)



- „Fast Breeder“
- Radially Migrating Breeding Zone
- Multiyear cycles
- Depleted U-238 –> Pu-239
- Metallic fuel
- No reprocessing
- Improved safeguards
- Open fuel rods?
- Efficient coolant purification
- Xiapu- 2 (Fujian, China)
- 600 MWe
- Operational 2023

Source: www.terrapower.com

Terrapower Molten Chloride Fast Reactor MCFR (Bill Gates)



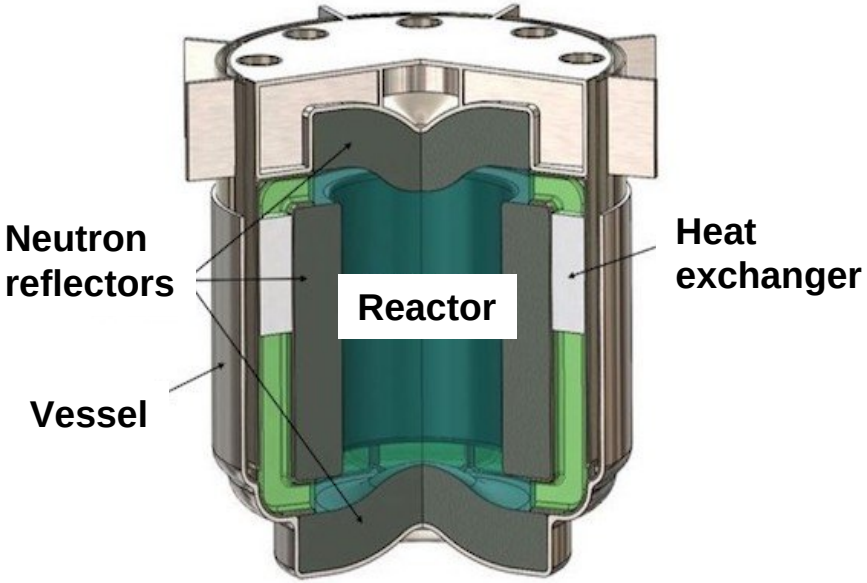
1966-73: Pilot project,
stopped due to unmanageable corrosion

Fuel Dissolved in Molten Salt

January 2016: 40 M$ funding (5a)
U.S. Department of Energy

Southern Company,
Oak Ridge National Laboratory,
Electric Power Research Institute
Vanderbilt University

Under design: Component test rigs



Source: www.terrapower.com

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SMR Project Flexblue (Sea Floor)

DCNS (Shipyard)/ Framatome/ CEA/ EdF
(Direction des Constructions Navales)

PWR 160 MWel, Gd- based absorber

Floating Nuclear Power Plant „Akademik Lomonossov“ KLT40S

1 Reactor
2 Steam generator
3 Reactor coolant pumps
4 Control rod drives
5 Emergency core cooling accumulator
6 Pressuriser (1st vessel)
7 Pressuriser (2nd vessel)
8 Steam lines
9 Isolation valves
10 Heat exchanger residual heat removal system

2x35 MWel, commissioning in 2019

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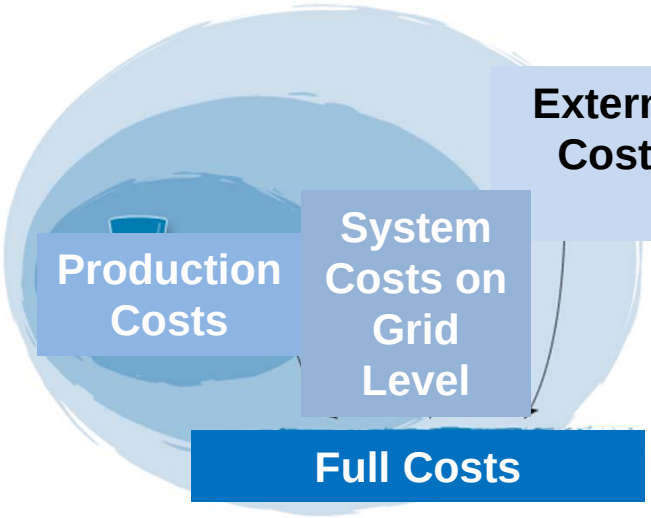
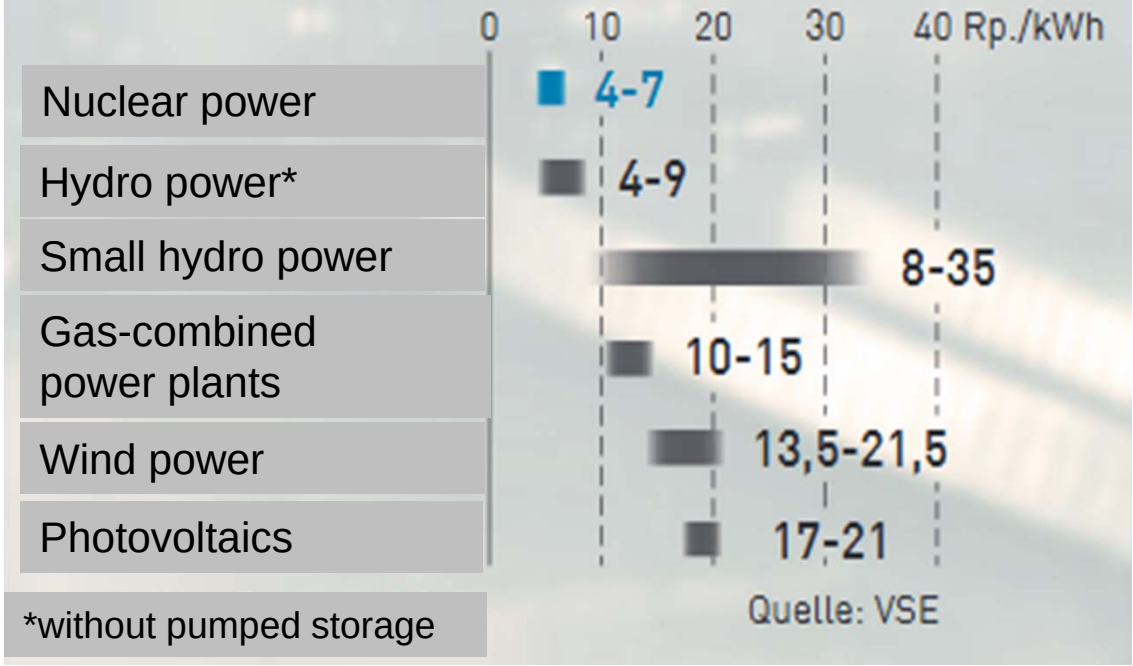
Costs of Generation (Example Switzerland 2017)

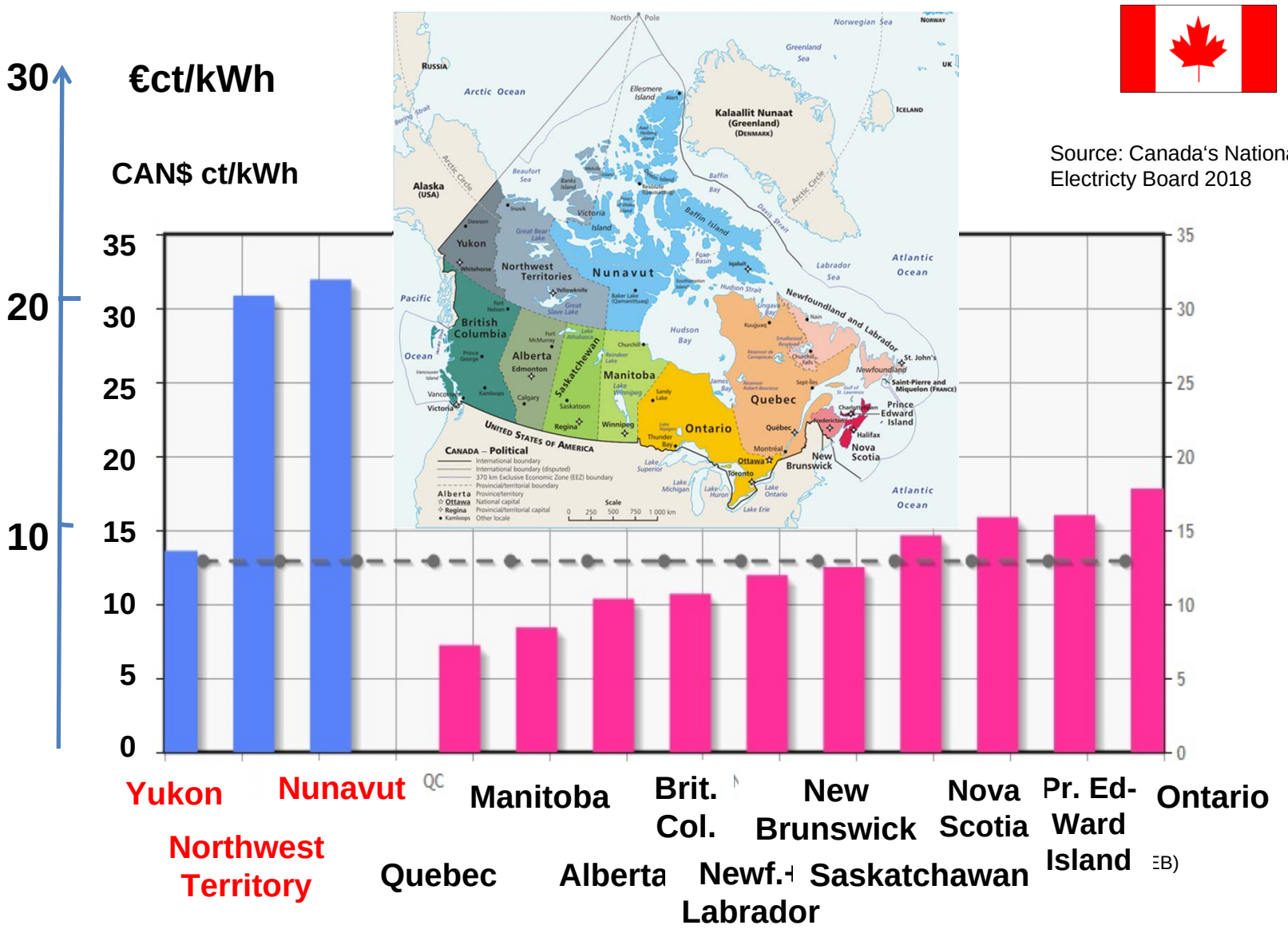


1 € = 1.15 SFr

Comparison of Average Production Costs



Electricity Prices in Canada in 2017



Source: Canada's National Electricty Board 2018

Licence Extensions in USA in Feb. 2018

Lifetime extension to 60 years:

- Authorised for approx. 90 reactors,
- remaining plants will follow

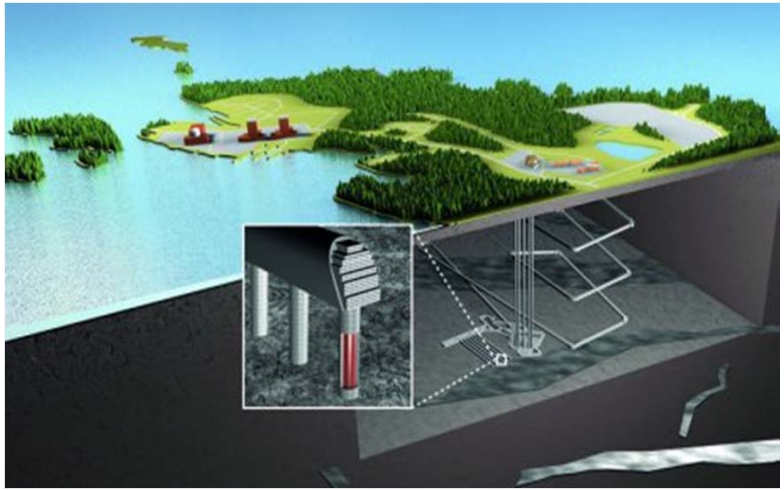
Lifetime extension to 80 years:

- Decision for submission for the first four reactors (Calvert Cliffs + …)

Finland: Final Repository ONKALO

First final repository worldwide for heat generating waste from NPPs *

- **2000: Government decision for a final repository for spent nuclear fuel**
- **2001: Decision in principle by Finnish parliament**
- **2012: Application of construction licence by Posiva (TVO/FORTUM) for Olkiluoto site**
- **2015: STUK** Confirmation that all safety criteria are met**
- **12 November 2015: Construcion licence for 6,500 t of spent fuel***
- **Next steps: Construction until 2020**
- **Before commissioning: Application for operation licence**

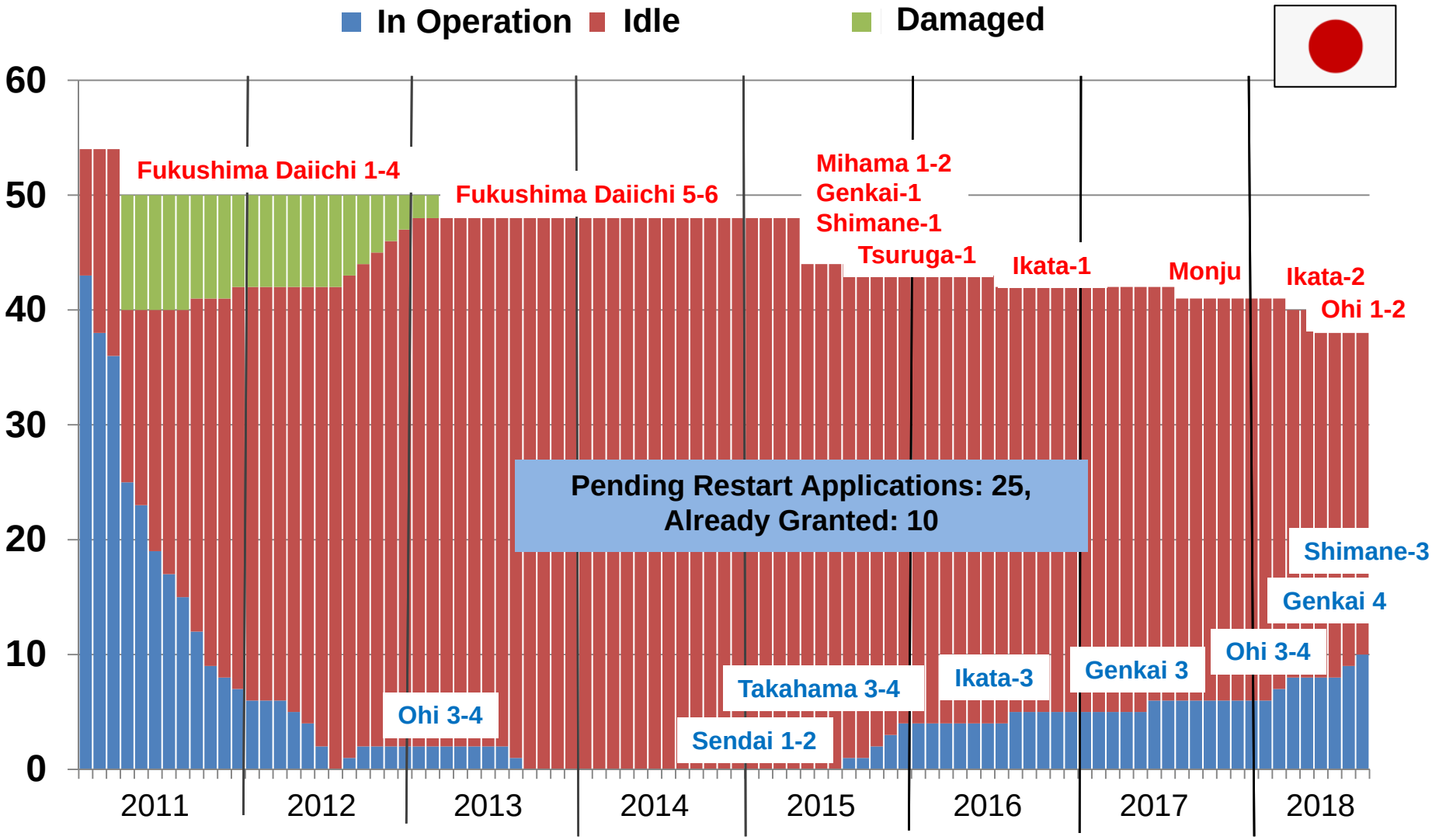


*: Enough for more than 50 a operation of 5 NPPs

** STUK: Finnish Radiation and Nuclear Safety Authority

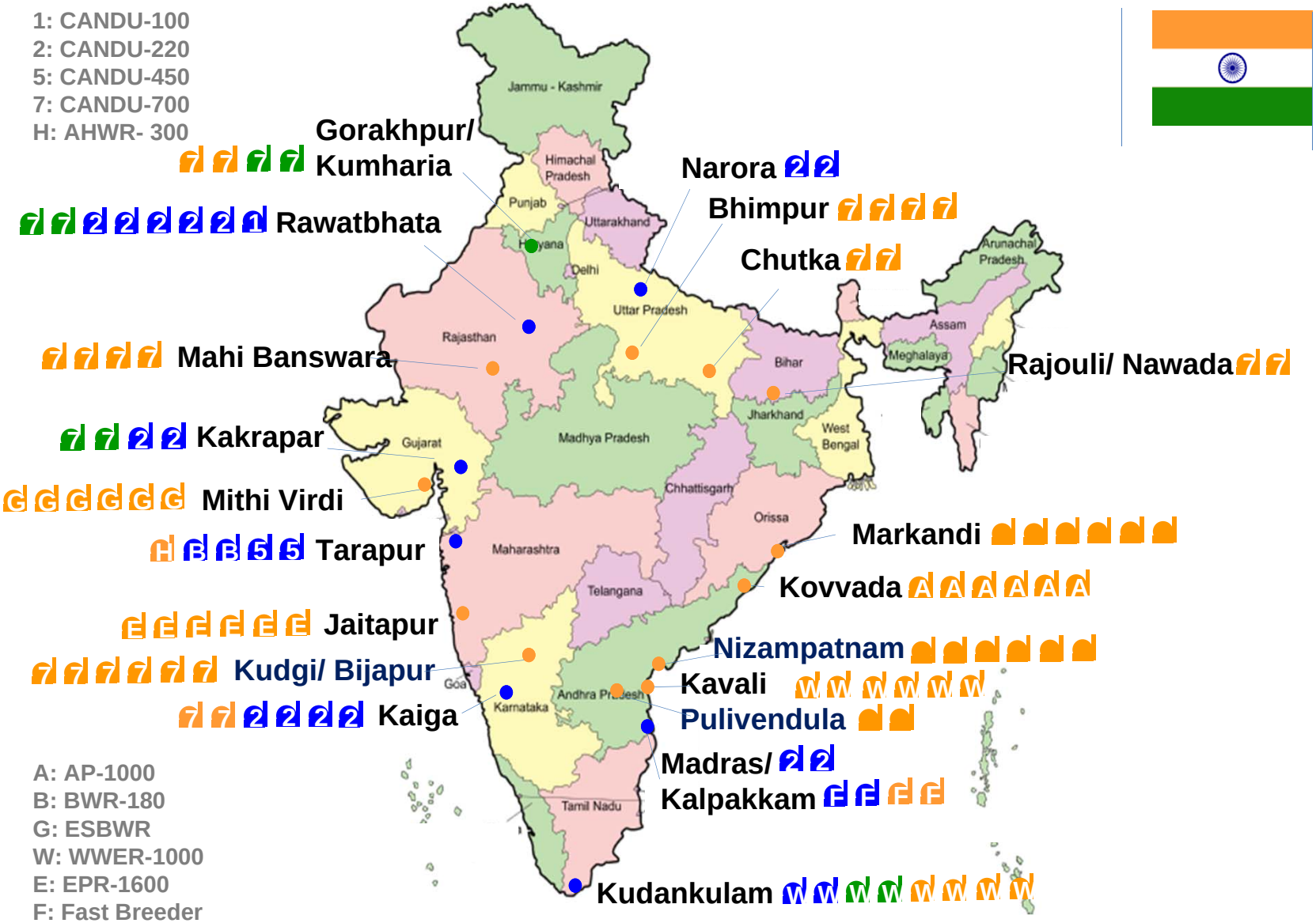
Sources: STUK, 02/2015, WNA 11/2015

Number of Nuclear Power Units in Japan



India: 24 In Operation, 8 Under Construction, 63 in Planning (<2035)

1: CANDU-100
2: CANDU-220
5: CANDU-450
7: CANDU-700
H: AHWR- 300

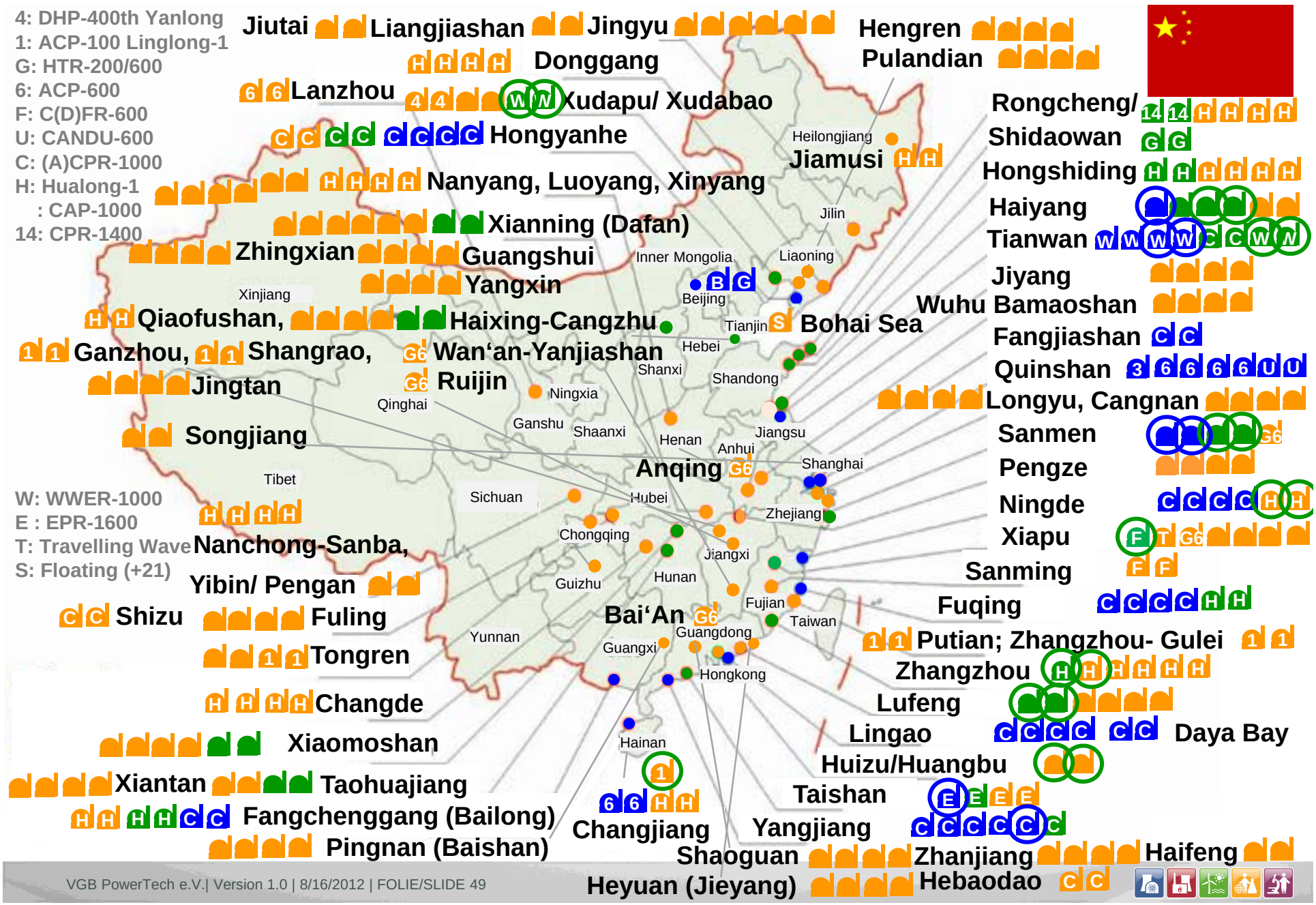


A: AP-1000
B: BWR-180
G: ESBWR
W: WWER-1000
E: EPR-1600
F: Fast Breeder

China: 46 Units (◯ 2018), 41 under Construction, 189 Planned (<2035)

4: DHP-400th Yanlong
1: ACP-100 Linglong-1
G: HTR-200/600
6: ACP-600
F: C(D)FR-600
U: CANDU-600
C: (A)CPR-1000
H: Hualong-1
: CAP-1000
14: CPR-1400

W: WWER-1000
E : EPR-1600
T: Travelling Wave
S: Floating (+21)



Résumé

Concluding Remarks:

1. **Highly developed technology, exportable**
2. **Operation-proven with more than 17,000 (reactor) years**
3. **Acceptance: 90 % of the Europeans live in countries with nuclear energy**
4. **Fukushima was not a residual risk incident, no radiation damages**
5. **Nuclear power plants do not age as other power plants,**
   early shutdown means an enormous destruction of financial assets
6. **Highly profitable if technical lifetime can be reached**
7. **Quasi-domestic**
8. **Carbon neutral**

Thank you very much for your attention!

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