PSI Center for Nuclear Engineering and Sciences

Neue Entwicklungen in der Kernenergie

Veranstaltung der AVES Schaffhausen, 23. Oktober 2024, Hotel Promenade, Schaffhausen

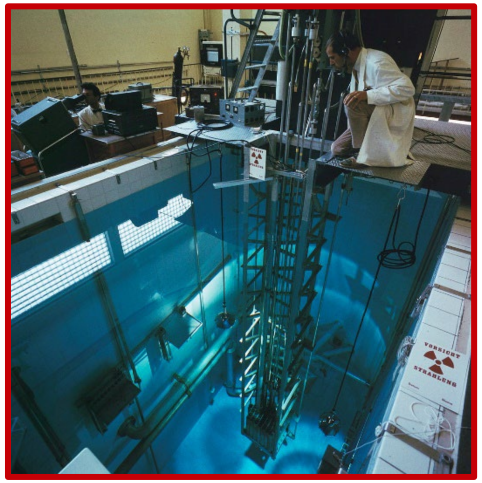
Andreas Pautz, Leiter des Zentrums für Nukleare Technologien und Wissenschaften, Paul Scherrer Institut (PSI)

Inhalt

- Ein paar Worte zur Kernenergie und Kernforschung in der Schweiz
- Entwicklungen in der Kernenergie: Langzeitbetrieb und Generation-III
- Kleine Modulare Reaktoren (SMR) und Mikroreaktoren
- Generation-IV: Hochtemperatur- und Molten Salt-Reaktoren

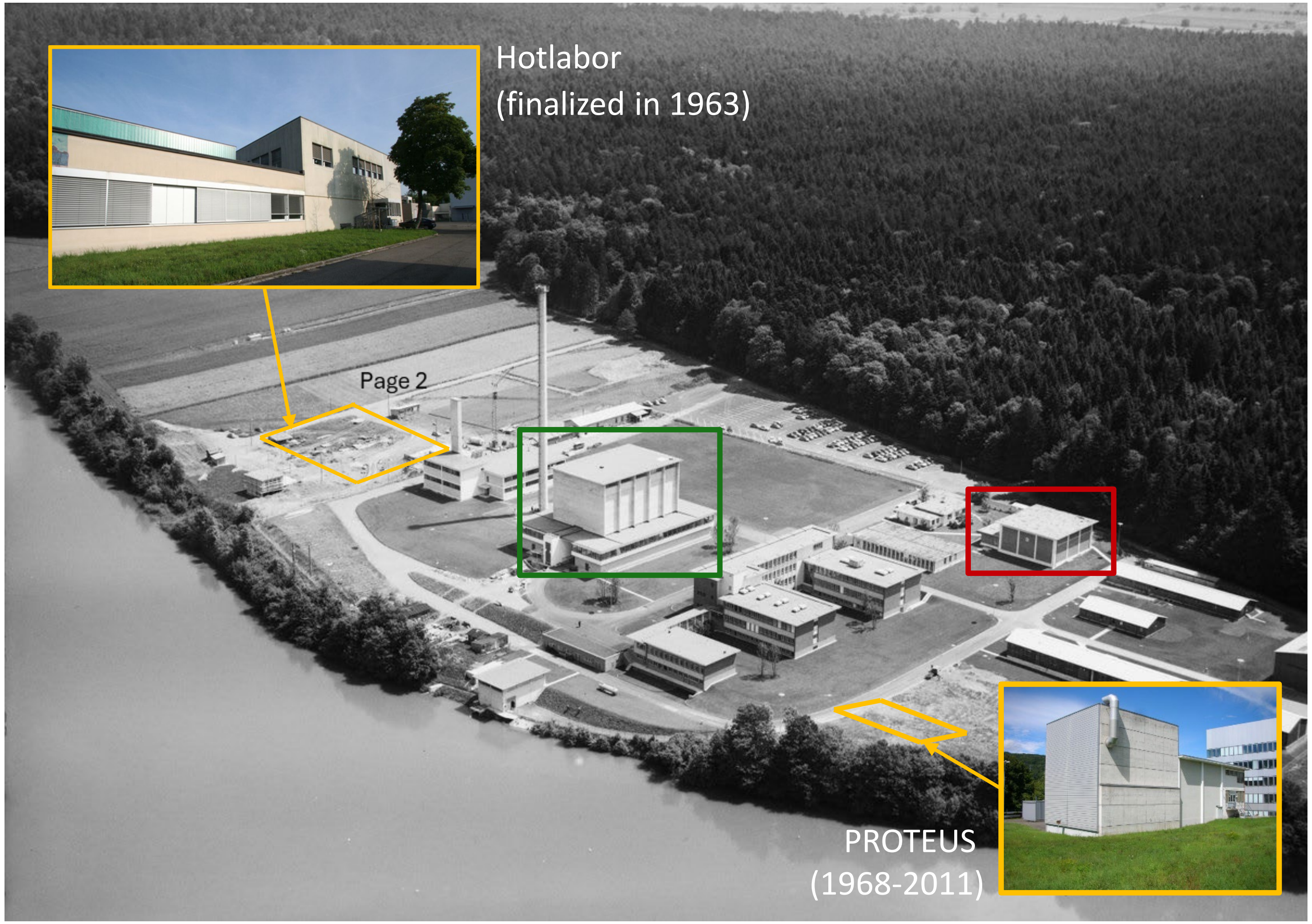
Ursprung des Paul Scherrer Instituts: EIR in 1960

PSI since 1988: merge of EIR (Swiss Federal Institute for Reactor Research) & SIN (Swiss institute for nuclear research)



SAPHIR (1957-1993), 10 MW_{th}

DIORIT (1960-1977), 20/30 MW_{th}



Aerial View of the Federal Institute for Reactor Research (today PSI Ost), around 1960

Das Paul Scherrer Institut

Die grossen Kernanlagen der Schweiz

Die grossen Kernanlagen der Schweiz

Die grossen Kernanlagen der Schweiz

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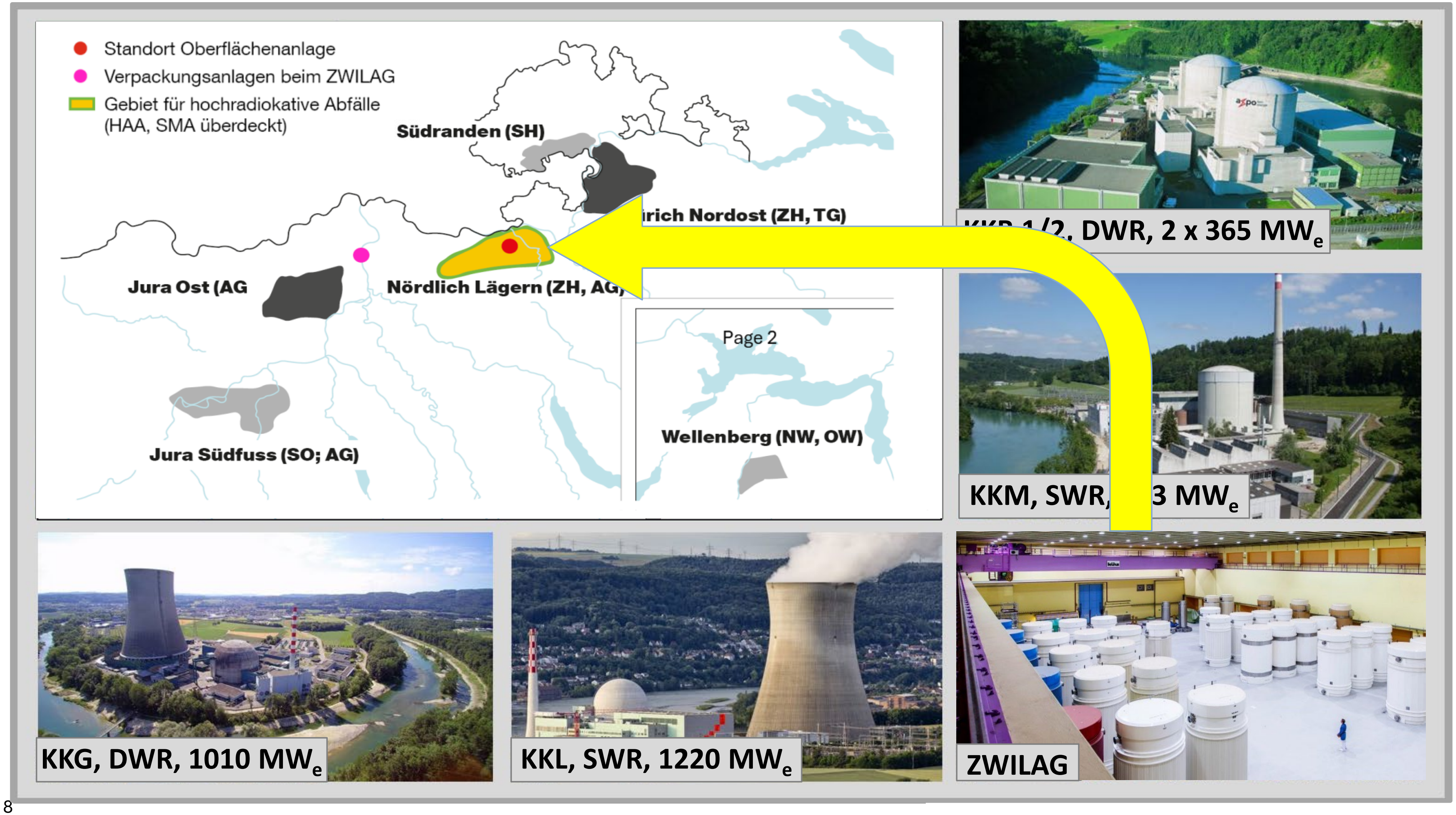
Entsorgung radioaktiver Abfälle in der Schweiz



Kernmissionen der Nuklearforschung am PSI

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Nuklearer Kompetenzerhalt

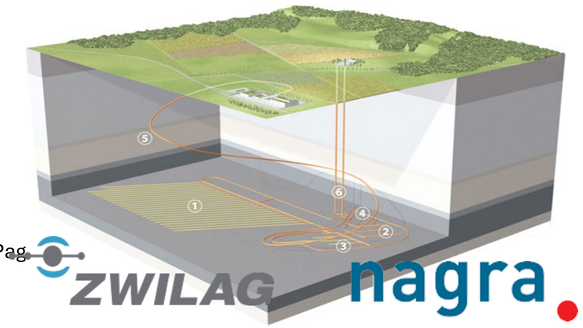
Technisch-wissenschaftliche Begleitung des **sicheren Langzeitbetriebs** der Schweizer Kernkraftwerke

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Nuklearsicherheitsinspektorat ENSI
Inspection fédérale de la sécurité nucléaire IFSN
Ispettorato federale della sicurezza nucleare IFSN
Swiss Federal Nuclear Safety Inspectorate ENSI

Untersuchungen nuklearer Brennstoffe im Auftrag der Schweizer KKW zur Optimierung von deren Sicherheit und Performance (Hotlabor)

Begleitung des gesamten **Entsorgungspfades radioaktiver Abfälle** und wissenschaftliche Absicherung der NAGRA-Analysen bei der Umsetzung des **Sachplans Geologische Tiefenlager**



Ausbildung der nächsten Generation von Radiochemikern, Nuklearwissenschaftlern und –ingenieuren

EPFL

PAUL SCHERRER INSTITUT
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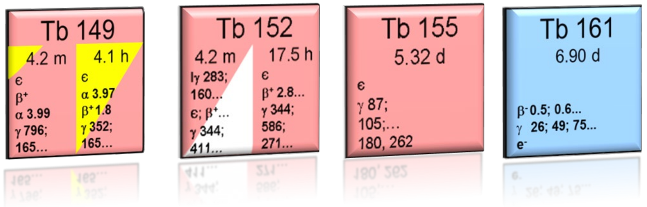
ETH Zürich

Kernmissionen der Nuklearforschung am PSI

Industrielle Forschungsplattform für Reaktortechnologien der III. und IV. Generation: Erhaltung, Einsatz und Ausbau der hervorragenden Infrastrukturen des PSI für neue internationale Nuklearentwicklungen

Technologiemonitoring: Objektive und umfassende Bewertung der **Sicherheit und Nachhaltigkeit fortgeschrittener Reaktorkonzepte** (gemäß Artikel 74a des Kernenergiegesetzes).

Unterstützung des PSI-Forschungsinfrastruktur-Projekts IMPACT-TATTOOS (2025-2028) für die **Produktion medizinischer Radionuklide**



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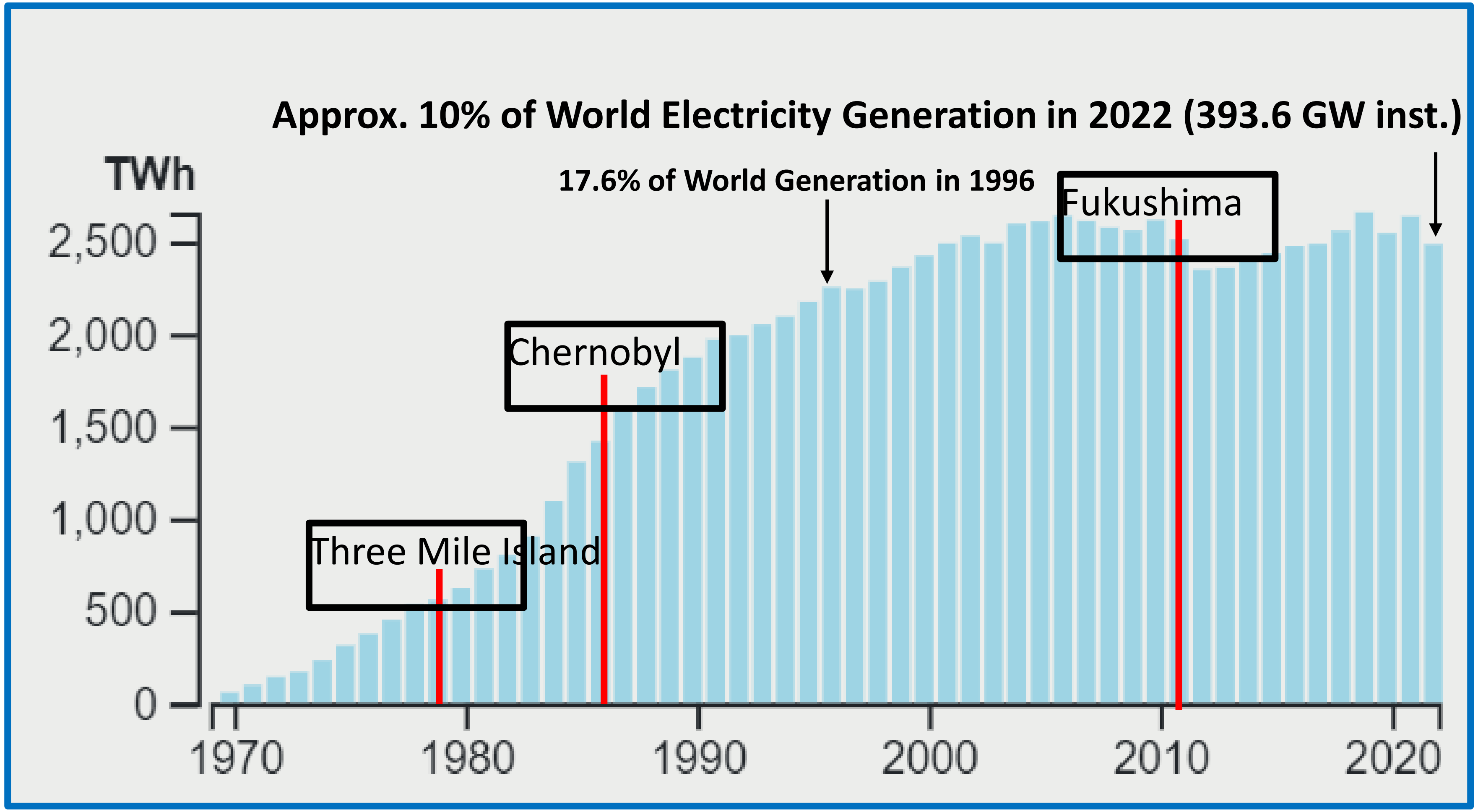
Entwicklungen in der Kernenergie: Langzeitbetrieb und Generation-III

Globale Entwicklung der nuklearen Erzeugungskapazitäten



There are currently 415 plants in operation worldwide (+21 waiting for restart in Japan), 57 plants under construction in 17 countries, and 85 in advanced project planning in 15 countries. 187 have been decommissioned.

Quelle: https://www.nuklearforum.ch/de/nuclearplanetfr

Weltweite Primärenergieerzeugung nach Quelle

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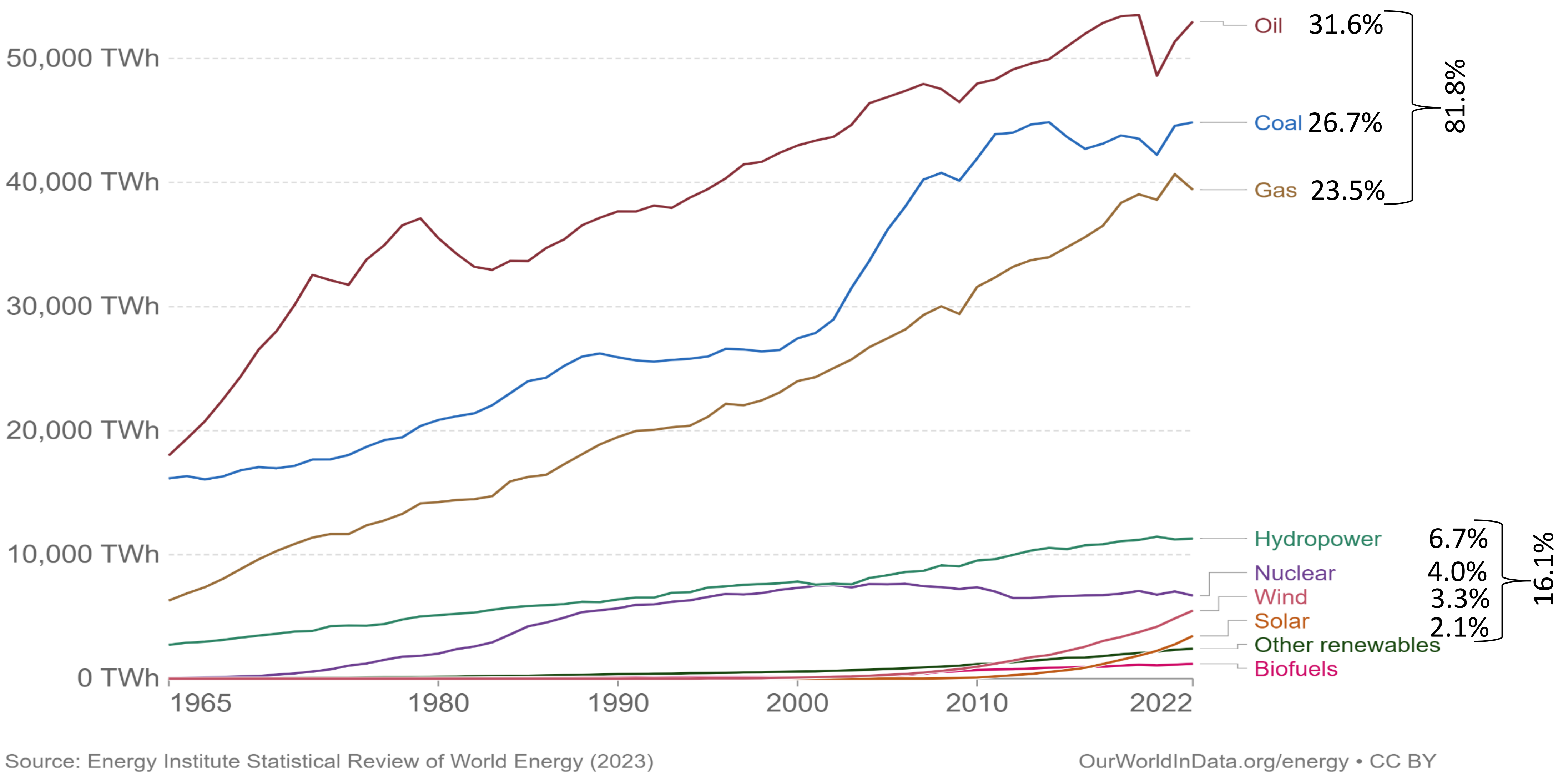

Developments in recent years

2022: Nuclear energy in EU Taxonomy

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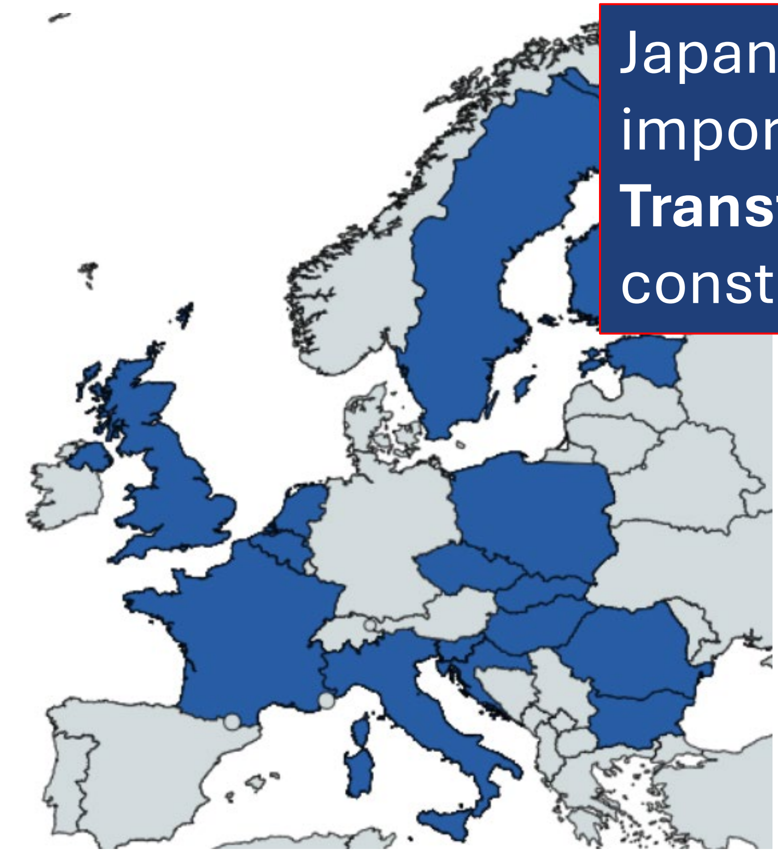
Japan - December 2022: Nuclear decleared as important part of government plan for „**Green Transformation**“. Restart of shutdown NPPs and construction of new NPPs planned



July 2023 – EU NUCLEAR ALLIANCE
Goal:
- Development of integrated nuclear industry.
- 150 GW nuclear in EU electricity mix by 2050

25 Countries: **USA**, Armenia, Bulgaria, **Canada**, Croatia, Czech Republic, Finland, **France**, Ghana, Hungary, Jamaica, **Japan**, South Korea, Moldavia, Mongolia, Marocco, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden, Ukraine, United Arab Emirates, **United Kingdom**.

INDUSTRIAL
SMRs
on launched
strial Alliance for Small Modular Reactors (SMRs).
~ 3000 European companies

Nuclear power officially labelled as 'strategic' for EU's decarbonisation

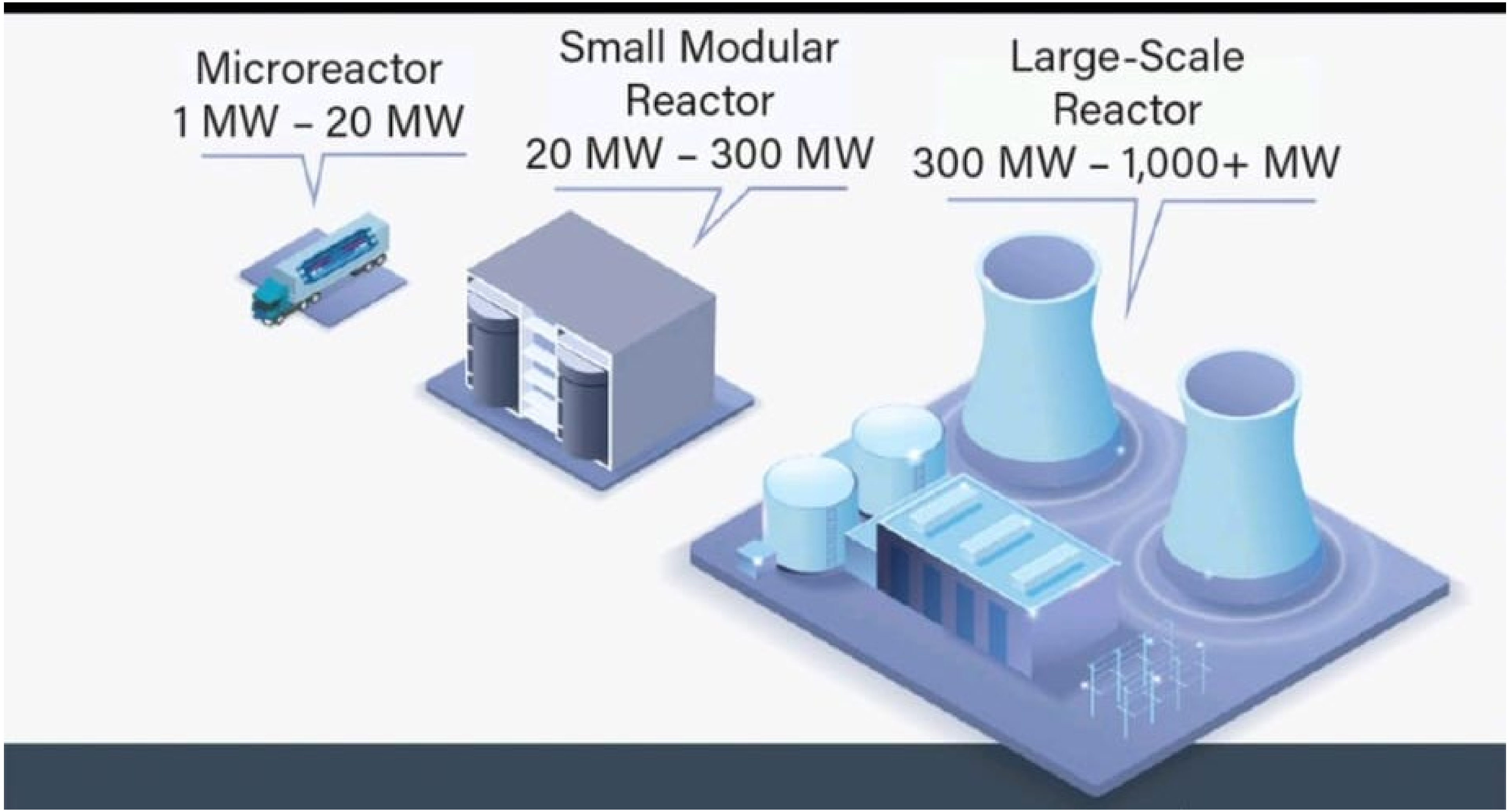
The Council of EU member states and the European Parliament agreed on Tuesday (6 February) to label nuclear power as a strategic technology for the EU's decarbonisation, following months of intense negotiations in Brussels over the Net-Zero Industry Act (NZIA).

Feb 2024

Baseload Electricity for AI-Data and Computing Centers

New Development in Reactor Design

NPPs – Size Classification



Die vier Generationen von Kernkraftwerken

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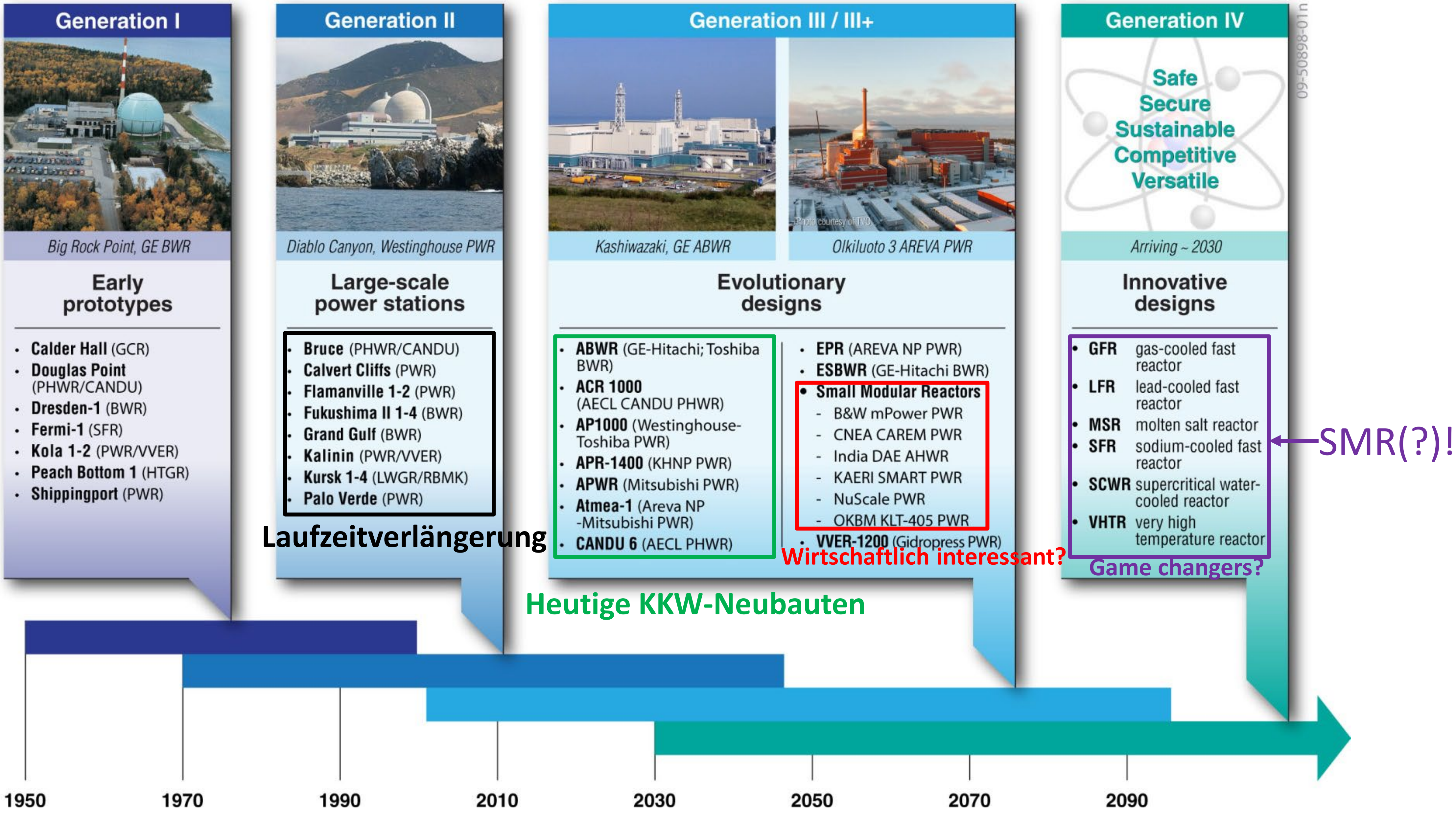
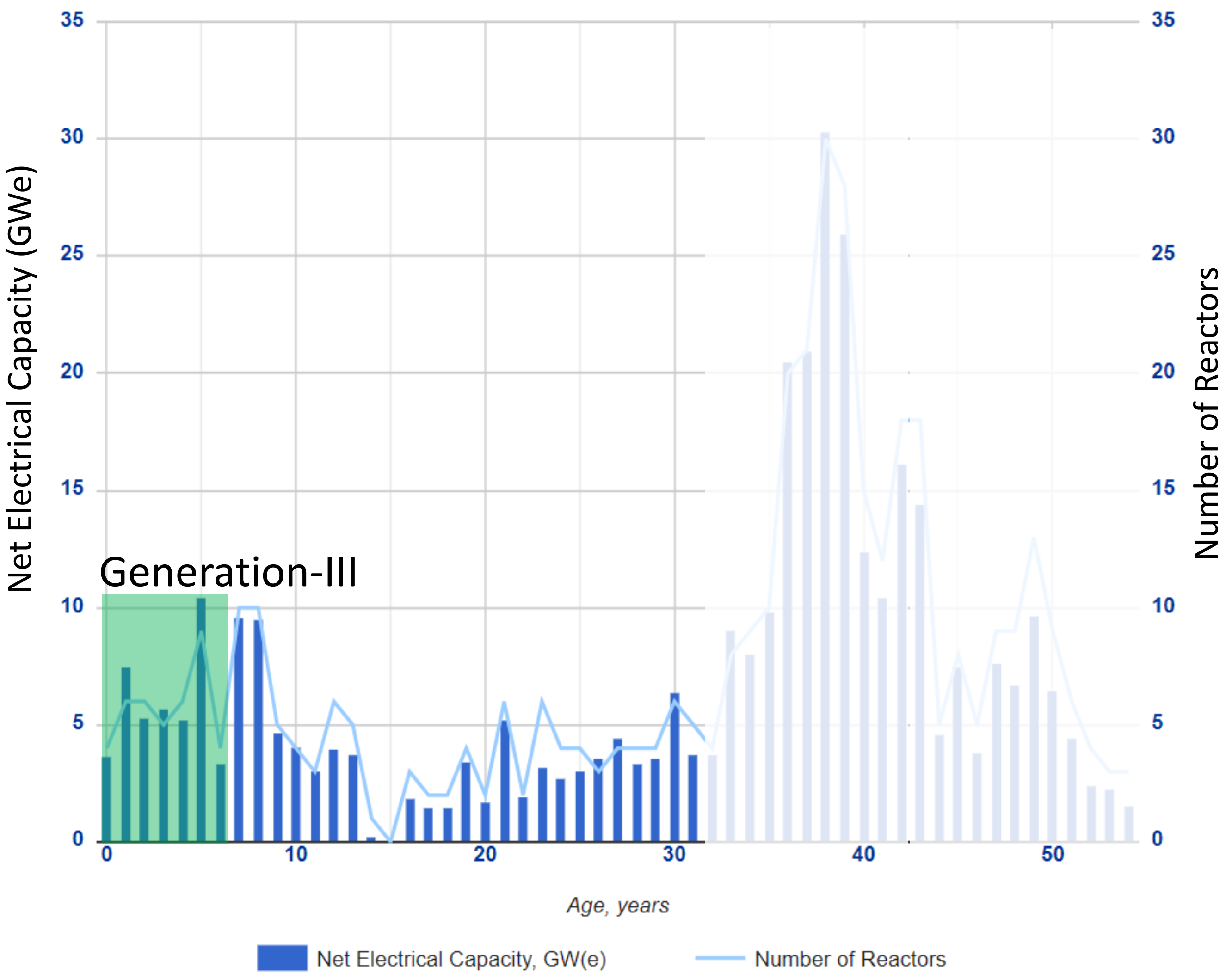


Langzeitbetrieb von Kernkraftwerken

- **Das durchschnittliche Alter** der weltweiten Kernkraftwerksflotte beträgt **ca. 32 Jahre**
- Von dieser Kapazität werden **15 %** (74 KKW) ihre 60-jährige Betriebsdauer bis 2040 erreichen, **61 %** (255 KKW) bis 2050
- Daher wird in mehreren Ländern, vor allem in den USA mit ihrer alternden Flotte, ein**, Langzeitbetrieb (LTO)** in Betracht gezogen
- Bis 2023 haben **sechs** US-KKW-Blöcke ihre erweiterte Betriebsgenehmigung (**bis zu 80 Jahre**) erhalten, **elf** werden von der NRC geprüft und **zwölf** sind in Vorbereitung
- Die US-NRC schließt die Möglichkeit einer **100-jährigen Lebensdauer (!)** nicht aus



Langzeitbetrieb von Kernkraftwerken

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Der langfristige Betrieb eines KKW erfordert ein tiefgehendes Verständnis der grundlegenden **Alterungs- und Degradationsmechanismen**

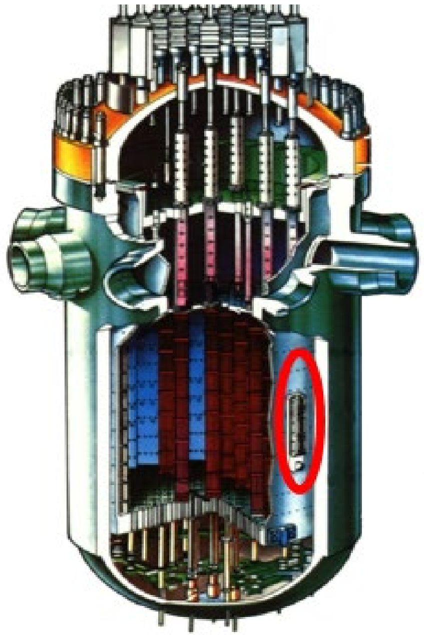
Der Reaktordruckbehälter (RDB) eines KKW ist die einzige Komponente, die **nicht ausgetauscht werden kann**

Das Material des RDB **versprödet** durch die **Bestrahlung mit Neutronen** zusehends

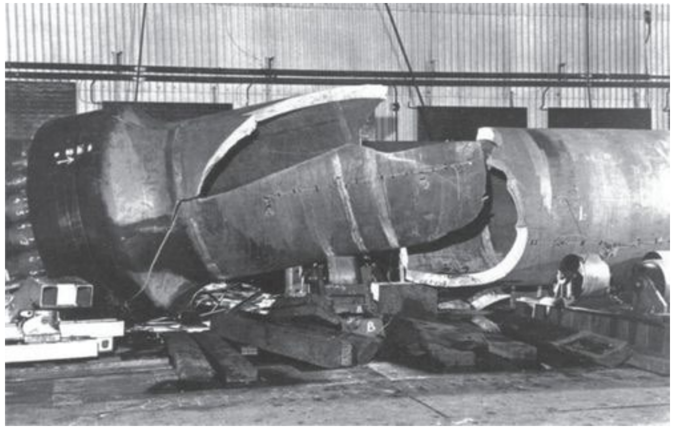
Sprödbruch des RDB ist ein Phänomen mit extrem geringer Eintrittswahrscheinlichkeit, aber drastischen Konsequenzen

Während für Gösgen und Leibstadt die Alterung des RDB unproblematisch ist, ist sie in **Beznau vermutlich Laufzeit-limitierend**

Druckbehälter des KKW Gösgen



RDB Beznau mit Vorlaufproben

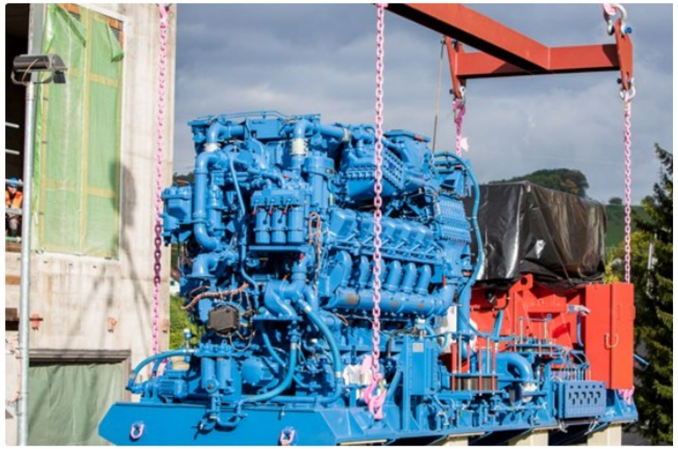


Katastrophaler Sprödbruch eines Druckbehälters

Langzeitbetrieb von Kernkraftwerken

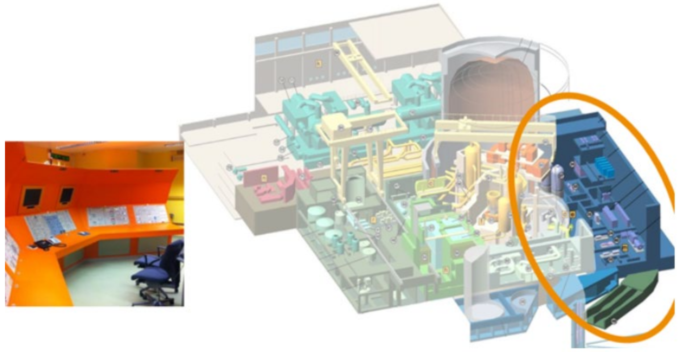
- **Verlängerung der Lebensdauer** (60 Jahre+) wird auch als Option für Schweizer KKW in Betracht gezogen
- Es wurden erhebliche Investitionen in Modernisierungs- und Nachrüstungsprojekte getätigt: KKL **1.800 Mio. CHF**, KKG **1.800 Mio. CHF**, KKB **2.600 Mio. CHF**
- Es gibt **konsolidierte Überwachungs-, Alterungs- und Austauschprogramme für** mechanische, elektrische und bauliche Komponenten und Strukturen
- Große Herausforderungen werden in den **sich ändernden regulatorischen Anforderungen** und der Aufrechterhaltung der **menschlichen Kapazitäten** gesehen

Exchange of Steam Generators in KKB



Autonomous bunkered power supply

Exchange of Pressure Vessel Head in KKB



Beznau NANO Emergency System

Grundlegende Kritik an der Nutzung der Kernenergie

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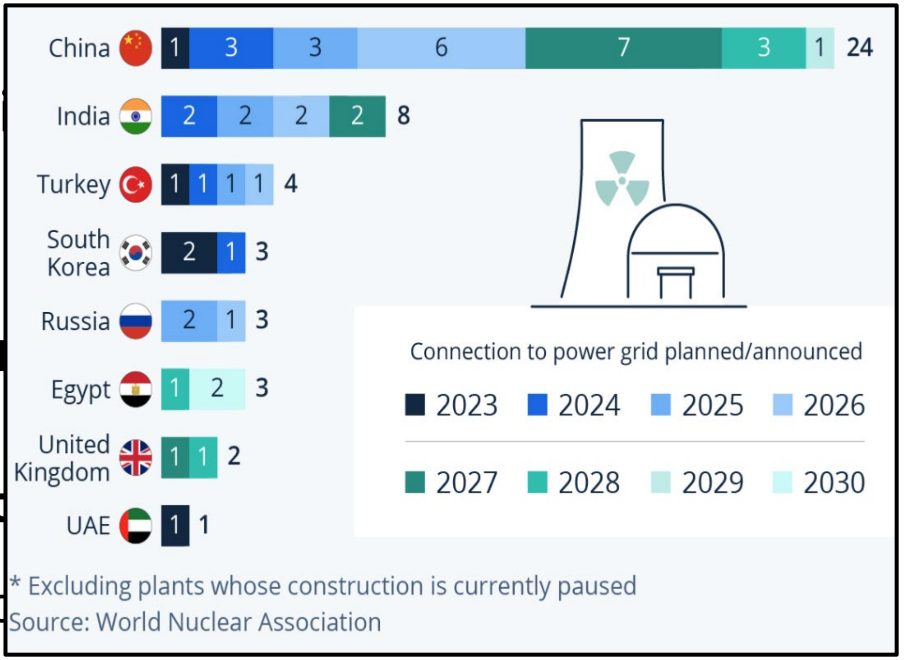
- **Nicht sicher:** **Risiko von Kernschmelzunfällen mit grosser Freisetzung von Radioaktivität, Ziel von Terror- und Cyberattacken, Proliferation** => Generation-III

- **Nicht wirtschaftlich:**
  - **grosse monolithische und kapitalintensive Kraftwerkseinheiten** => SMR
  - **Klumpenrisiko** für die Versorgungssicherheit bei Ausfall => SMR
  - **bestenfalls moderater thermischer Wirkungsgrad (<35%)** => Generation-IV

- **Nicht nachhaltig:** => Generation-IV
  - **Endlichkeit der Uranressourcen**: damit kann Kernkraft nur Brückentechnologie sein
  - **Keine Brennstoff-Kreislaufwirtschaft** und kein befriedigendes **Abfallentsorgungskonzept** (jenseits der geologischen Tiefenlagerung der radioaktiven Abfälle)

Neubauten von KKW der Generation-III

Der weitaus größte Anteil der Anlagenneubauten bewährte grosse Leichtwasserreaktor-Technologi Siedewasserreaktoren)



Die Reaktoren der 3. Generation (Gen-III) erweiter der 2. Generation:

- verstärkter Einsatz **aktiver und passiver Sicherheit**
  - Berücksichtigung schwerer Störfallabläufe / Kernsc
  - Kernschadenswahrscheinlichkeit < 10^{-6}/Jahr
- **„Praktische Eliminierung"** von Störfallsequenzen, die zu einer frühen Freisetzung von Radioaktivität führen (<10^{-7}/Jahr), mit *bis zu einer Woche Karenzzeit* bis zum menschlichen Eingriff
- Generation-III-Reaktoren sind damit um einen **Faktor 10-100** besser gegen schwere Kernschmelzunfälle geschützt als die am besten nachgerüsteten Altanlagen

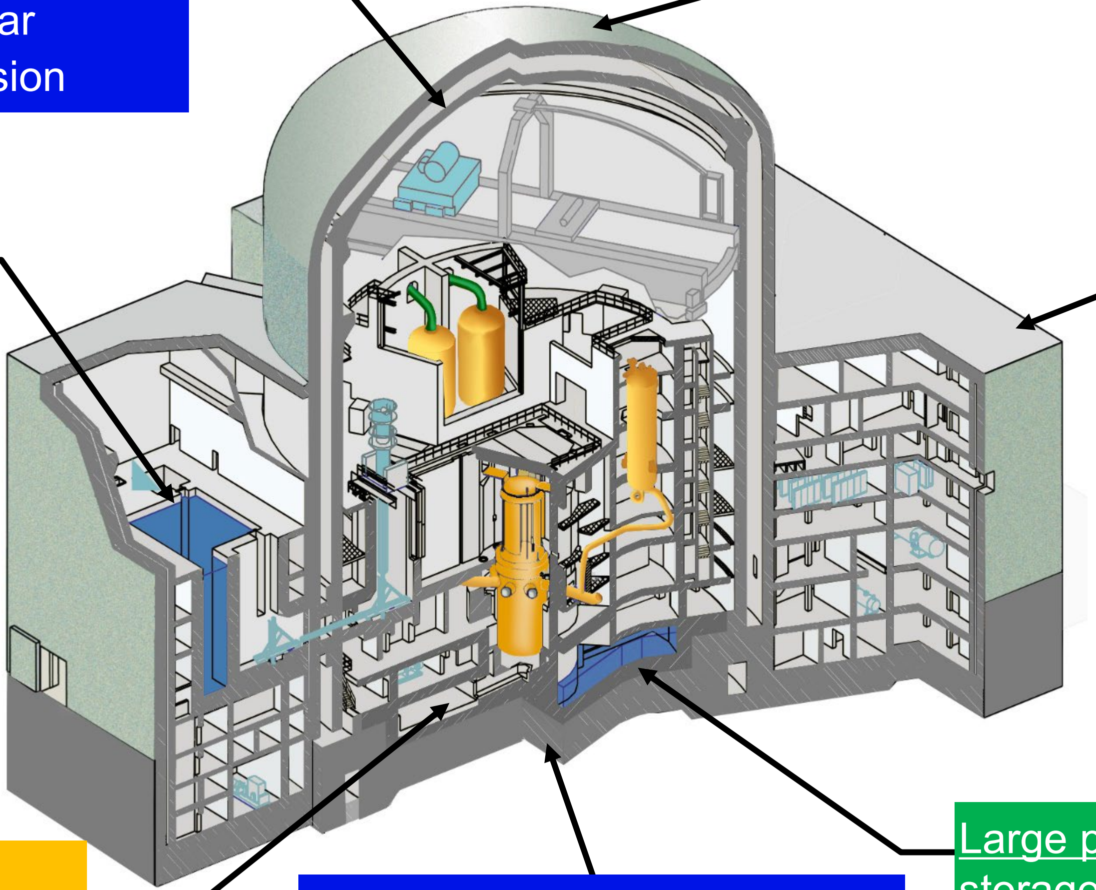
Sicherheitssysteme von Generation-III-Reaktoren: EPR

<u>Internal Containment</u>:
- Steel shell
- Leak-proof up to 6.5 bar
- Exclusion of H_2-Explosion

<u>External Containment:</u>
Air Plane Crash Protection

<u>Wet Fuel Storage:</u>
protected against air plane crash

<u>Active/Passive Safety systems:</u>
bunkered against external hazards, designed throughout 4-times (2v4) redundant with several diversified levels of safety systems



Probability of a core melt accident <10^{-6}/Jahr

Probability of an early release <10^{-8}/Jahr

<u>Core Catcher:</u>
Safe containment of molten core

<u>Earthquake-proof: designed</u> against 100’000-year earthquake

<u>Large protected in-containment water storage</u> for coping with severe accidents

Von Generation-II zu Generation-III: Evolutionäre Konzepte

Fukushima Daichi, Units I-IV, Japan

Olkiluoto-III (EPR), Finland

1970
Generation-II

→

2020
Generation-III

Von Generation-II zu Generation-III: Evolutionäre Konzepte

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1970
Generation-II

→

2020
Generation-III

International aktive Anbieter von Kraftwerken der dritten Generation

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EPR (Framatome) in Olkiluoto (FI), 1600 MW

Wirtschaftliches Reaktorprojekt:

Baukosten/-zeit:

4’000-5’000 $/ kW installiert,

Bauzeit 5-7 Jahre:

LCOE: 6-10 ct./kWh

AP-1000 (Westinghouse) in Vogtle (USA), 2 x 1200 MW

VVER-1200 (Rosatom) in Tianwan (China), 2 x 1250 MW

APR-1400 (KEPCO) in Barakah (UAE), 4 x 1400 MW

Entwicklungen in der Kernenergie:
Kleine Modulare Reaktoren und Mikroreaktoren

Grosse KKW: Herausforderungen

- Große, komplexe, ineffiziente Baustellen
- Hohe Kapitalkosten und lange Amortisationszeiten (weniger attraktiv für Privatunternehmen)

Kleine Modulare Leichtwasserreaktoren (LWR-SMR)

- **Kleine modulare Reaktoren** (SMR) werden zunehmend als interessante Option angesehen:
  - **Geringere Leistung (20-300 MW_e)** bei vergleichbaren oder geringeren Kosten (<4’000 $/kW) als grosse Anlagen => **Modulbauweise und Serienfertigung**
  - **Deutlich einfacheres Design** als große Leichtwasserreaktoren durch passive Sicherheitskomponenten
  - Je nach Bedarf können **mehrere Module gleichzeitig am selben Standort** gebaut oder nacheinander errichtet, zu- und abgeschaltet werden
  - **Deutlich reduzierte Errichtungsdauer** für jedes Einzelmodul
  - **Kompakte Bauweise** eröffnet die Möglichkeit für Errichtung unter Grund
  - **«Walk-Away-Safe»**
  - **Wesentliche Verkleinerung der Notfallplanungszone (bis auf das Werksgelände) möglich**

Grössenvergleich SMR gegen grosse Leichtwasserreaktoren (1000 MW)

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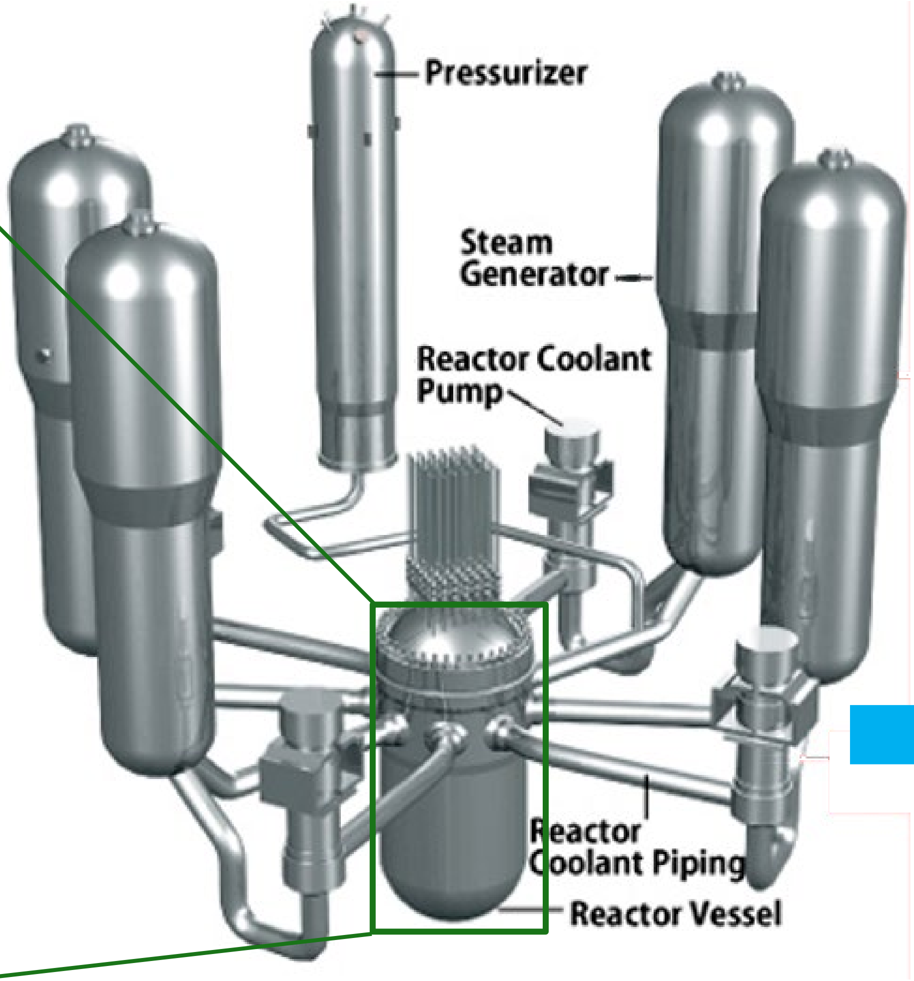
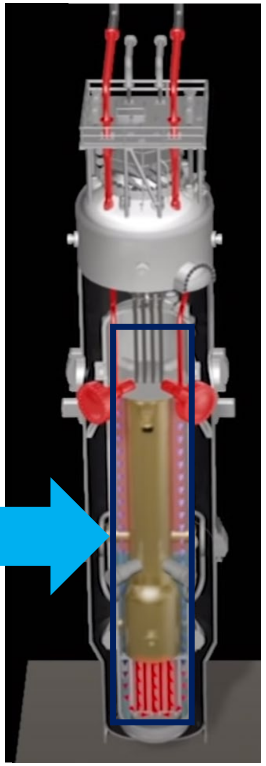
- Entire class of accidents eliminated by design (e.g. LBLOCAs)
- Fabricated in factory and transported to plant site

~ 11 m



Siemens KWU DWR, 1300 MW



NuScale Modul 77 MW

Grössenvergleich SMR gegen grosse Leichtwasserreaktoren (1000 MW)

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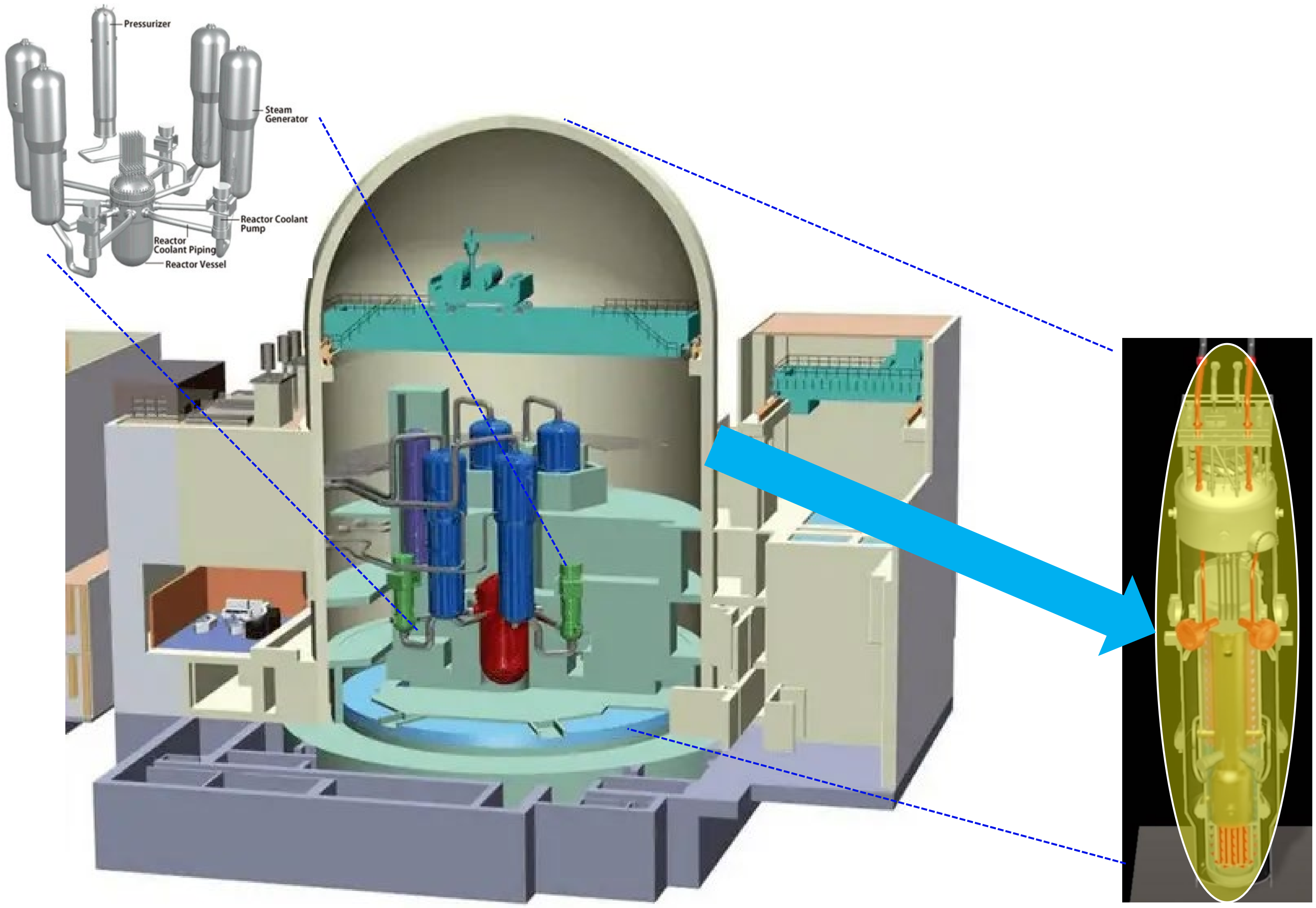
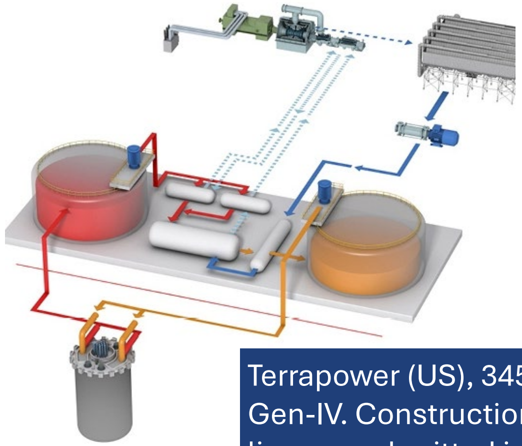


SMRs already on the market or available by 2030

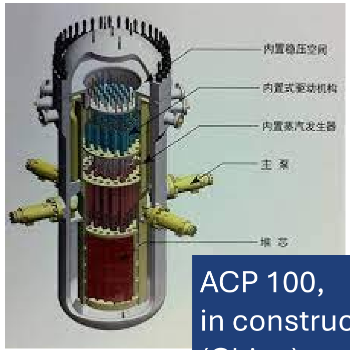
RITM-200 (Russia)
several in operation

BWRX-300 (GE/Hitachi)
4 units in Ontario Power, from 2028
Construction license expected in 2024



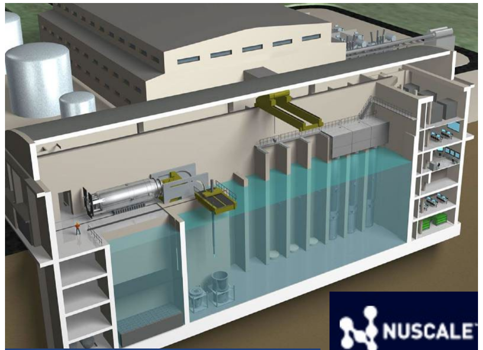
Terrapower (US), 345 MW
Gen-IV. Construction
license submitted in 2024

X-energy (USA)
DOW, construction
planned for 2026



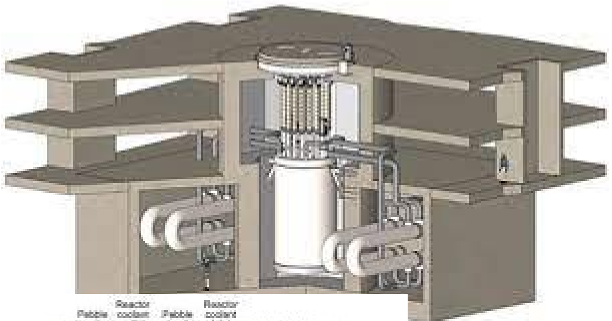
ACP 100,
in construction
(China)

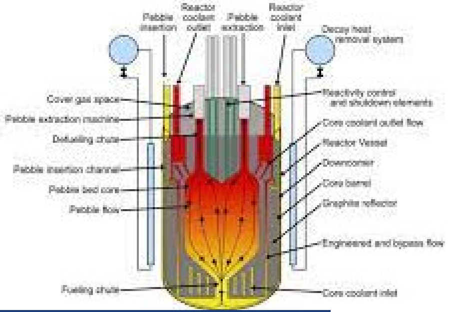
2xHTR-PM
in operation (China)



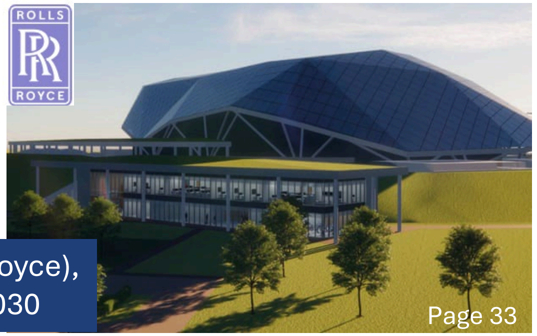
NuSCALE (6 x 77 MW)
Licensed in USA

NUWARD (EdF/Technicatome)
170 MW, from 2030





Kairos (US). Construction
licensed received in March
2024 (Tennessee)



UK SMR (Rolls Royce),
443 MW, from 2030

Russia: 8 in operation (LWR), several planned (LWR/SFR)
China: 2 in operation (HTGR), 3 in construction (1 LWR), 2 SFR)
Canada: 4 ordered, **Argentina:** 1 in construction
USA: 1 in construction (Kairos), several planned

NuScale: Das erste lizenzierte SMR-Design in den USA

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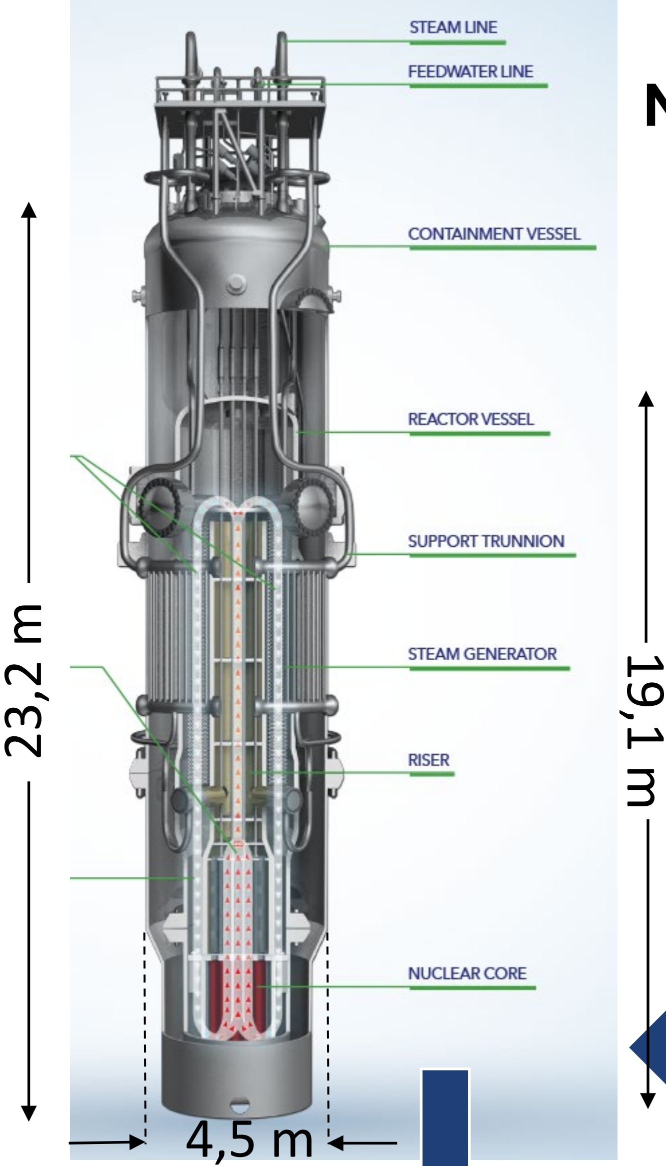
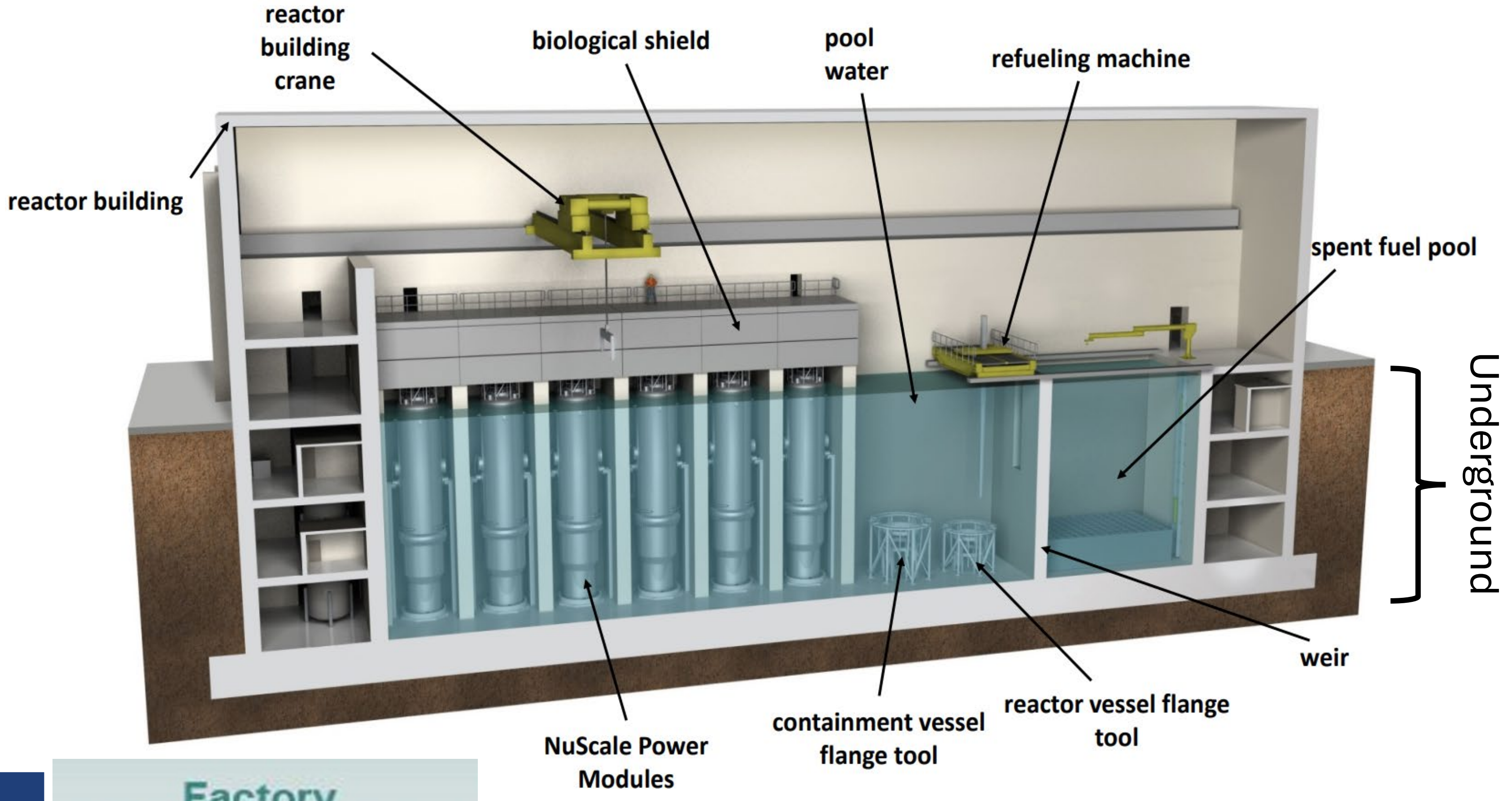
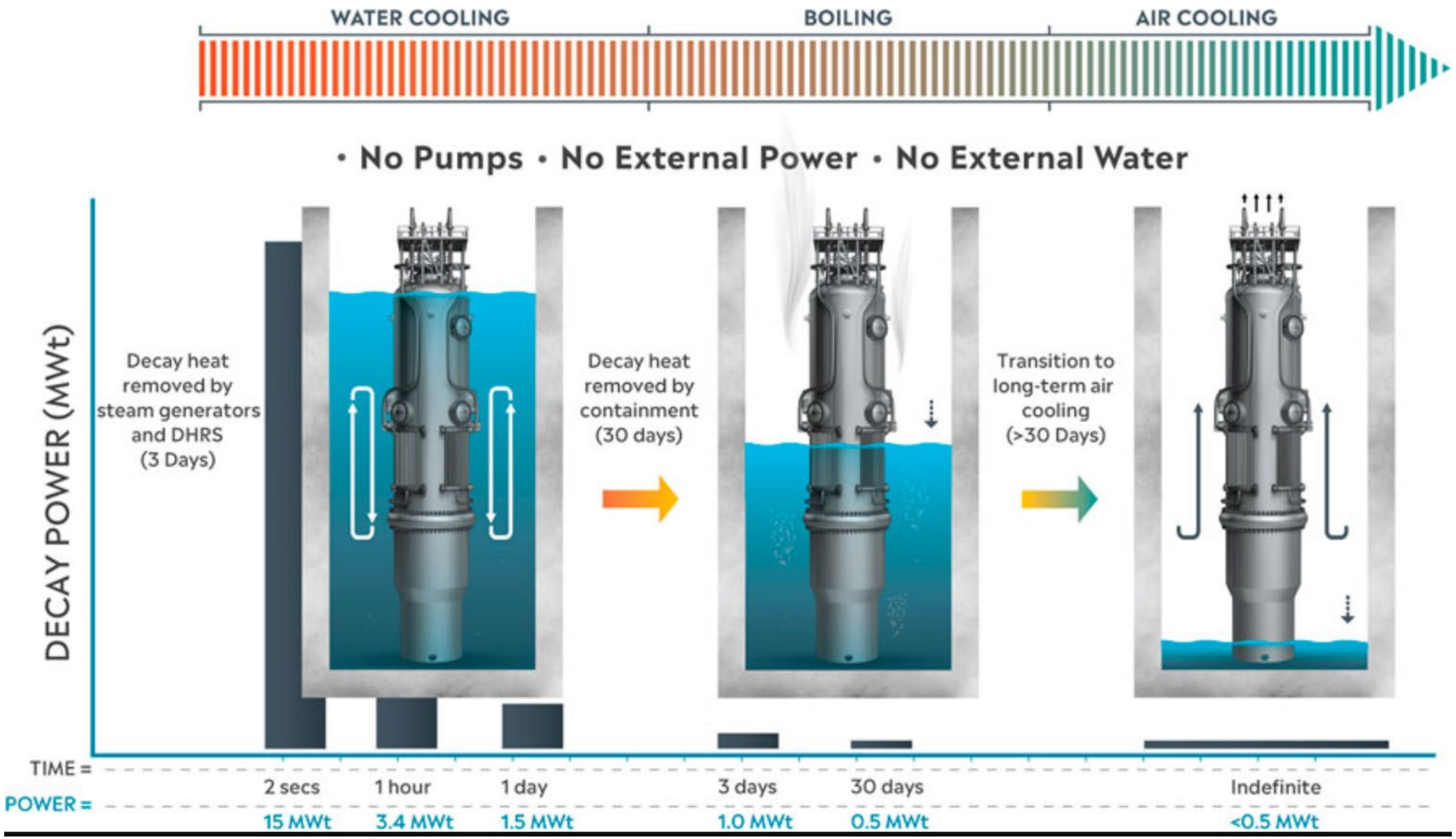




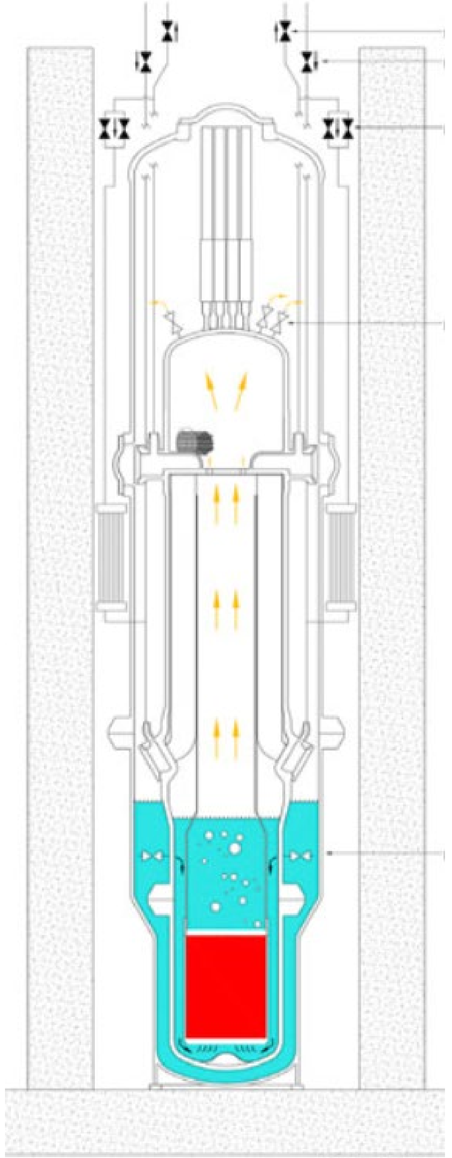
Each Module is refueled underwater while the remainder of the plant produces power

- Refueled once every 24 months
- Capable of 48-month fuel cycle
- 10 Day Refueling Target

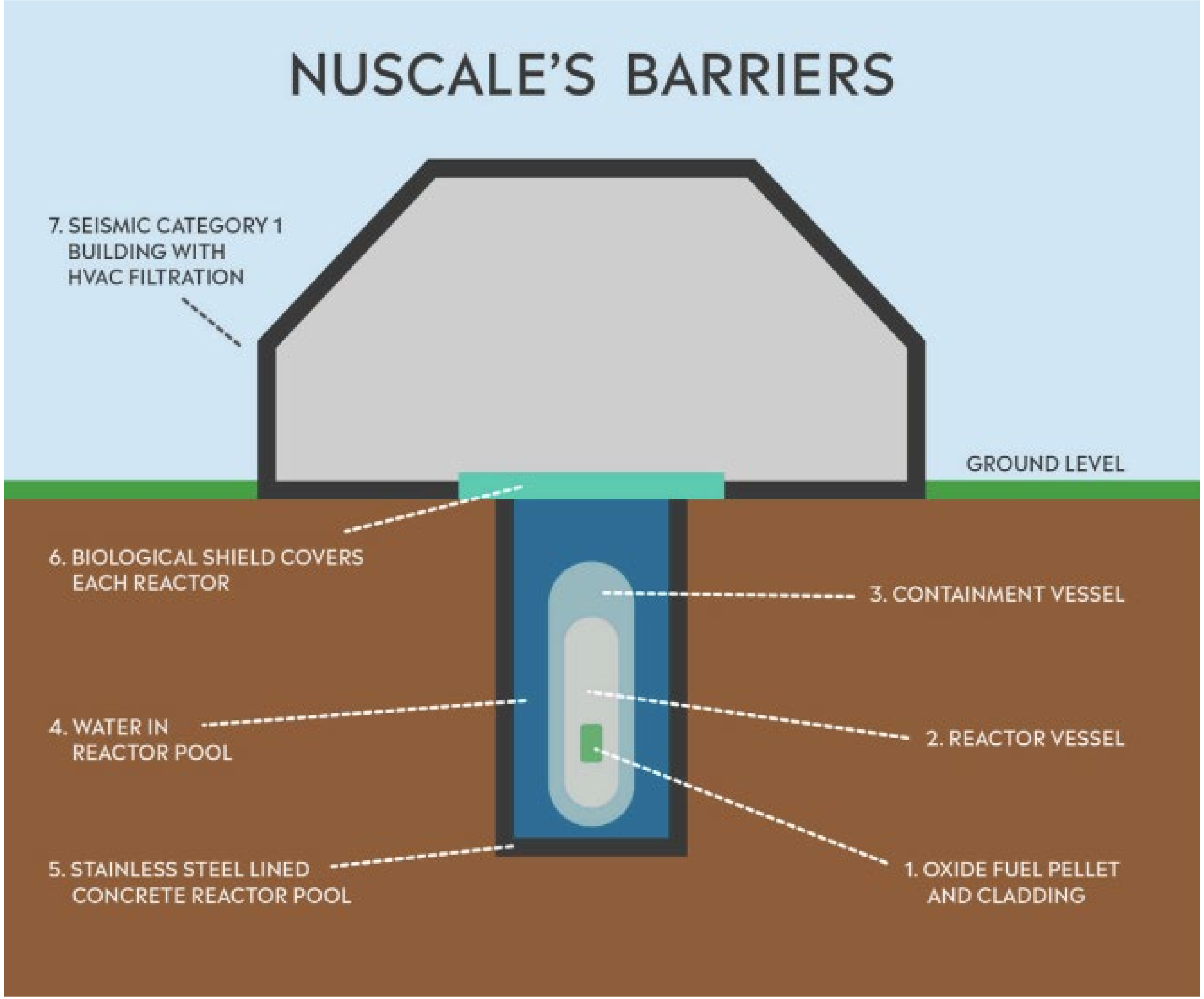
Passive Sicherheitssysteme: «Walk-Away Safety»

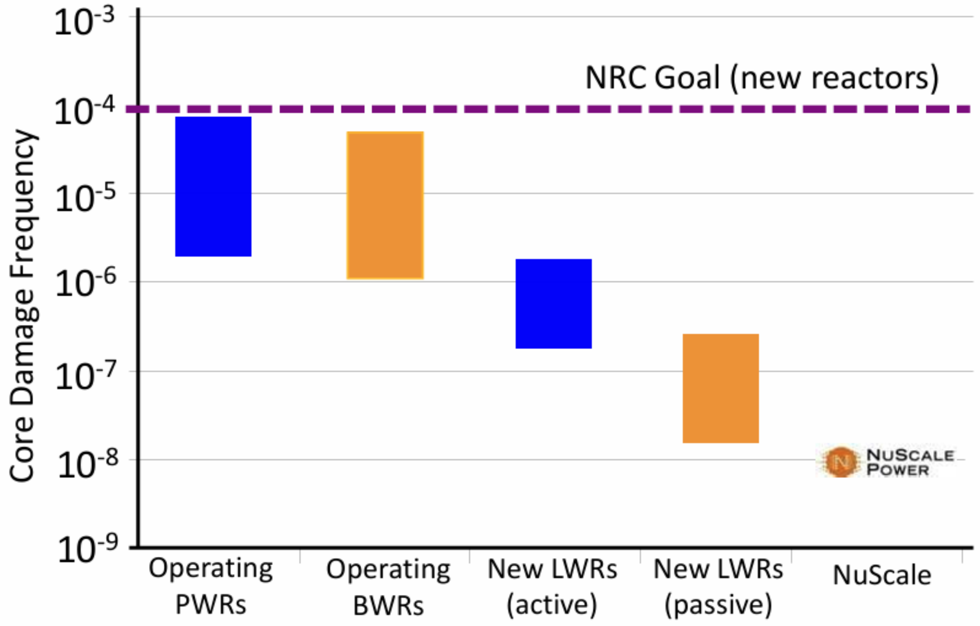


Decay Heat Removal after Reactor Shutdown (Long-Term Station Blackout Scenario)



Reactor Core remains Covered at all Times





Emergency planning zone (PEZ) limited to the site boundary (no evacuation required, even in case of severe accidents)

GE-Hitachi BWRX-300

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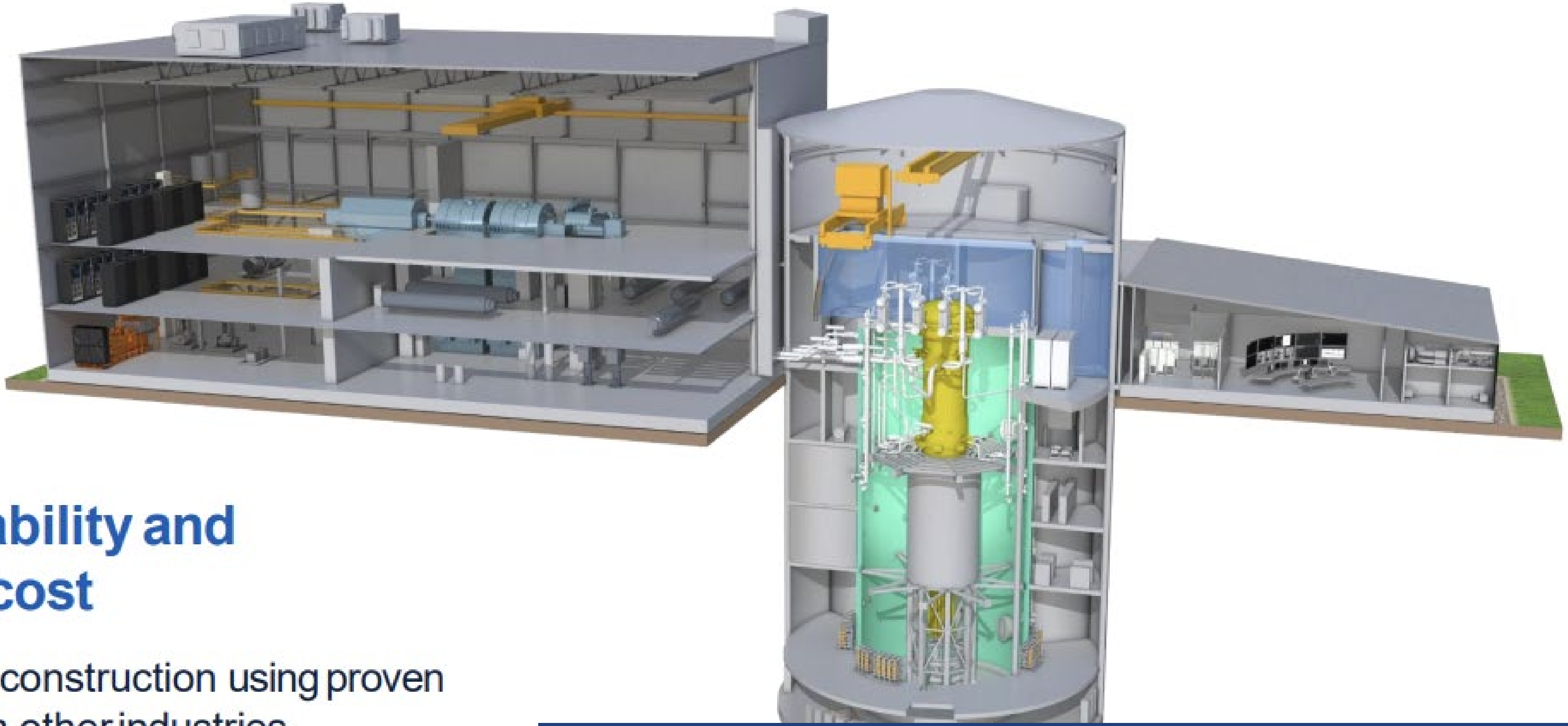

Constructability and Design-to-cost

- Underground construction using proven methods from other industries
- Maximum use of catalogue items
- “Off the shelf” turbine/generator

Canada has already ordered 4 units.
Site preparation started.
Expecting construction license by end of 2024
Capital cost at 700 Mio. $, 2250 $/kWh, O&M cost<16 $/MWh,
Claimed LCOE at ~40 $/MWh

GEN IV International Forum
Expertise | Collaboration | Excellence

The Generation-IV Reactor Concepts

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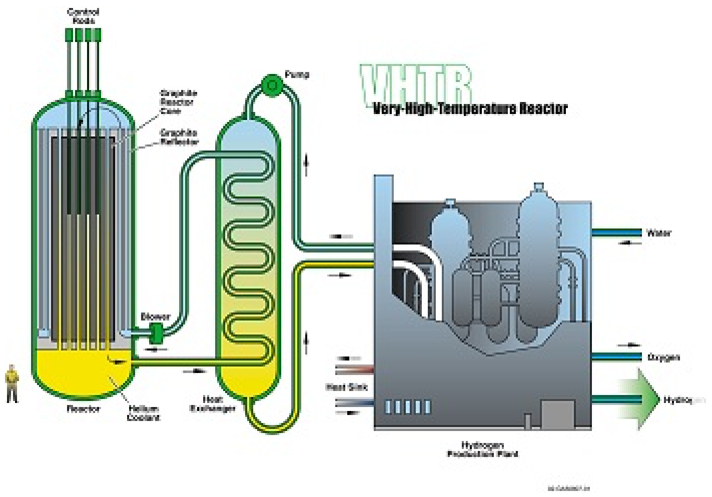
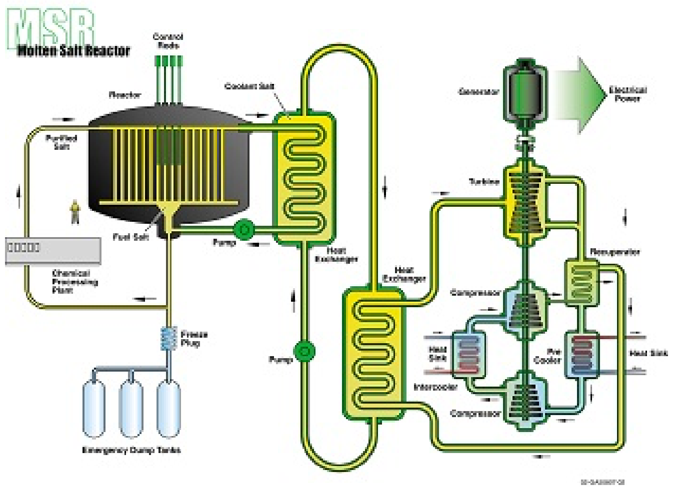
High Temperature Reactor (HTR)



Lead Cooled Fast Reactor (LFR)

Supercritcal LWR (SCWR)



Gas-Cooled Fast Reactor (GFR)

Sodium-Cooled Fast Reactor (SFR)

Molten Salt Reactor (MSR)

Generation-IV: Hochtemperaturreaktor (HTR)

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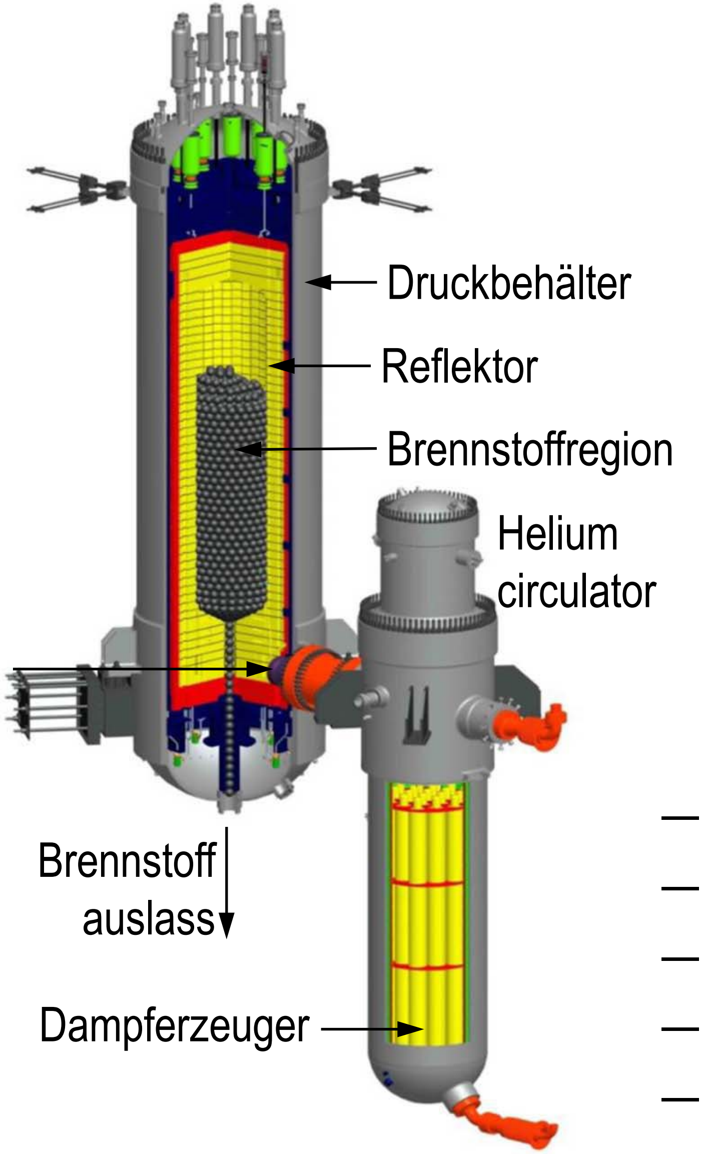

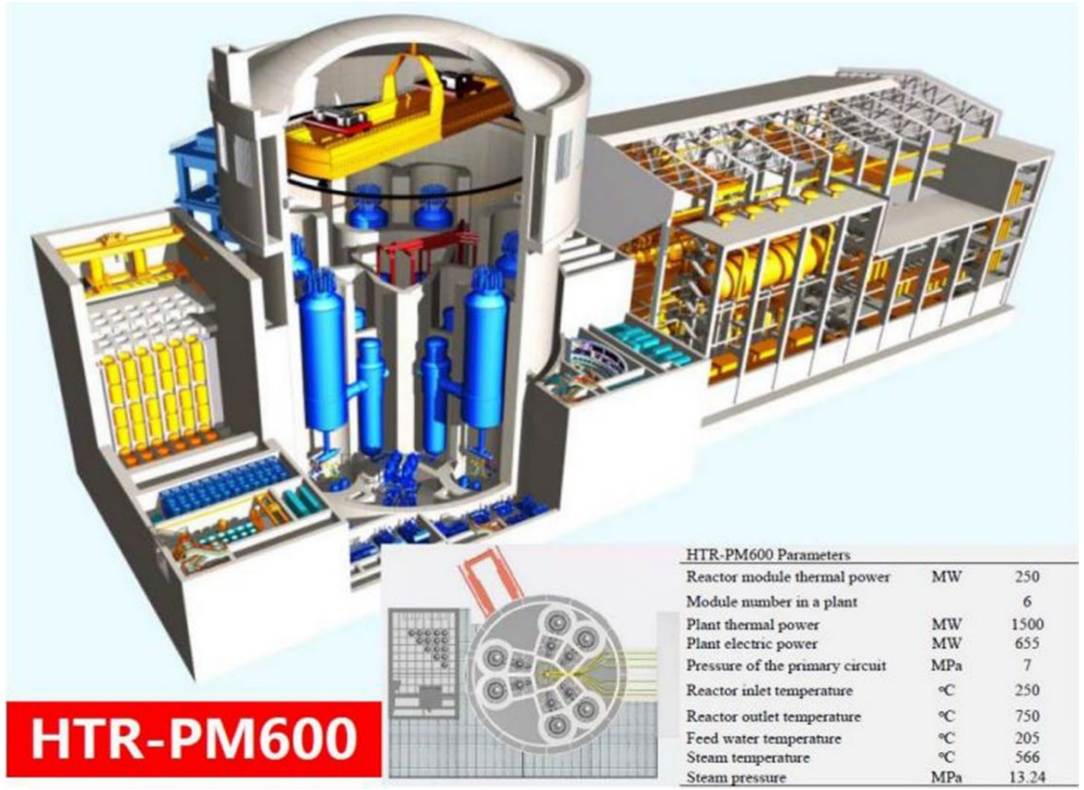

HTR-PM600 Parameters

Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	°C	250
Reactor outlet temperature	°C	750
Feed water temperature	°C	205
Steam temperature	°C	566
Steam pressure	MPa	13.24

- Brennstoff als “Fuel Pebbles”, stabil bis mindestens 1600 °C
- Reaktor ist inhärent sicher und “Walk-Away”-safe
- Betriebstemperatur: 800 °C, thermischer Wirkungsgrad: 44%
- 2 x 110 MW Anlage seit 2021 in Betrieb
- 6 x 110 MW-Anlage im Bau

Simulation Pebble Flow
Paul Scherer Institut

Anwendungsspektrum für Gasgekühlte Reaktoren

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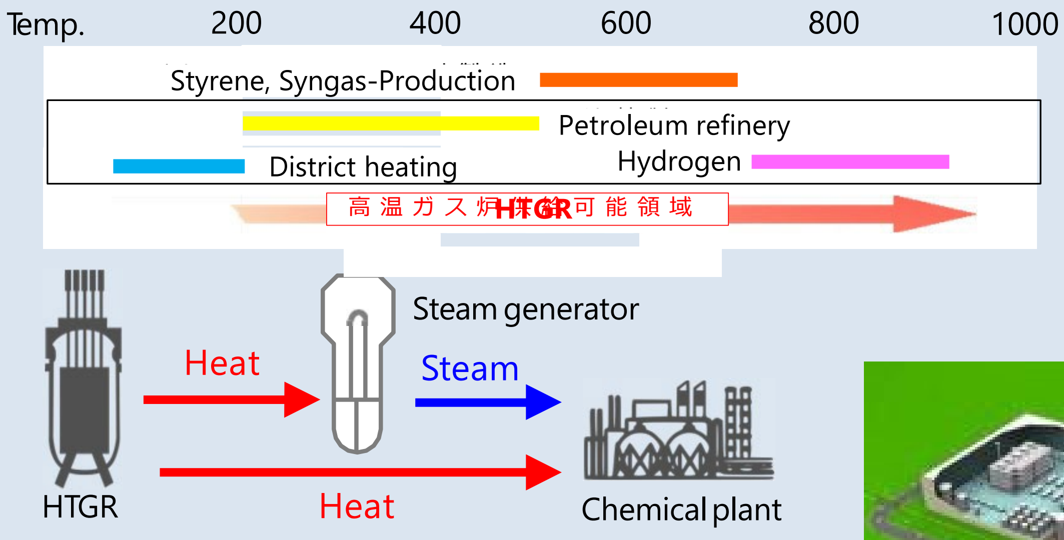
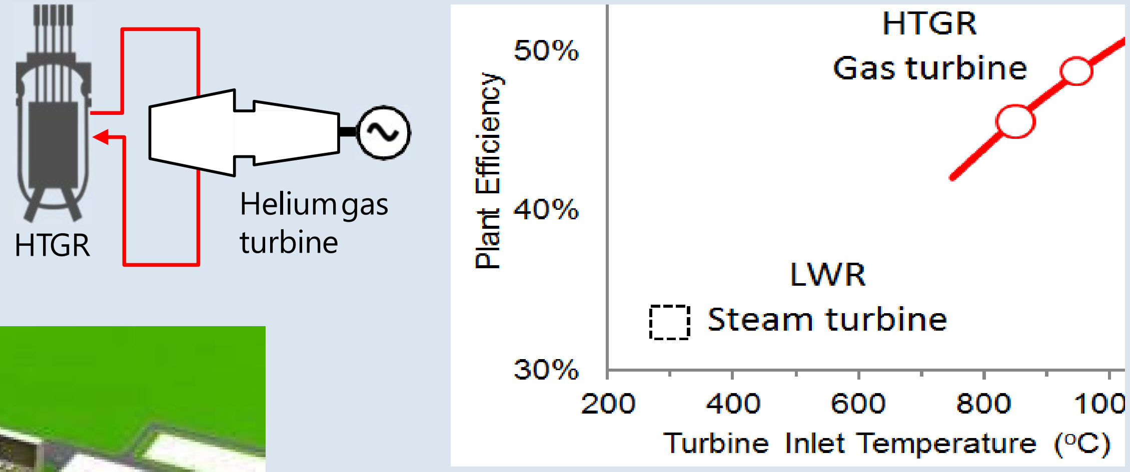
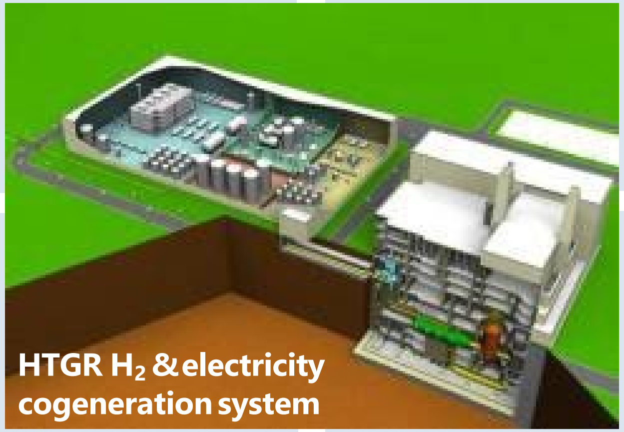
Industrial use of nuclear heat

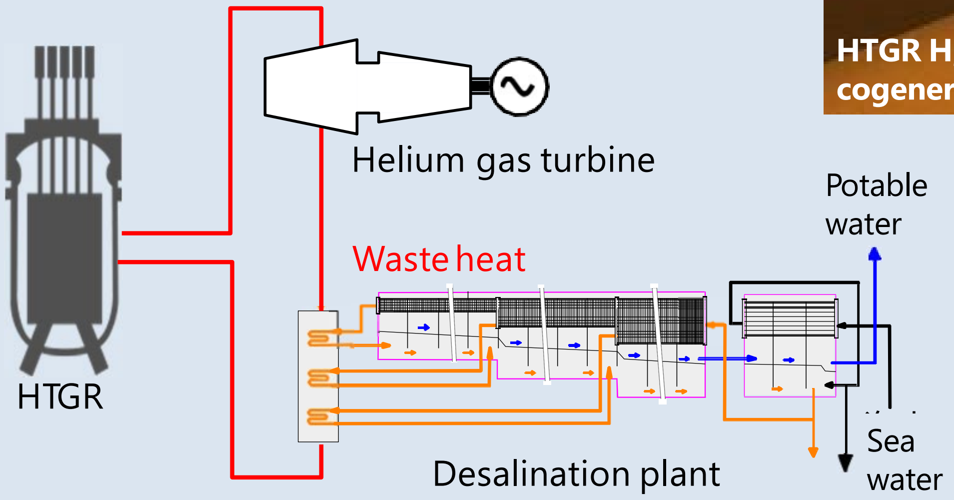


High Efficient Gas Turbine Power Generation

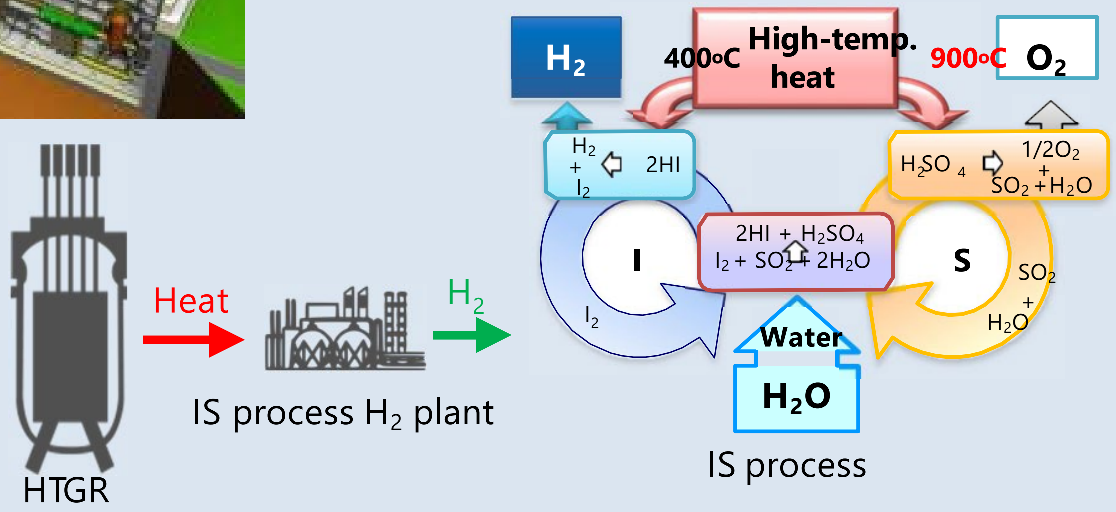




Desalination using waste heat

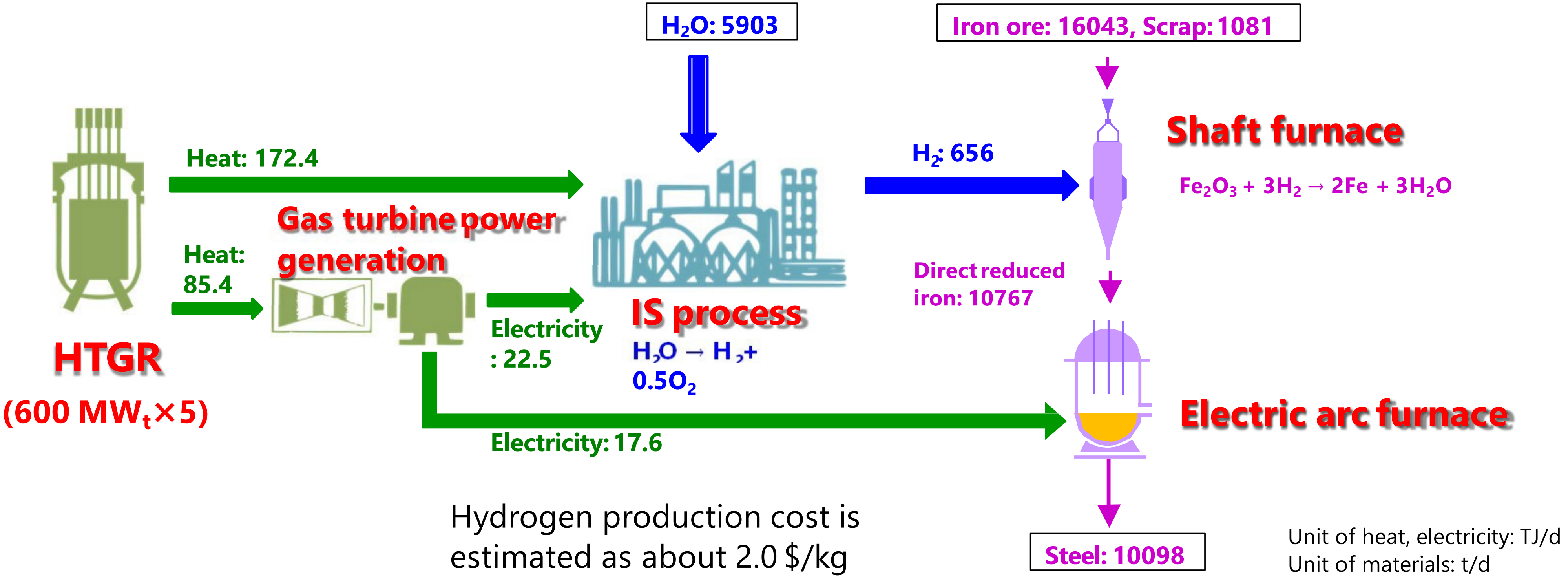


Carbon-free H_2 production



HTGR Energy Supplied Steelmaking System

- Steelmaking by hydrogen and electricity produced by the HTGR-IS cogeneration system
- CO_2 emission from steel plants can be cut by 100% (104 million ton/year in Japan[*1]).



Hydrogen production cost is estimated as about 2.0 $/kg

Unit of heat, electricity: TJ/d
Unit of materials: t/d

Energy and material balance of a plant to produce steel of 10,000 ton/d [*2]
(Scale of a standard steel plant) [*3]

*1 : Data of 2016. Ref.: Greenhouse gas emission data in Japan (1990-2016 definite report), Greenhouse Gas Inventory Office of Japan (May 29th, 2018 update).
*2 : Domestic steel production: c.a. 290,000 t/d (2016).
*3 : Kasahara and Ogawa, Production of Green Energy and Its Utilization in Ironmaking and Steelmaking Processes, Iron and Steel Institute of Japan, 123-143, 2012.

Mikroreaktoren – Leistung bis zu ~ 10 MW_{el}

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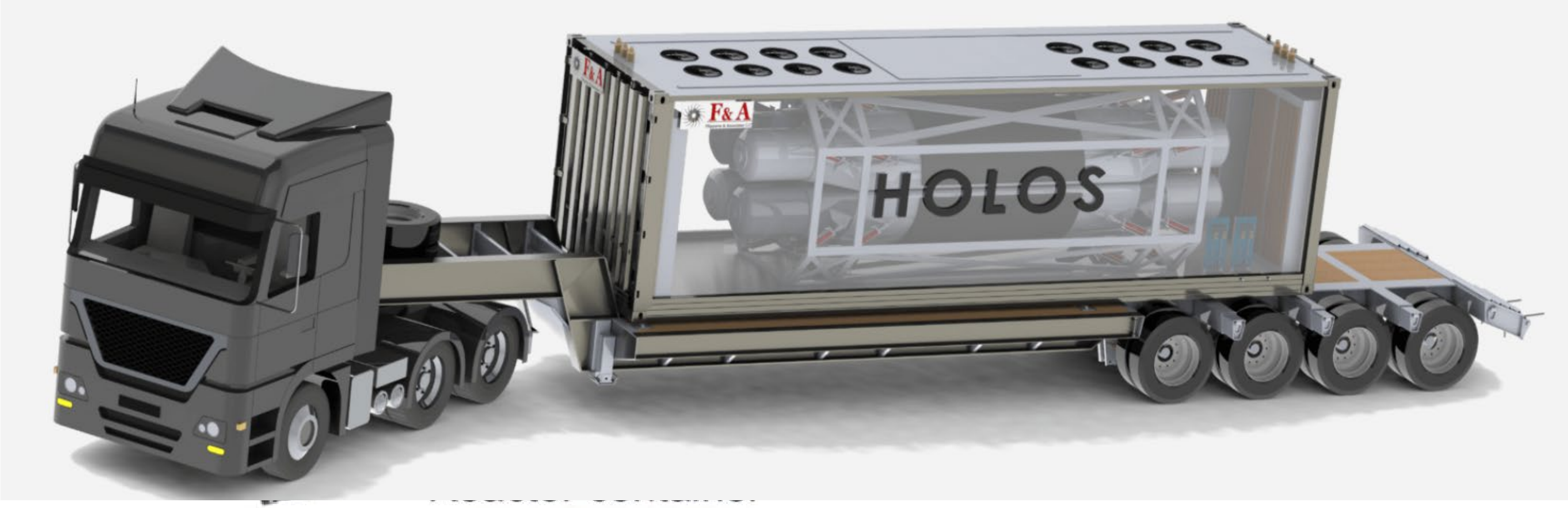


Commercial PLAYERS (USA)

- MARVEL (INL, in construction)
- Westinghouse (INL, 2026)
- BWRT (INL, 2025)
- Kairos (ORNL, 2026; in constr.)
- X-Energy
- Ultra Safe Nucl. Corp.
- OKLO
- HOLOS (in licensing phase)

- „Plug-and-Play" connection (< 1 month)
- Reduced space needed (~15 m^2), small site (< 2000 m^2)
- Offsite Refueling once every 10 years
- No water needed for cooling (heat pipes)
- As part of grid, microgrid or independent from grid
- Build in factory, and transported on site with ISO container
- For desalination, hydrogen production, and other industries

Zusammenarbeit des PSI mit Copenhagen Atomics


NZZ am Sonntag

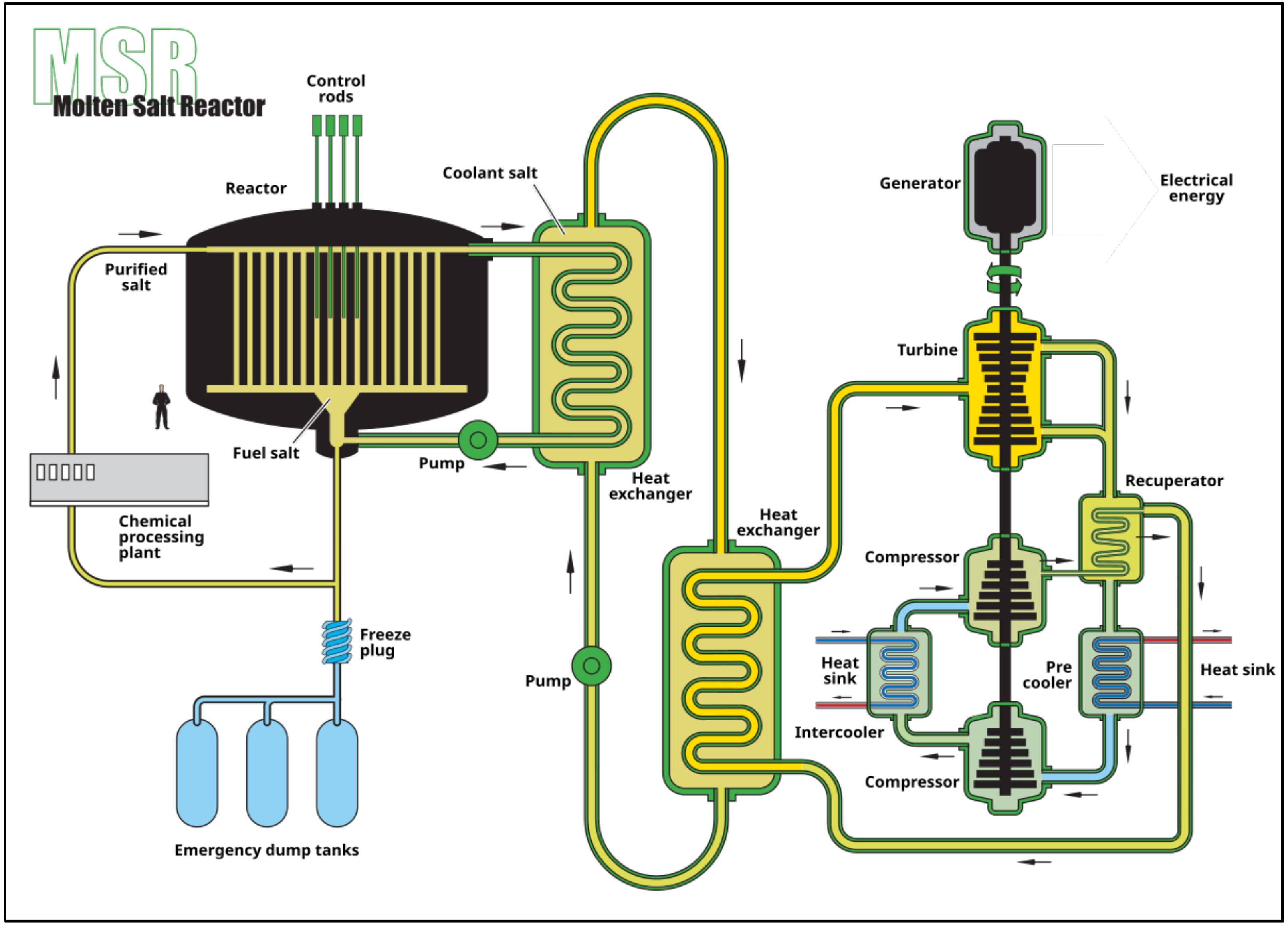
Kriegspropaganda setzt auf Kinder – gibt es keine Grenzen mehr?

Was Trumps Hintermänner wirklich vorhaben

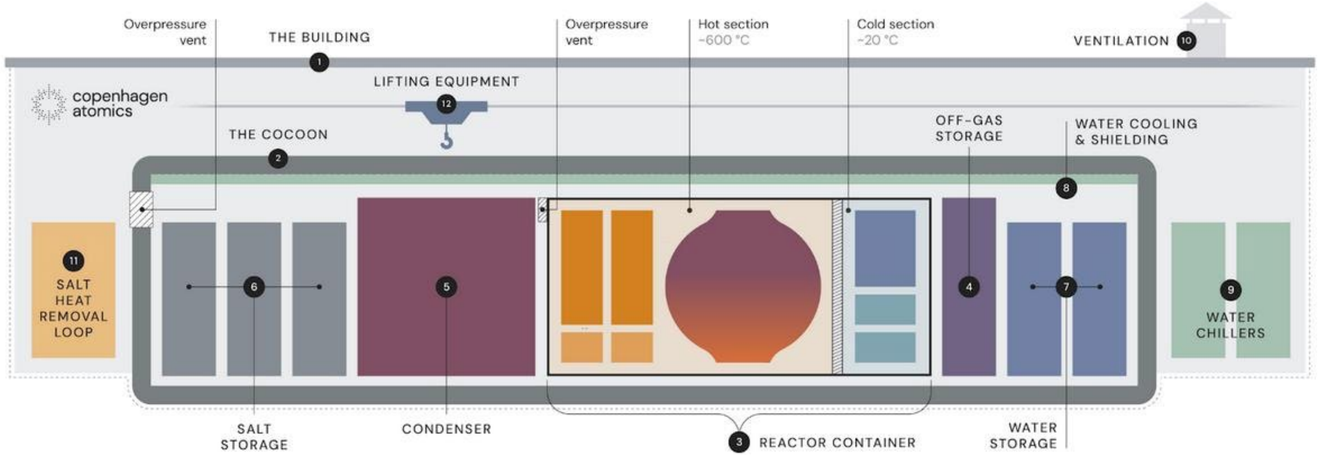
Wirtschaft

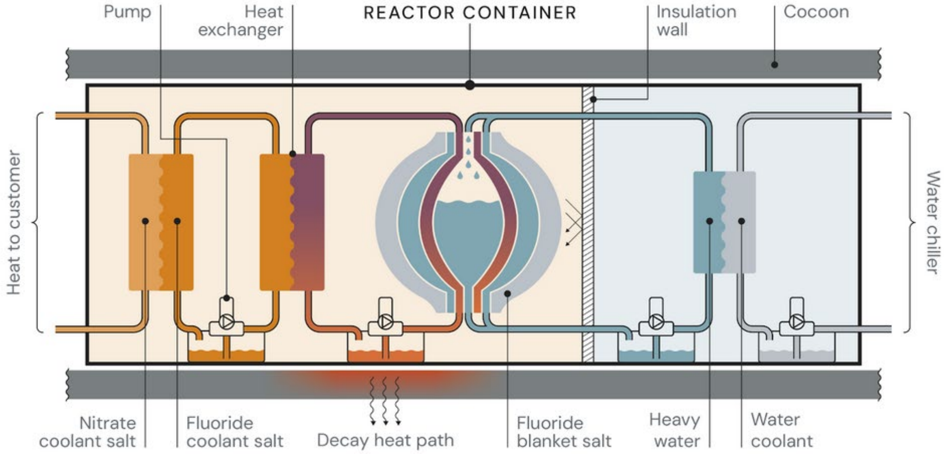
Ein Mini-AKW für den Hausgebrauch

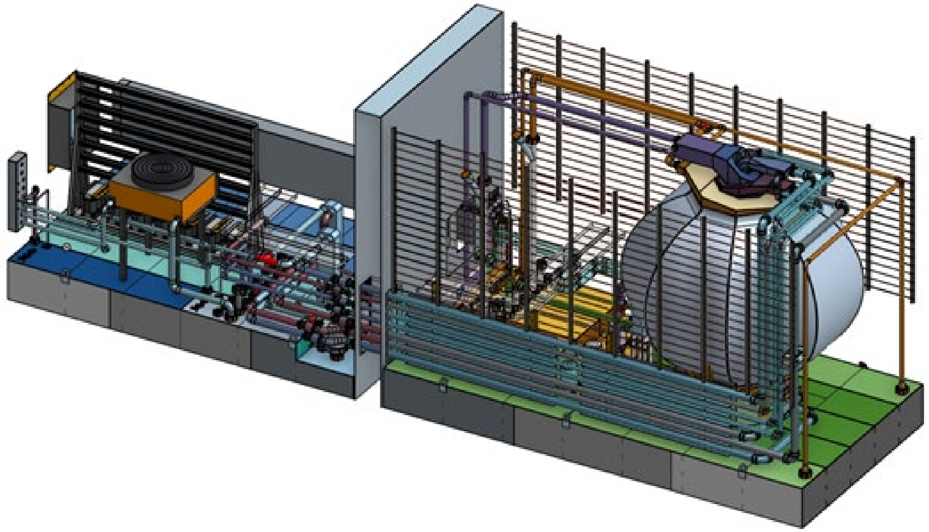
Das Paul-Scherrer-Institut baut gemeinsam mit dem Startup Copenhagen Atomics im Aargau einen Testreaktor. Der Kleinreaktor soll bereits in drei Jahren errichtet werden – und dann von der Schweiz aus die Welt erobern. Von Jürg Meier



Das MSR Design-Konzept von CA







Das MSR Design-Konzept von CA

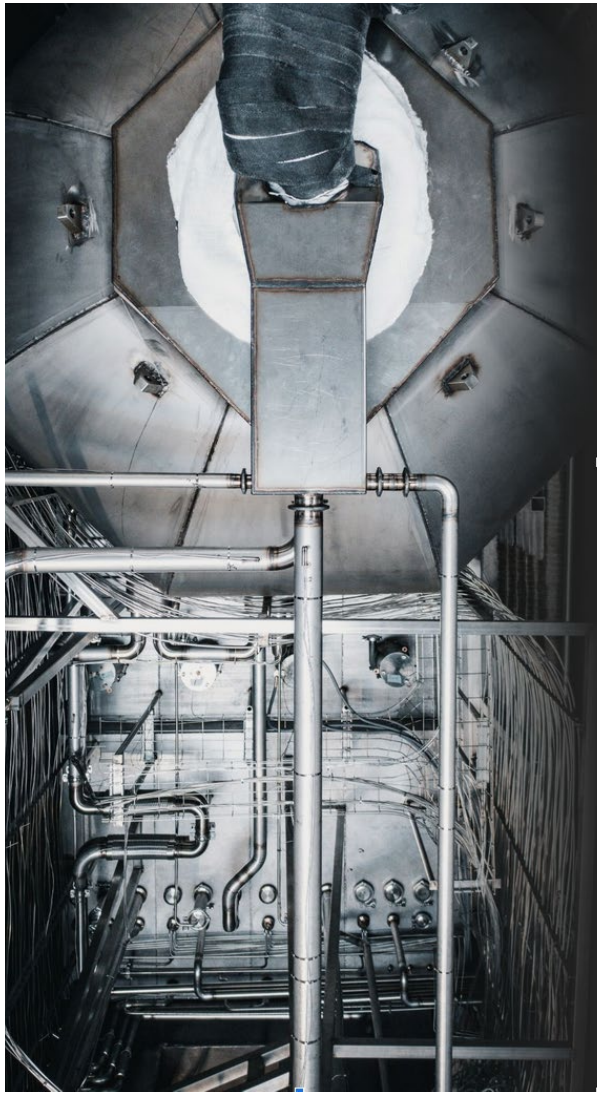
copenhagen atomics PSI

MSR-Prototyp für das Experiment am PSI

- Testreaktor in Originalgrösse aber mit reduzierter Leistung < 1 % Nennleistung (<1MW_{therm})
- Inhärent sicher
- Autonomes Reaktorbetriebssystem

Schlüsseldaten:

• Starter Salz:	F-Li-LEU (5% angereichert), ~ 500 l, 2,4 t Gesamtmasse mit 1,5 t Uran-Masse
• Brut Salz:	F-Li-Th ~ 2500 l 11,1 t Gesamtmasse mit 6,7 t Thorium-Masse
• Moderator:	D_2O bei 20^0 C, ~ 3200 l
• Wände:	SS-316, Zirkalloy, 0,9 t Gesamtmasse
• Abschirmung:	10 cm Stahl 20 cm 5% borierter Kunststoff 5 cm Blei



Ziel: Kernanlage mit geringem Gefährdungspotential

Kernenergie, quo vadis?

Die meisten Kernkraftwerke der Generation-II werden **Laufzeitverlängerungen** beantragen und 60 und mehr Jahre laufen

Grosse Kernkraftwerke der Generation-III werden kontinuierlich weitergebaut werden, insbesondere in Schwellenländern, aber nach und nach auch in Mittel-/Osteuropa (EU-Taxonomie!) und den USA.

SMR werden ab 2030 beginnen auf den Markt zu drängen. Untersuchungen der OECD kommen bis 2060 auf einen Anteil von 10-30% SMR an der nuklearen Gesamtkapazität

Reaktoren der **Generation-IV** werden parallel entwickelt und stehen möglicherweise kommerziell bereits ab 2035 zur Verfügung, einige Mikroreaktoren sogar früher. Sie ermöglichen effiziente Kogenerationstechnologien und eine **nachhaltige Brennstoffnutzung**

Die nukleare Stromerzeugung wird, gemäss der grossen Mehrheit von Energiesystemstudien, zwischen **10 und 20% an der weltweiten Gesamtstromerzeugung** ausmachen

Wir schaffen Wissen – heute für morgen

Gestehungspreise verschiedener Stromerzeugungstechnologien

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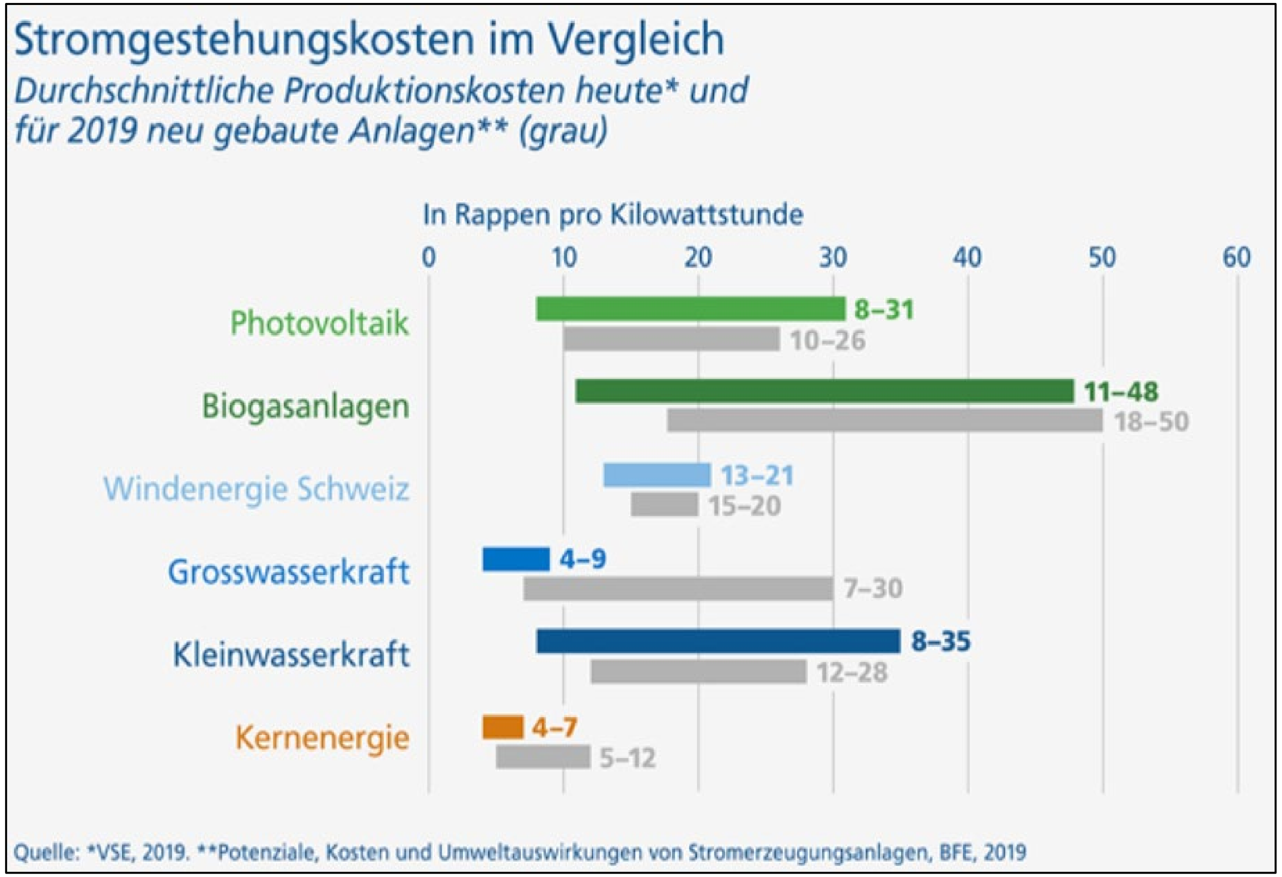
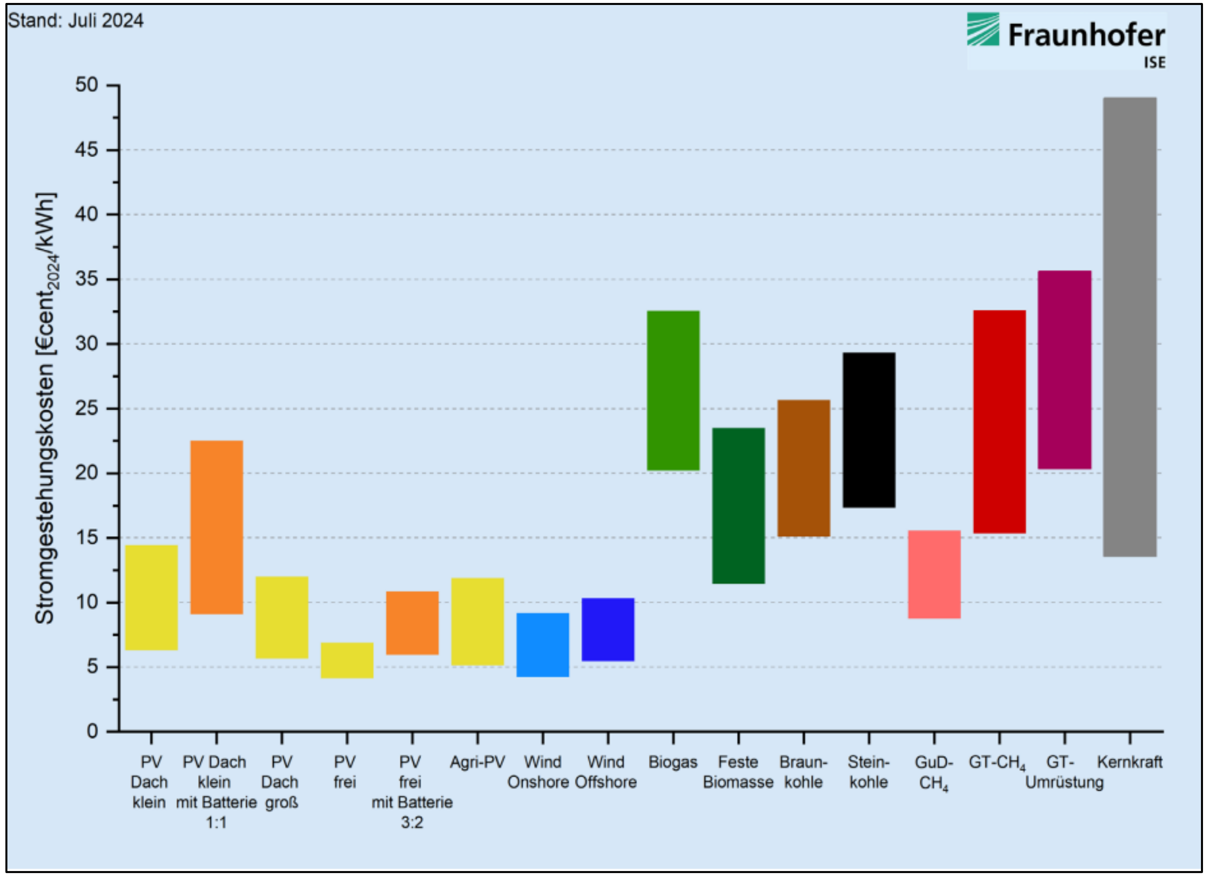


Studie des PSI im Auftrag des BFE (CH), 2019

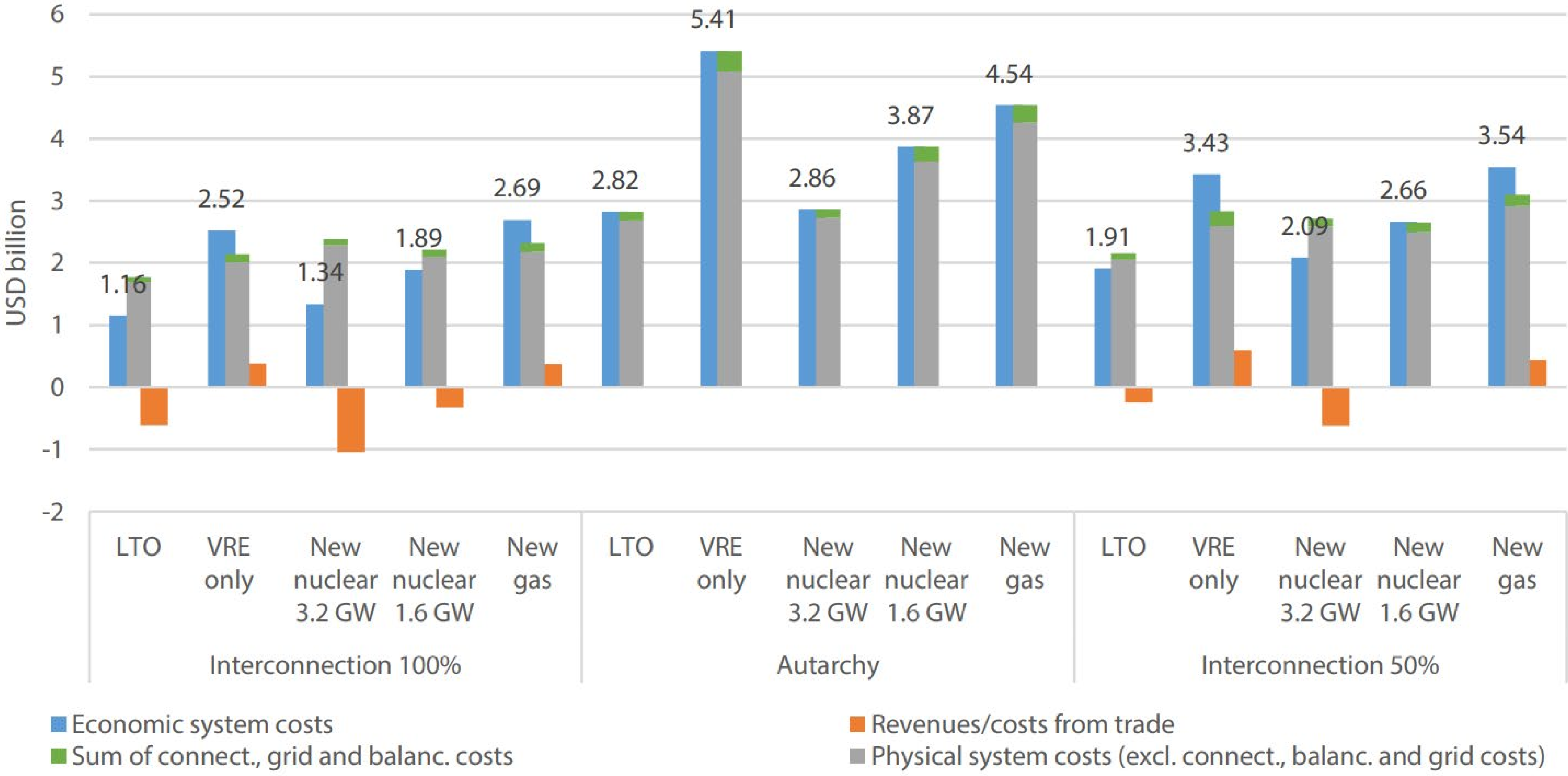


Studie des Fraunhofer-Institut für Solarenergie (D), 2024

OECD Study on Total Costs of Electricity Generation for CH (2022)

PSI

Figure 4.3. **Total system costs of the five net zero scenarios under different electricity trade constellations (USD billion)**

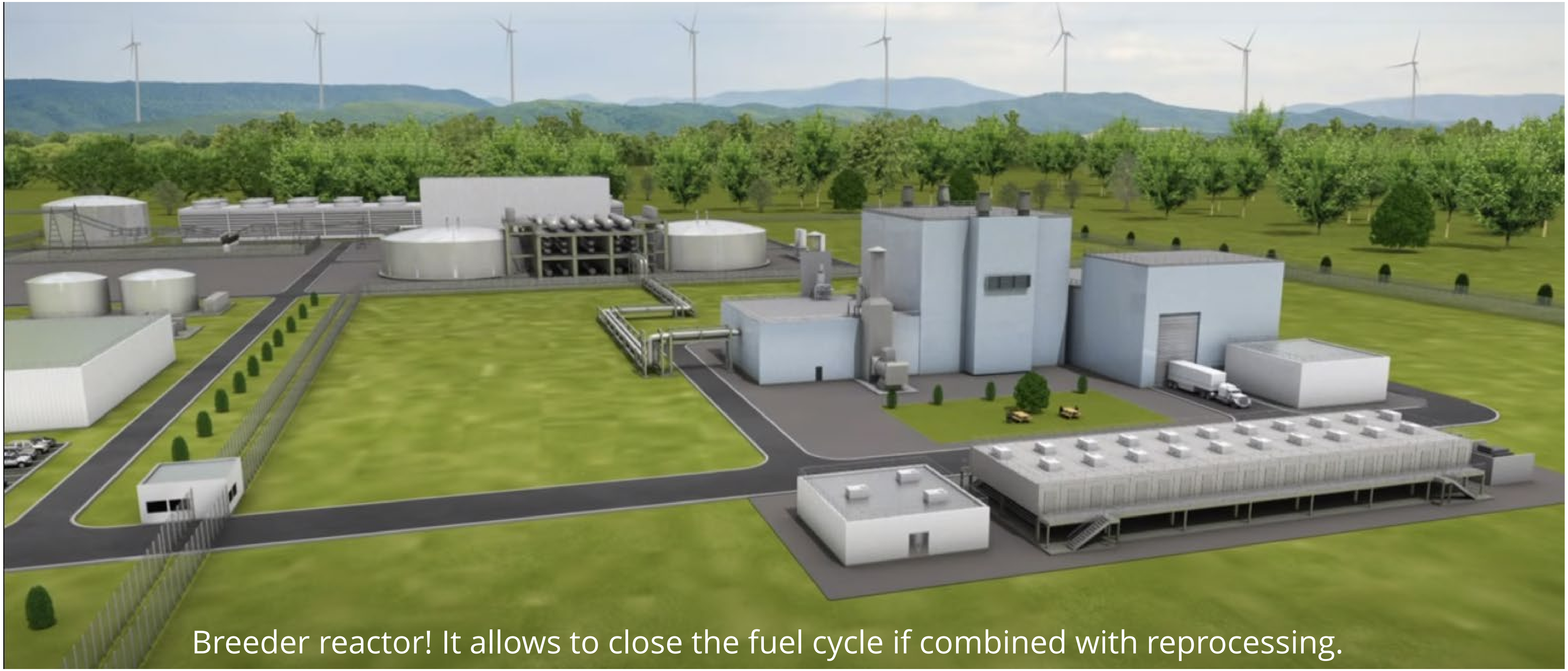


Gen IV / Sodium-cooled SMR

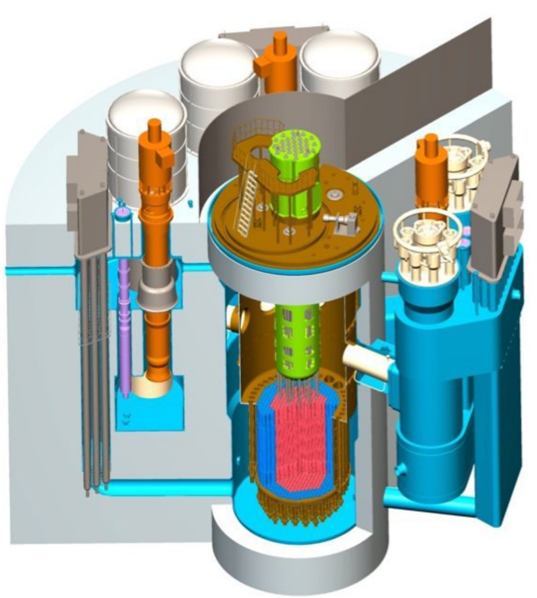
- Gen-IV-Reaktor (sodium-cooled) SMR
- With integrated storage (molten salt)

Construction license submitted in March 2024 (Wyoming)

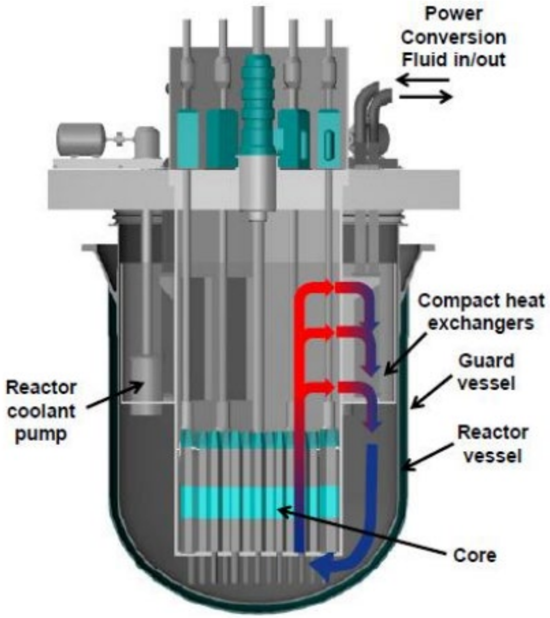
TERRAPOWER – 345 MWe
1 GWh Energy Storage



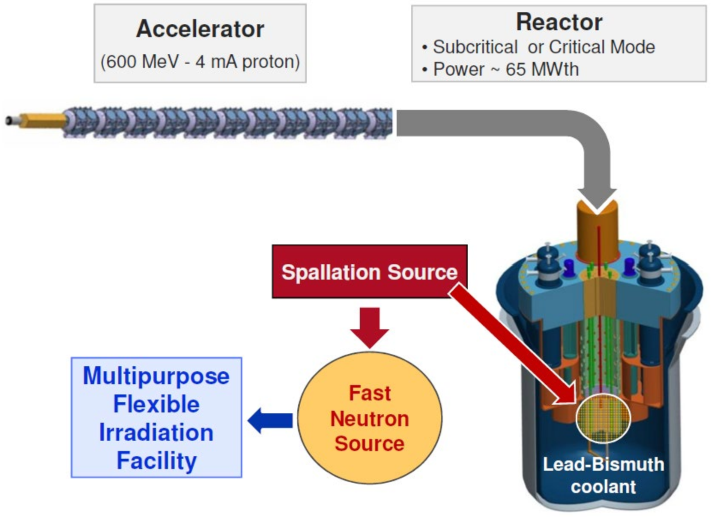
LFR Projects in Construction and Advanced Development



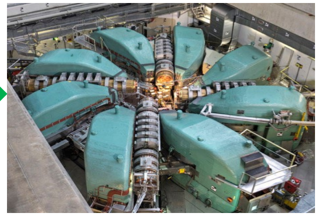
***BREST-OD 300**, the Rosatom LFR demonstrator, completion in 2026*



***Westinghouse Lead Fast Reactor** at 450 MW_e, with a time horizon 2035*



***MYRRHA** at the Belgian Research Center SCK.CEN, Demonstrator for Accelerator-Driven System based on LFR*

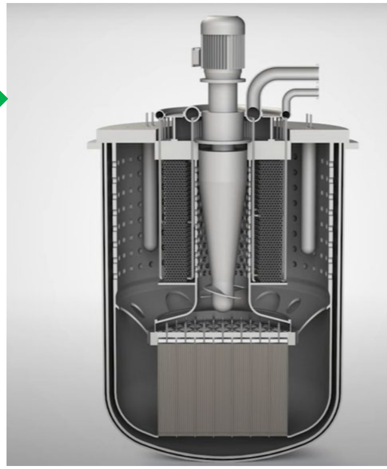


PSI Proton Accelerator

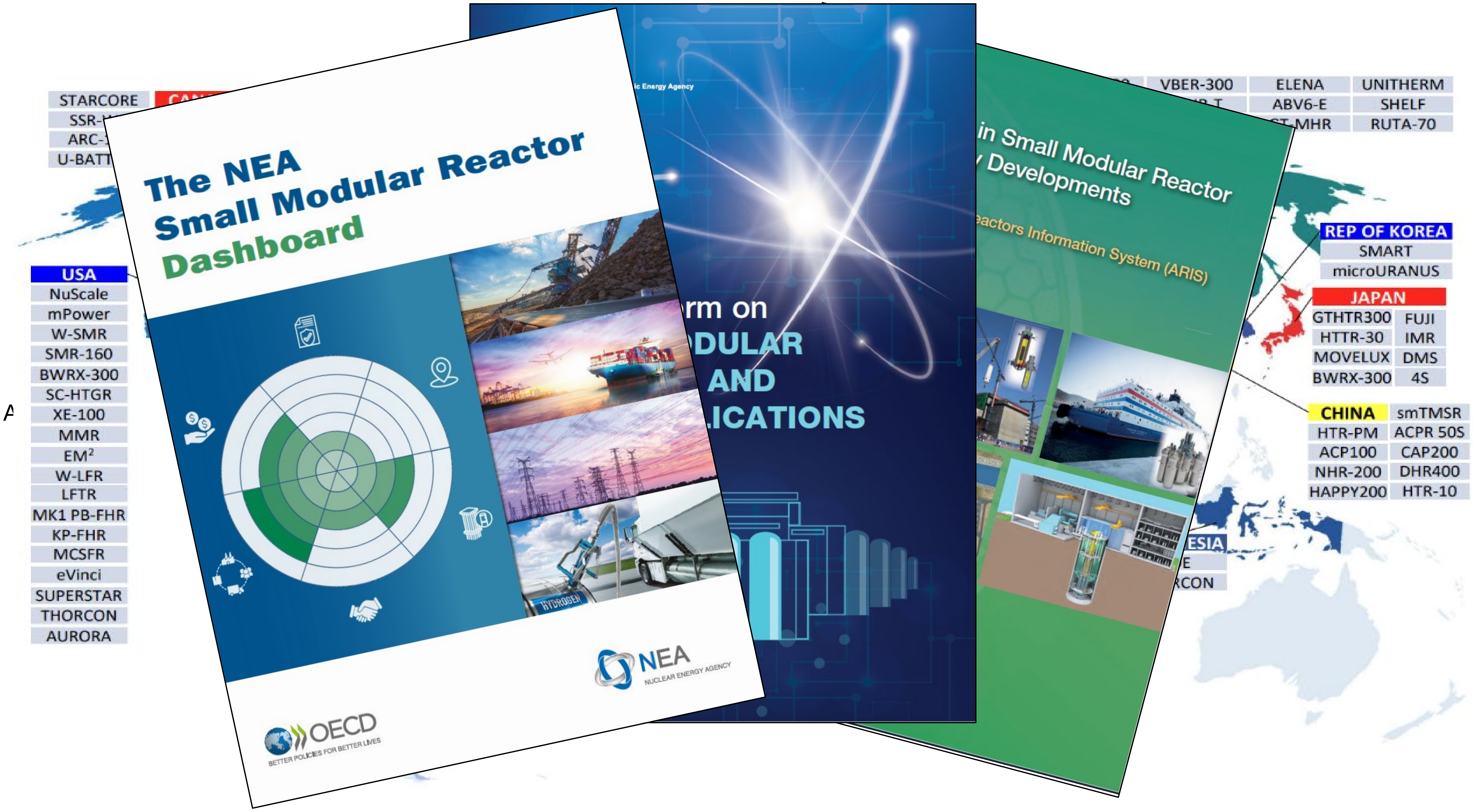
Transmutex START Reactor,
a Swiss startup pioneering ADS/LFR technology for nuclear Waste transmutation

PSI Hot Laboratory

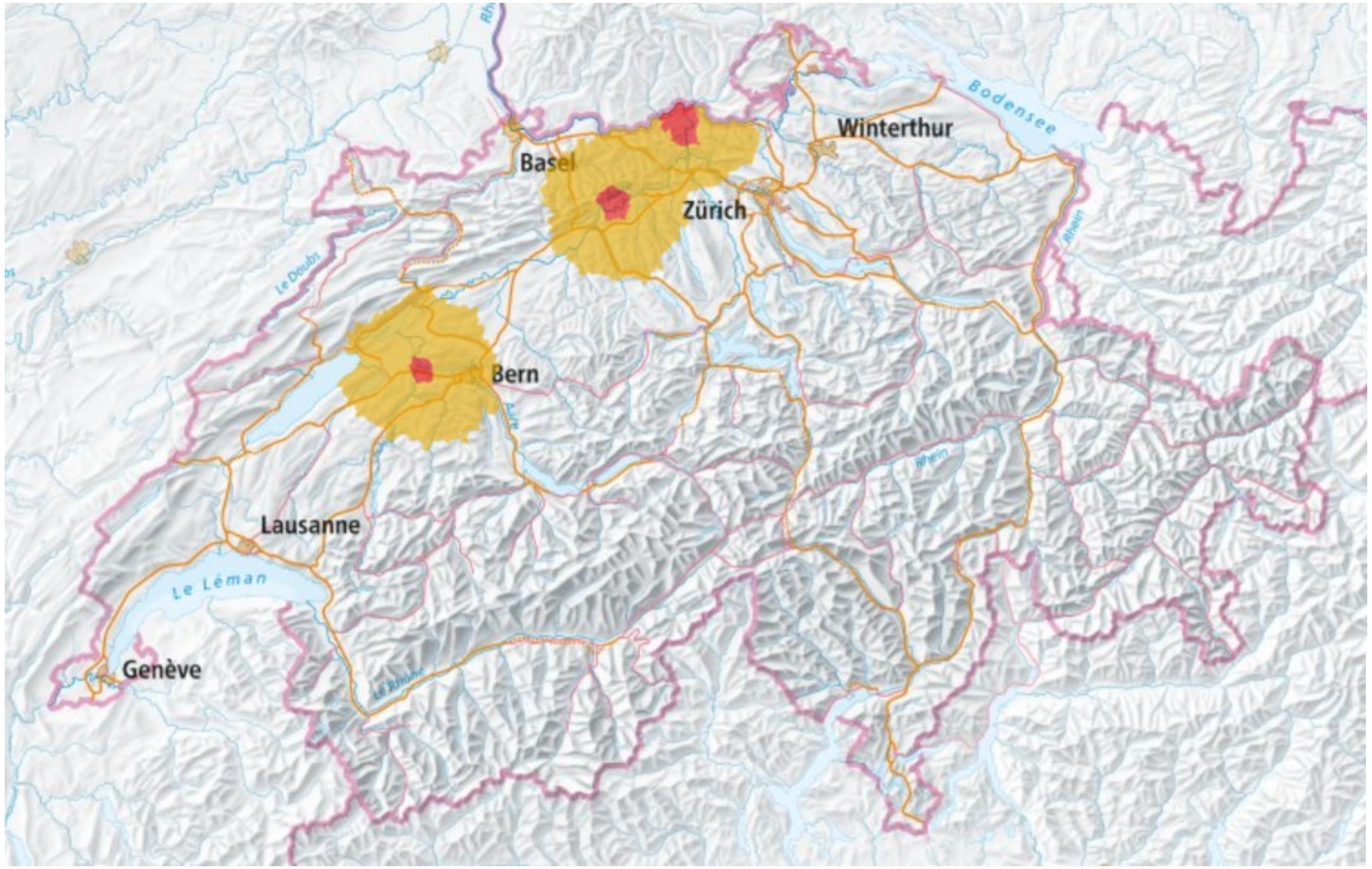
Newcleo AS-30/200,
A one-billion Euro capitalized Startup in UK/IT/CH, developing a Generation-IV LFR

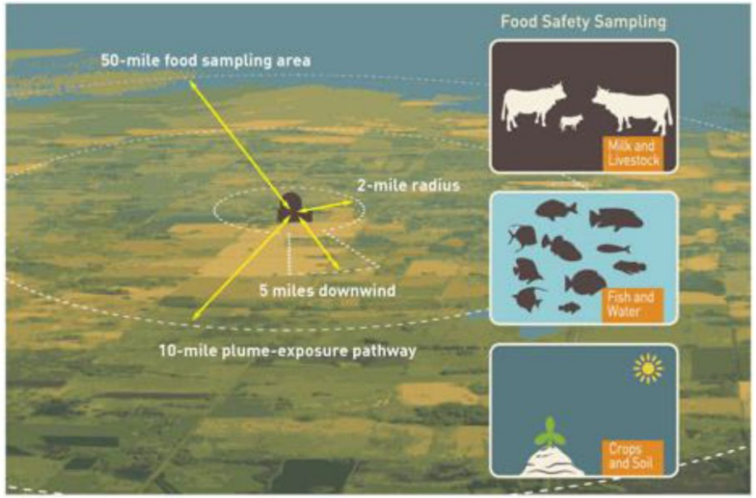


Small Modular Reactors: are they available today?



Notfallplanungszonen





Emergency zones and distances	Suggested maximum radius (km)	
	100 to 1000 MWth	≥ 1000 MWth
Precautionary Action Zone (PAZ)	3 to 5	
Urgent Protective action planning Zone (UPZ)	15 to 30	
Extended Planning Distance (EPD)	50	100
Ingestion and Commodities Planning Distance (ICPD)	100	300

Zones and distances	SMR designs
No off-site EP plan	VK-300, GT-MHR, 4S
Simplified EP plan	CAREM-25, mPower, NuScale, CCR, HTR-PM, G4M
400 meters	PBMR
1000 m, no off-site evacuation	KLT-4S, VBER-300, ABV
1500 m	SMART
2000 m	IRIS
Not specified	IMR, GTHTR300, PASCAR

Microreactors – cogeneration applications

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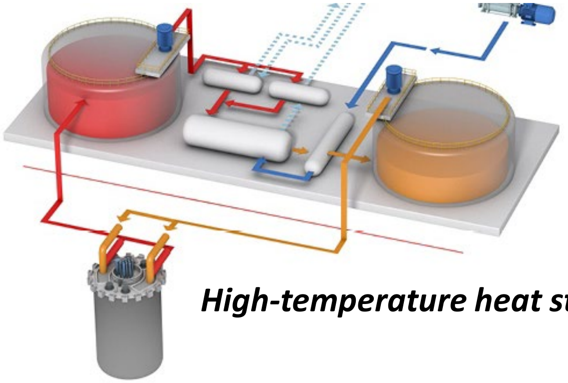


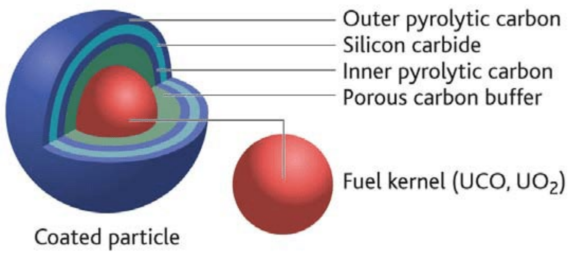
High-temperature heat storage

Reactor available from 2028 onwards

30 + 24 MCHF for reactor + fuel

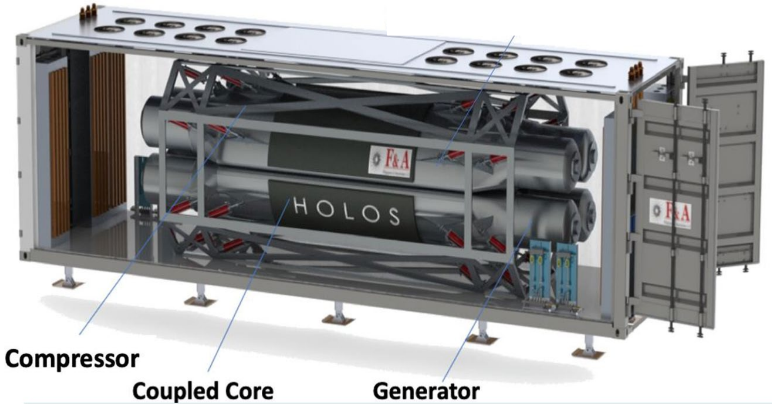
Openness for PPP on vendor's side

LCOE: ~3.6 ct./kWh



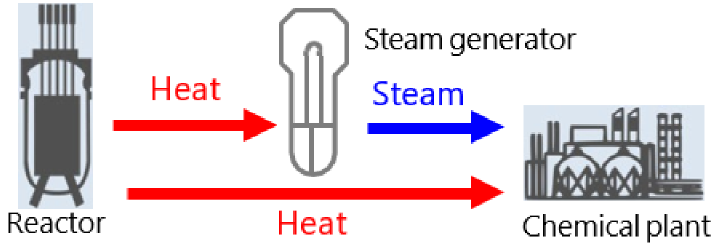
Ultimately safe by reactor and TRISO fuel design ("walk-away safe")

CO_2-neutral concrete production

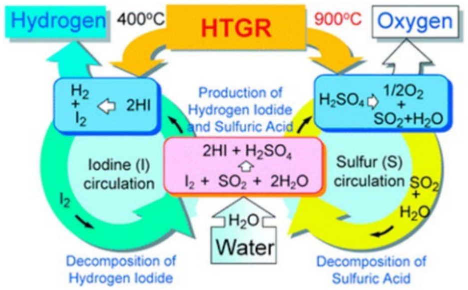


Nuclear microreactor with 30 MW_{th}/14 Mw_{el}, up to 12 years non-stop operation, outlet temperature 900 °C (!)

Potential for radioisotope generation



High quality steam / process heat for wide range of applications (District heating, synfuels, petroleum refining etc.)



Reaktoren der Generation-IV: Nachhaltigkeit?

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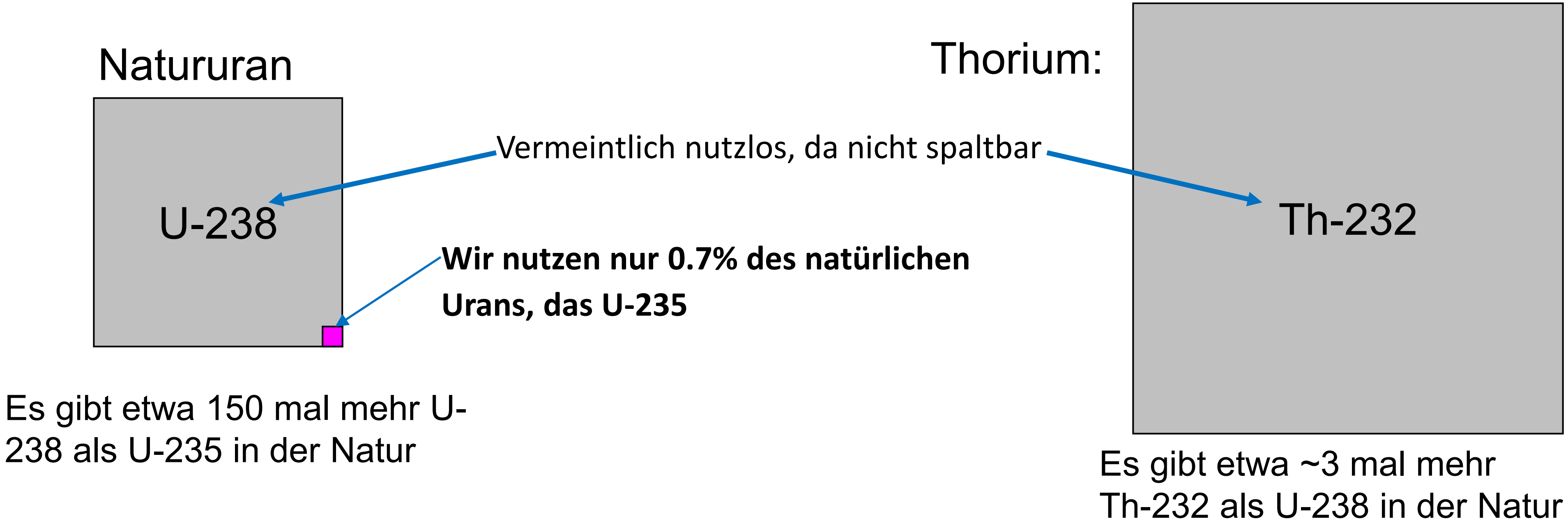
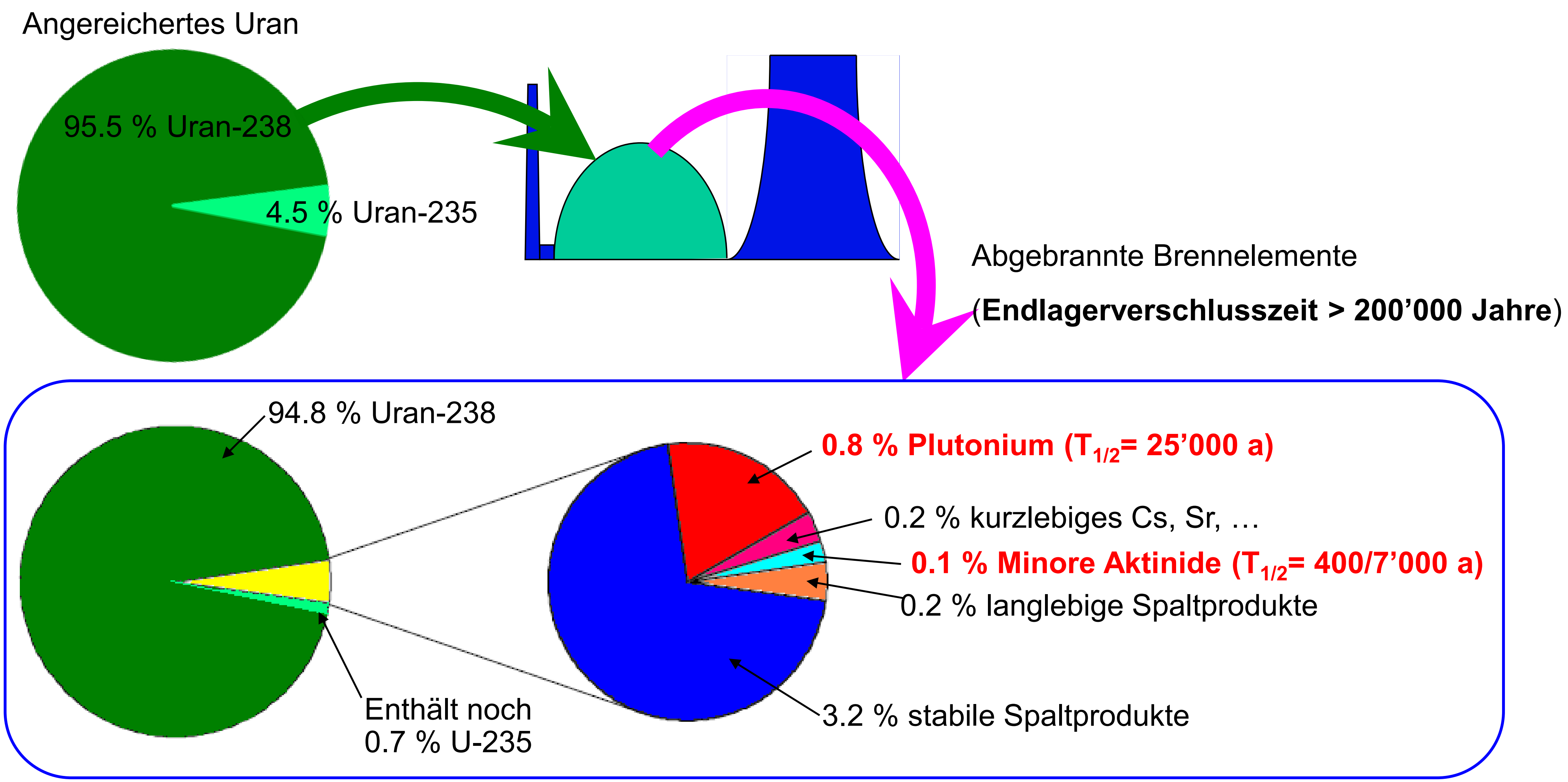
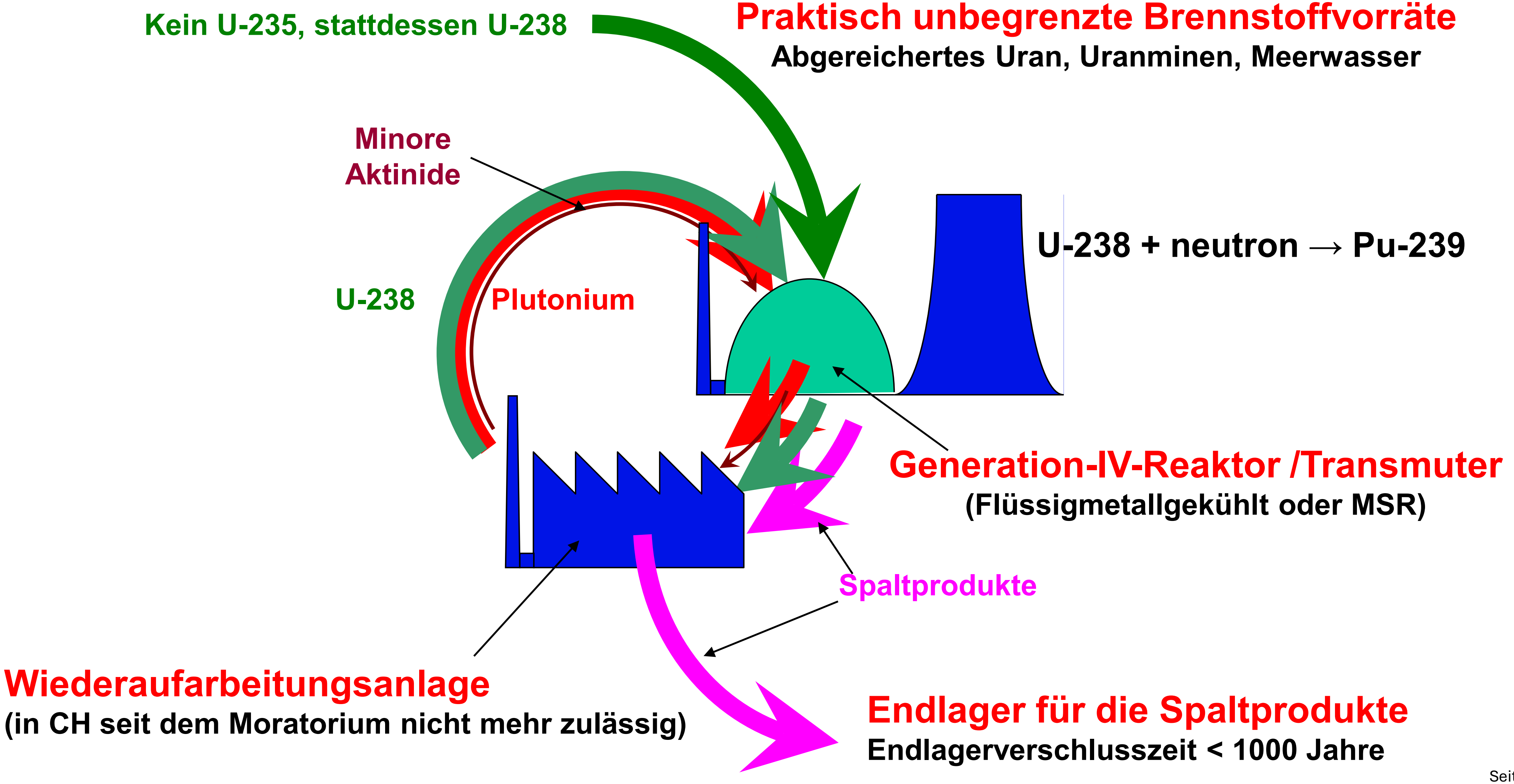
- **Die Generation-IV tritt mit den Zielen an:**
  - Vergleichbares oder besseres Sicherheitsniveau als Generation-III
  - Bessere Ökonomie, z.B. durch SMR-Bauweise, höhere Temperaturen/Wirkungsgrade, **hybride Anwendungen jenseits der Stromerzeugung**, lange Lebensdauer (>60 Jahre)
  - **Reduktion des langlebigen radiotoxischen Abfalls auf ein Minimum und Etablierung einer Kreislaufwirtschaft für die endlichen Uran- und Thoriumressourcen**



Leichtwasserreaktoren: Offener Brennstoffkreislauf



Vollständiges Brennstoffrecycling



Transmutation: das “Erbrüten” von neuem Brennstoff

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Natururan

U-238

Vermeintlich nutzlos, da nicht spaltbar

U-235, 70'000 kWh_{el}/kg U-nat

Das «Arbeitspferd» U-235: spaltbar

Es gibt etwa 150 mal mehr U-238 als U-235 in der Natur

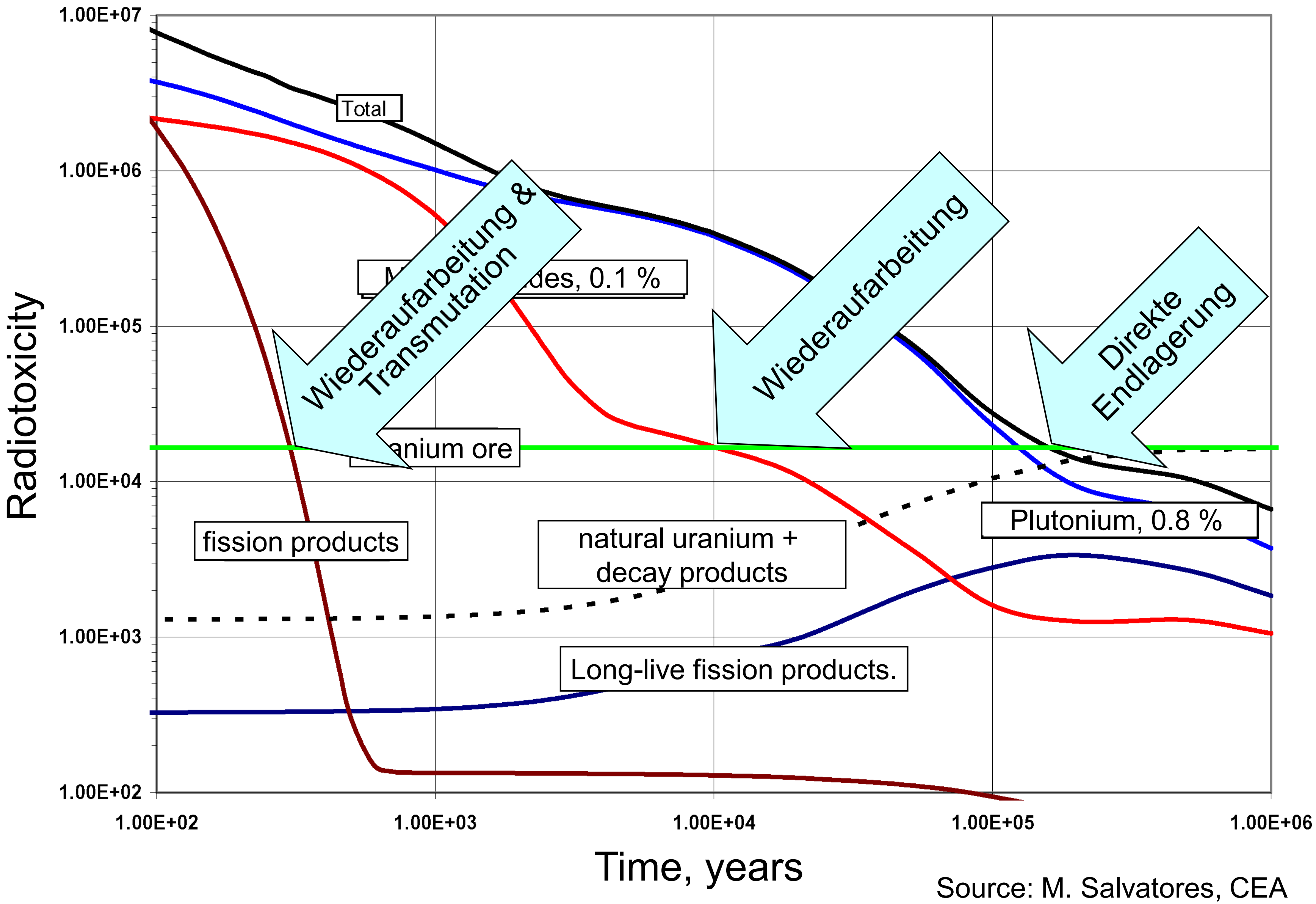
Thorium:

Th-232

Es gibt etwa ~3 mal mehr Th-232 als U-238 in der Natur

Spaltbar!

Transmutation zur Reduktion der Radiotoxizität in abgebranntem Brennstoff



Source: M. Salvatores, CEA

Übergang zu einer perfekten nuklearen Kreislaufwirtschaft

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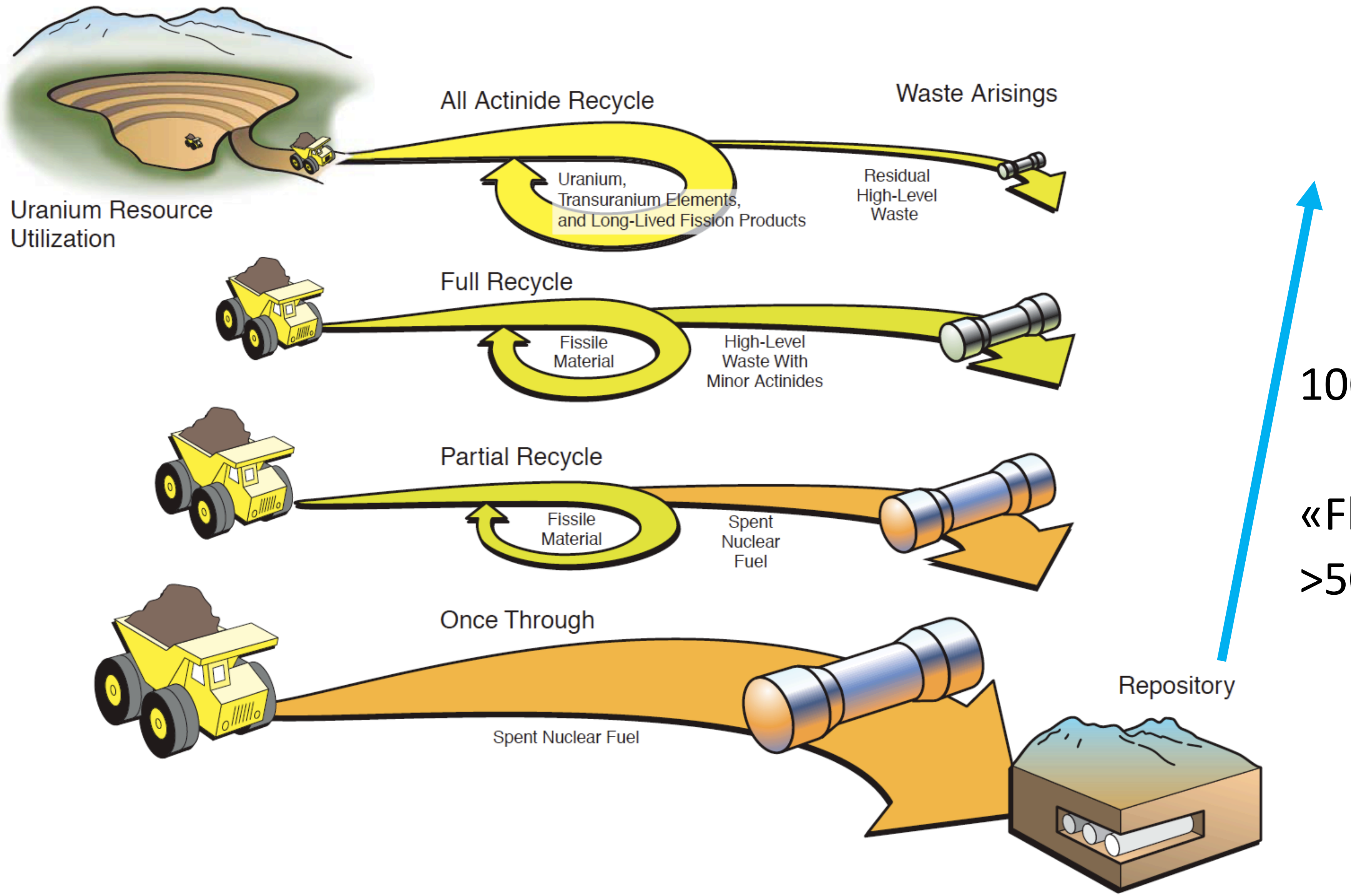
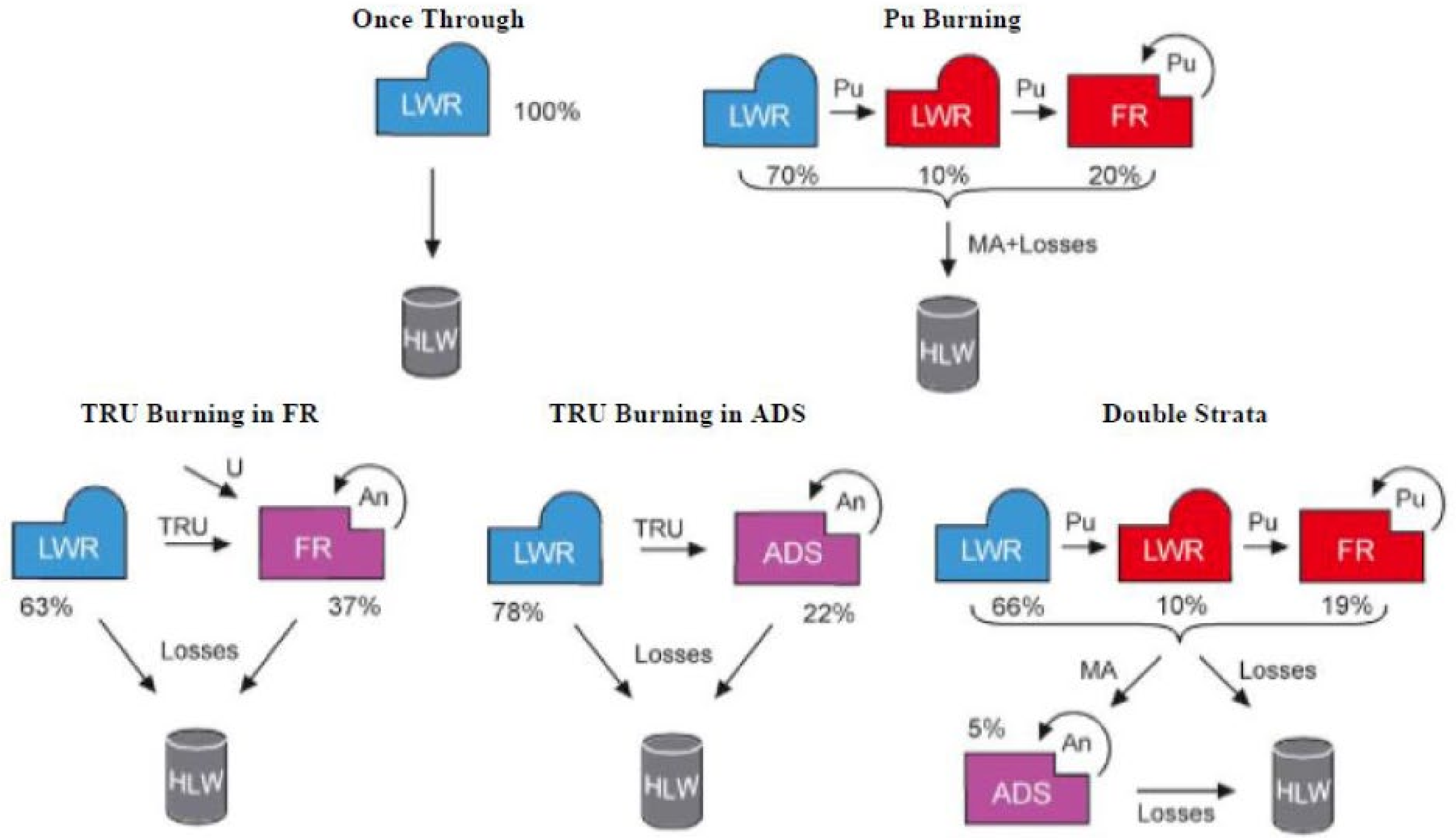


100 Jahre

«Flotte» von

>50 Reaktoren

Französisches Flottenkonzept für vollständige Abfallvernichtung



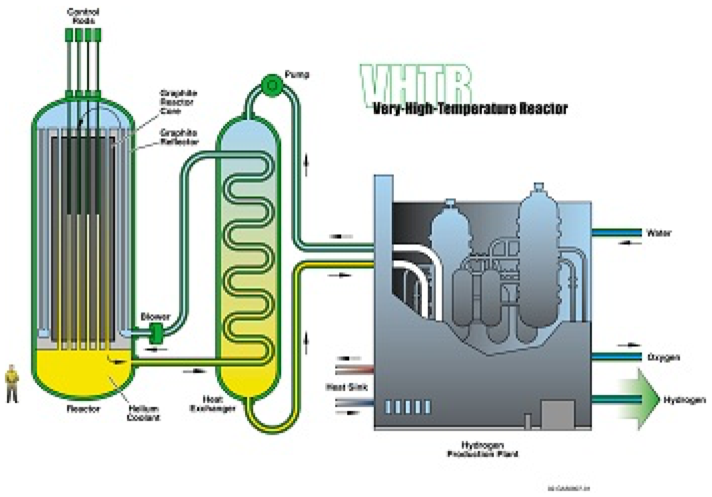
Glossar

PSI

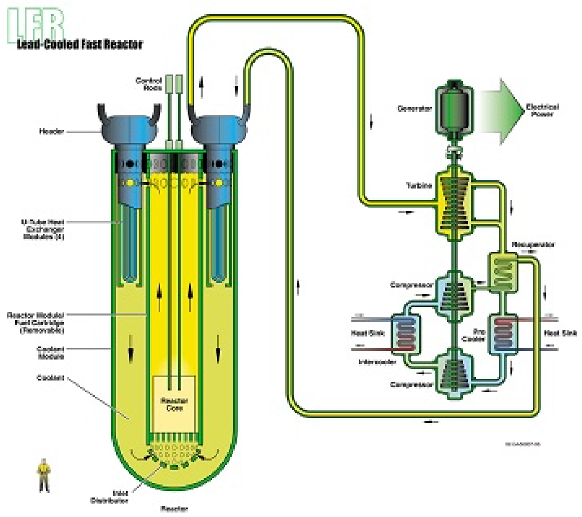
- In herkömmlichen Leichtwasserreaktoren entfallen auf jedes gespaltene Uranatom etwa 0.3 – 0.5 neu erzeugte Plutoniumatome
- In Schnellen Reaktoren können prinzipiell mehr Plutoniumatome erzeugt werden, als Uranatome gespalten werden => der Reaktor «erbrütet» mehr neuen Brennstoff als er verbrennt (!)
- Gleichzeitig kann ein Schneller Reaktor auch fast alle Minoren Aktinide spalten, im Gegensatz zu einem Leichtwasserreaktor
- Damit ist es grundsätzlich möglich, den radioaktiven Abfall auf die Spaltprodukte zu reduzieren, während Plutonium und MA vollständig «verbrannt» (d.h. gespalten) werden
- Ein Endlager wird immer nötig sein, mit einer Verschlusszeit < 1'000 Jahre

Die Reaktorkonzepte der Generation-IV

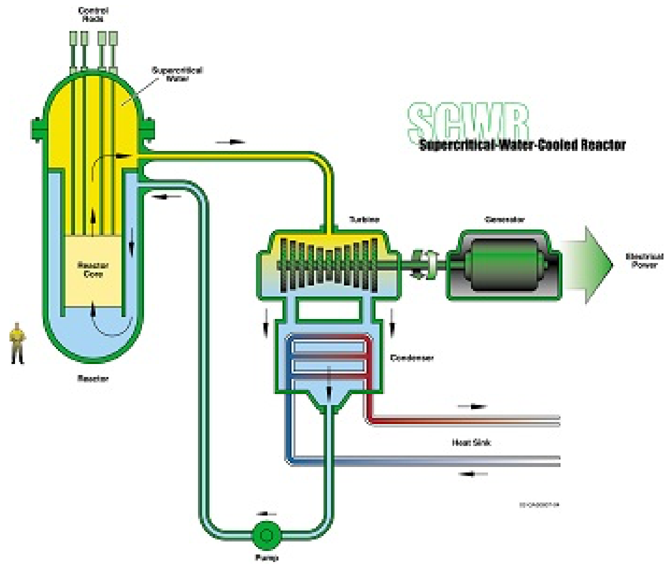
Hochtemperaturreaktor

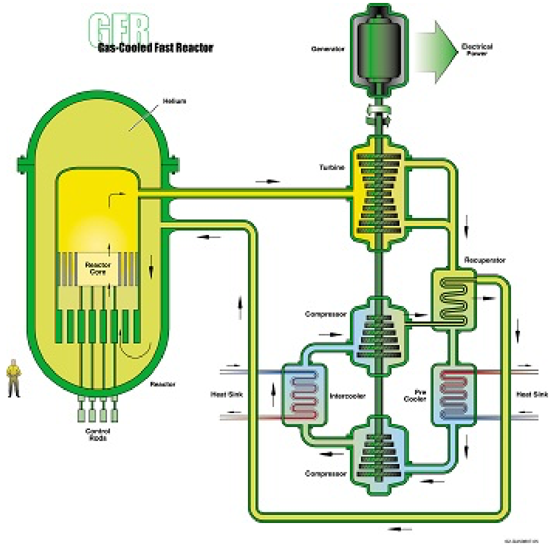


Bleigekühlter Schneller Reaktor

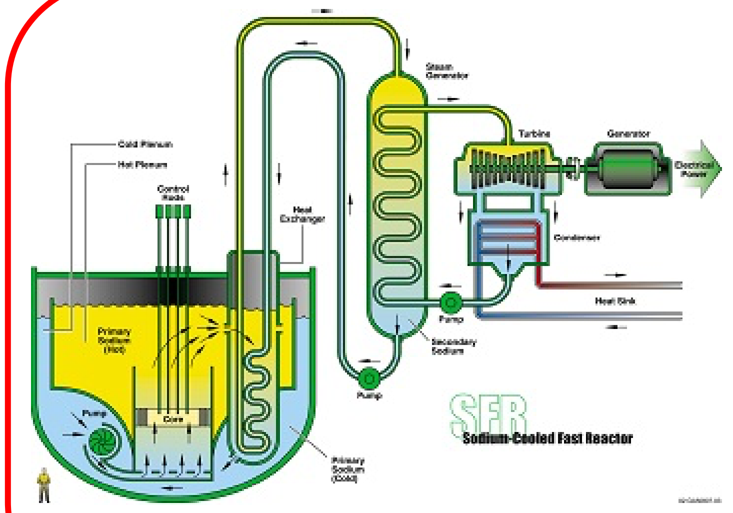


Superkritischer LWR

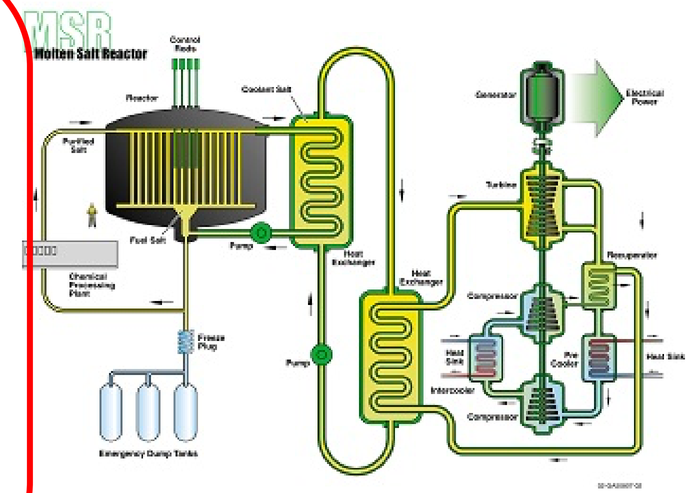




Gasgekühlter Schneller Reaktor



Natriumgekühlter Schneller Reaktor



Salzschmelze-Reaktor

Sodium-cooled Fast Reactor: fact sheet

- **Advantages**
  - — Potential for **new fissile breeding** due to fast neutron spectrum
  - — Excellent thermal conductivity of sodium → **VERY efficient cooling**
  - — Large margin to boiling → **no pressurization required**
  - — **Significant operational experience** (300+ reactor-years)

- **Challenges**
  - — **Chemically active** in contact with water or air → intermediate circuit needed
  - — **positive reactivity effect** → special safety measures needed

- **Designs under development**
  - — PFBR (India), BN-1200 (Russia), ASTRID (France), ESFR (EU), Natrium™

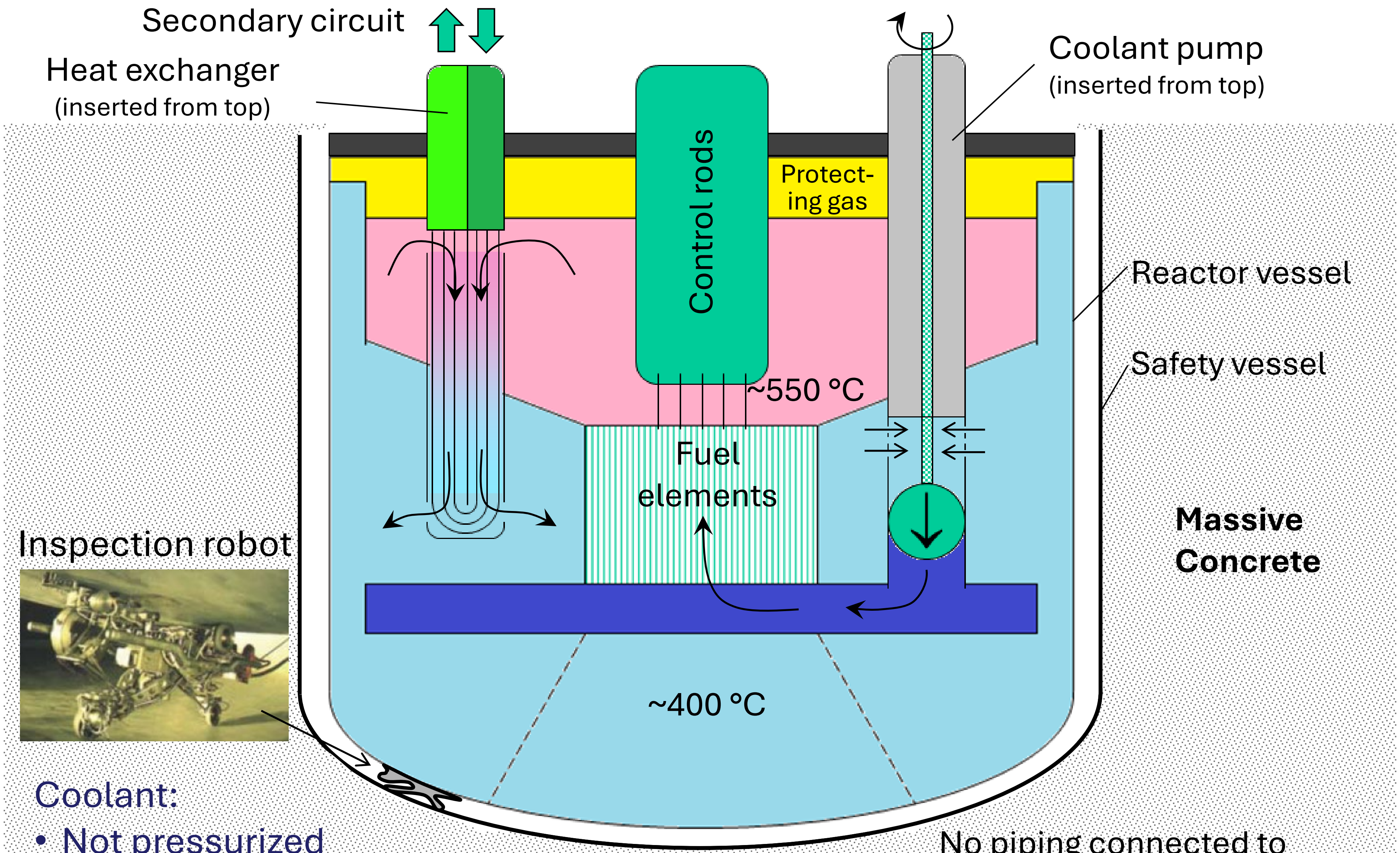
- **Several reactors under operation!**
  - — BN-600, BN-800 (all Russia), CFR-600 (China) since 2023

Fast Breeder Reactor BN-800, Beloyarsk, Russia

Chinese Fast Reactor CFR-600, Units 1 & 2, Xiapu

Rosatom/TVEL fuel production facility for CFR-600 and BN-800

Principle of Pool-Type Reactors: SFR



Coolant:

- Not pressurized
- Leak deterministically excluded

No piping connected to reactor vessel

ESFR (EU): primary system

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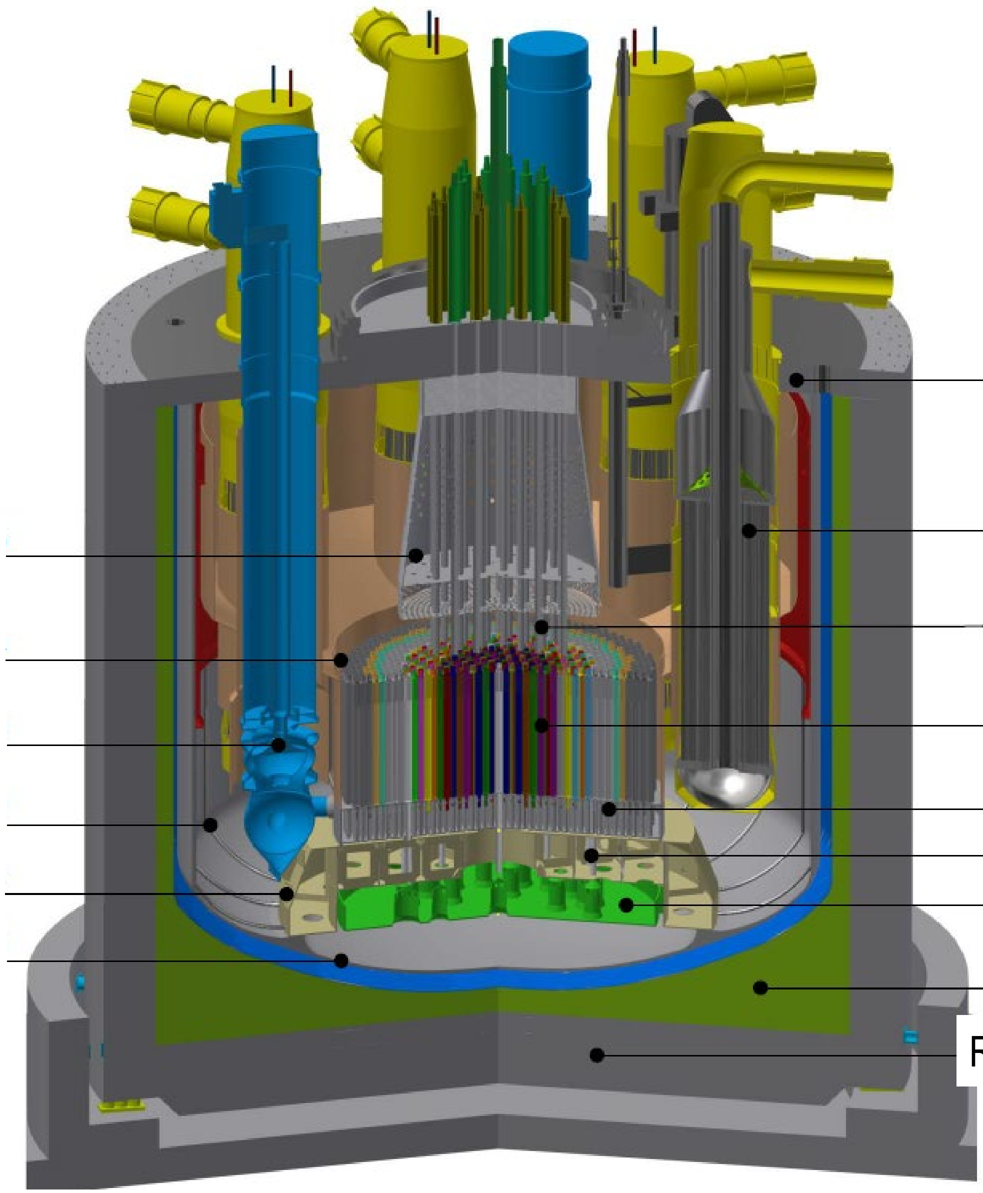

ESFR (EU): global view from above

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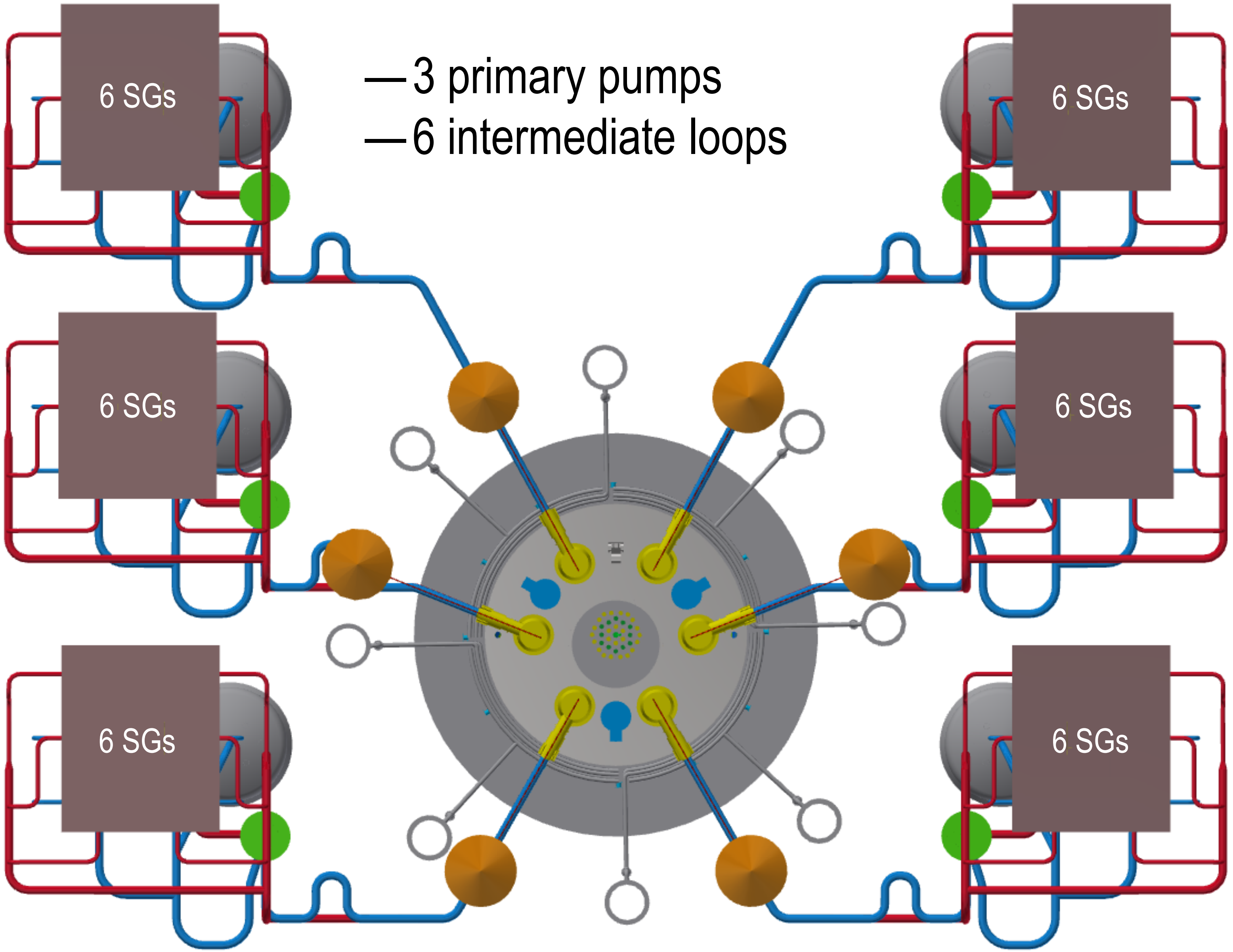
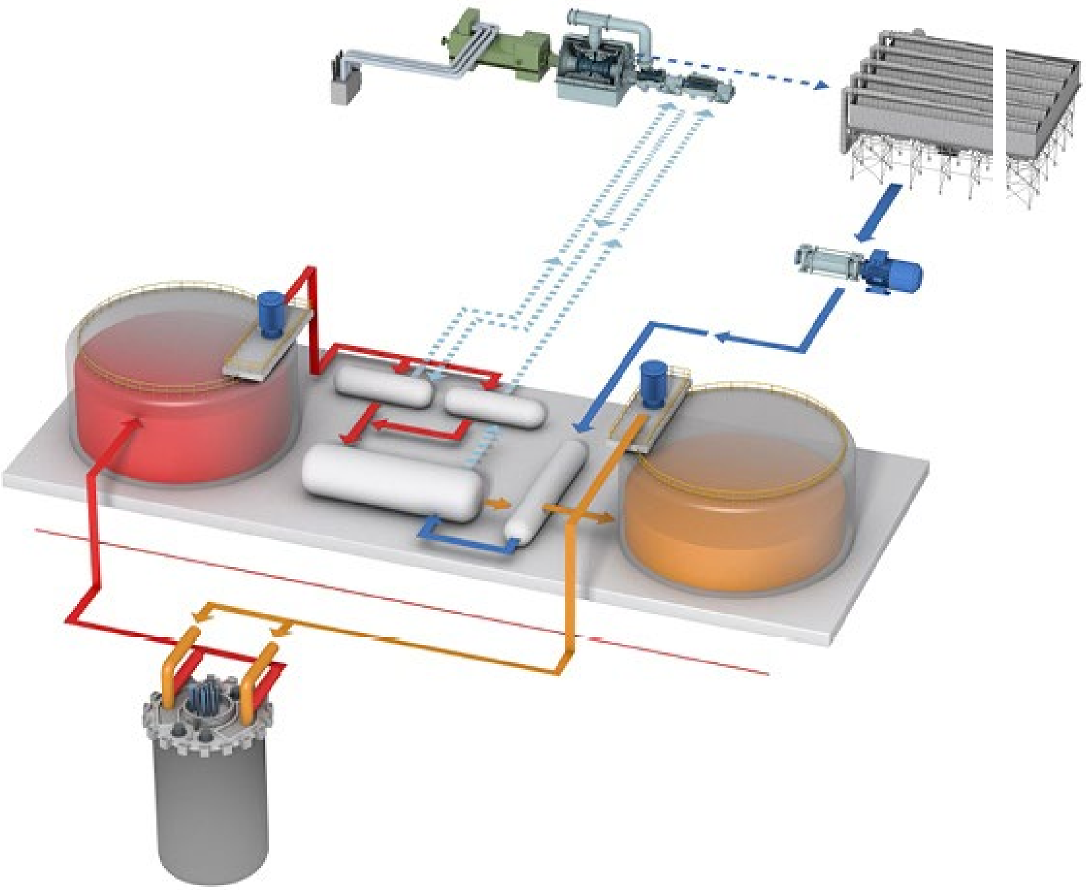
- 3 primary pumps
- 6 intermediate loops



SMR der Generation-IV mit Hochtemperaturanwendungen

PSI



- **Natrium™**, ein mit flüssigem Natrium gekühlter Reaktor mit 345 MW_e Leistung und einer Kühlmitteltemperatur **um 550 °C**

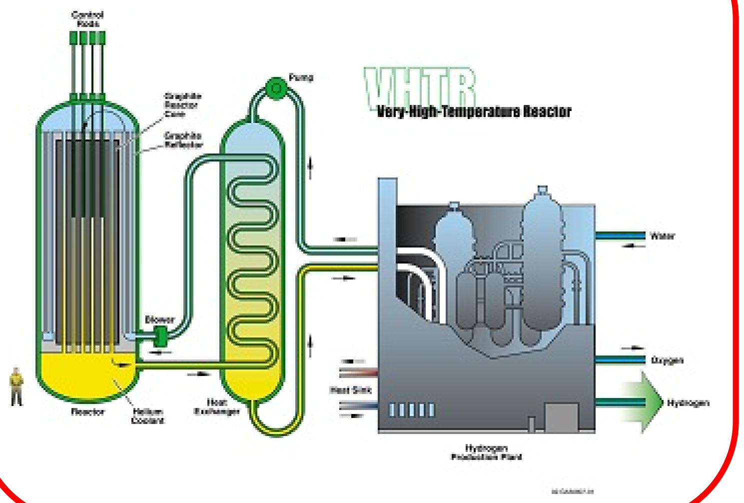
- Der Reaktor ist an einen **thermischen Salzschmelzespeicher** gekoppelt, der ca. 1 GWh Energie speichern kann. Damit kann die Anlage über mehrere Stunden die **Leistung auf 500 MW_e erhöhen**

- Wird seit 2008 von der Firma Terrapower mit Unterstützung von **Bill Gates und Warren Buffett** entwickelt.

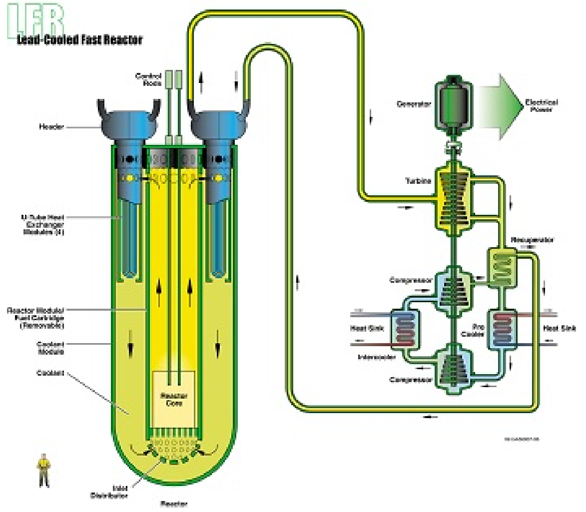
- **Die Anlage soll voraussichtlich bis 2028 am Standort Kemmerer (Wyoming) fertiggestellt werden**

Die Reaktorkonzepte der Generation-IV

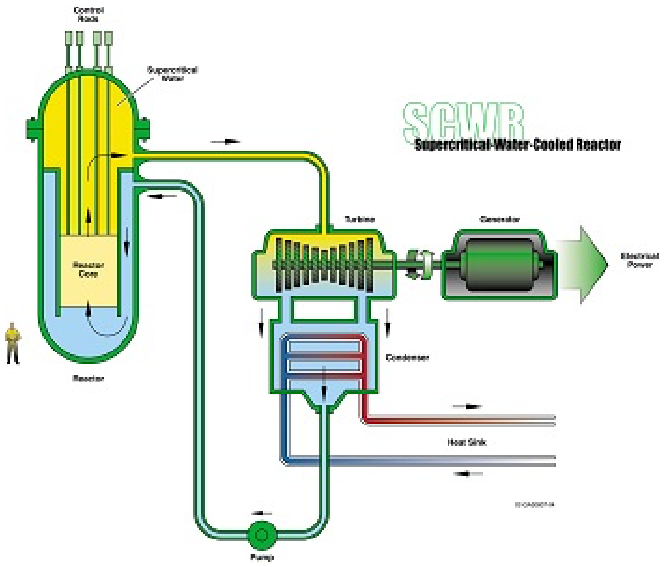
Hochtemperaturreaktor

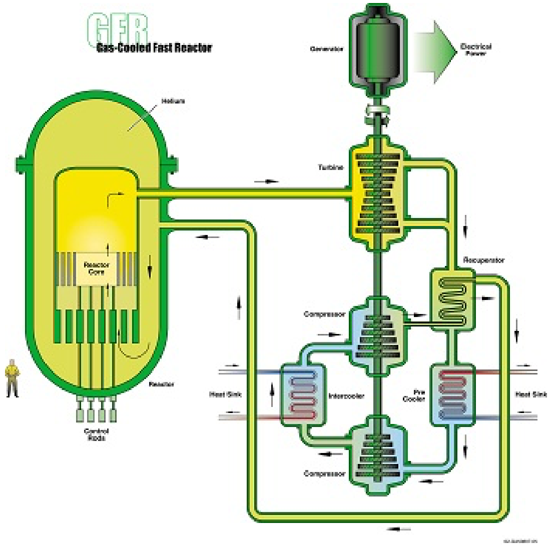


Bleigekühlter Schneller Reaktor

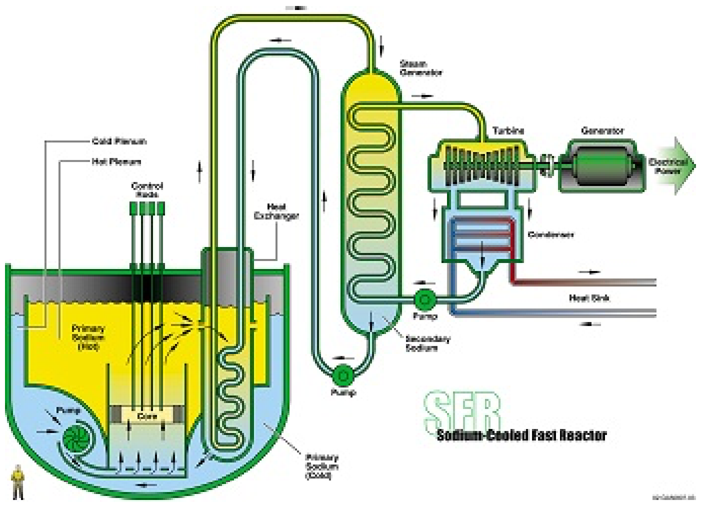


Superkritischer LWR

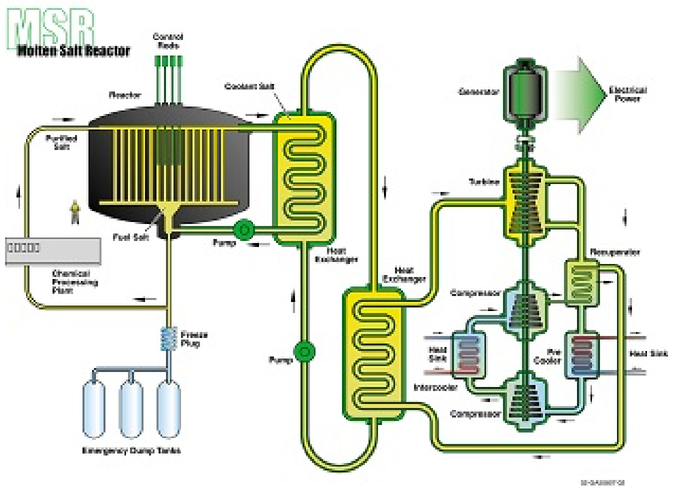




Gasgekühlter Schneller Reaktor



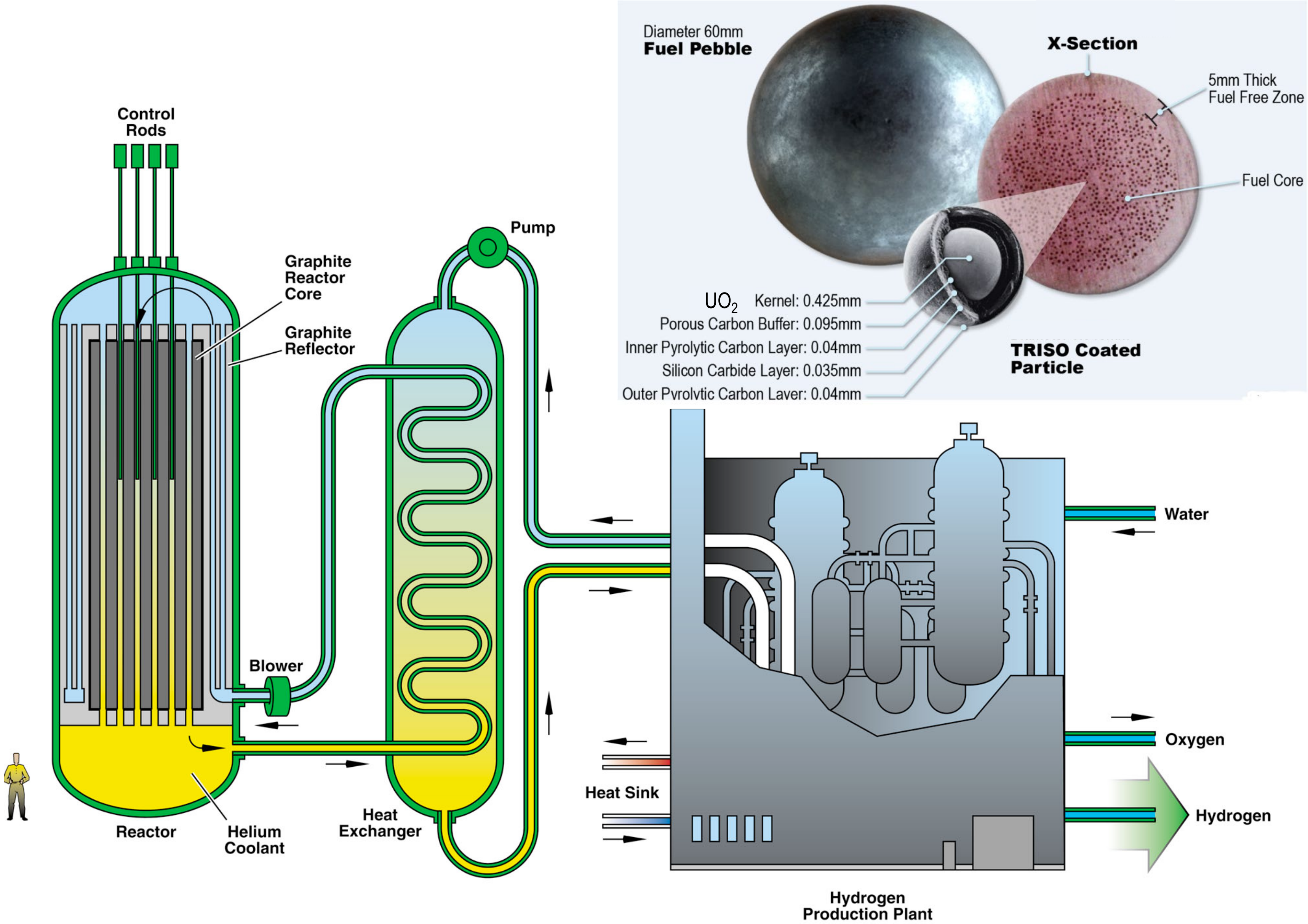
Natriumgekühlter Schneller Reaktor



Salzschmelze-Reaktor

Generation-IV: Hochtemperaturreaktor

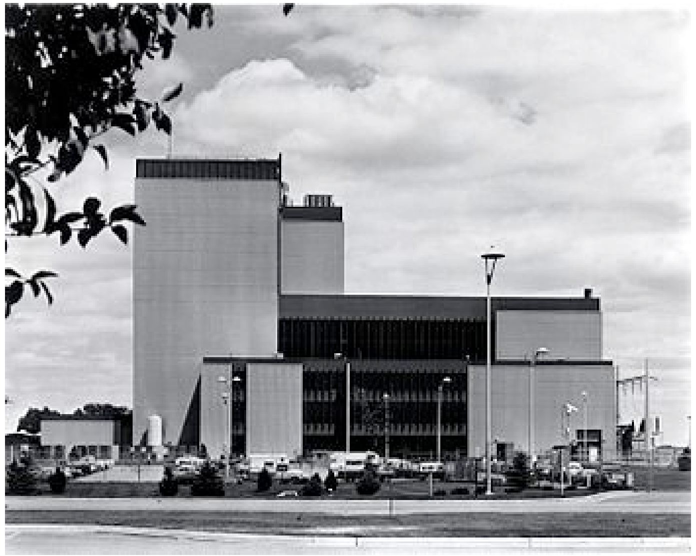
PSI



- **Power**: 300 to 600 MWt
- **Coolant**: Helium, under pressure (40 – 90 bar)
- **Moderator**: Graphite
- **Coolant temperature at the outlet of the core**: 850°C to 1000°C (or more)
- **Fuel**: Uranium low enriched (8 to 15%); pebbles or compacts

Betriebserfahrung von frühen Hochtemperaturreaktoren

PSI



USA

Fort St. Vrain

1976 -1989

Burnup up to 90 MWd/kg

P = 842 MW_{th}, 330 MWe

Helium : 350°C / 750°C

- Prismatic fuel compacts, Mixed U/Th-Oxide Fuel
- Severe corrosion issues with the Helium circulators
- Testing of materials under the flux
- Thermal efficiency 39%, good load-follow capabilities

GERMANY

THTR-300

1985-1988

P = 760 MW_{th}

307 MW_{e}

Helium Tmax: 750°C

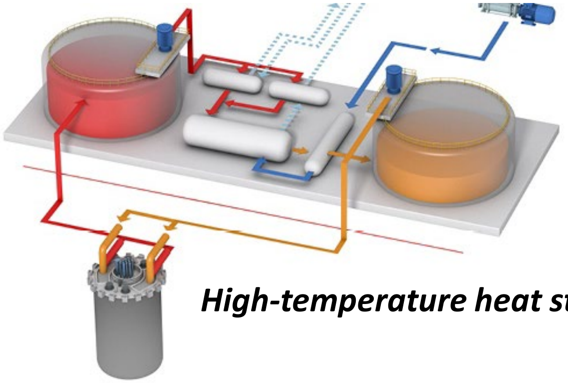
(inlet temperature 250 °C)

- 423 Full Power Days Operation only
- Mixed U/Th-Oxide Fuel
- Significant number of damaged fuel pebbles
- Radioactive release at the same time as Chernobyl
- No mature reprocessing concept

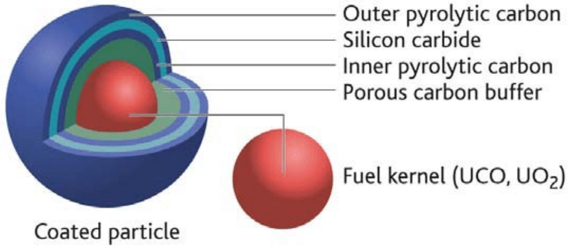
Nukleare Kogeneration für industrielle Anwendungen

PSI

Reactor available from 2028 onwards
30 + 24 MCHF for reactor + fuel
Openness for PPP on vendor's side



High-temperature heat storage



Ultimately safe by reactor and TRISO fuel design ("walk-away safe")

CO_2-neutral

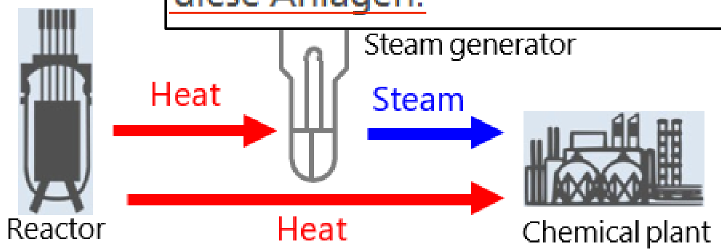
generation

Art. 12 Bewilligungspflicht

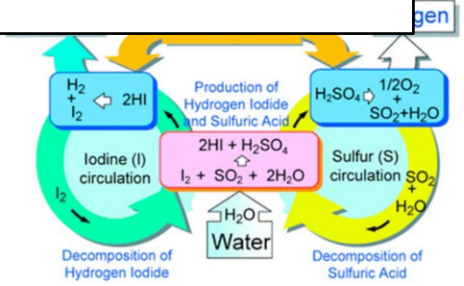
1 Wer eine Kernanlage bauen oder betreiben will, braucht eine Rahmenbewilligung des Bundesrates. Vorbehalten bleibt Artikel 12a.[7]

2 Auf die Erteilung einer Rahmenbewilligung besteht kein Rechtsanspruch.

3 Kernanlagen mit geringem Gefährdungspotenzial bedürfen keiner Rahmenbewilligung. Der Bundesrat bezeichnet diese Anlagen.

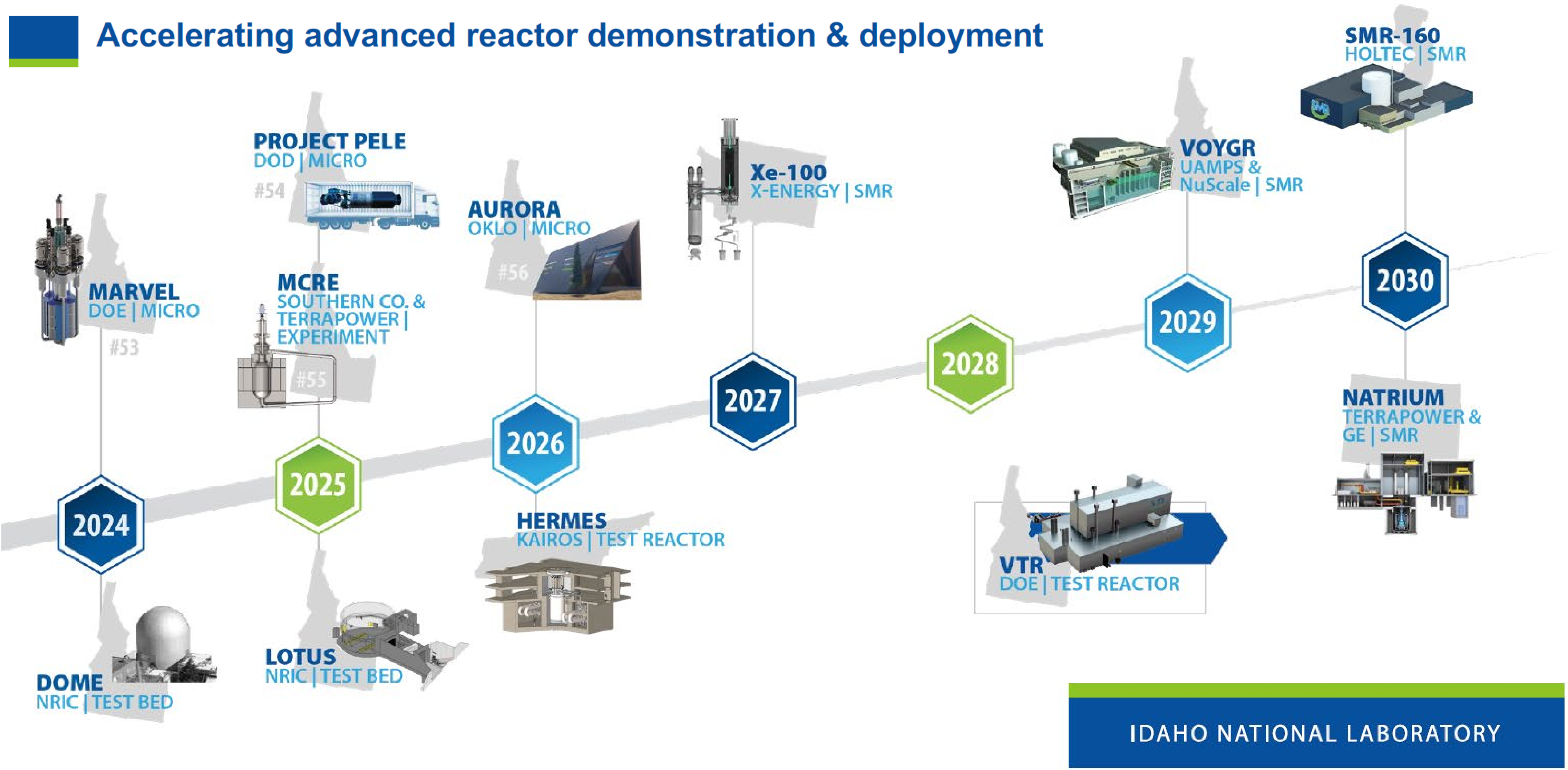


High quality steam / process heat for wide range of applications (District heating, synfuels, petroleum refining etc.)



Efficient high temperature H_2 production (thermochemical or electrochemical)

Zeitperspektive neuer Reaktor-Prototypen in den USA



Floating reactors

AKA
Operat

Reacto
PWR

Refere
32 MV

Constr
15 Ap

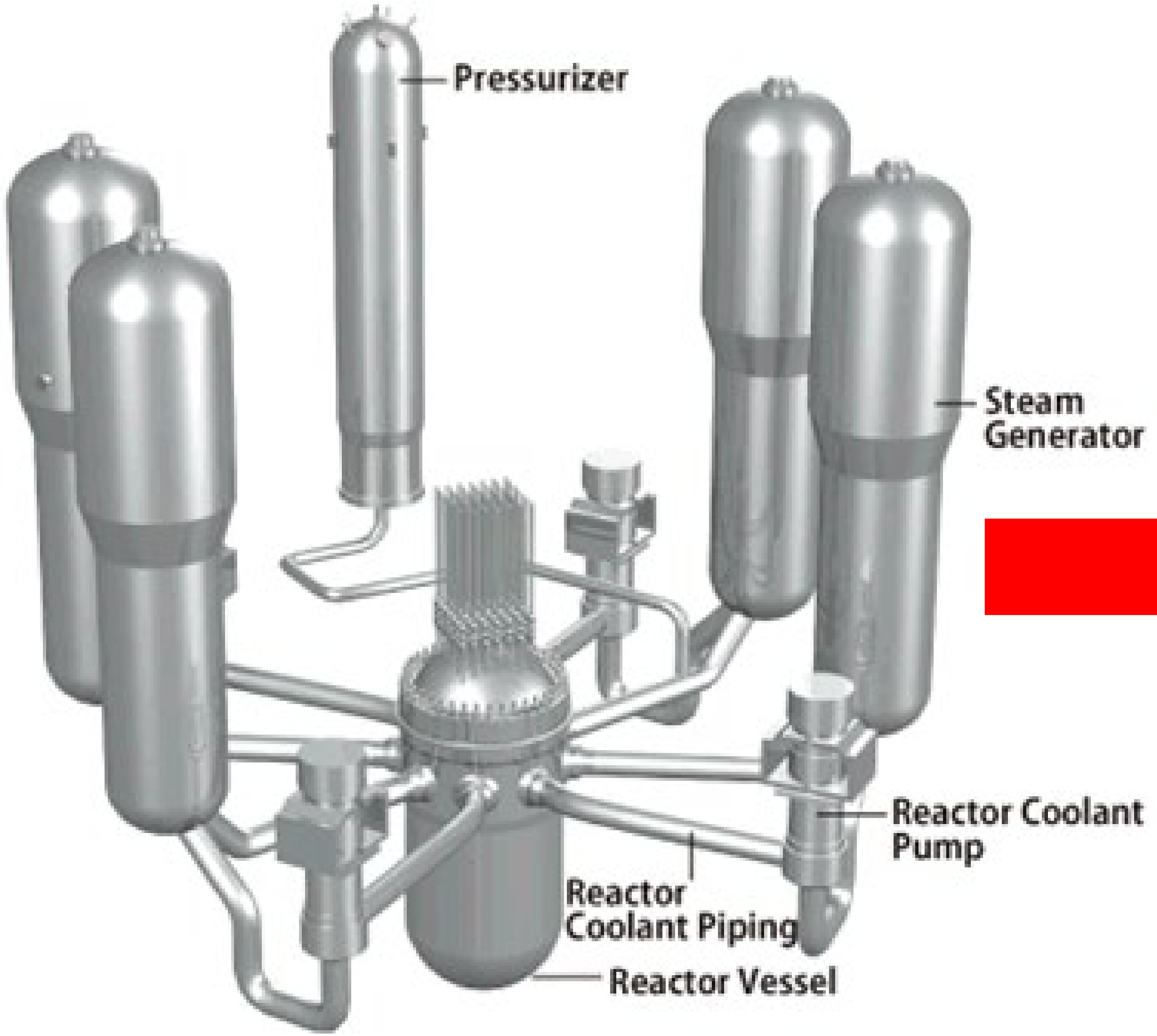
First G
19 De

oncern

Operator
Joint Stock Company 'Concern Rosenergoatom'

Thermal Capacity
150 MW_t

Grössenvergleich SMR gegen grosse Leichtwasserreaktoren (1000 MW)



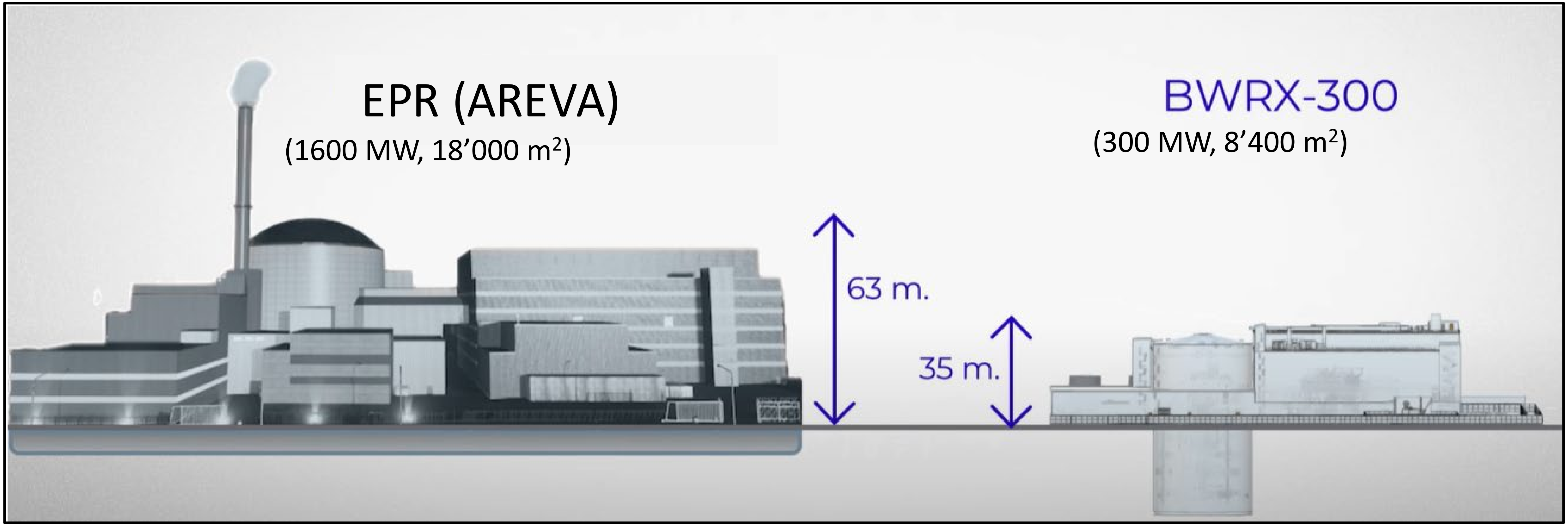
RITM-200 on Russian Icebreaker (55 MW_{el})

The Answer: Small Modular Light Water Reactors (LWR-SMR)?

PSI

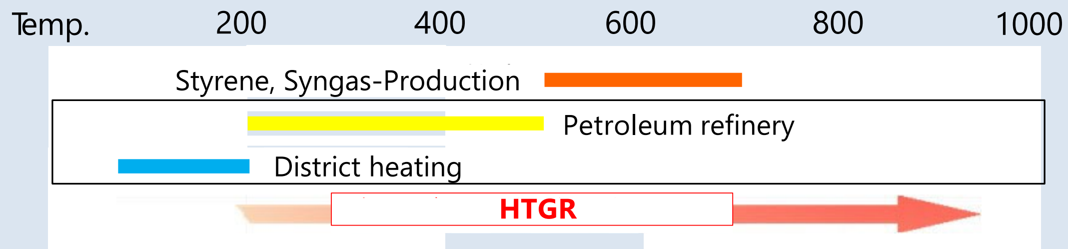
- Power up to ~300 MWe
- Smaller / less monolithic units and therefore reduced CAPEX
- Modules are factory-built and factory-tested before installation on site
- Significant shorter construction times for individual modules (goal: 2 – 4 years)
- Higher flexibility to better integrate with renewables
- Transportable by truck, train, boat or plane
- Applications include heat to isolated sites not connected to the electric grid
- Compact design allows the possibility for underground construction
- Passive safety
- „Walk-away" safe and therefore significant reduction of emergency planning zone (EPZ), which is limited to plant site perimeter (no evacuation zone required:
    - NuScale licensed 500 meter perimeter, 1 km for GE-Hitachi BWRX-300)

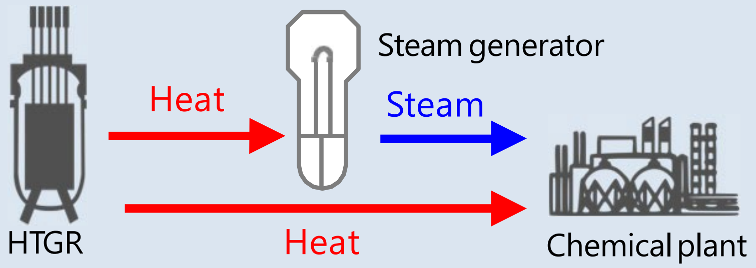
Large LWR vs. LWR-SMR: Comparison in Size



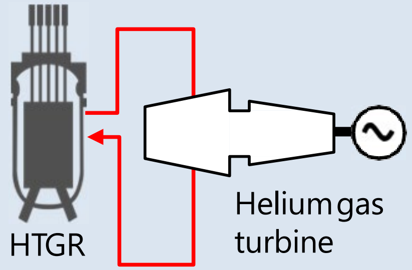
Applications for Combined Heat & Electricity (Hybrid) Generation

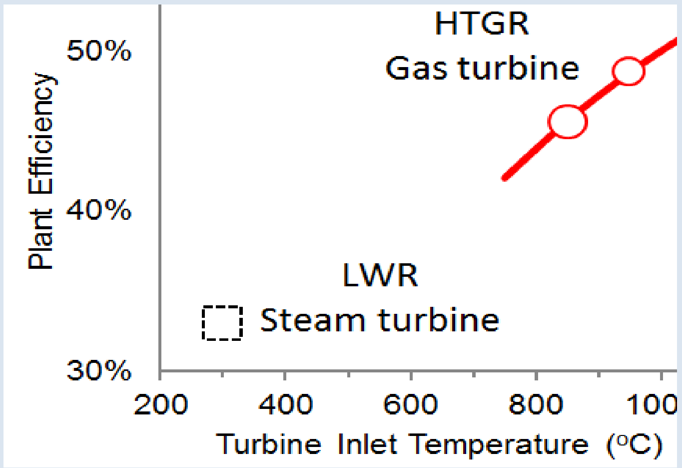
Industrial use of nuclear heat

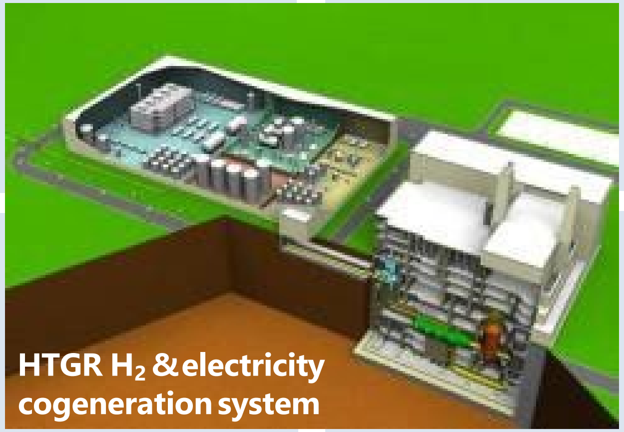




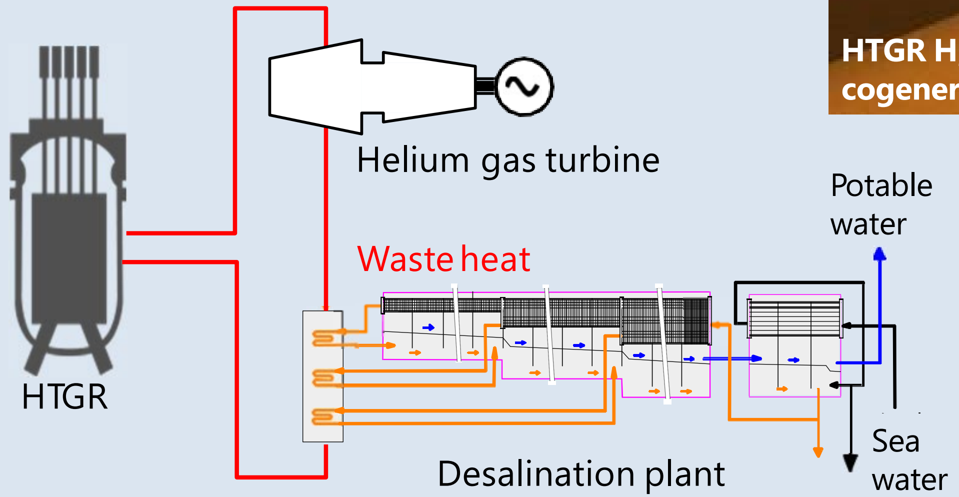
High Efficient Gas Turbine Power Generation



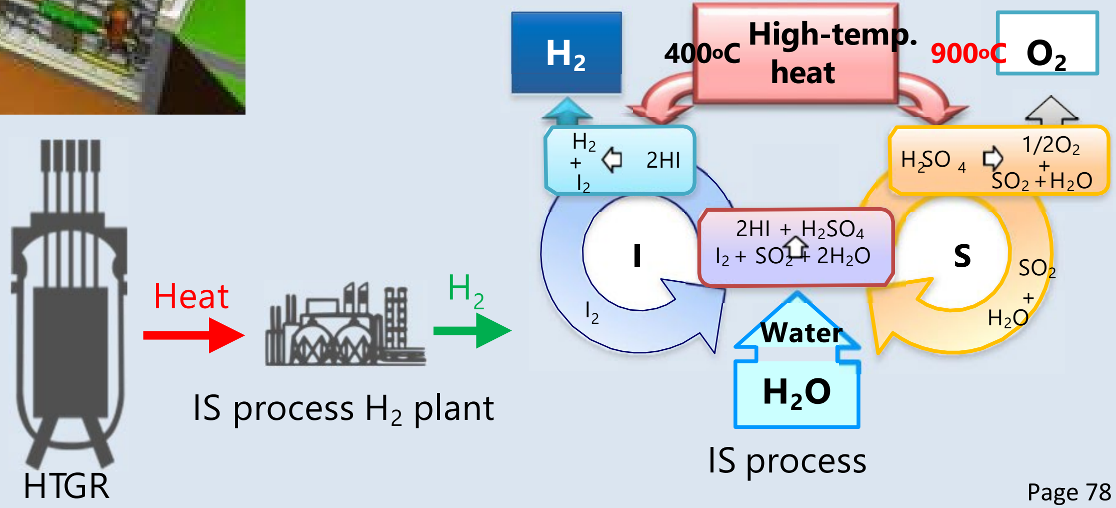




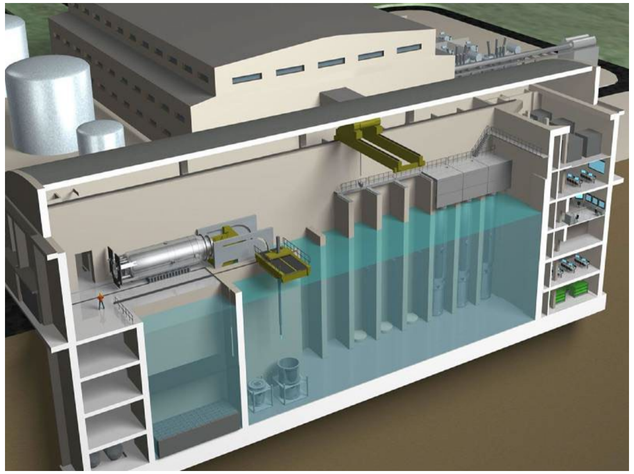
Desalination using waste heat



Carbon-free H_2 production

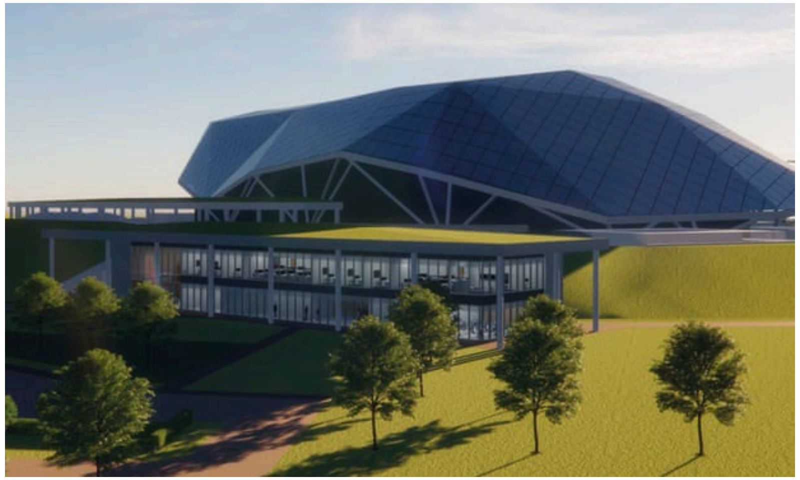


SMR (Generation-III) with Credible Time Horizon around 2030



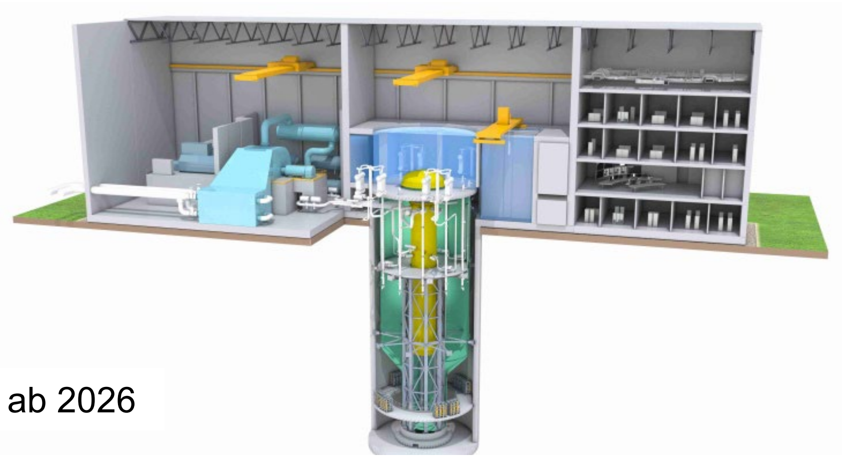
NuSCALE (6x77 MW), Utah contract canceled
LCOE> 95$/MWh, 6'000 $/kW installed

UWARD (EdF/Technicatome), 170 MW, from 2030



UK SMR (Rolls Royce), 443 MW, from 2030

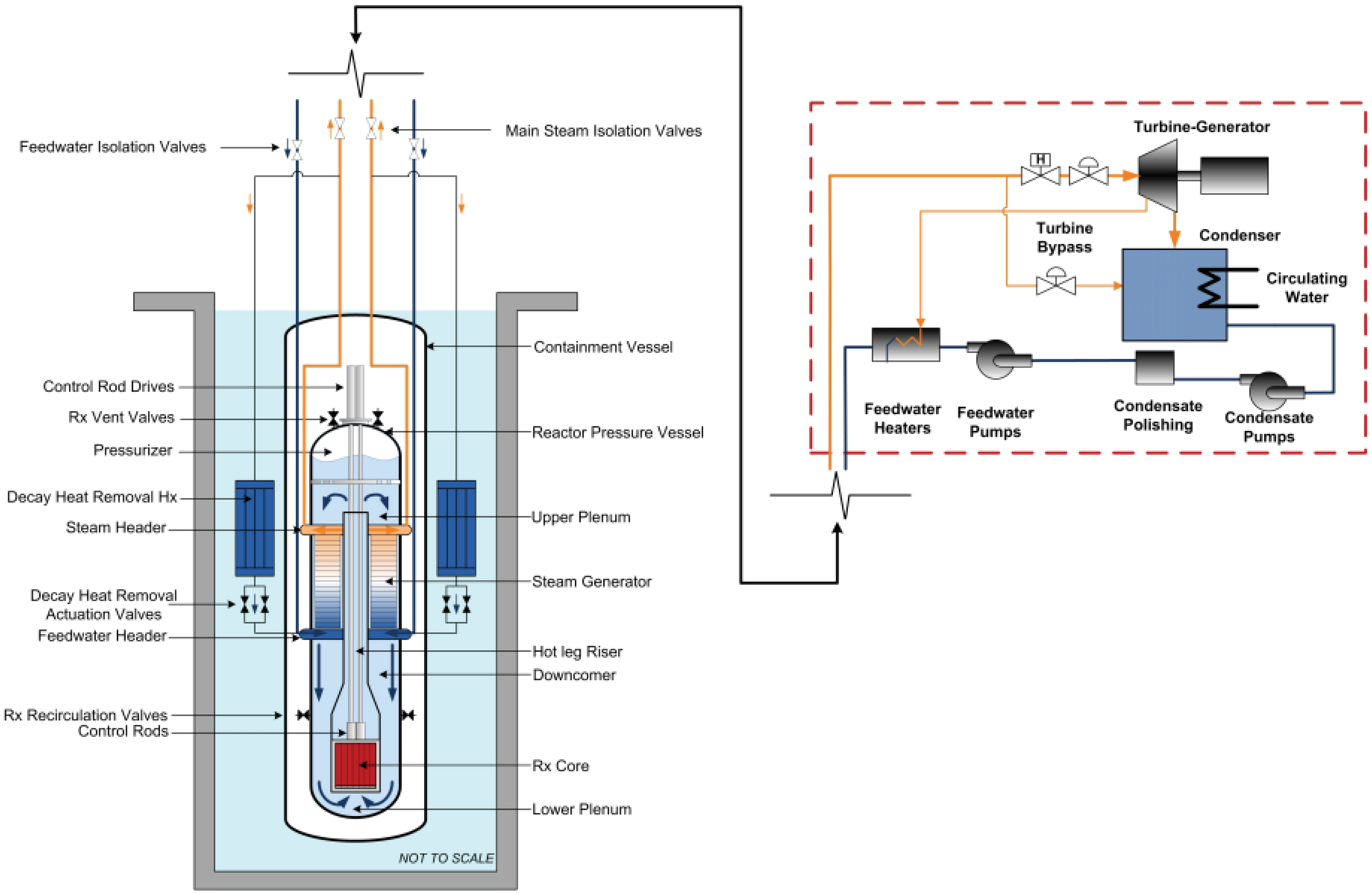
SMART (Korea), 100 MW, Betrieb in Saudi-Arabien ab 2026



BWRX-300 (GE/Hitachi) for Ontario Power, operation from 2028, targeted construction costs: **2'250 $/kW installed**

RITM-200 on Russian Icebreaker

Large NPPs vs SMR

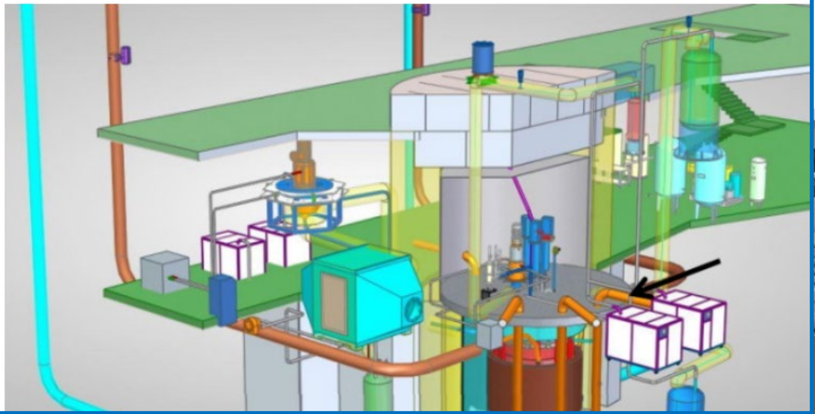


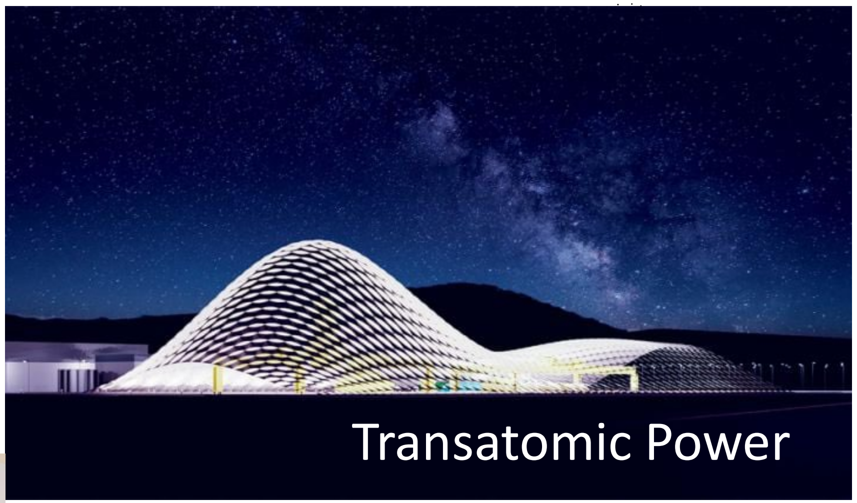
MSR: Playground for Start-Ups ?

Operating permit issued for Chinese molten salt reactor

15 June 2023

The Shanghai Institute of Applied Physics (SINAP) of the Chinese Academy of Sciences has been an operating licence for the experimental TMSR-LF1 thorium-powered molten-salt reactor, const of which started in Wuwei city, Gansu province, in September 2018.





Demonstration reactor to be built in Rwanda

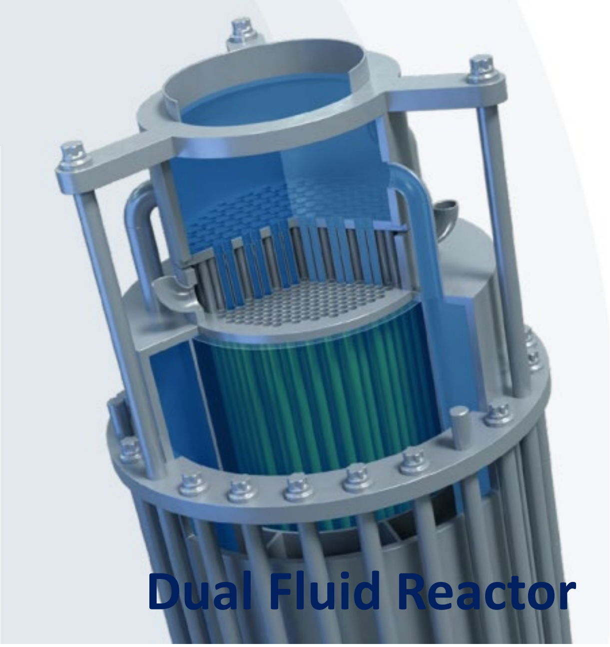
14 September 2023

Share

The Rwanda Atomic Energy Board (RAEB) has signed an agreement with Dual Fluid to collaborate on the development of a demonstration Dual Fluid nuclear reactor in Rwanda. The demonstration reactor is expected to be operational by 2026.

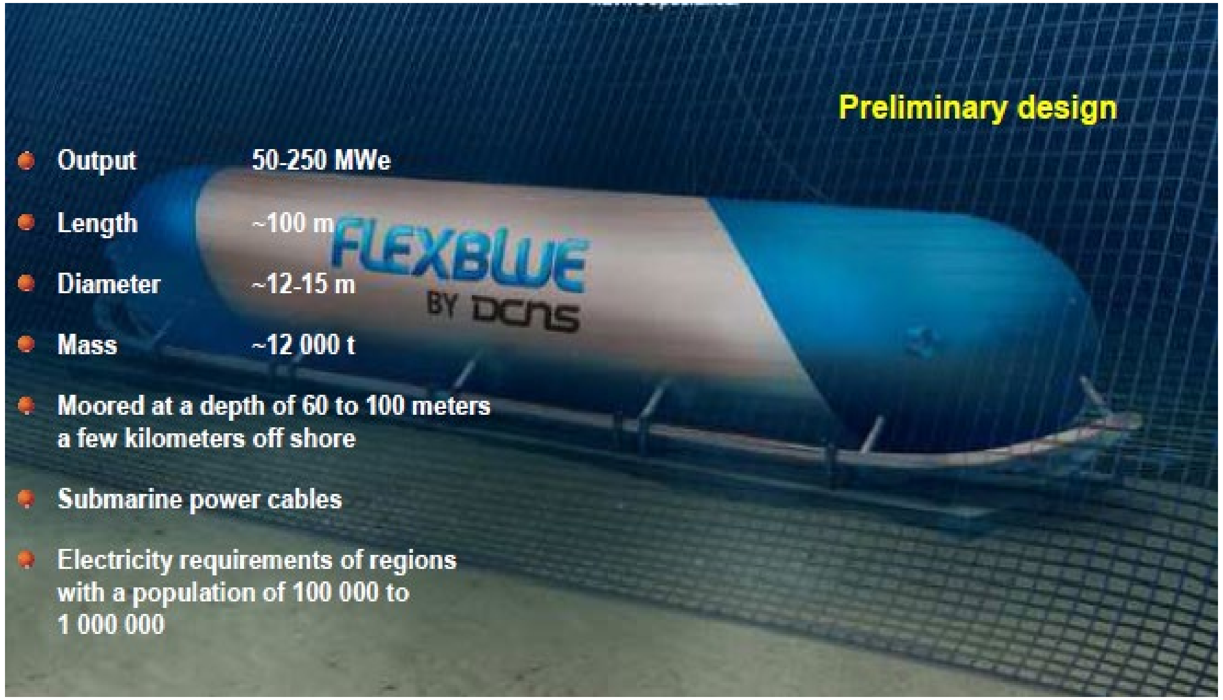
The signing ceremony was witnessed by Minister of Infrastructure Ernest Nsabimana (Image: Ministry of Infrastructure)

The Government of Rwanda has agreed to provide the site and infrastructure for the project, while Dual Fluid is responsible for the technical implementation of the partnership. Rwandan scientists will also receive practical training in nuclear technology.



FLEXBLUE (Design: DCNS): Concept 50-250 MW_e for a PWR in 100 m water depth

- Small PWR with passive safety systems similar to the AP-1000.
- Fully remote-controlled system (no operating crew on board).
- Emergency cooling system self-sufficient for approx. one week until human intervention (emergency measures) is required



Safety Systems of Generation-III Reactors: EPR

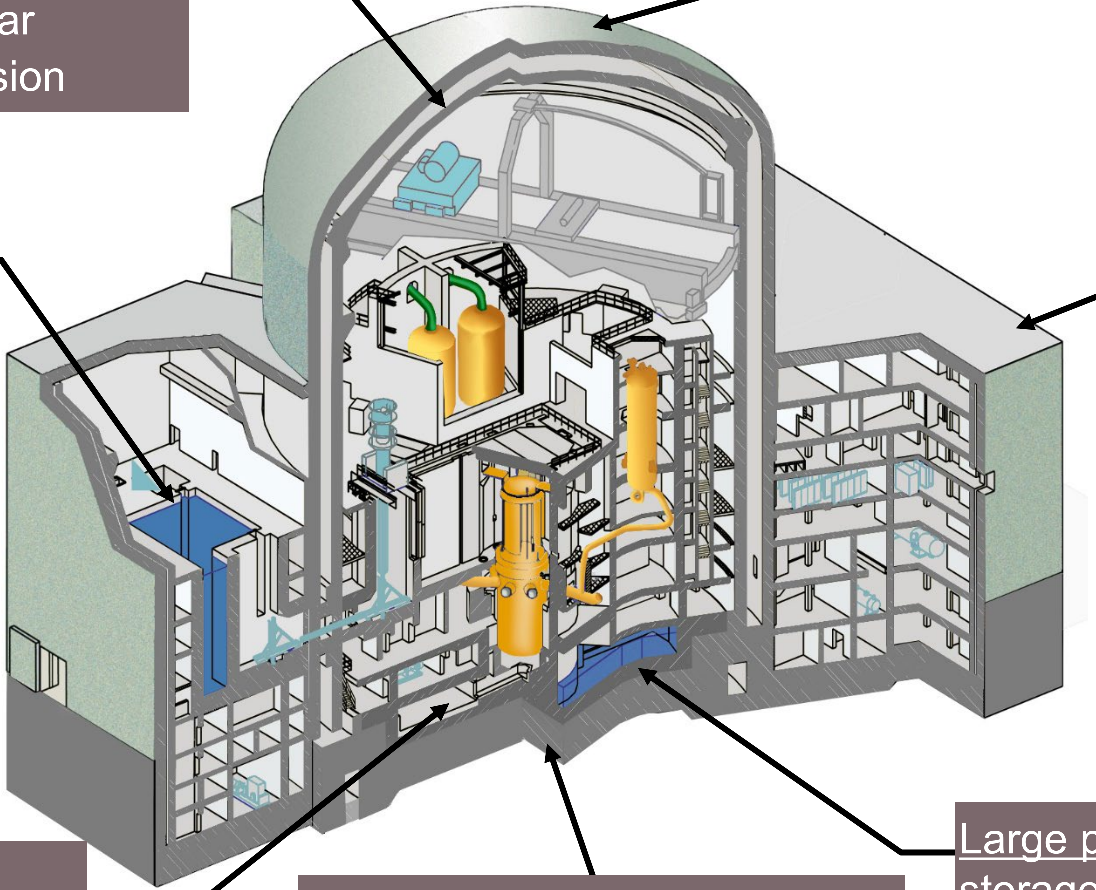
PSI

Internal Containment:
- Steel shell
- Leak-proof up to 6.5 bar
- Exclusion of H_2-Explosion

External Containment:
Air Plane Crash Protection

Wet Fuel Storage:
protected against air plane crash

Active/Passive Safety systems:
bunkered against external hazards, designed throughout 4-times (2v4) redundant with several diversified levels of safety systems



Probability of a core melt accident $<10^{-6}$/Jahr

Probability of an early release $<10^{-7}$/Jahr

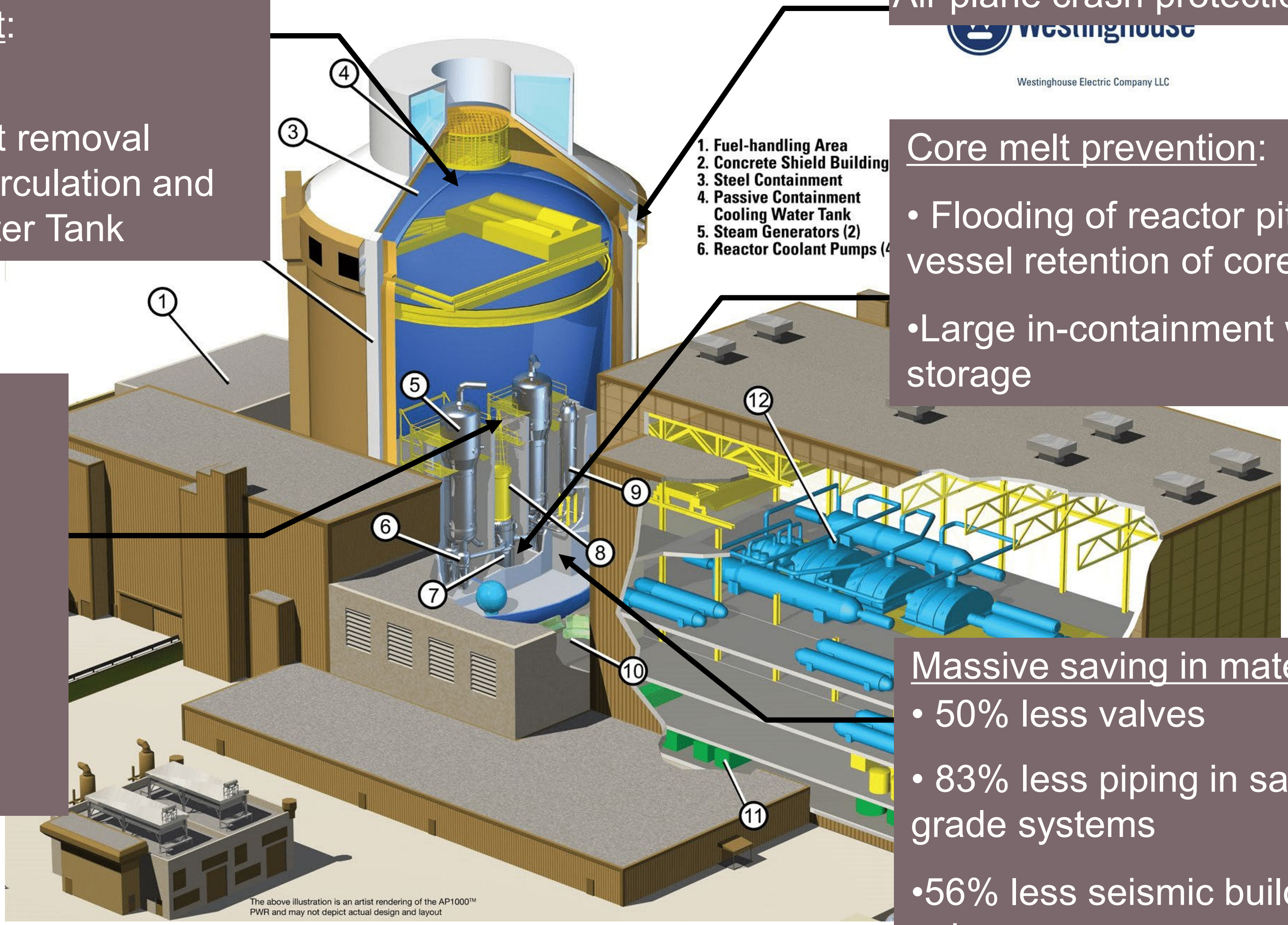
Core Catcher:
Safe containment of molten core

Earthquake-proof: designed against 100’000-year earthquake

Large protected in-containment water storage for coping with severe accidents

Sicherheitssysteme von Generation-III-Reaktoren: AP-1000

PSI



External Containment:
Air plane crash protection

Internal Containment:
- Steel shell
- Passive decay heat removal through natural air circulation and Passive Cooling Water Tank

Core melt prevention:
- Flooding of reactor pit for in-vessel retention of core melt
- Large in-containment water storage

Passive Safety Systems philosophy:
- Practically no more active components
- Controlled through gravity, buoyancy, natural convection
- Elimination of operator intervention

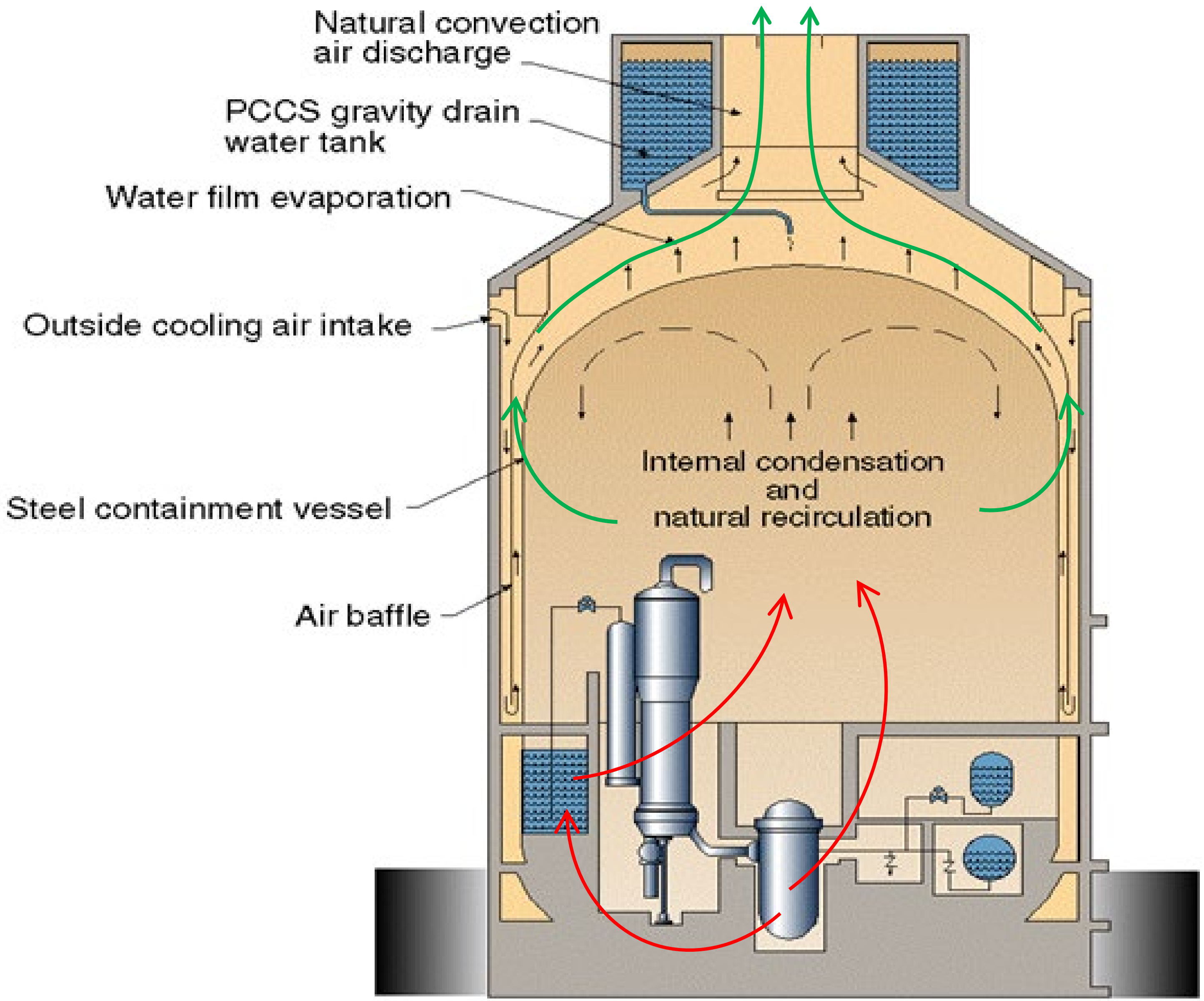
Massive saving in materials:
- 50% less valves
- 83% less piping in safety-grade systems
- 56% less seismic building volume

Westinghouse AP-1000: Passive Sicherheitssysteme

1) Passives Kernkühlungssystem

- **Sicherheitseinspeisung** (Hoch- und Niedrigdrucksysteme)
- **Direkte Einspeisung** in den Druckbehälter
- Nachwärmeabfuhr und Druckabbau mit dem grossen **Vorratsbehälter IRWST** und dem Containment
- **Notflutung der Reaktorgrube** (als Massnahme bei Kernschmelze)

2) **Passives**



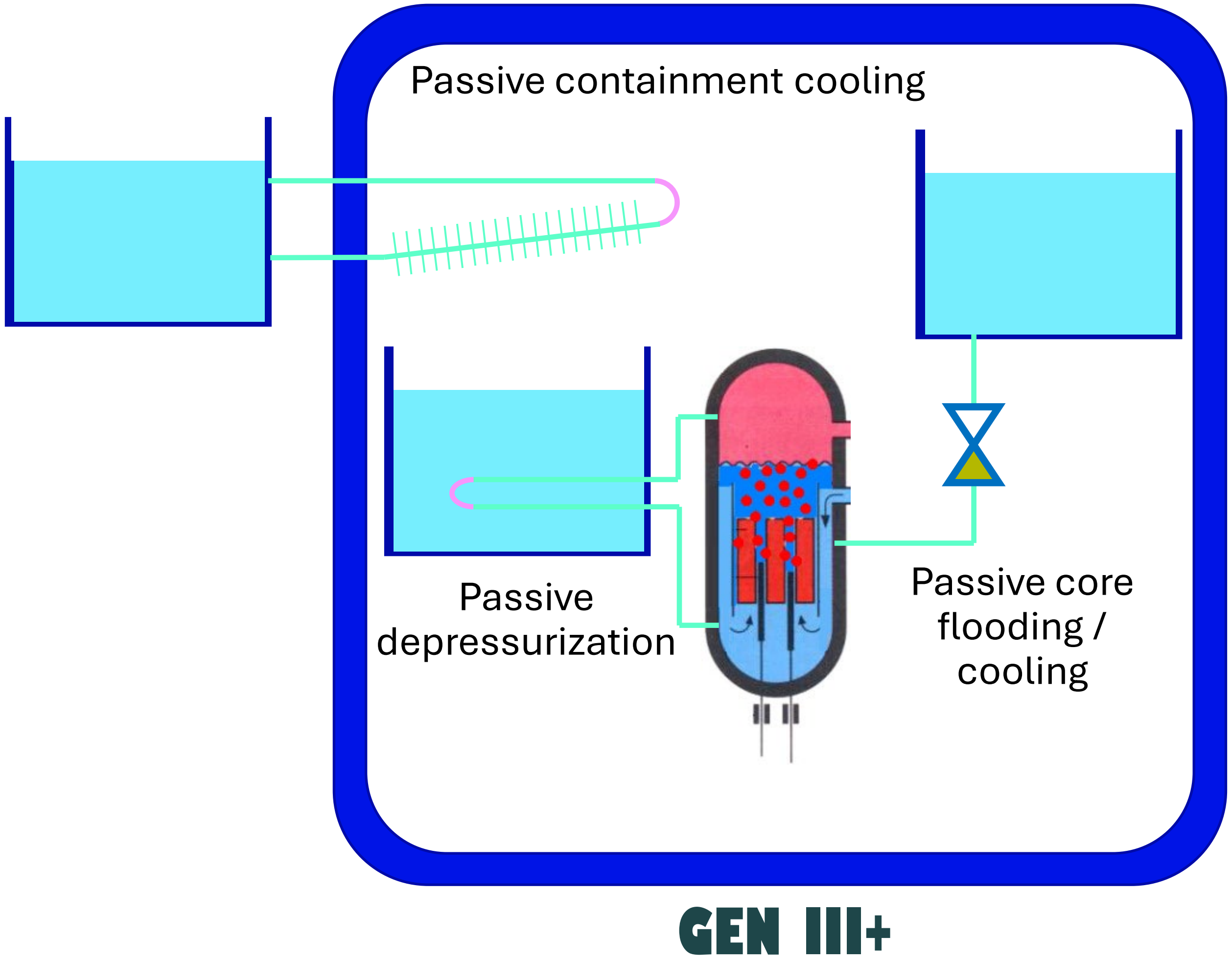
Gen-III+: Passive Safety Systems

Passive Safety Systems:

They function based on physical processes (Heat transfer, natural circulation, gravity, buoyancy, etc.) without the need for electricity of operator intervention

Core melt is not the full story...

- „Grace period“ extended from 30 minutes to 3-7 days, until operator intervention is needed
- „Practical Elimination“ of accidents which could lead to important releases of radioactivity to the environment ($<10^{-7}$/year)



Kraftwerkstypen der Generation-III am Markt

EPR (Framatome) in Olkiluoto (FI), 1600 MW)

AP-1000 (Westinghouse) in Sanmen (CN), 1200 MW

Wann sind diese Reaktoren wirtschaftlich?

Baukosten:

3’500-4’500 $/kW installiert

Bauzeit:

5-7 Jahre

=> Stromgestehungskosten:

60-100 $/MWh

VVER-1200 (Rosatom) in Novovoronesh (RU), 1250 MW

APR-1400 (KEPCO) in Barakah (UAE), 1400 MW

Kraftwerkstypen der Generation-III am Markt

EPR (Framatome) in Olkiluoto (FI), 1600 MW)

- Geschätzte Baukosten > 7’000 $/kW
- Bauzeit (Finnland): 17 Jahre
- Gestehungskosten > 140 $/MWh

- Hersteller hatte seit 2000 keine Anlage mehr in Betrieb genommen
- Bisher nur eine Anlage im kommerziellen Betrieb, 4 in Bau

Wann sind diese Reaktoren wirtschaftlich?

Baukosten:

3’500-4’500 $/kW installiert

Bauzeit:

5-7 Jahre

=> Stromgestehungskosten:

60-100 $/MWh

AP-1000 (Westinghouse) in Vogtle (USA), 1200 MW

- Geschätzte Baukosten (USA) > 9’000 $/kW
- Bauzeit (USA): >10 Jahre
- Gestehungskosten > 150 $/MWh

- Hersteller hatte seit 1996 keine Anlage mehr in Betrieb genommen
- Bisher nur eine Anlage im kommerziellen Betrieb, 2 in Bau, 2 Projekte abgebrochen

Kraftwerkstypen der Generation-III am Markt

- Baukosten (Indien) < 4’000 $/kW
- Bauzeit (Indien/Bangladesh): 6 Jahre
- Gestehungskosten ~70 $/MWh

- Rosatom hat seit 2010 mehr als 20 VVER-Anlagen in Betrieb genommen
- Zwischen 2022 und 2027 sollen 5 VVER-1200 in Russland und weitere 14 VVER weltweit fertiggestellt werden

VVER-1200 (Rosatom) in Novovoronesh (RU), 1250 MW

Wann sind diese Reaktoren wirtschaftlich?
Baukosten:
3’500-4’500 $/kW installiert
Bauzeit:
5-7 Jahre
=> Stromgestehungskosten:
60-100 $/MWh

- Baukosten (UAE) ~4’300 $/kW
- Bauzeit (UAE): 5-10 Jahre
- Gestehungskosten < 80 $/MWh

- KEPCO hat bereits 6 Anlagen dieses Typs in Korea in Betrieb genommen
- Die 4 Anlagen in den UAE sind das erste Auslandsprojekt des Herstellers

APR-1400 (KEPCO) in Barakah (UAE), 1400 MW

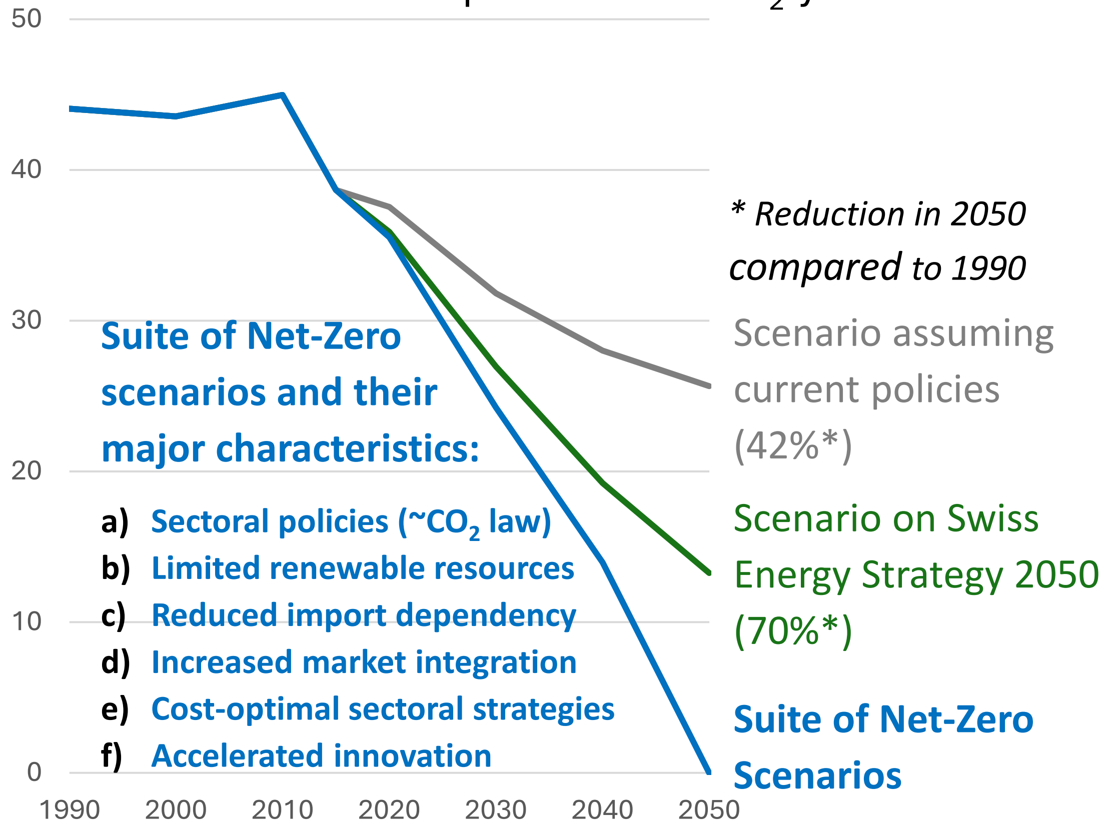
Energiesystemanalyse

«Price tags» of the Swiss energy transition

PSI

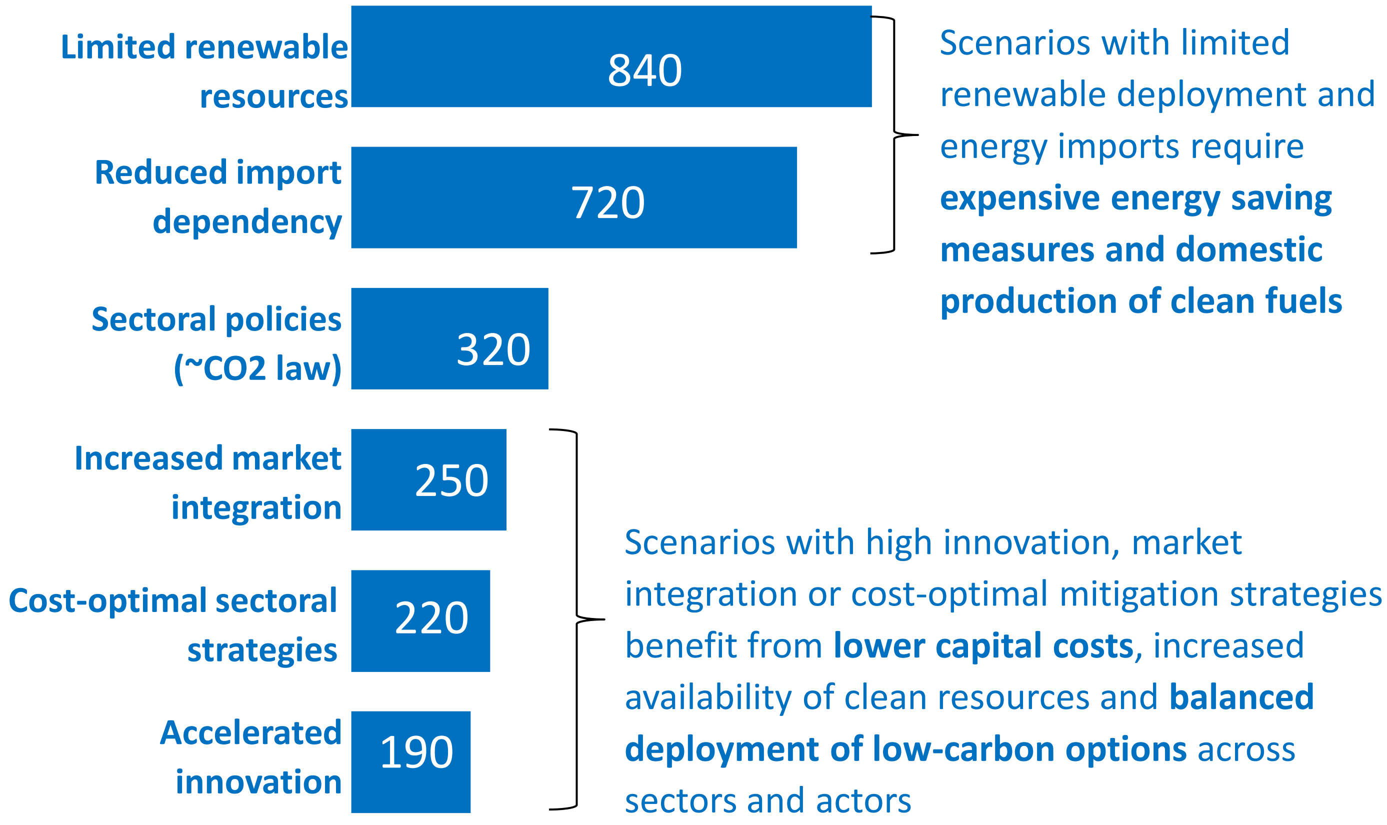
Future energy system transformation pathways

CO_2 emissions from fuel combustion and industrial processes $MtCO_2$/yr



Quantification of system cost implications

Discounted policy costs expressed in CHF per person and year for the period 2020-2050

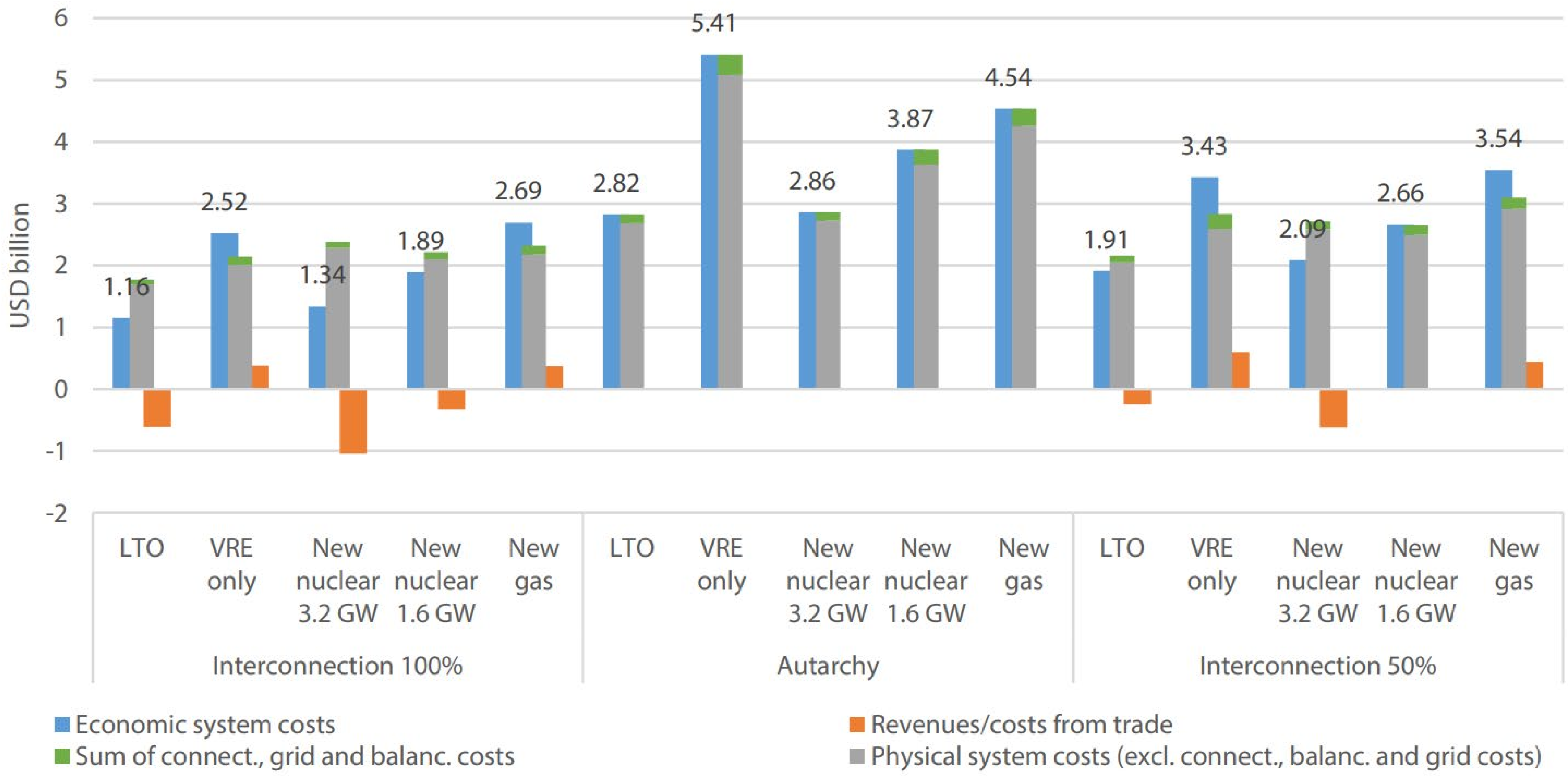


Panos, E., et al. (2021)

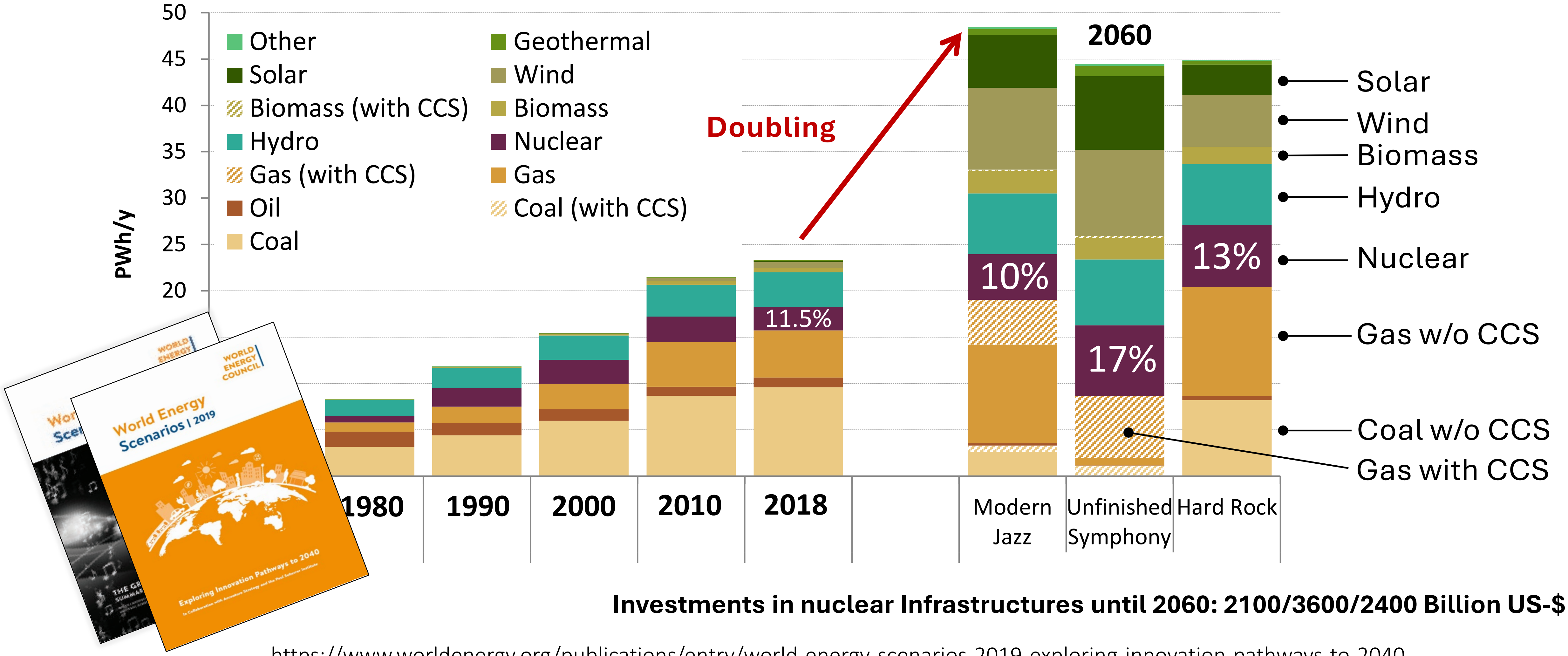
OECD Study on Total Costs of Electricity Generation for CH (2022)

PSI

Figure 4.3. **Total system costs of the five net zero scenarios under different electricity trade constellations (USD billion)**

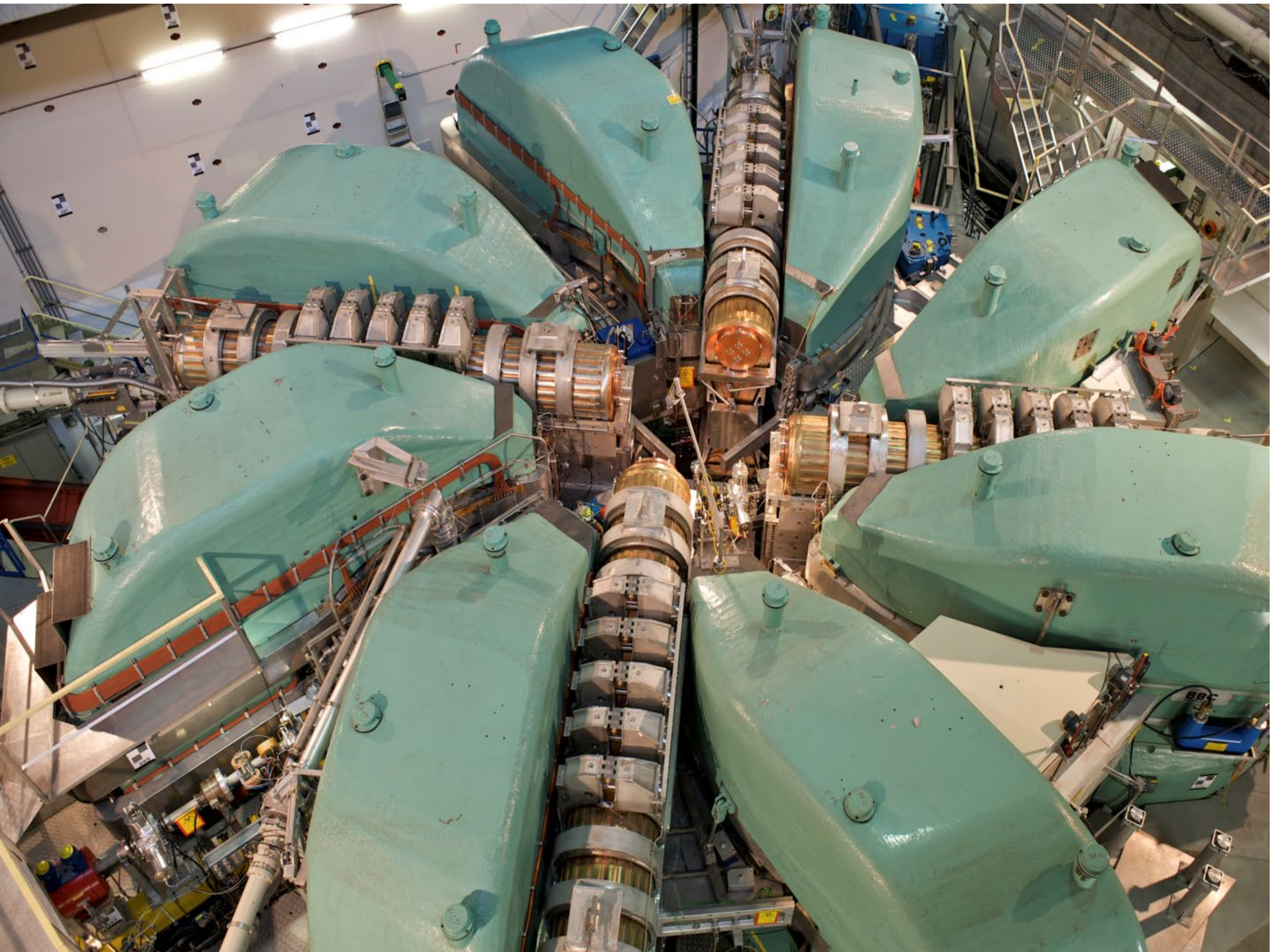


Electricity Generation Worldwide: Scenarios



Investments in nuclear Infrastructures until 2060: 2100/3600/2400 Billion US-$

https://www.worldenergy.org/publications/entry/world-energy-scenarios-2019-exploring-innovation-pathways-to-2040



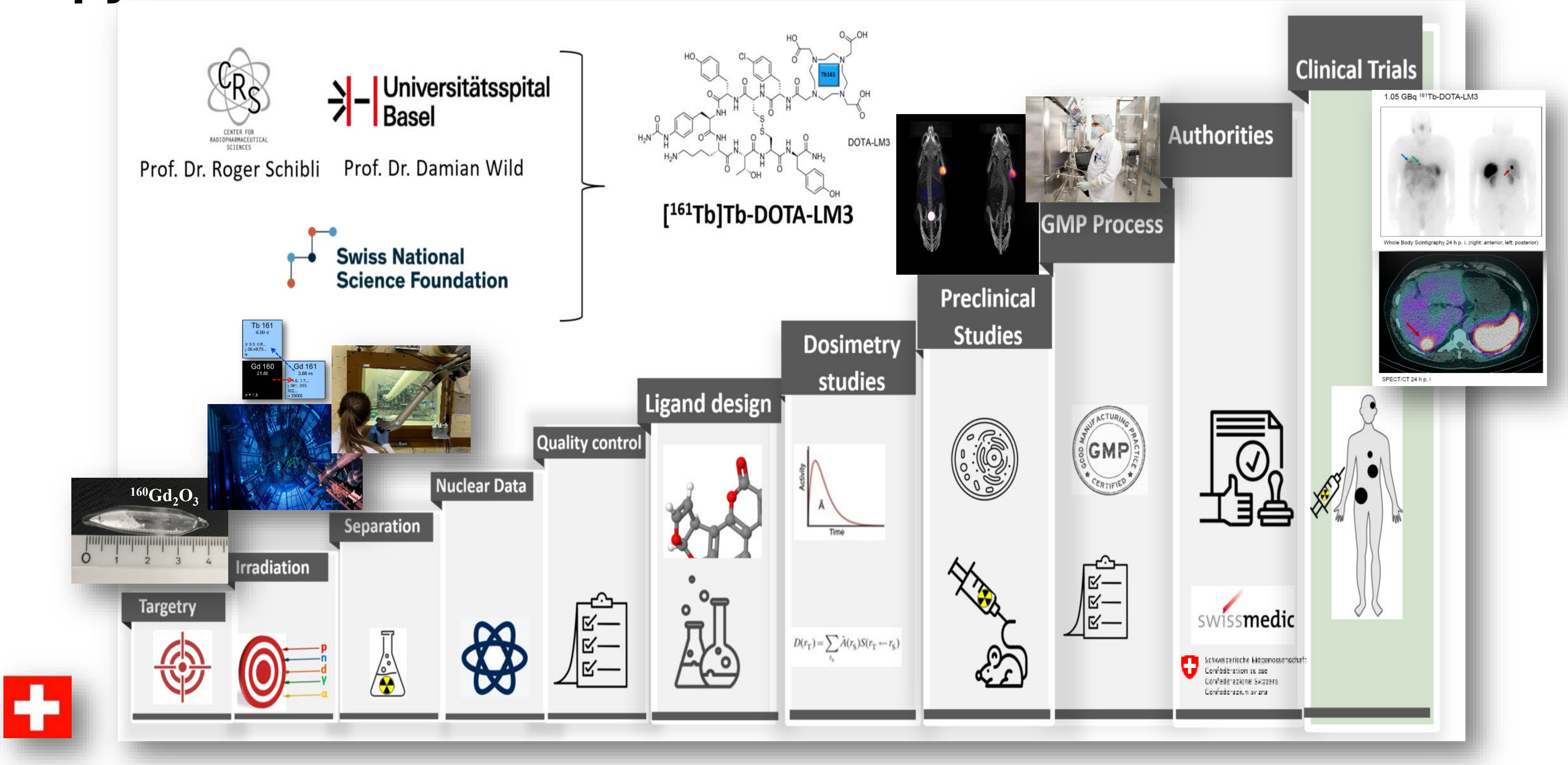
PSI

HIPA (High Intensity Proton Accelerator)

- CW 590 MeV,
- up to 2.4 mA (1.44 MW beam power)
- Feeds **SINQ neutron spallation source**

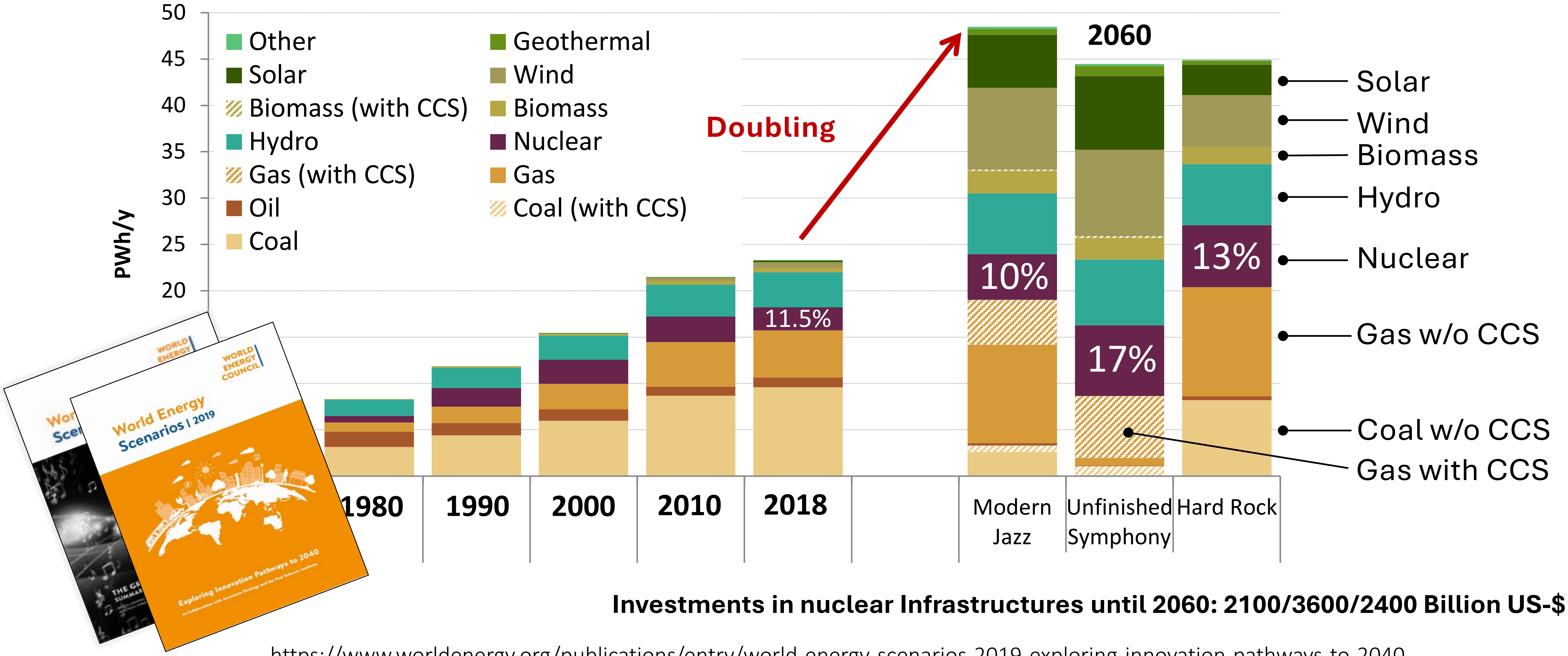
NES-BIO collaboration: clinical application of ^{161}Tb for cancer therapy

PSI



Electricity Generation Worldwide: Scenarios

PSI



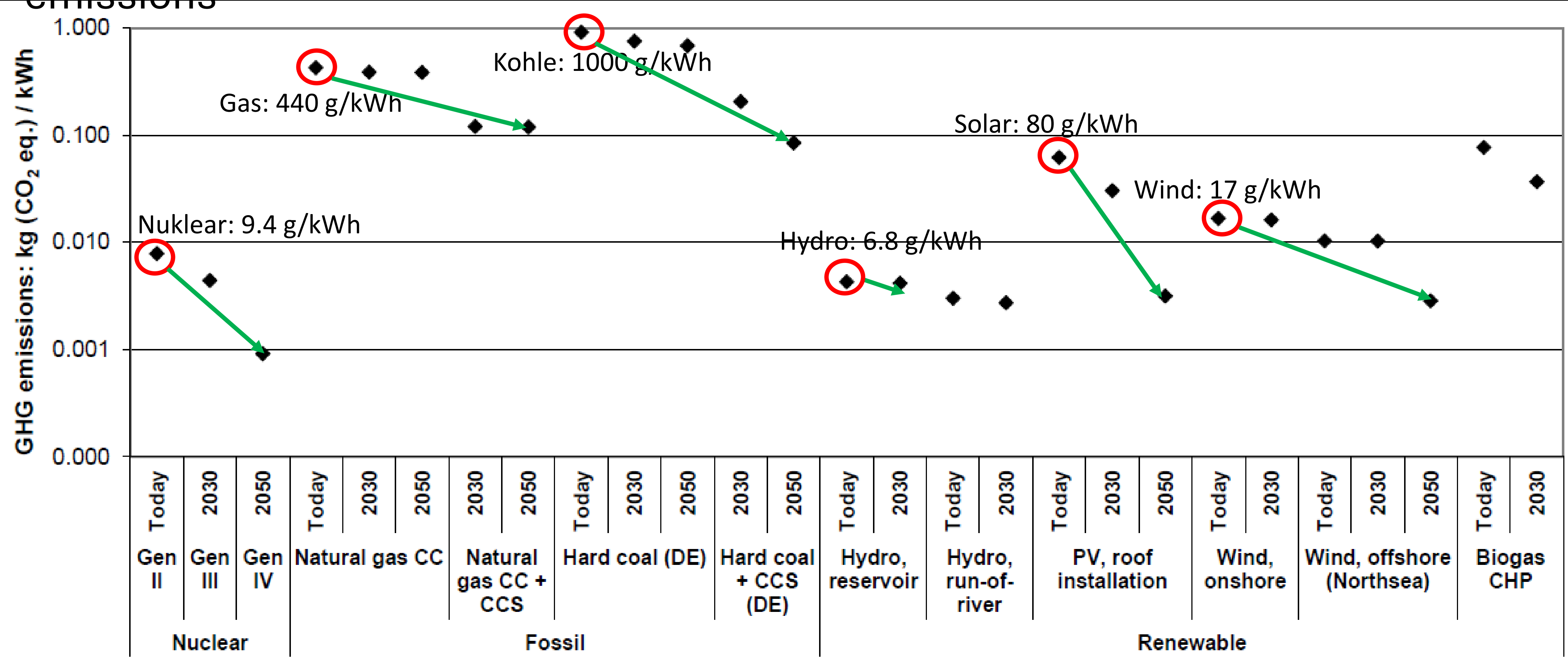
Investments in nuclear Infrastructures until 2060: 2100/3600/2400 Billion US-$

https://www.worldenergy.org/publications/entry/world-energy-scenarios-2019-exploring-innovation-pathways-to-2040

CO_2-Emissions of Electricity Generation

PSI

- Nuclear power is virtually CO_2-free in operation; calculated over the entire life cycle (incl. uranium mining, enrichment, and construction), only hydropower has lower CO_2 emissions

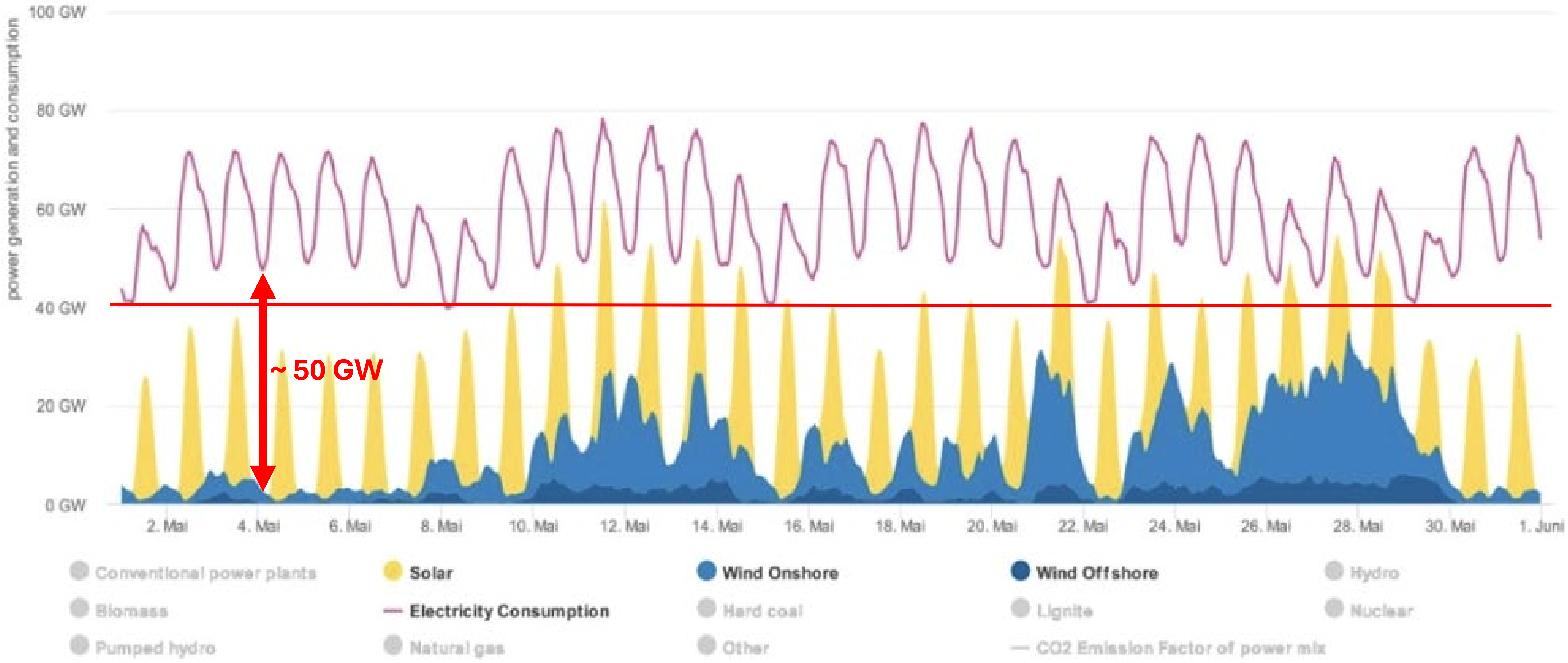


Xiaojin Zhang, Christian Bauer, Technology Assessment Group, Laboratory for Energy Systems Analysis, Paul Scherrer Institut (PSI): Life Cycle Assessment (LCA) of Nuclear Power in Switzerland, Download unter: https://www.psi.ch/de/ta/projects/life-cycle-assessment-lca-of-nuclear-power-in-switzerland

The Relevance of Baseload Generation

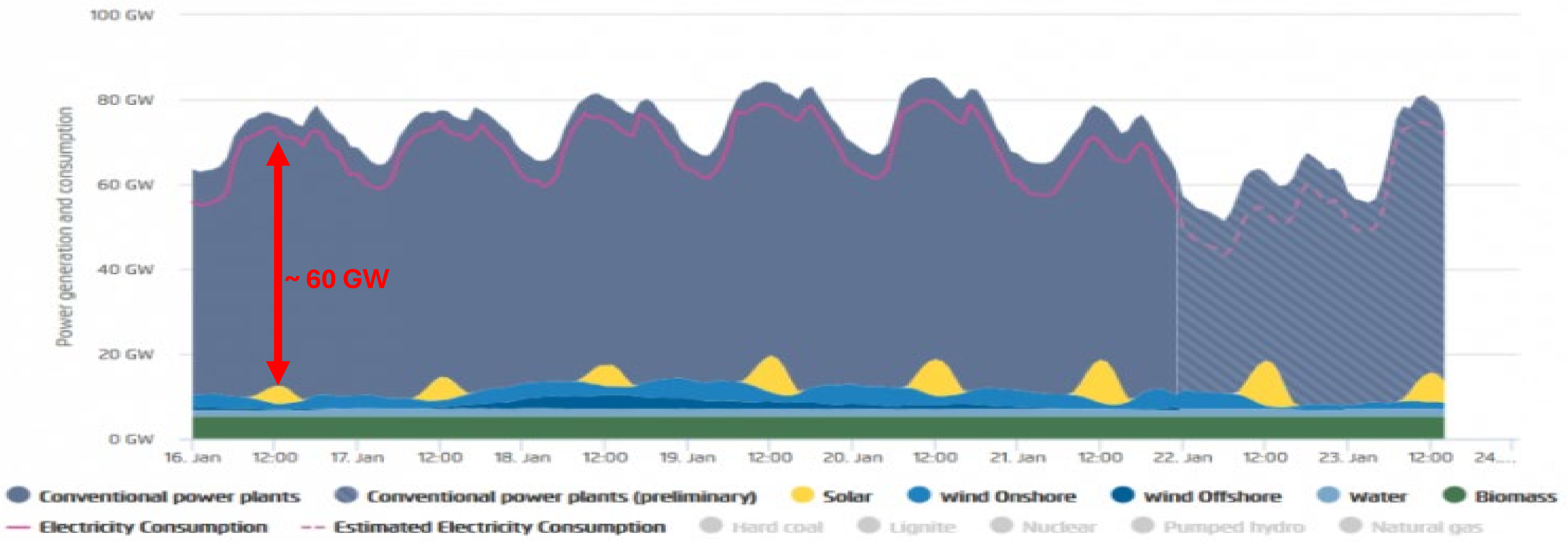
PSI

Germany Supply/Demand of electricity – May 2022

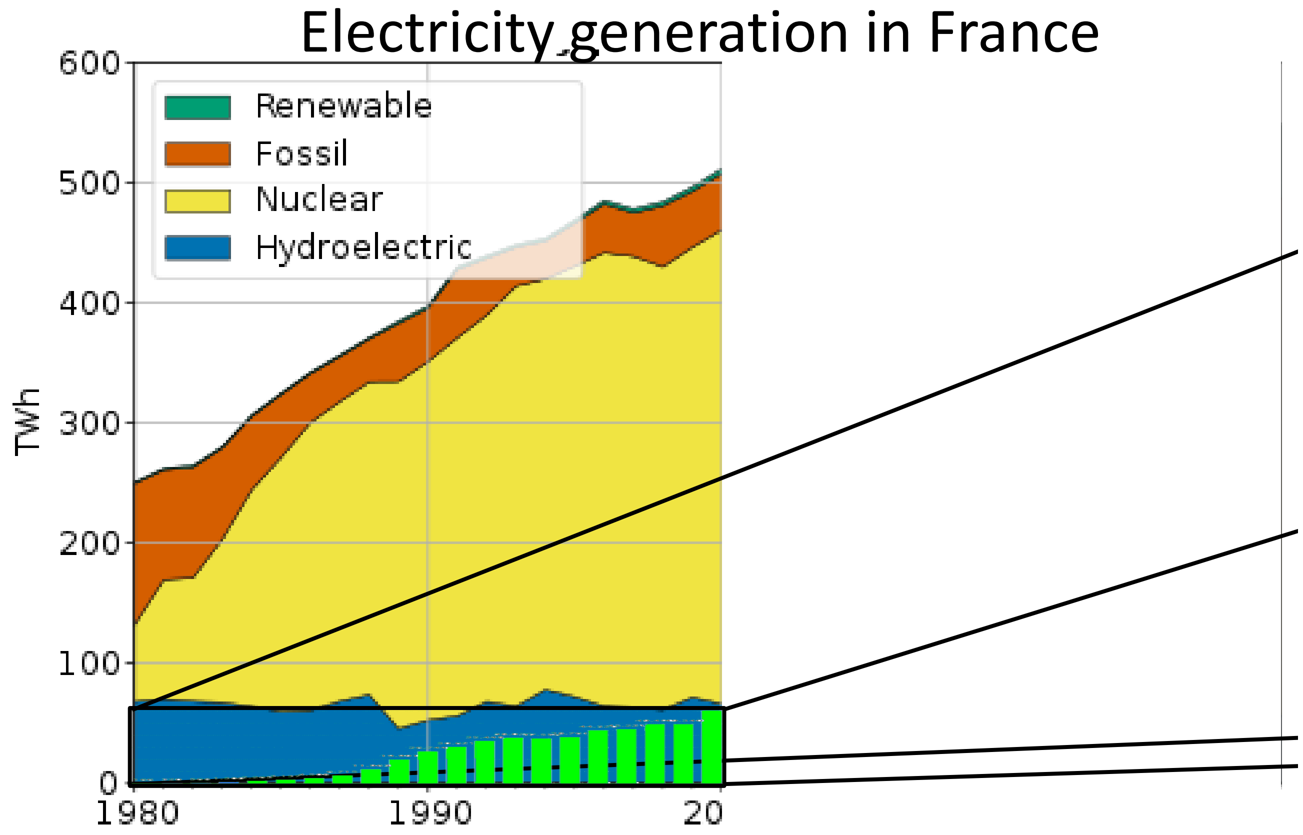


The Relevance of Baseload Generation

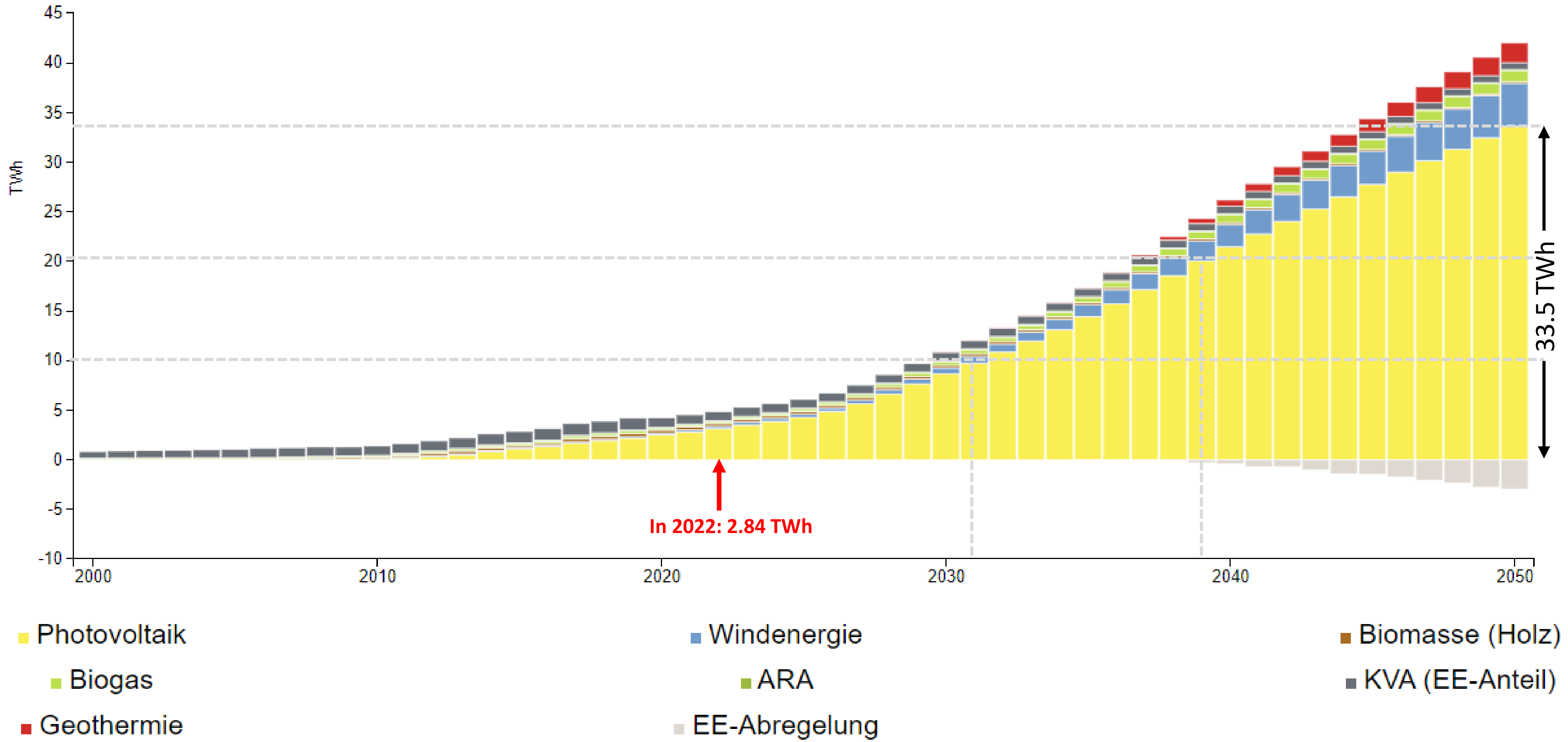
Germany Supply/Demand of electricity – a Week in January 2022



20-year Capacity Buildup in Germany and France



The Swiss Scenario for the Expansion of Solar



The Swiss Scenario for the Expansion of Solar

23,3	GWh	**Gondosolar data**
42	MCHF	
100,000	m²	

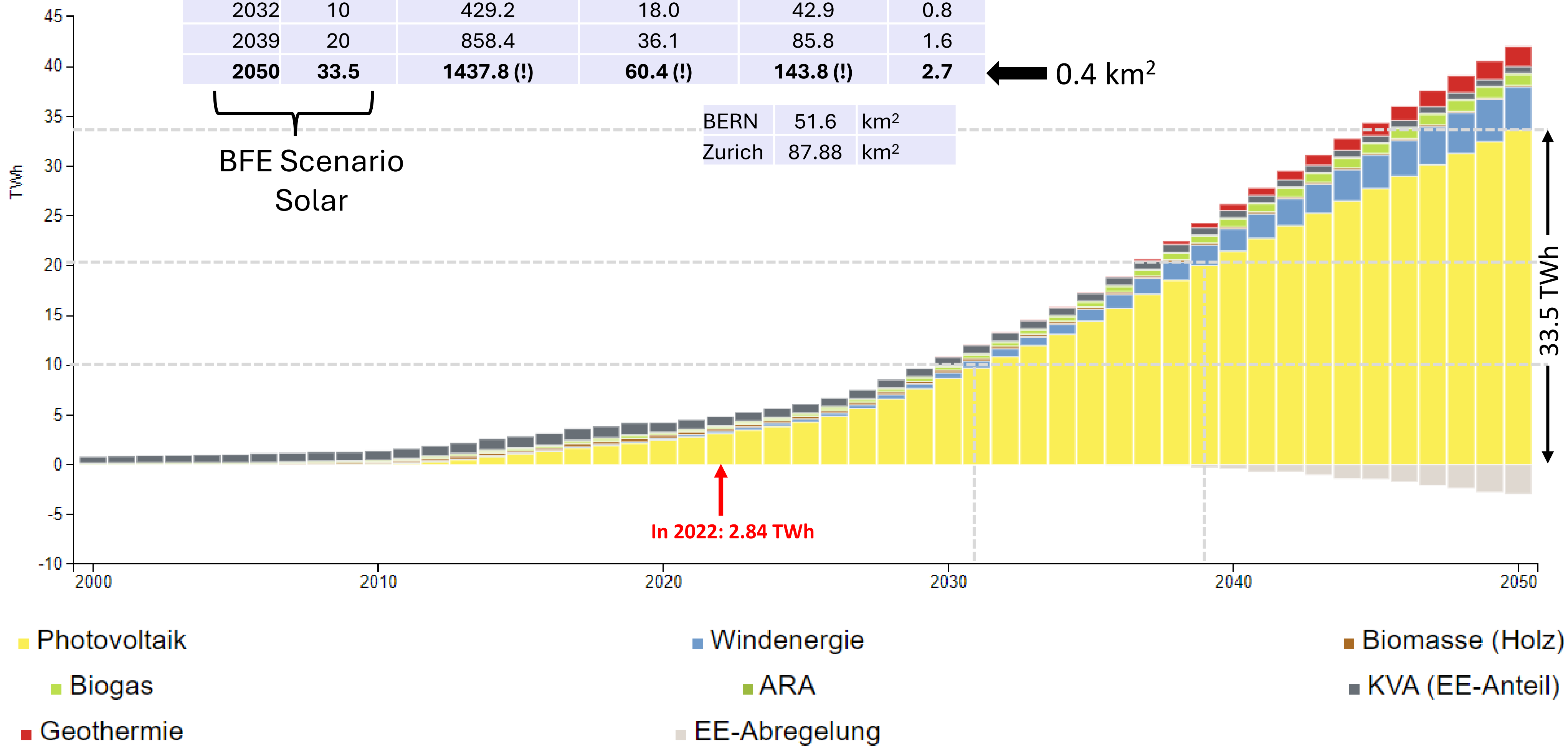
YEAR	TWh	Units Gondosolar Equivalent	Price [Billion CHF]	km²	# of EPRs
2032	10	429.2	18.0	42.9	0.8
2039	20	858.4	36.1	85.8	1.6
2050	**33.5**	**1437.8 (!)**	**60.4 (!)**	**143.8 (!)**	**2.7**

← 0.4 km²

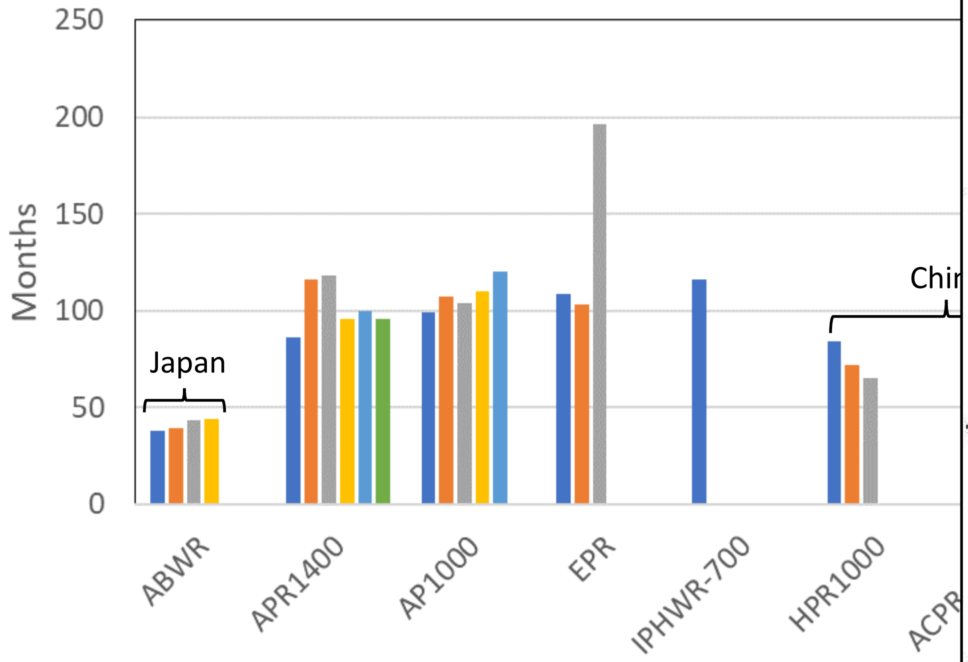
BFE Scenario Solar

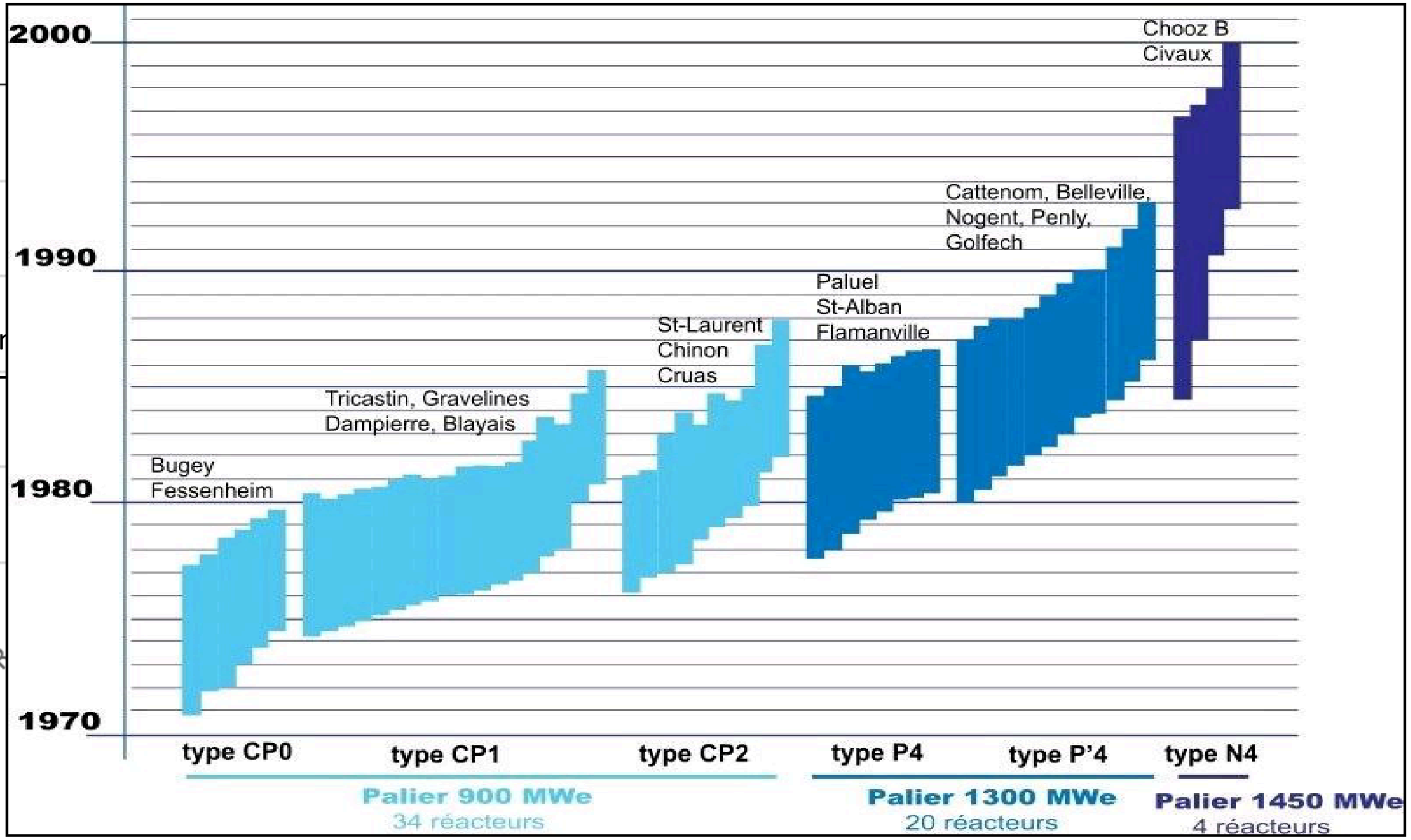
BERN	51.6	km²
Zurich	87.88	km²

To realize the BFE scenario, we need the equivalent of 1438 gondosolar (or 2.7 NPPs like EPR).



Large Generation III/III+ NPPs on the market and already in operation (construction times)





In Europe and the USA:

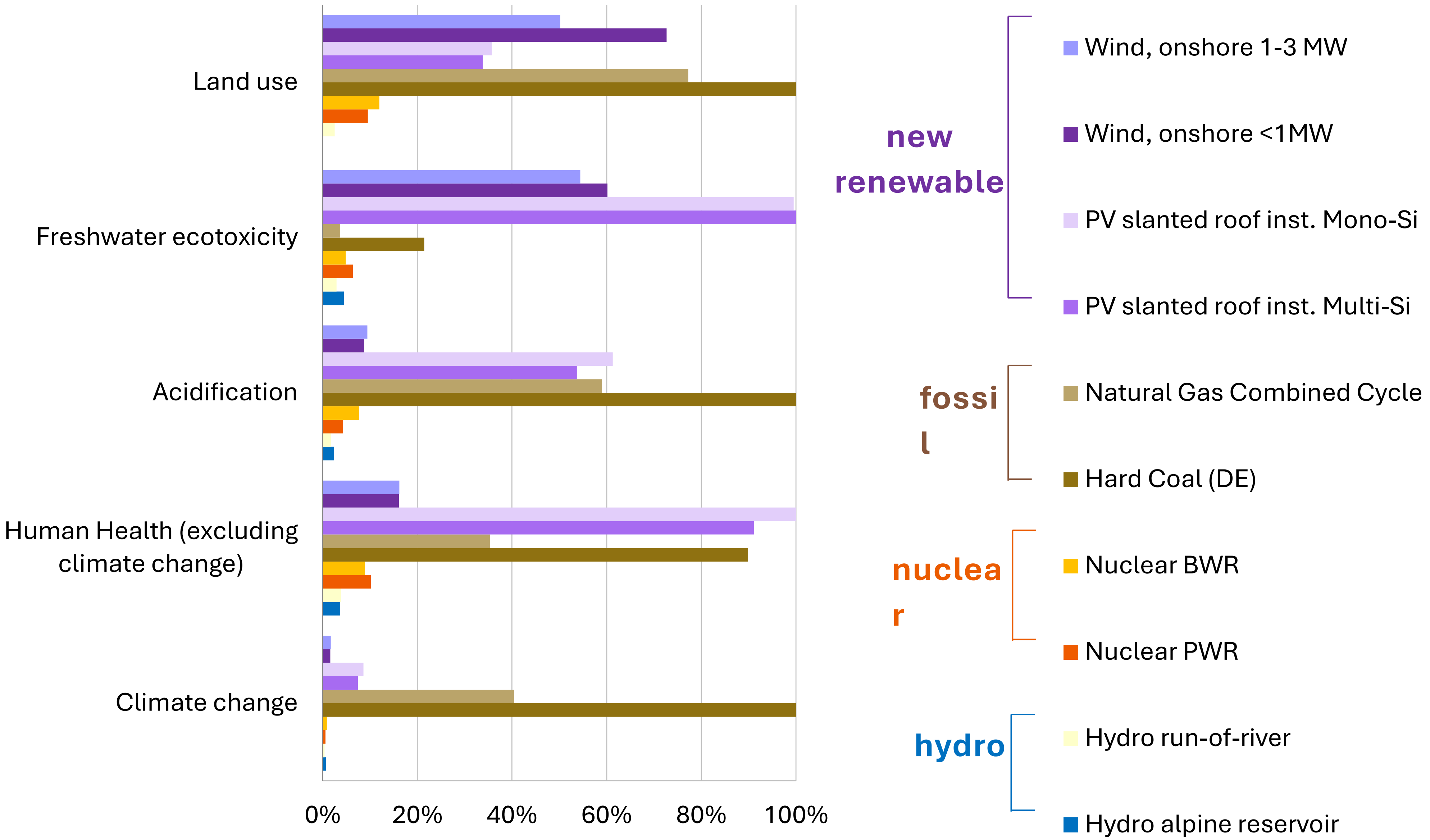
- Need to rebuild the supply chain (no new nuclear power plants for over three decades)
- Difficult regulatory framework:
- OL3 (FI), Vogtle 3&4 (USA), Hinkley Point (UK): changes to requirements during construction of NPP. Example Hinkley Point: 7000 changes requested!

Land Use (and Costs) of Solar vs. Nuclear

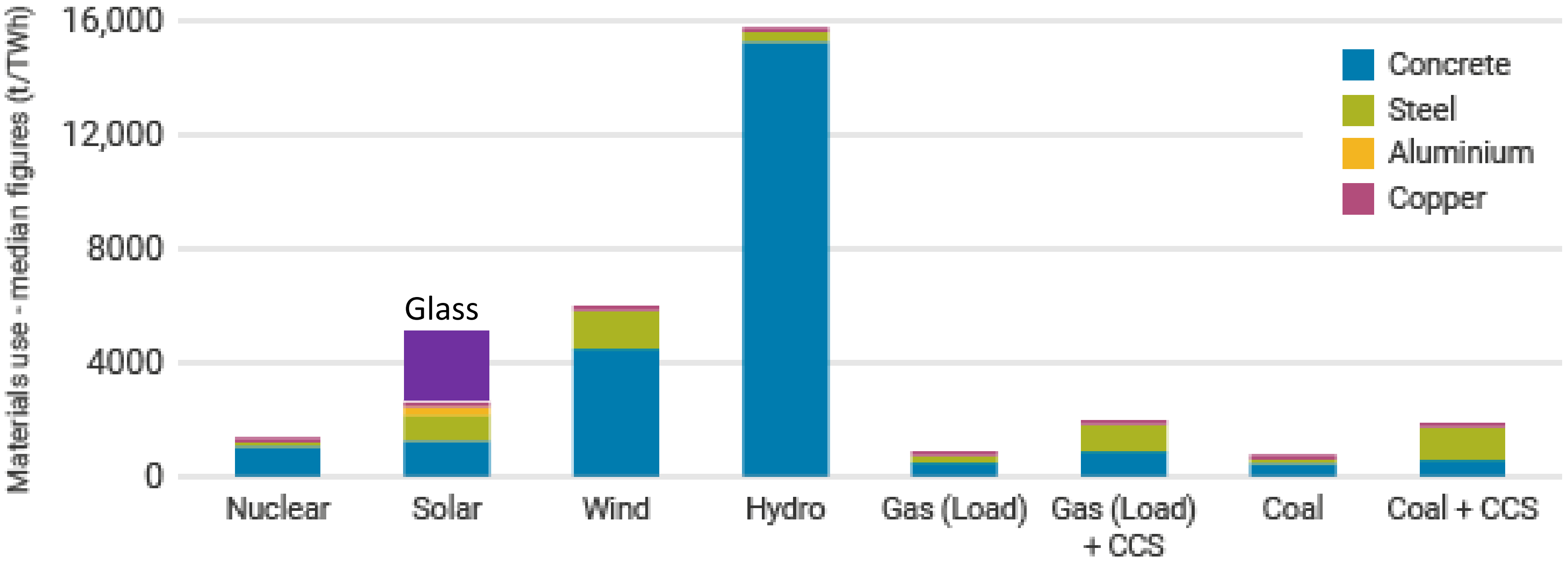
Taicun Village Solar (China, 20 MW_{peak}) ~ Gondosolar (18 MW_{peak})

Switzerland Gondosolar	
23,3	GWh/Jahr
42	MCHF
100,000	m^2
18	MW_{peak}

Environmental Impacts of Electricity Generation Technologies in CH (Quelle: PSI)



Material Usage of Different Energy Sources

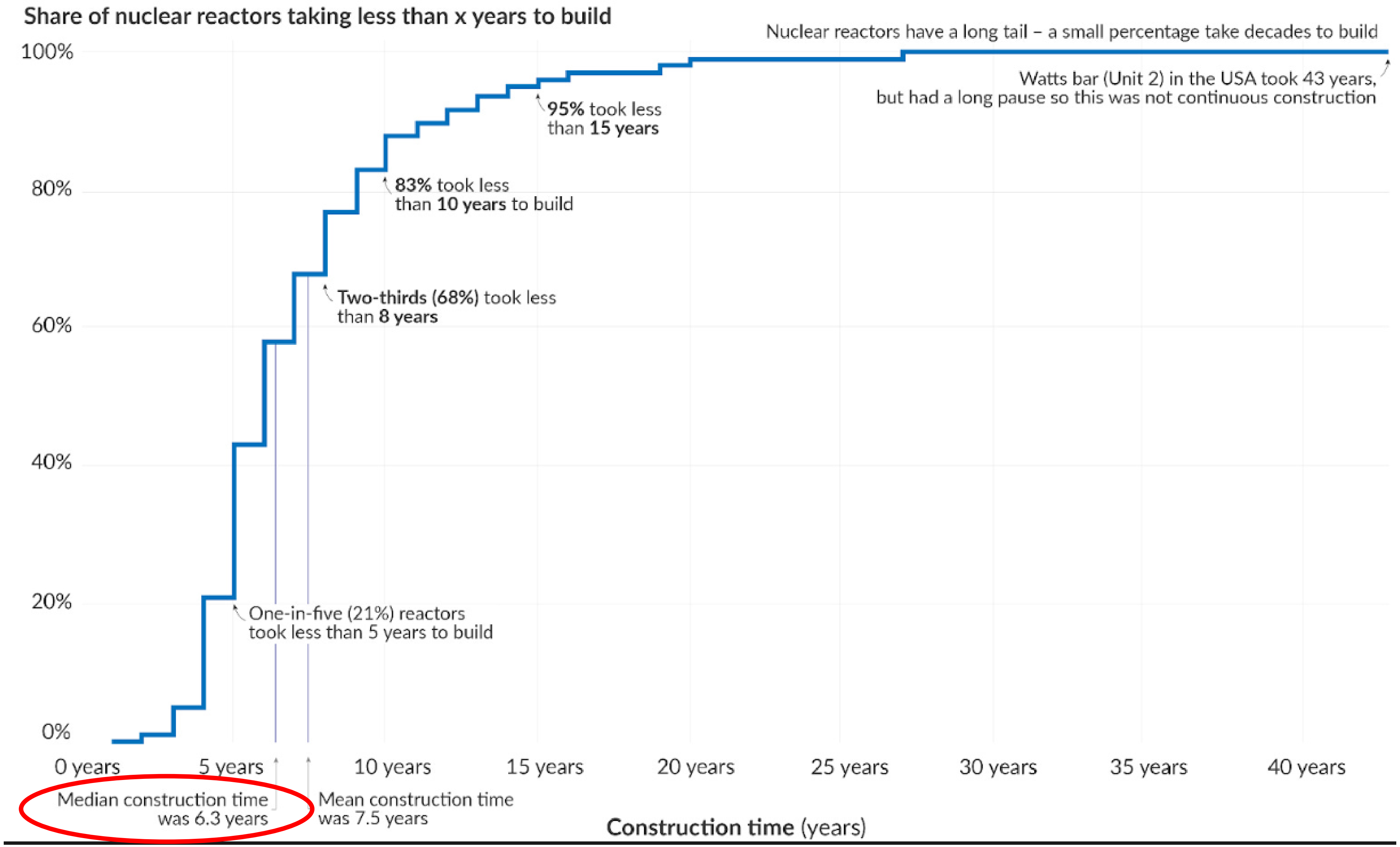


	Nuclear PWR	Solar	Wind	Hydro	Gas (load following)	Gas (load following) + CCS	Coal	Coal + CCS
Concrete	1060	1220	4470	15,320	390	820	450	520
Steel	130	940	1450	330	320	970	160	1170
Aluminium	0.3	287.5	17.4	8.7	5.7	21.4	1.6	37.4
Copper	2.5	68.0	39.1	4.8	5.4	8.8	3.0	11.8
Capacity f.	85%	28%	35%	50%	30%	30%	85%	85%
Lifespan	60	30	30	100	60	60	60	60

Table 2 and Figure 4: Major materials for different generating technologies, tonnes per TWh (source: Bright New World)

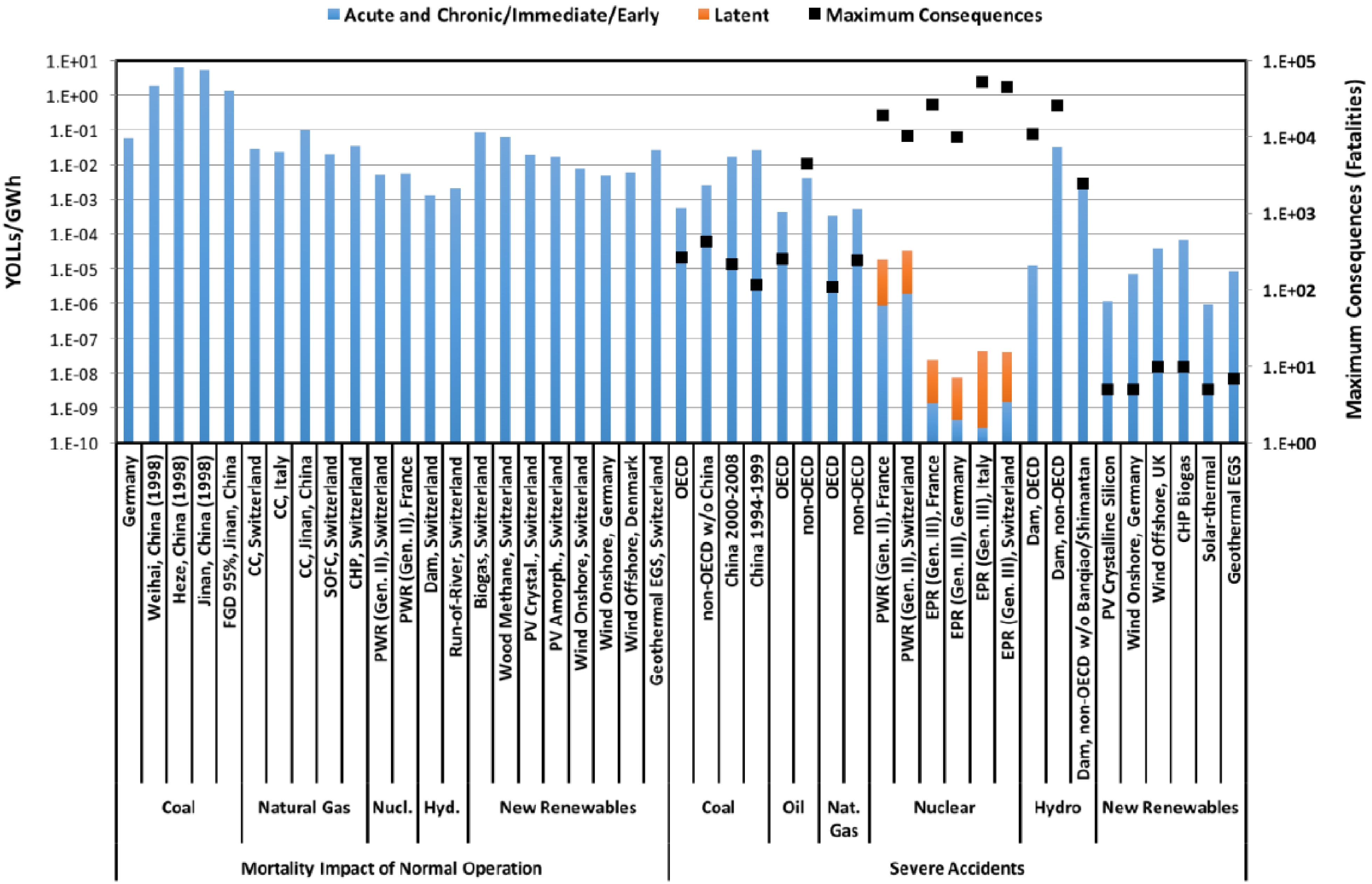
How long does it take to build a nuclear reactor?

Construction time of nuclear reactors that were operable by March 2023. This includes reactors still in operation, plus those that had been shut down or decommissioned.



Life Cycle Assessment of Nuclear Power in CH (Quelle: PSI)

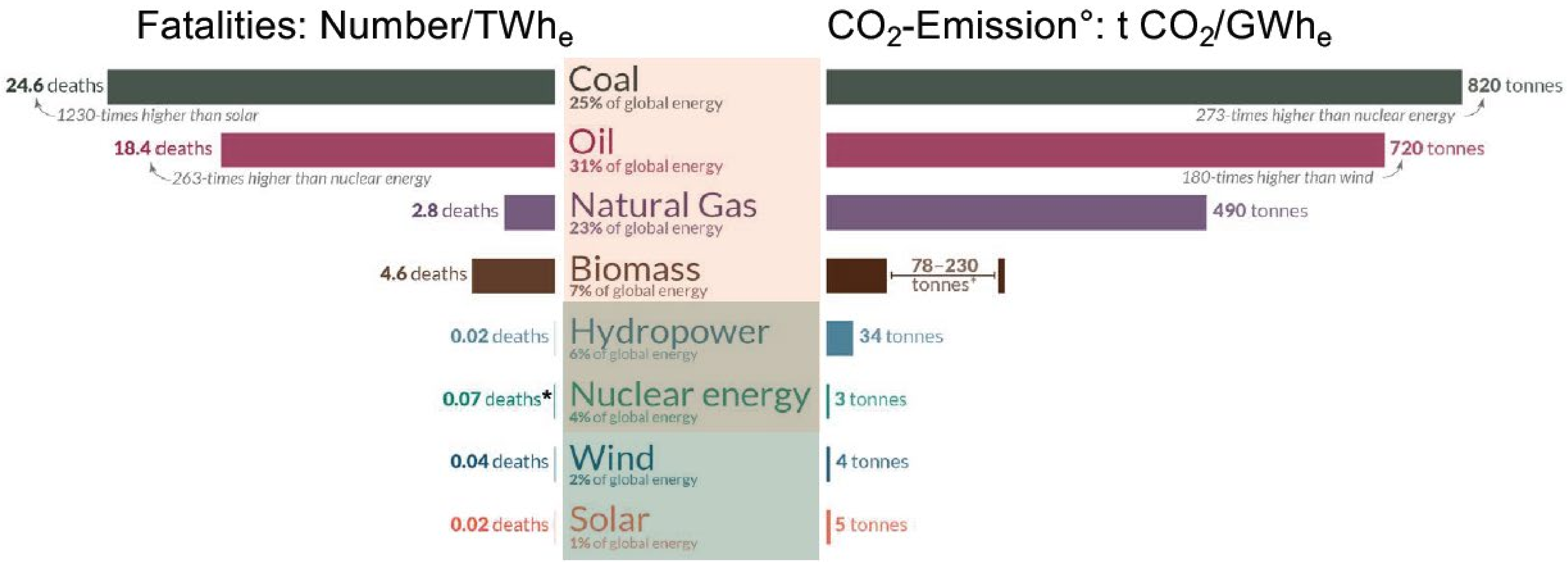
PSI



Quelle: P. Burgherr, S. Hirschberg: Comparative risk assessment of severe accidents in the energy sector, Energy Pol, 74 (Supplement 1) (2014), pp. S45-S56

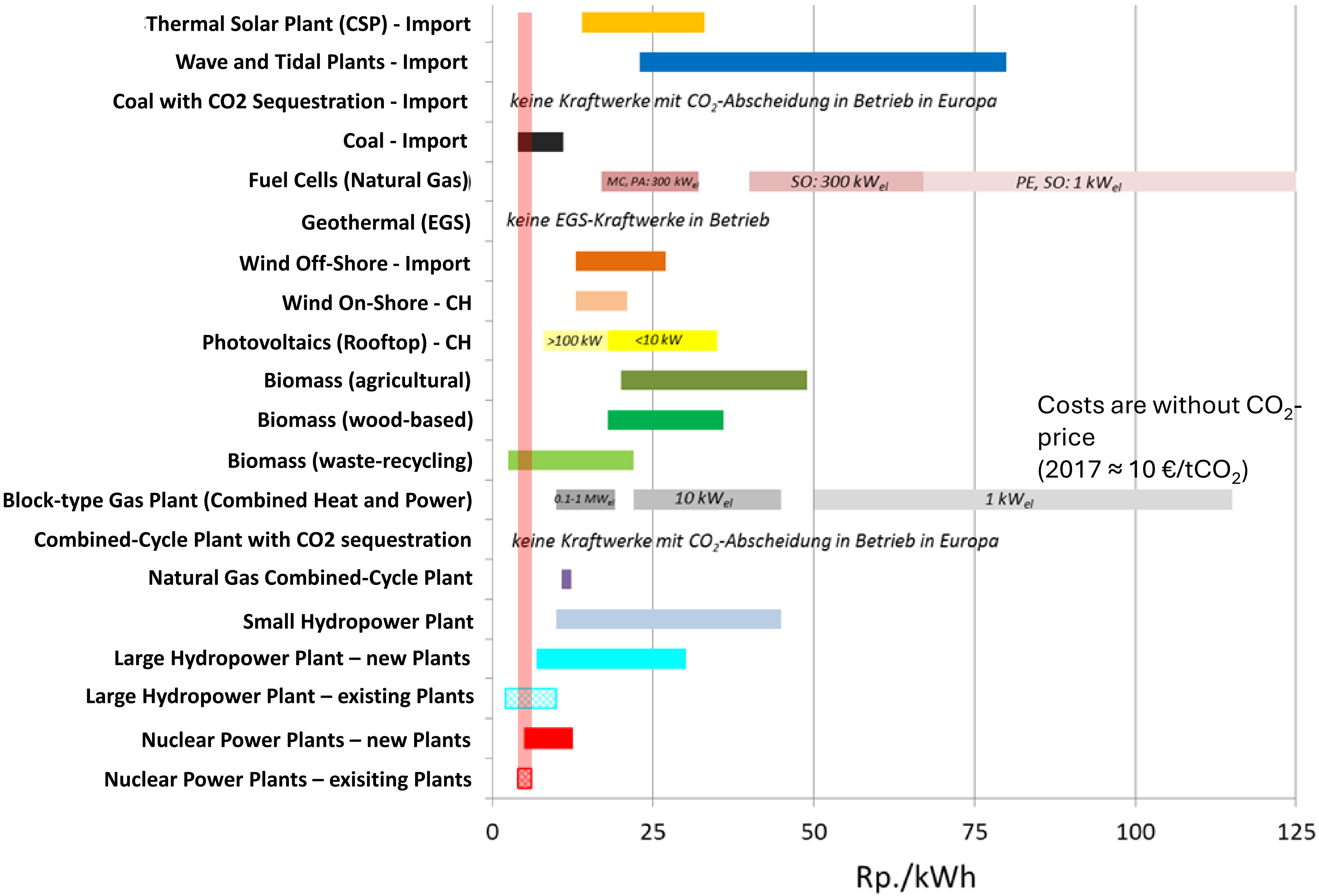
How Dangerous is the Generation of Energy?

PSI



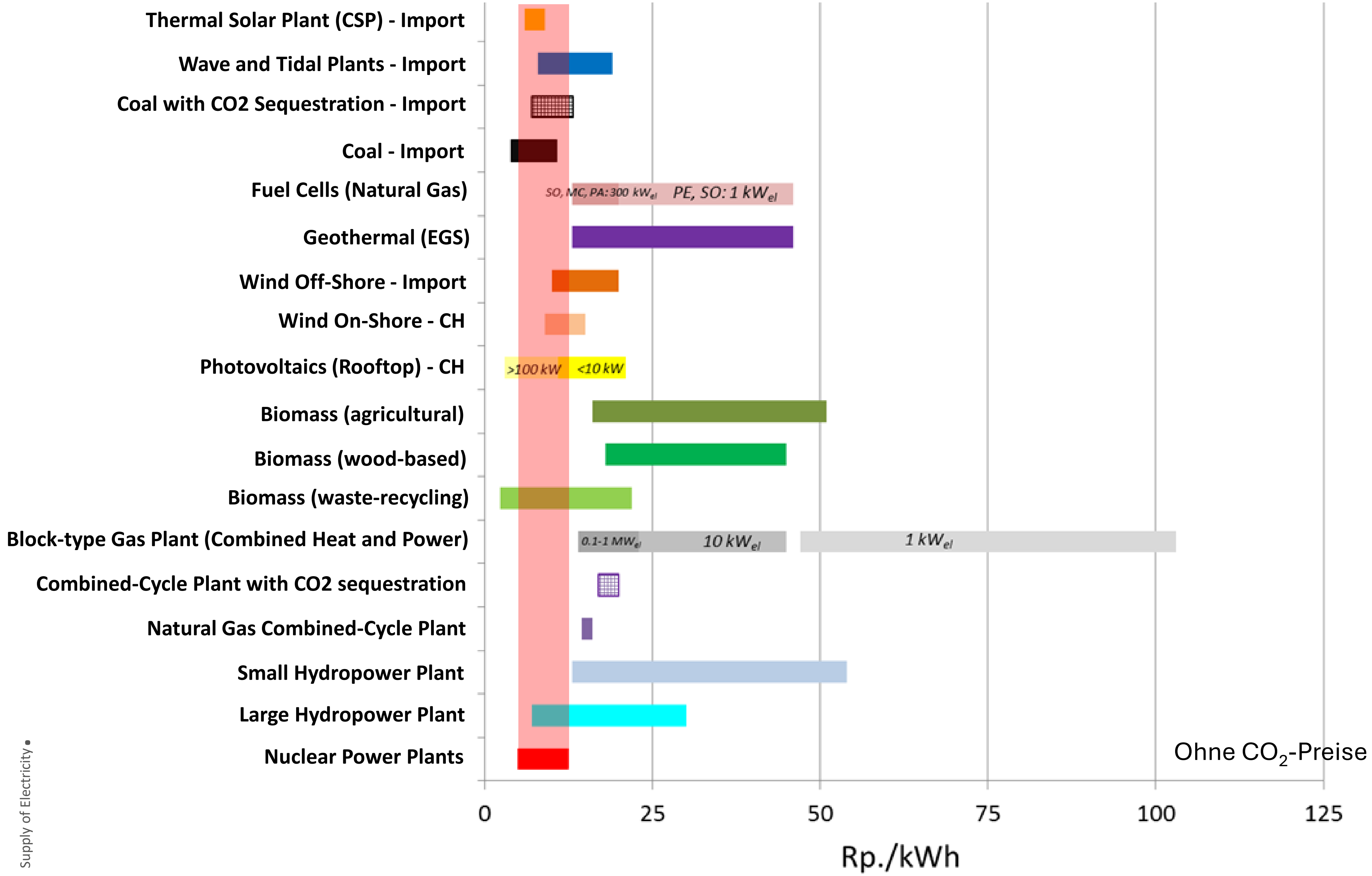
Levelized Costs of Electricity 2018/2019 (Source: PSI)

PSI



Bauer, C. (ed.), Cox, B., Heck, T., Zhang, X. (2019). Potentials, costs and environmental assessment of electricity generation technologies - An update of electricity generation costs and potentials. Paul Scherrer Institute (PSI) adn Swiss Competence Center for Energy Research (SCCER) -

Levelized Costs of Electricity 2050 (Source: PSI)



Bauer, C. (ed.), Cox, B., Heck, T., Zhang, X. (2019). Potentials, costs and environmental assessment of electricity generation technologies - An update of electricity generation costs and potentials. Paul Scherrer Institute (PSI) adn Swiss Competence Center for Energy Research (SCCER) - Supply of Electricity •

Financing of Post-Operation, Decomissioning, and Disposal

PSI

The costs for post-operation, decommissioning and disposal of radioactive waste are included in the price of nuclear electricity **at approx. 1 ct./kWh:**

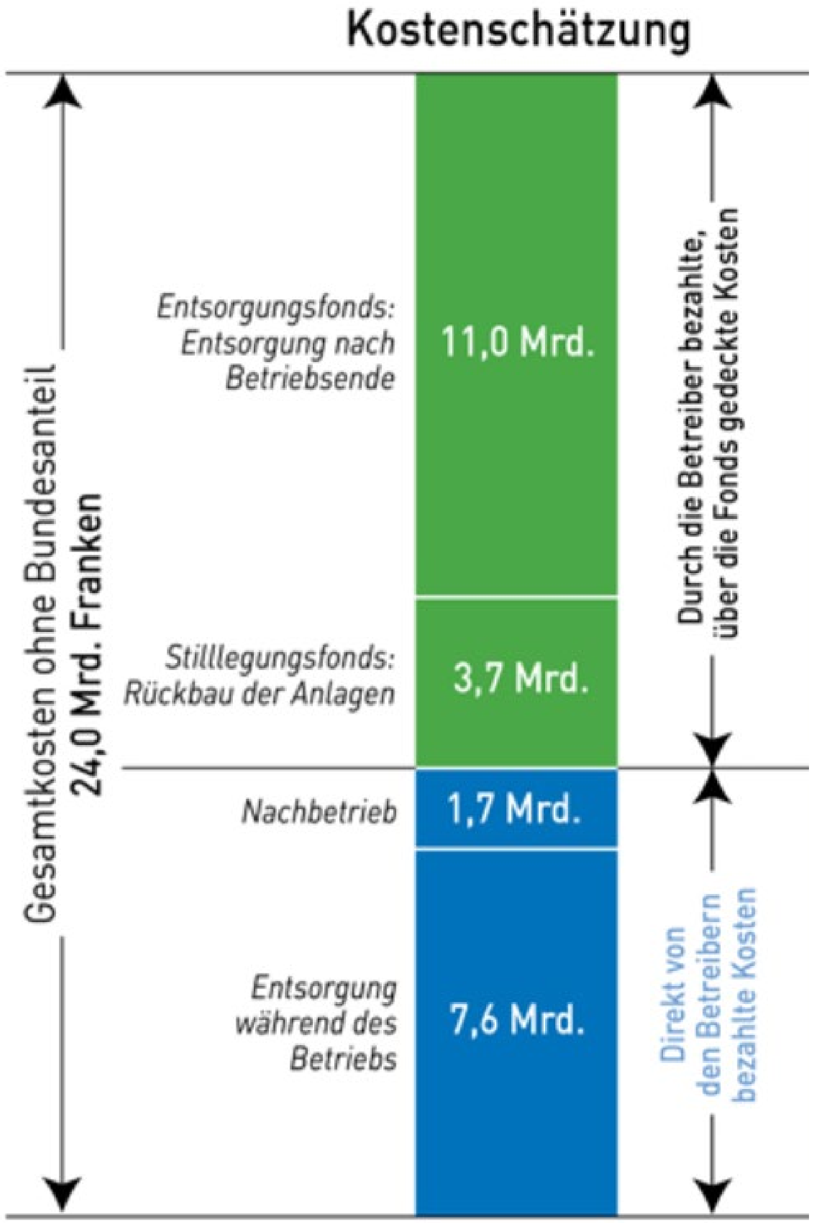
Disposal during operation: transport, containers, ZWILAG operation, NAGRA.

Post-operation, approx. 3-5 years after shutdown.

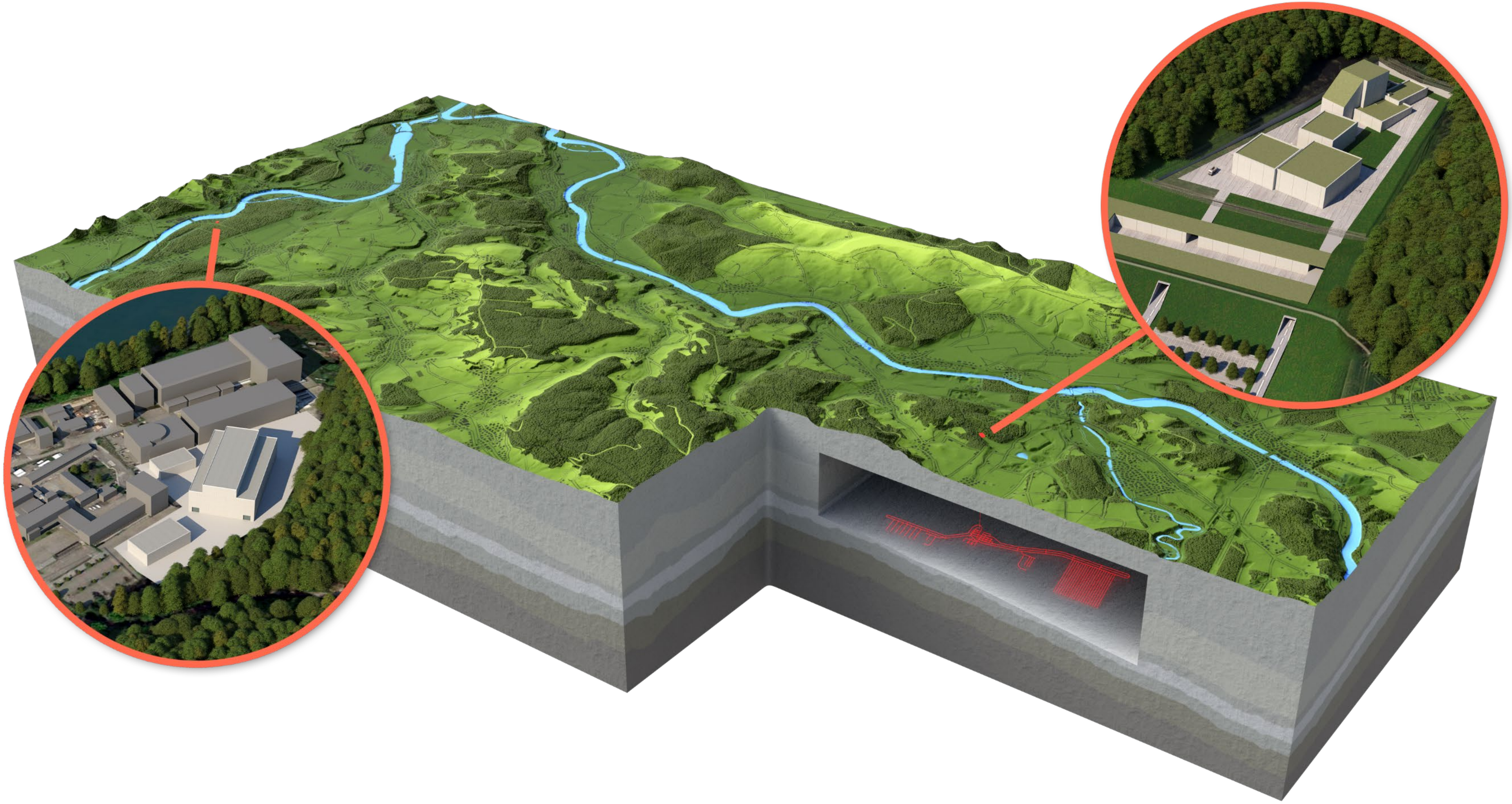
Decommissioning: Dismantling of the plant to the "green field".

Disposal after end of operation until closure of **deep geological repository**

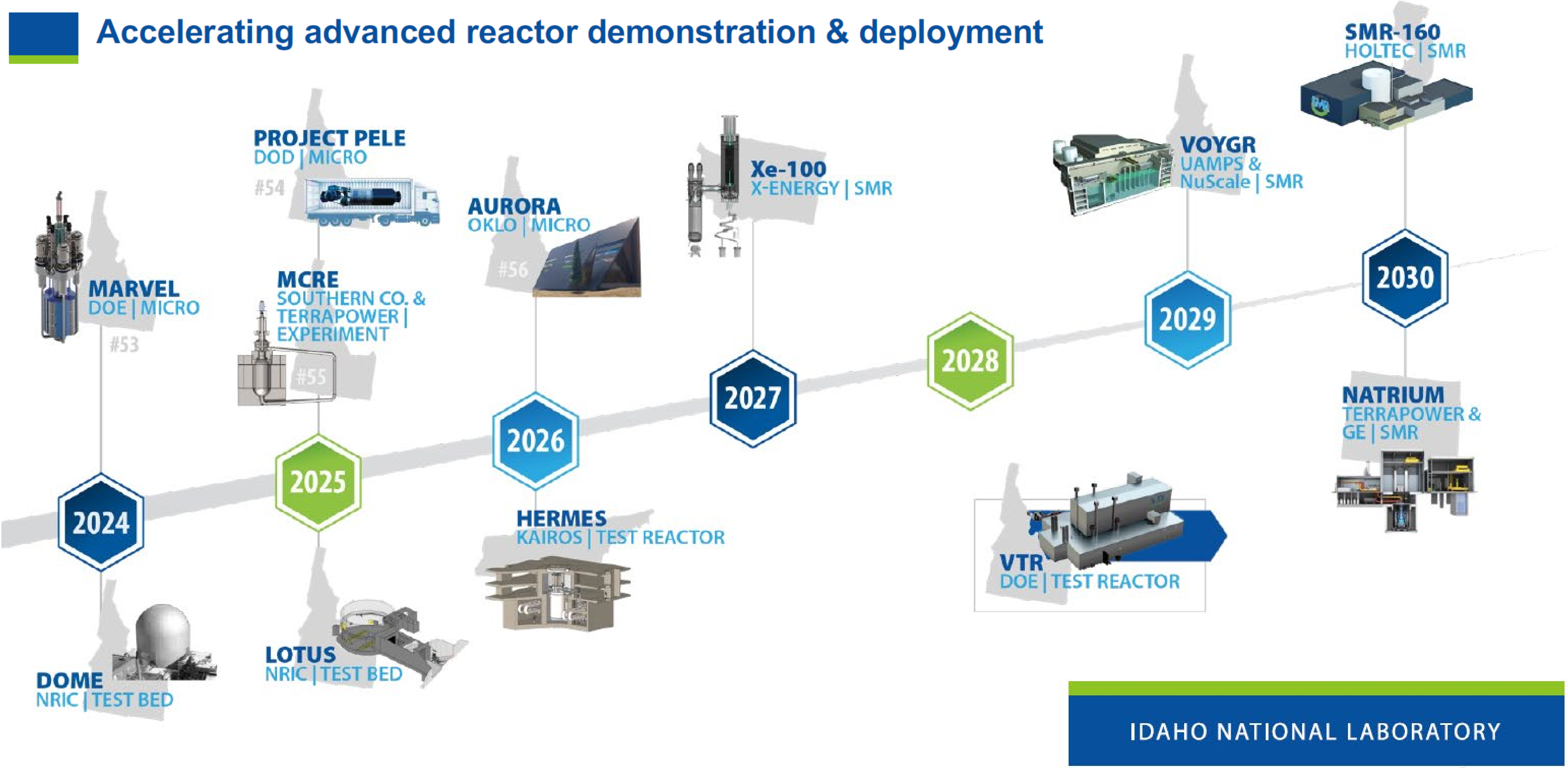
Total costs: approx. 24 billion SFr.



https://www.swissnuclear.ch/de/Kosten-Stillegung-und-Entsorgung.html



Construction and Deployment of New Reactors in the USA



Nuklearforschung in der Schweiz: Unsere Mission

Die Nuklearforschungslandschaft der Schweiz

PSI

PAUL SCHERRER INSTITUT

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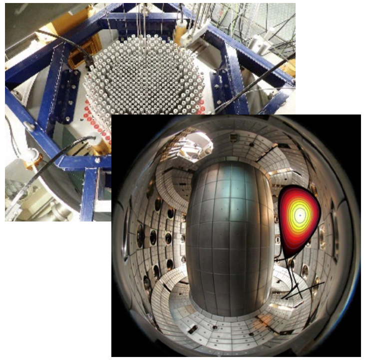
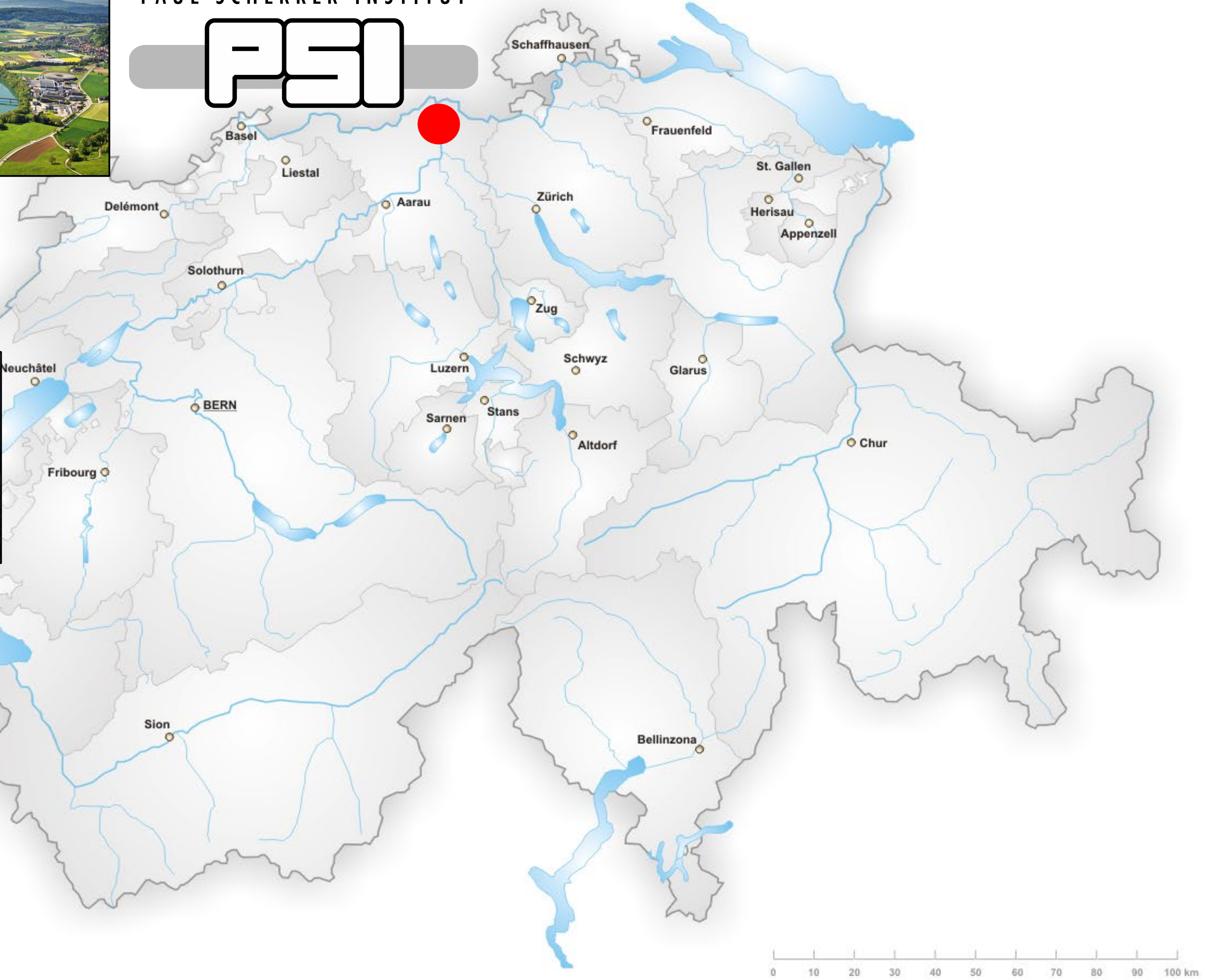
EPFL





Die Nuklearforschungslandschaft der Schweiz

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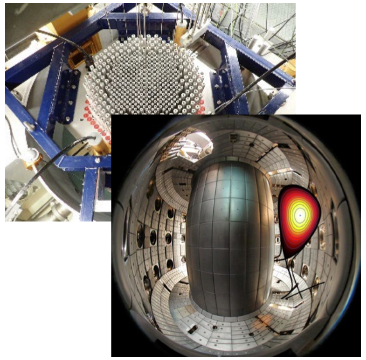
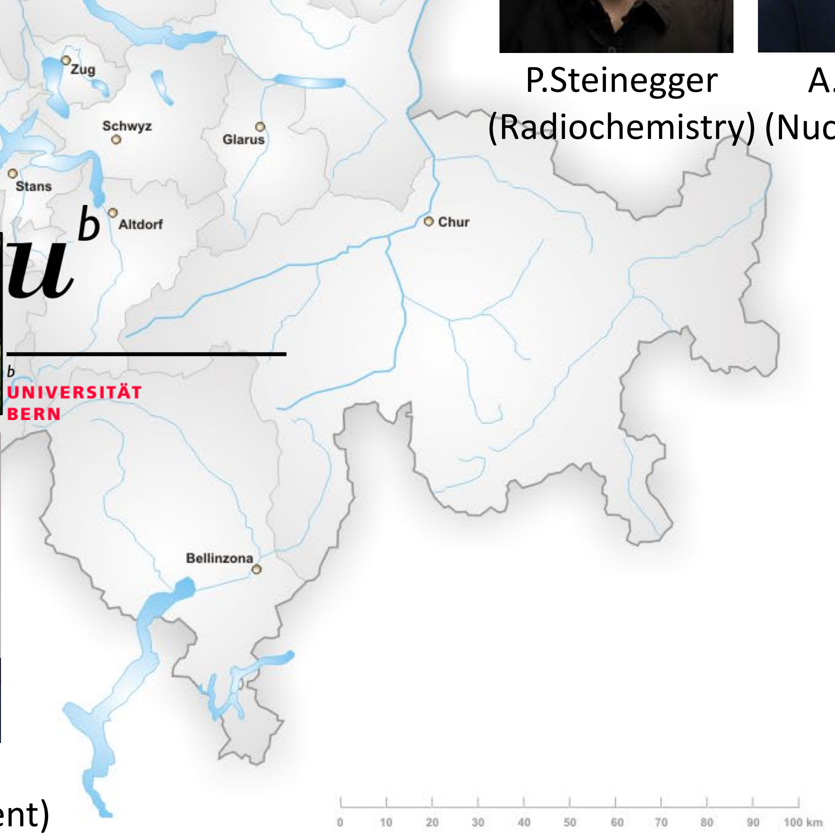


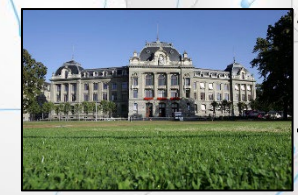
EPFL



ETH zürich

P.Steinegger
(Radiochemistry)

A. Manera
(Nuclear Safety)



u^b
b
UNIVERSITÄT
BERN

S. Churakov
(Waste Management)

A. Fasoli
(Nuclear Fusion)

A. Pautz
(Reactor Physics)

Die Nuklearforschungslandschaft der Schweiz

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P.Steinegger
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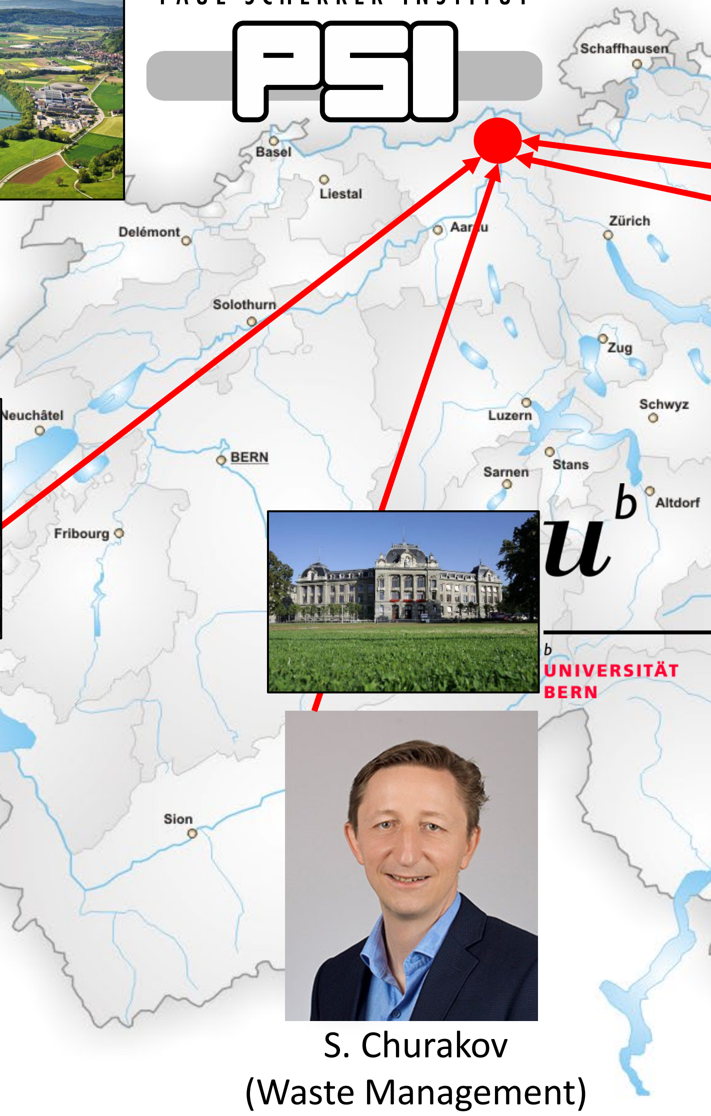
EPFL



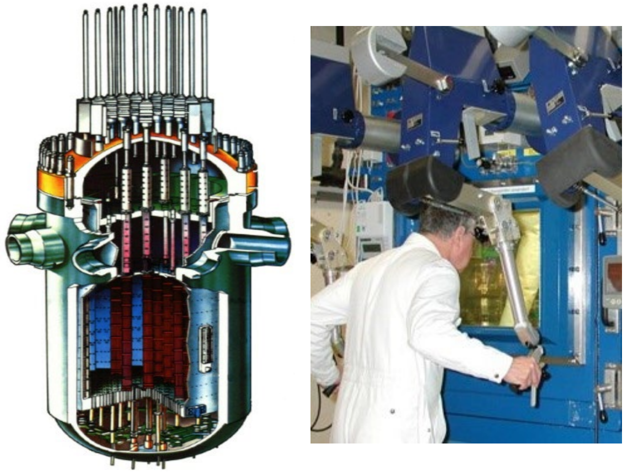
A. Fasoli
(Nuclear Fusion)

A. Pautz
(Reactor Physics)

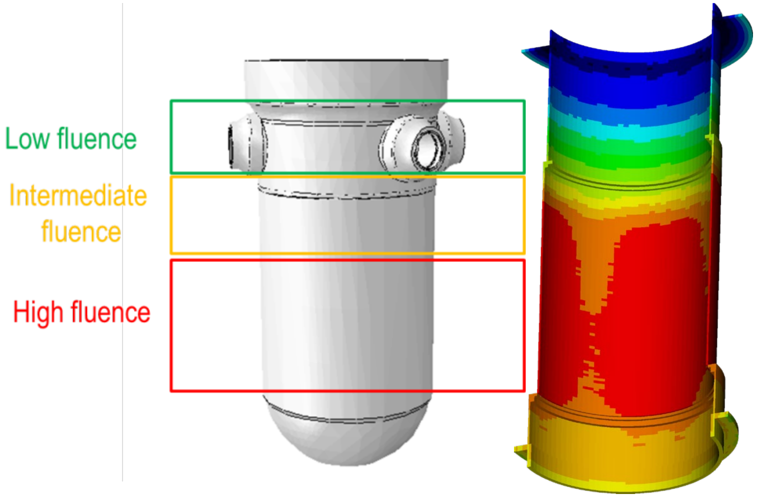
S. Churakov
(Waste Management)

Energieforschungsbudget 2022	Betrag (Mio. CHF)
Energieforschung (gesamt)	**364.85 (100%)**
Energieeffizienz	84.60 (23%)
Erneuerbare Energien	106.49 (29%)
Fossile Energie (inkl. CCS)	9.34 (3%)
Kernfusion	**35.82 (10%)**
Kernspaltung inkl. Endlagerung	**20.56 (6%)**
Wasserstoff und Brennstoffzellen	22.86 (6%)
Andere Speicher und Netze	24.44 (7%)
Energiesystemanalyse	31.00 (9%)

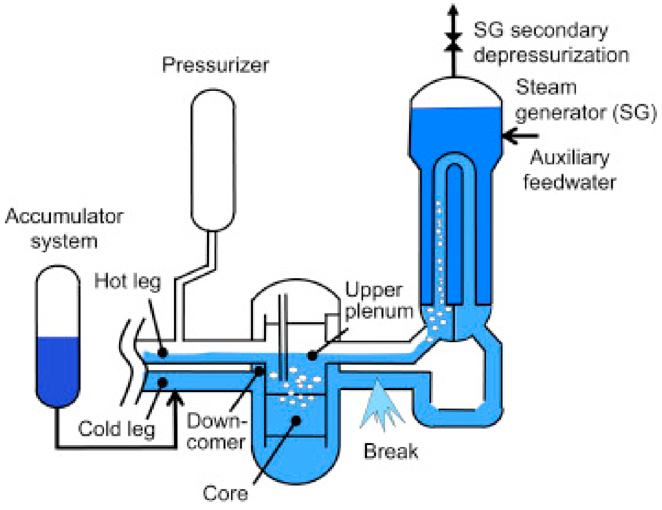
Integrität des Reaktordruckbehälters



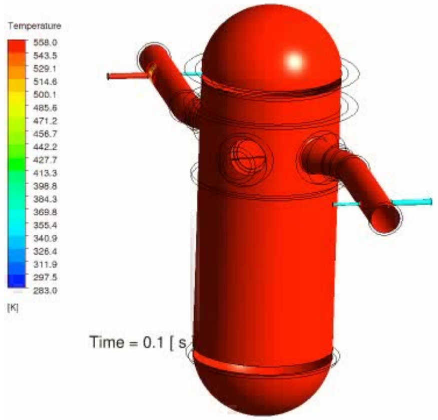
Entnahme von RDB-Proben (KKB) und mechanische Tests im Hotlab



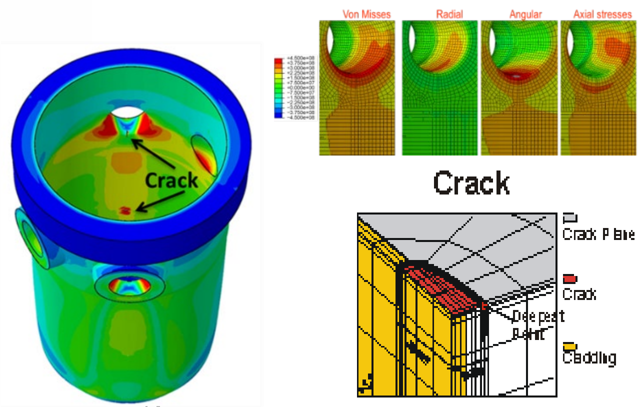
Ermittlung der Neutronenfluenz durch umfangreiche Monte-Carlo-Rechnungen



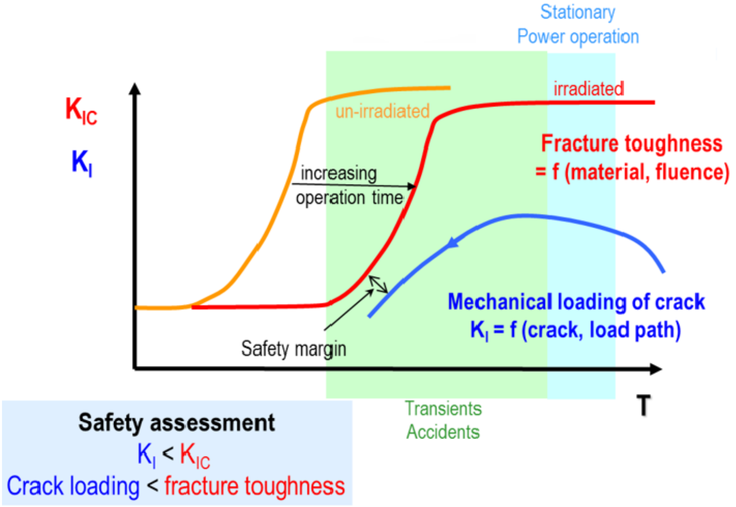
Ermittlung der ungünstigsten Störfall-Sequenz für die Sprödbruchanalyse



Ermittlung des Temperaturfeldes während des limitierenden Störfalles

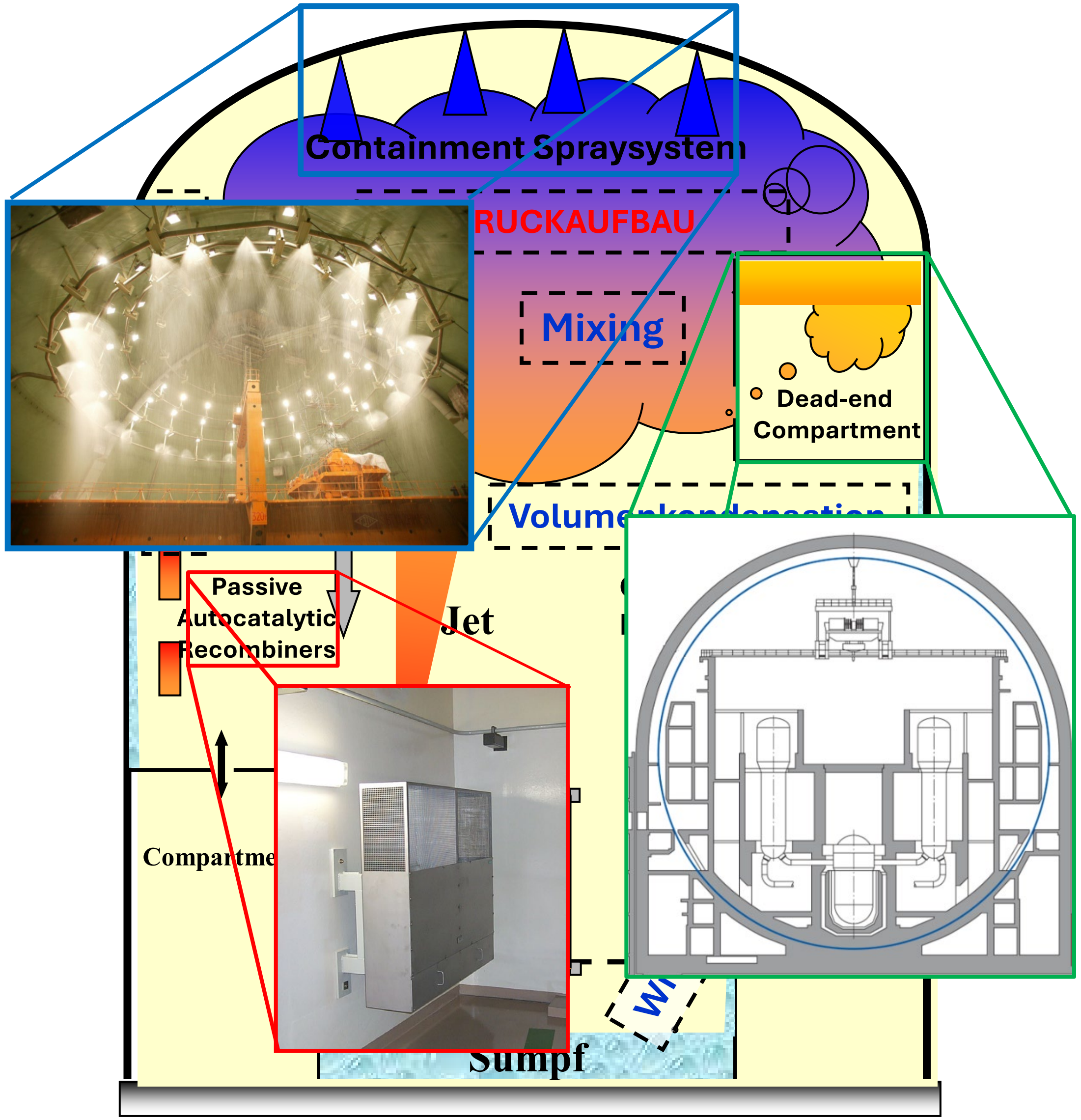


Auswahl der Rissklasse und Ermittlung der Risslasten

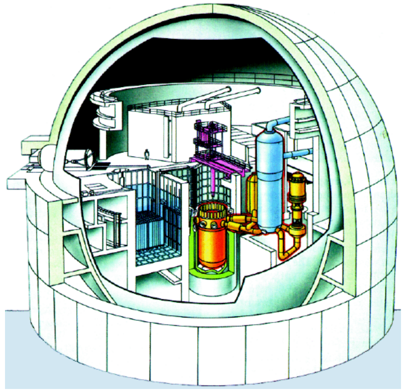


Nukleare Sicherheit: Containment

PSI

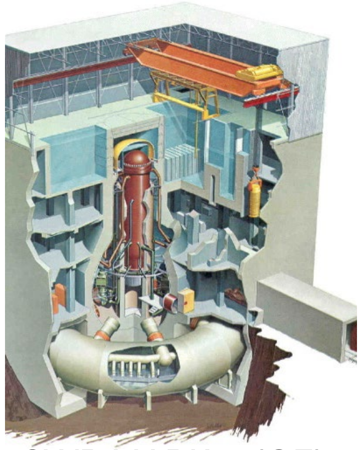


Komplexe Prozesse im Containment während eines Störfalls



KONVOI (Siemens)

EPR 1600 (Framatome)



SWR MARK-1 (GE)

Das Containment ist die letzte Barriere gegen die **Freisetzung von Radioaktivität**

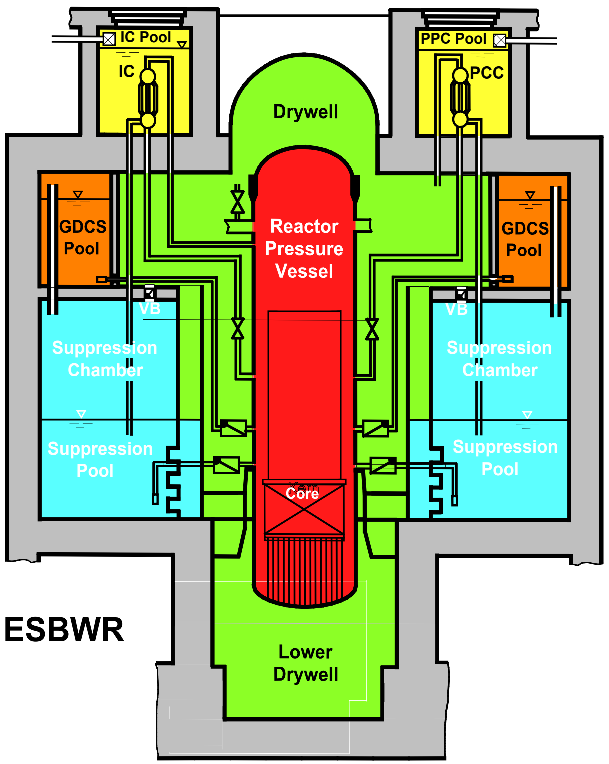
Viele unterschiedliche Designs mit komplexer Geometrie, komplexen Mehrphasen-Strömungsphänomenen, aktiven und passiven Sicherheits-systemen (u.a. zur Vermeidung hoher Wasserstoffkonzentrationen)

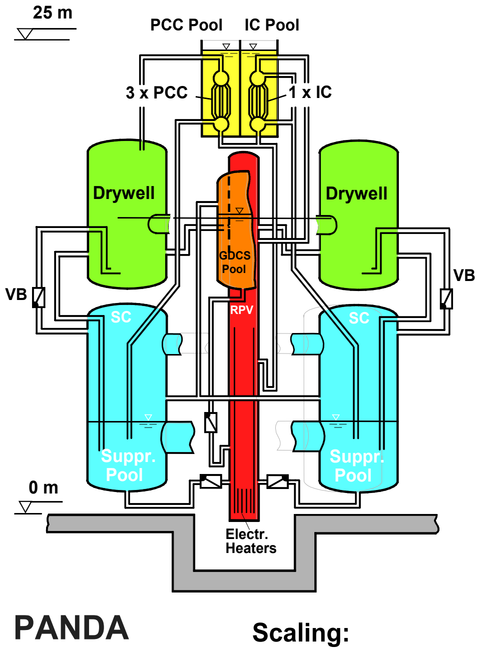
Experimente zu prototypischen Containment-Phänomenen in grossen, international finanzierten Versuchsanlagen als Datenbasis

Nutzung der Experimentaldaten als Grundlage zur **Validierung fortgeschrittener Störfall-Simulationscodes**

Kraftwerke nutzen validierte Software zum **Störfallnachweis und Optimierung der Sicherheitssysteme**

Die experimentelle Grossanlage PANDA





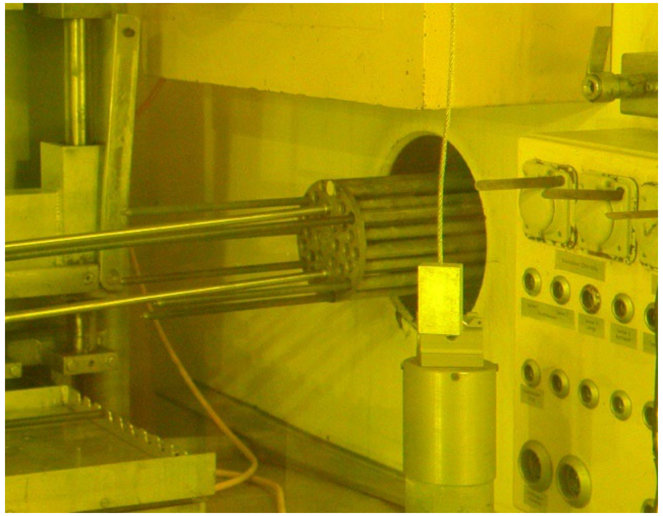
Scaling:
Height ~ 1 : 1
Volume ~ 1 : 40
Power ~ 1 : 40

PANDA: eine international anerkannte Referenzanlage (laut OECD/NEA eine „Forschungseinrichtung von kritischer Bedeutung“) für Containment-Sicherheitsphänomene

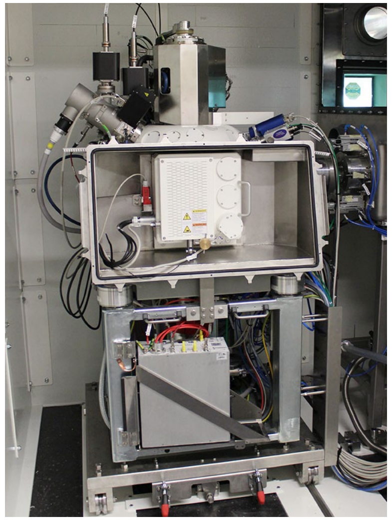
Seit Juli 2021 arbeitet das PSI am OECD/NEA-Projekt „PANDA-SMR“, an dem viele OECD-Mitgliedstaaten beteiligt sind und das einen besonderen Schwerpunkt auf kleine modulare Reaktoren legt.

Das Hotlabor: die zentrale nukleare Infrastruktur des PSI

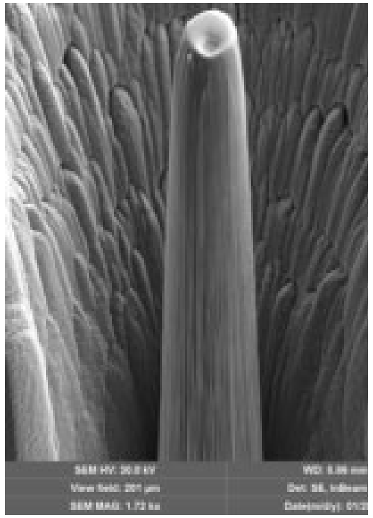
- Das **Hotlabor am PSI** ist eines der wenigen Labore in Europa, das noch abgebrannte Brennstäbe in voller Länge aufnehmen kann
- **Nachbestrahlungsuntersuchungen** von Brennstäben bleiben notwendig, mindestens solange die KKW laufen
- **Hohe Relevanz auch für den PSI-Betrieb**, z. B. für Targetuntersuchungen und Abfallkonditionierung
- Exzellente **analytische Infrastruktur**, einzigartig in **Kombination mit den Grossforschungsanlagen** des PSI (z.B. SINQ und SLS)



Anlieferung von Brennstäben



Hot Lab Shielded FIB

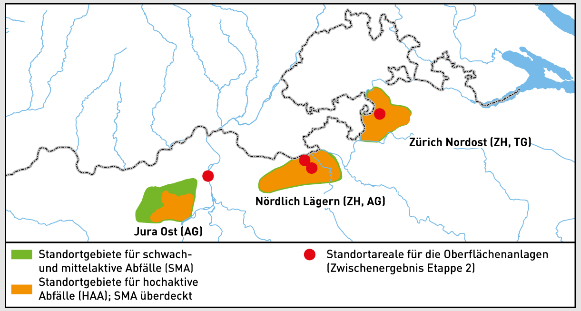


Herstellung von Mikroproben

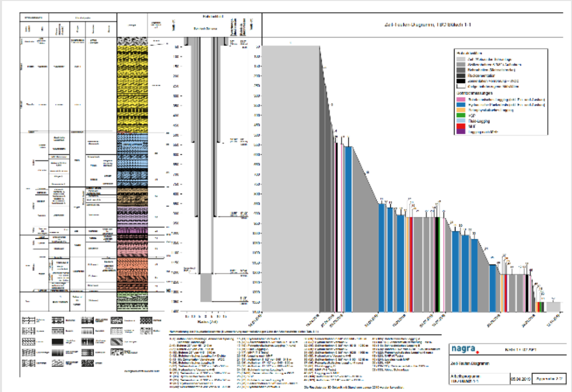
Imaging an der Swiss Light Source (SLS)

Unterstützung der Tiefbohrkampagnen der Nagra

Mögliche Standorte in der Nordschweiz

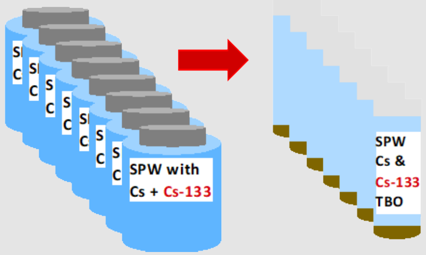


Bülach: Bohrprofile und Bohrplattform

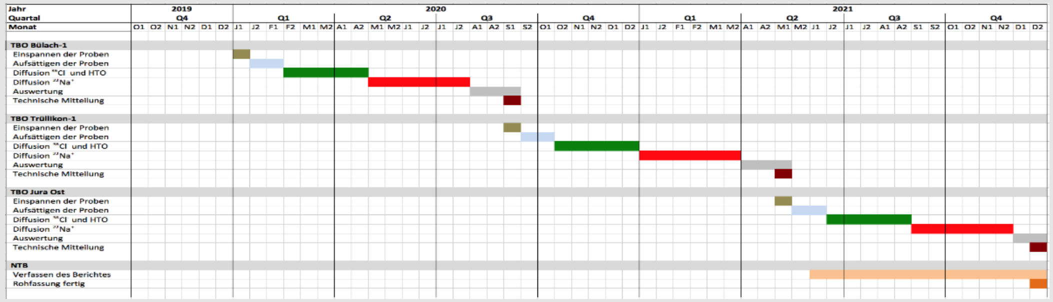


Diffusionsexperimente mit kompaktierten Gesteinsproben

Adsorptionsexperimente mit gemahlenen Gesteinsproben



Projekt-plan



SCK CEN erhält 100 Millionen Euro für Forschung an modularen Kernreaktoren

Veröffentlicht am 24.05.2022 um 16:33

Das Kernforschungszentrum SCK CEN in Mol (bei Anwerpen) wird von der Föderalregierung ein Forschungsbudget von 100 Millionen Euro erhalten. Dies sagte Premierminister Alexander De Croo (Open VLD) am Dienstag anlässlich der Feierlichkeiten zum 70-jährigen Bestehen des SCK CEN.

Government to permit final disposal of spent nuclear fuel at Forsmark

Published 27 January 2022

The Government has today decided to permit the final disposal of spent nuclear fuel at Forsmark in Östhammar Municipality. The Government has also decided to permit construction of the encapsulation plant that is needed to handle the spent nuclear fuel in Oskarshamn Municipality.

"Sweden and Finland are the first countries in the world to take responsibility for nuclear waste. This will be a secure spent fuel repository that will provide safety for both the environment and people. In addition, it provides long-term conditions for the Swedish electricity supply and Swedish jobs," says Minister for Climate and the Environment Annika Strandhäll.

ENERGY • EDITORS' PICK

Finland Breaks Ground On World's First Deep Geologic Nuclear Waste Repository

James Conca Former Contributor ⓘ
I write about nuclear, energy and the environment

Follow

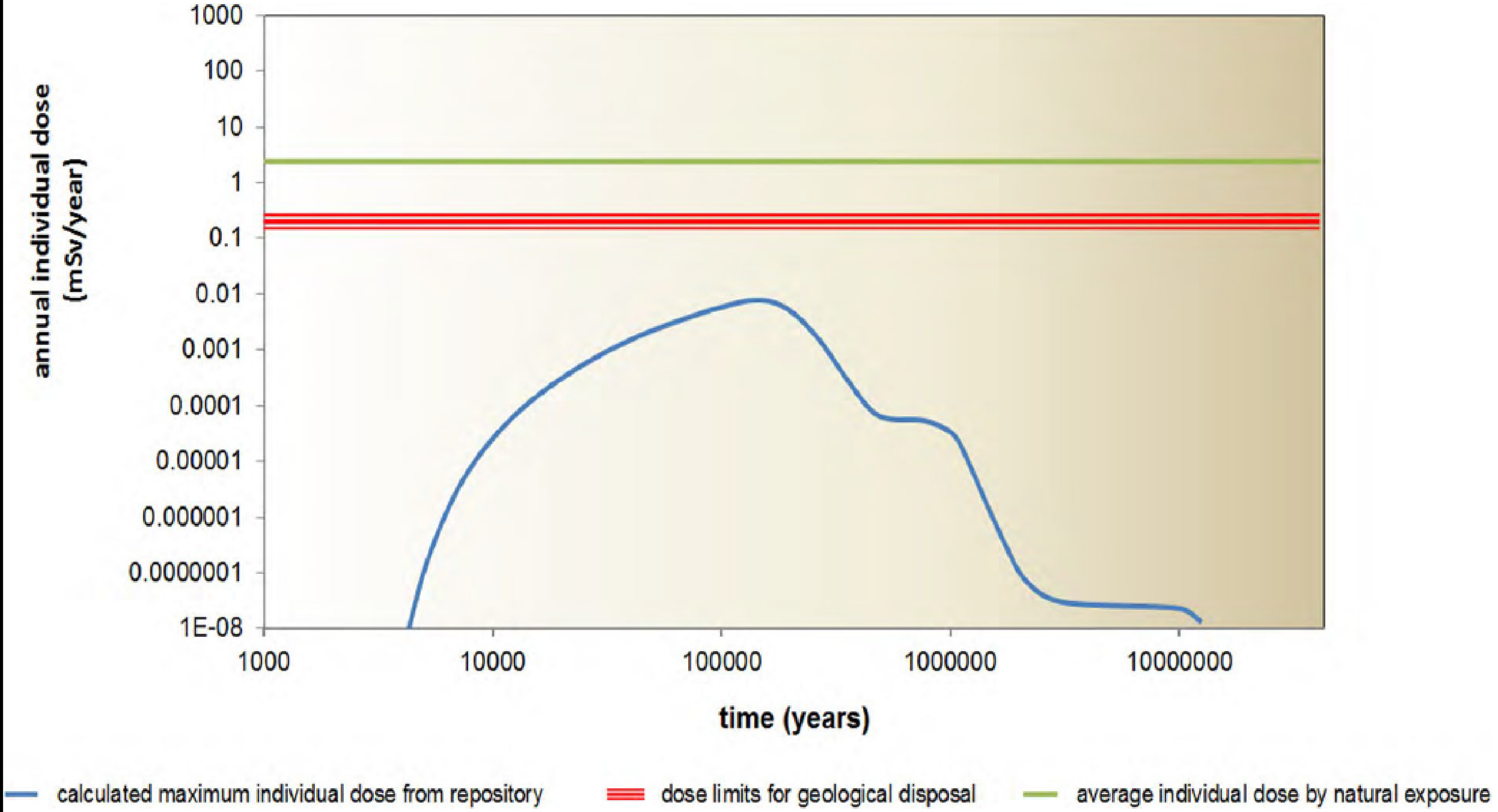
May 31, 2021, 08:00am EDT

Listen to article 10 minutes

The Radiation and Nuclear Safety Authority of Finland has certified the process. Operation of the repository is expected to begin in 2023. The total cost estimate is about €2.6 billion ($3.4 billion).

Release of Radioactivity from Nuclear Waste

Figure 1-1. Example of modelling the performance of the geologic repository for high level waste (Belgian case): expected radiation dose to most exposed individual, compared to maximum allowed dose and to natural radiation dose



Quelle: “Technical assessment of nuclear energy with respect to the ‘do no significant harm’ criteria of Regulation (EU) 2020/852 (‘Taxonomy Regulation’)”, 2021 Joint European Research Center of the European Commission

Was bedeutet nukleare Sicherheit?

PSI

Primäres Ziel ist der Schutz von Mensch und Umwelt vor den Gefahren radioaktiver Strahlung

- Wirksamer Einschluss radioaktiver Substanzen innerhalb des Kraftwerks: **Gestaffeltes Sicherheits- und Barrierenkonzept (*Defense-in-Depth*)**
- **Best Practices in Design**: inhärente Sicherheit, State-of-the-Art-Berechnungsmethoden, aktive und passive Sicherheitssysteme, hohe Qualitätsmassstäbe
- **Aus Fehlern lernen:** Akkumulation von internationaler Betriebserfahrung, Meldesystem für Ereignisse, internationales Kontrollregime
- Demonstration der Vermeidung und Beherrschung von Störfallszenarien durch **Simulation und Experiment**
- Und deswegen: **Sicherheitsforschung**!

Betriebserfahrung, neue Sicherheitsaspekte, Ereignisse

IAEA

NEA Nuclear Energy Agency

triggert

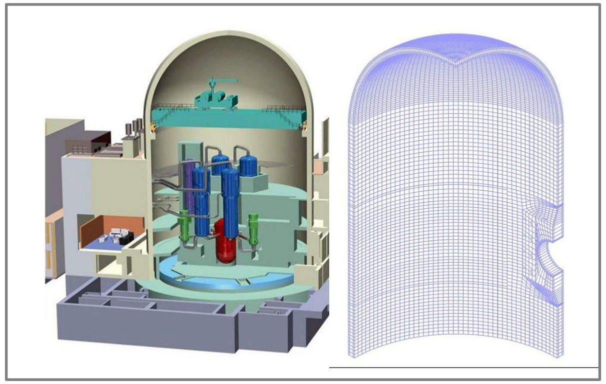
Grossskalige Experimente

Nachrüstung

Verbessertes Design

Validierung

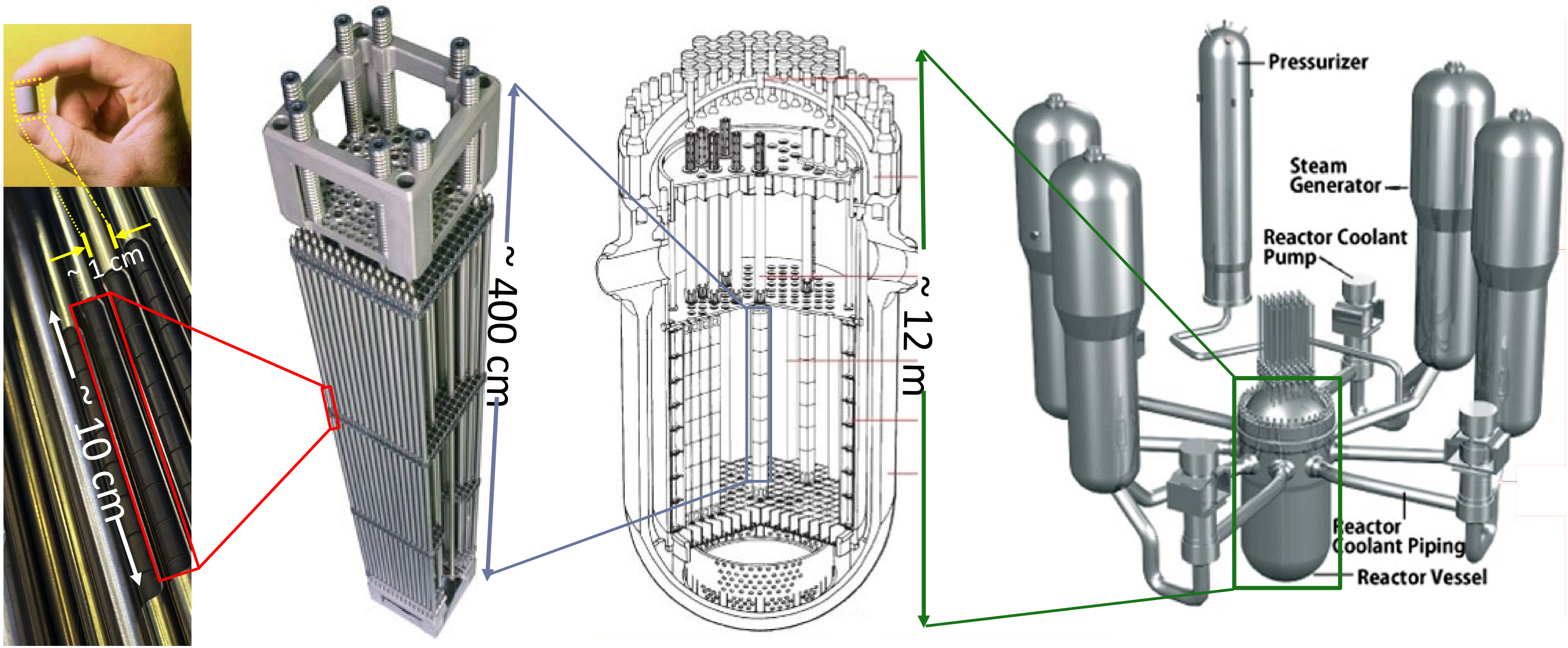
Design und Optimierung



Simulation und Modellierung

Gestaffelte Sicherheit: Barrierenkonzept

PSI



1. Barriere: Hüllrohr
Fuel Pellet und Hüllrohr

Brennelement (DWR)
(ca. 200-300 Brennstäbe)

Druckbehälter (DWR)
(ca. 150-200 Brennelemente bzw. bis zu 60’000 Stäbe)

2. Barriere: Primärkreislauf (DWR)
(300 °C, 150 bar, 30 t/s Kerndurchsatz)

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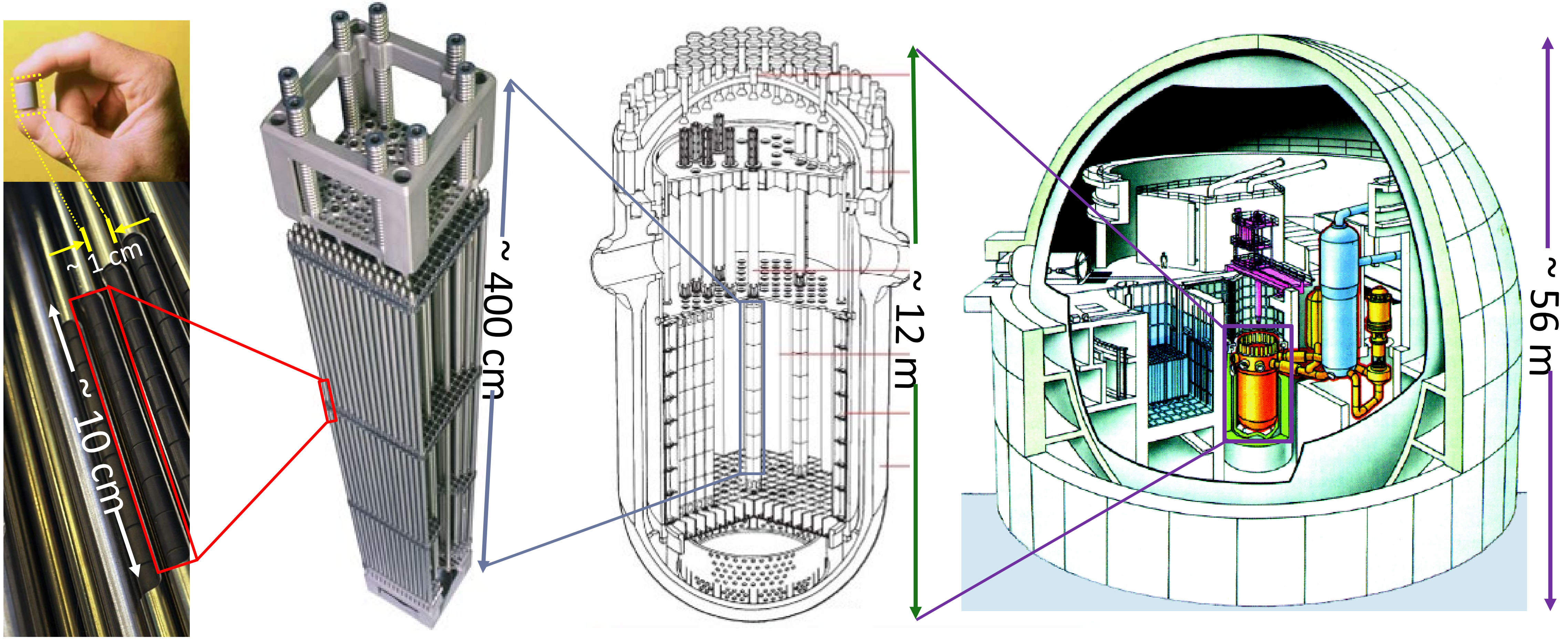

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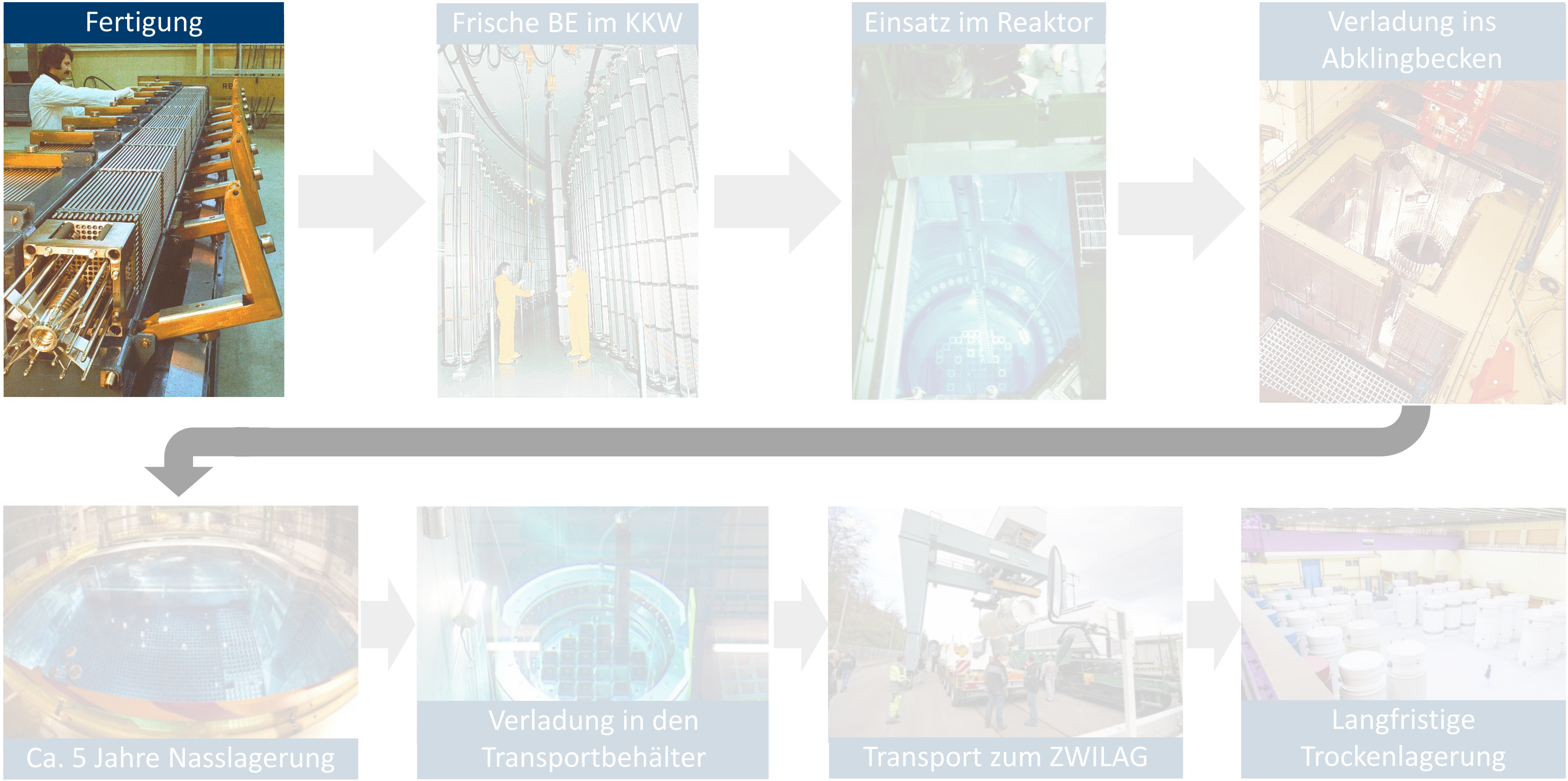
3. Barriere: Containment (KKW Gösgen)
(V=91’000 m^3, Auslegungsdruck 6,3 bar)

Lebenszyklus des Schweizer Nuklearbrennstoffs

PSI



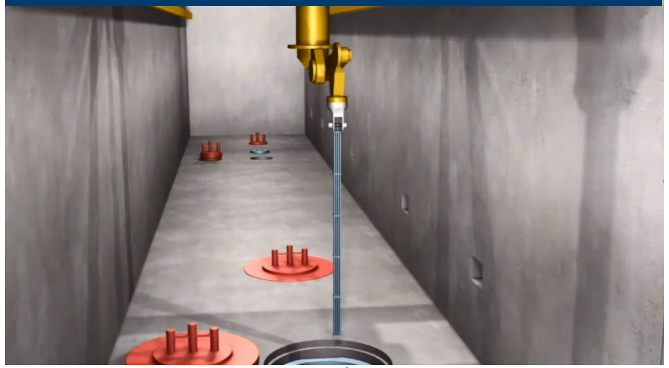
Lebenszyklus des Schweizer Nuklearbrennstoffs

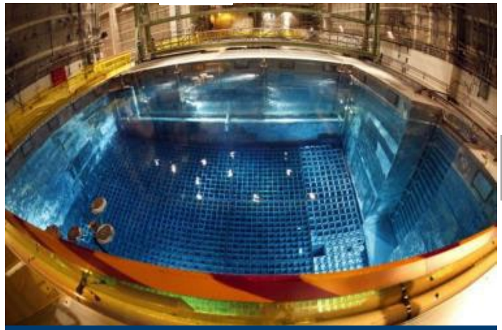
PSI

Endlagerung im Barrierensystem

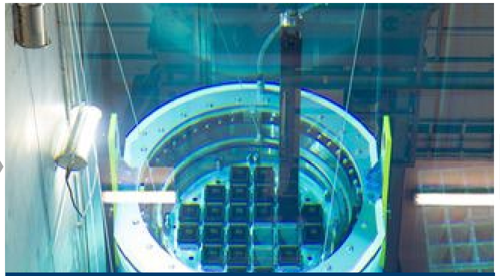
Transport in das Geologische Tiefenlager

Verladen von Transport- in Endlagerbehälter





Ca. 5 Jahre Nasslagerung

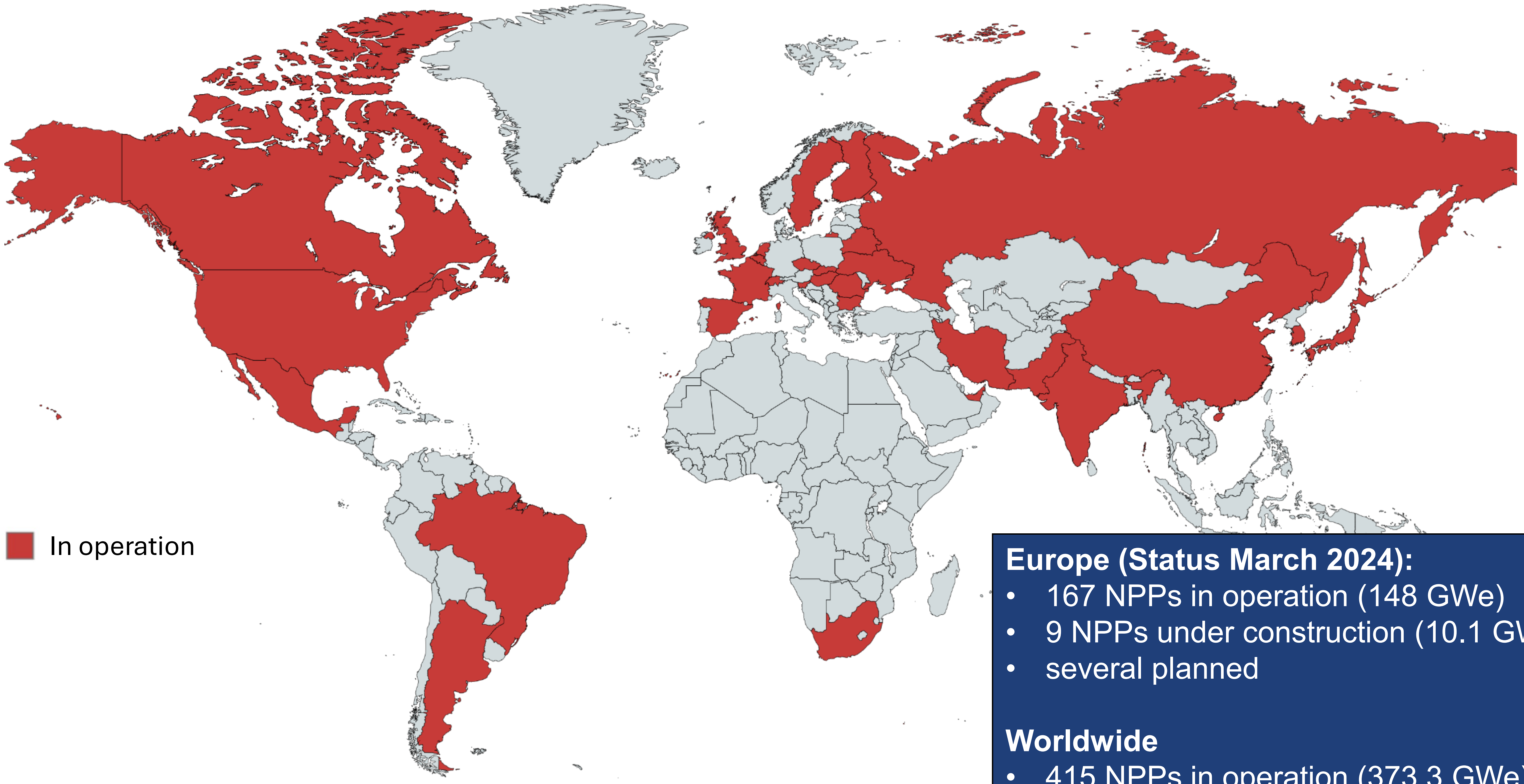


Verladung in den Transportbehälter

Transport zum ZWILAG

Langfristige Trockenlagerung

NPPs in operation



Europe (Status March 2024):

- 167 NPPs in operation (148 GWe)
- 9 NPPs under construction (10.1 GWe)
- several planned

Worldwide

- 415 NPPs in operation (373.3 GWe)
- 57 NPPs under construction (59.2 GWe)

NPPs under construction

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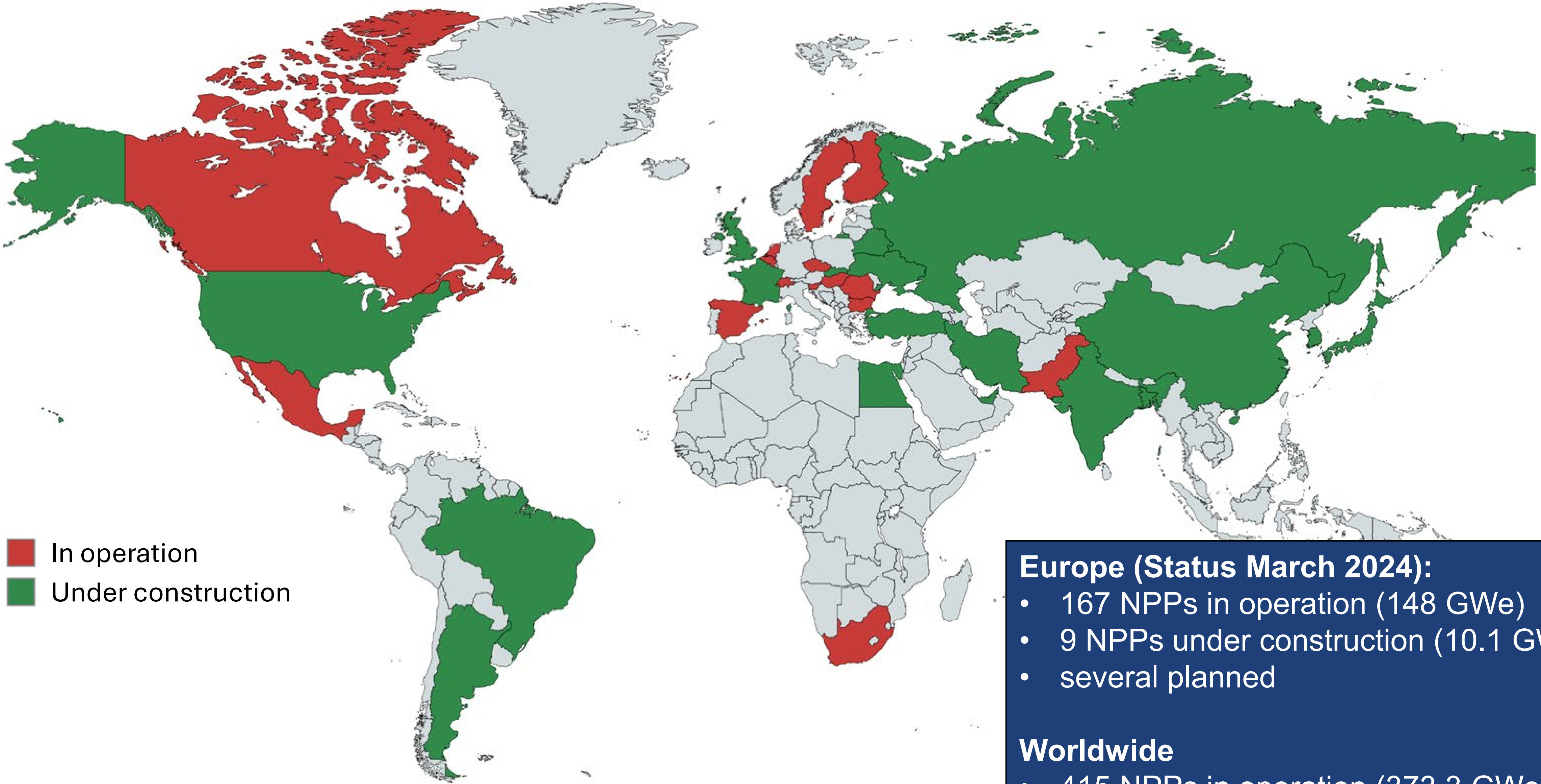

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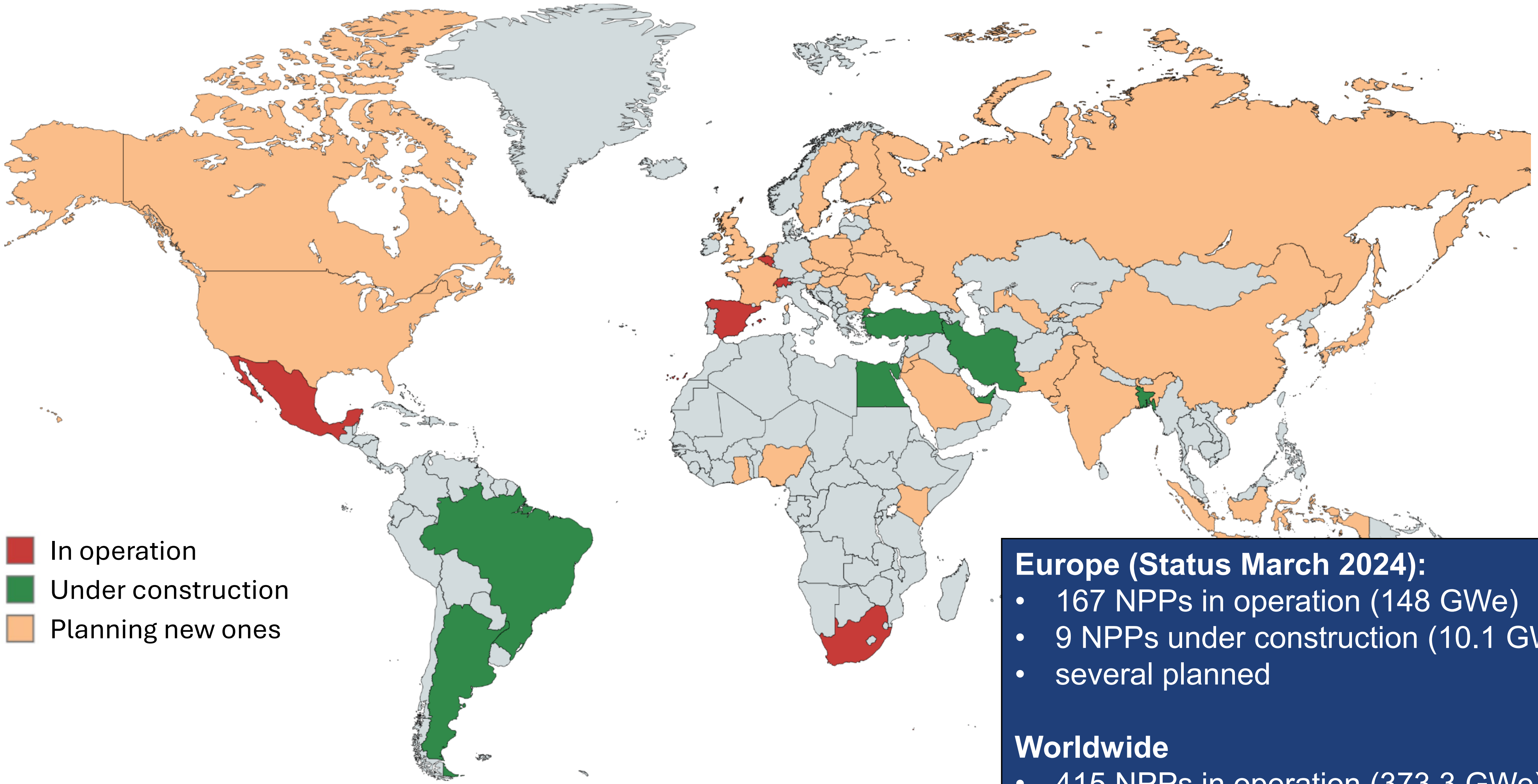
NPPs planned



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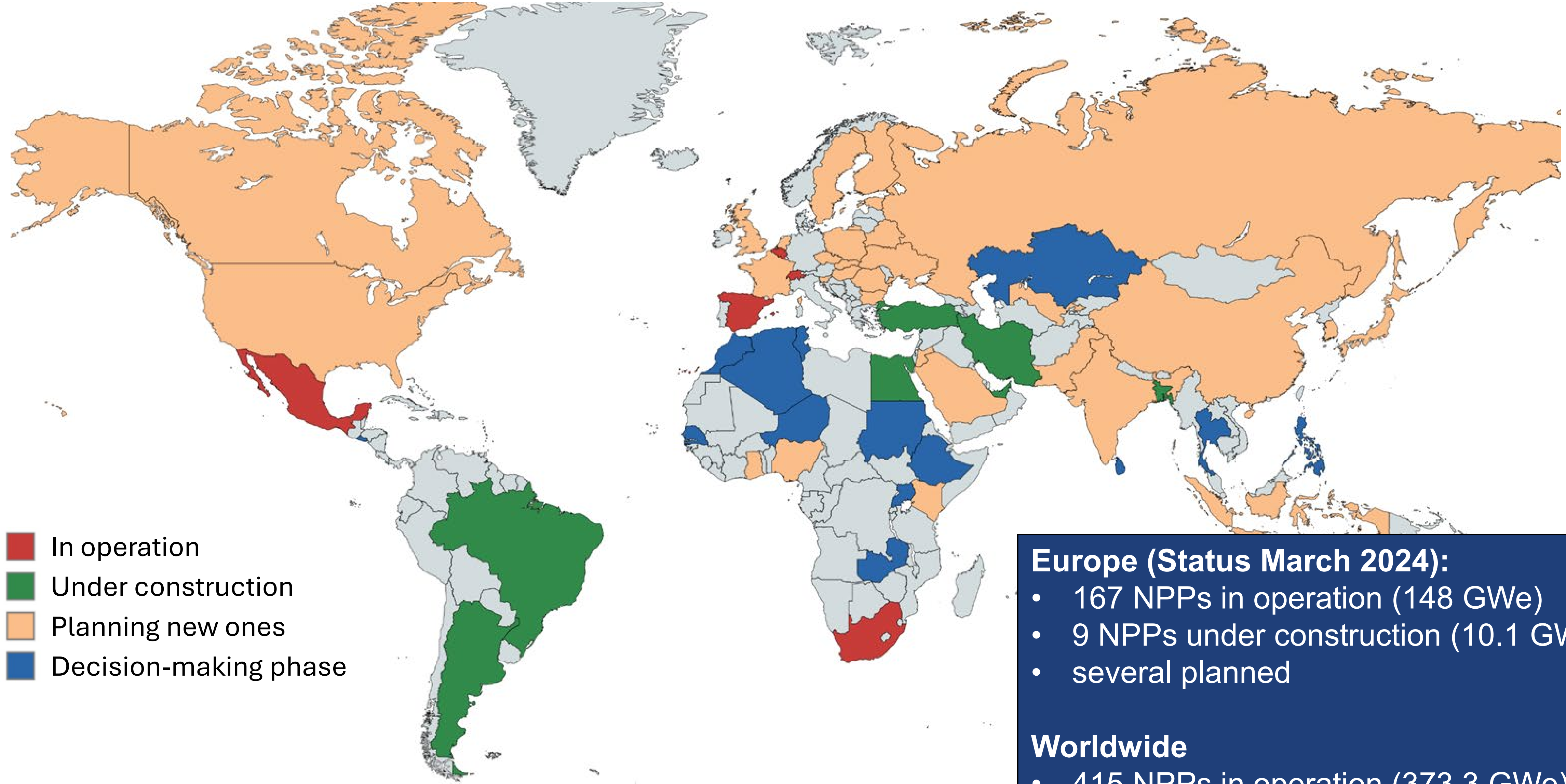
Countries in decision-making phase



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NUWARD (France)

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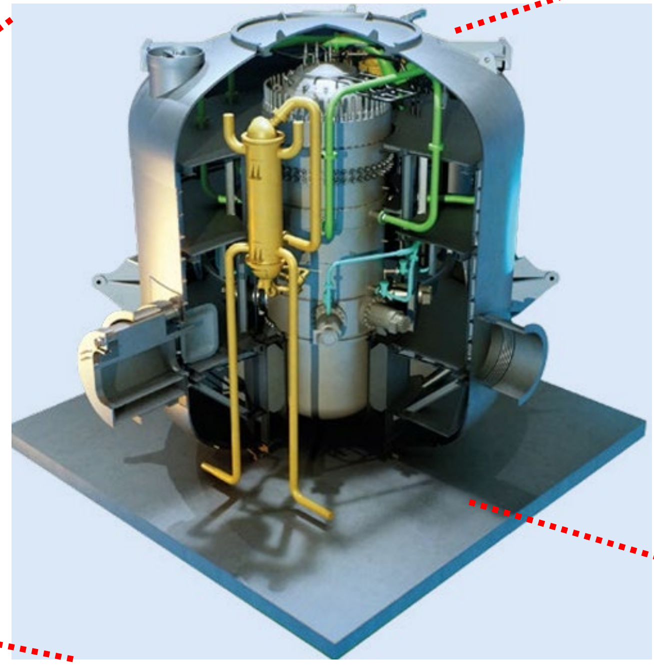
Flexible operation between 20% to 100% of rated power

Containment



RPV

General characteristics

- 2 reactors of 540 MWth
- 2 containment structures submerged in water
- 1 Nuclear Island semi-buried (25 m) protected against aircraft crash
- 2 generation units of 170 MWe

STRATEGIC SUPPORT FROM FRENCH GOV.

2020: EUR 50 M (French Recovery Plan) for Conceptual Design

2022: EUR 500 M ("France 2030" plan)

2026: Start of licensing procedure, first concrete by 2030

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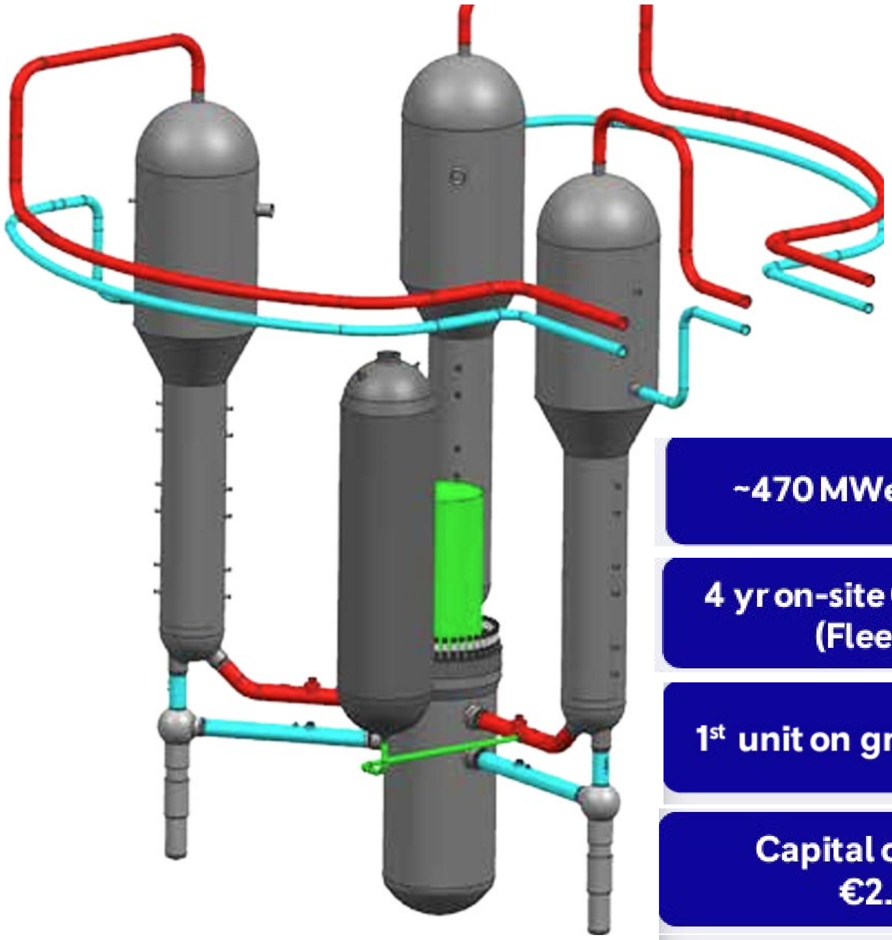
Rolls-Royce (UK)



~470 MWe net output

4 yr on-site Construction (Fleet unit)

1st unit on grid early 2030s

Capital cost under €2.3bn*

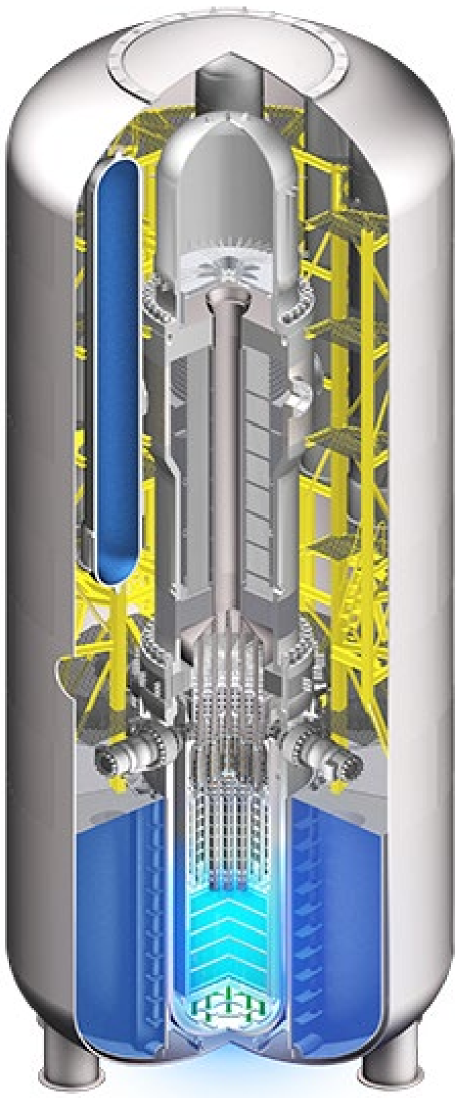
LCOE range €39-€56 per MWh**

* 2021 economics, fleet unit; £1:€1.1406 (5yr average), costs based on UK labour rates

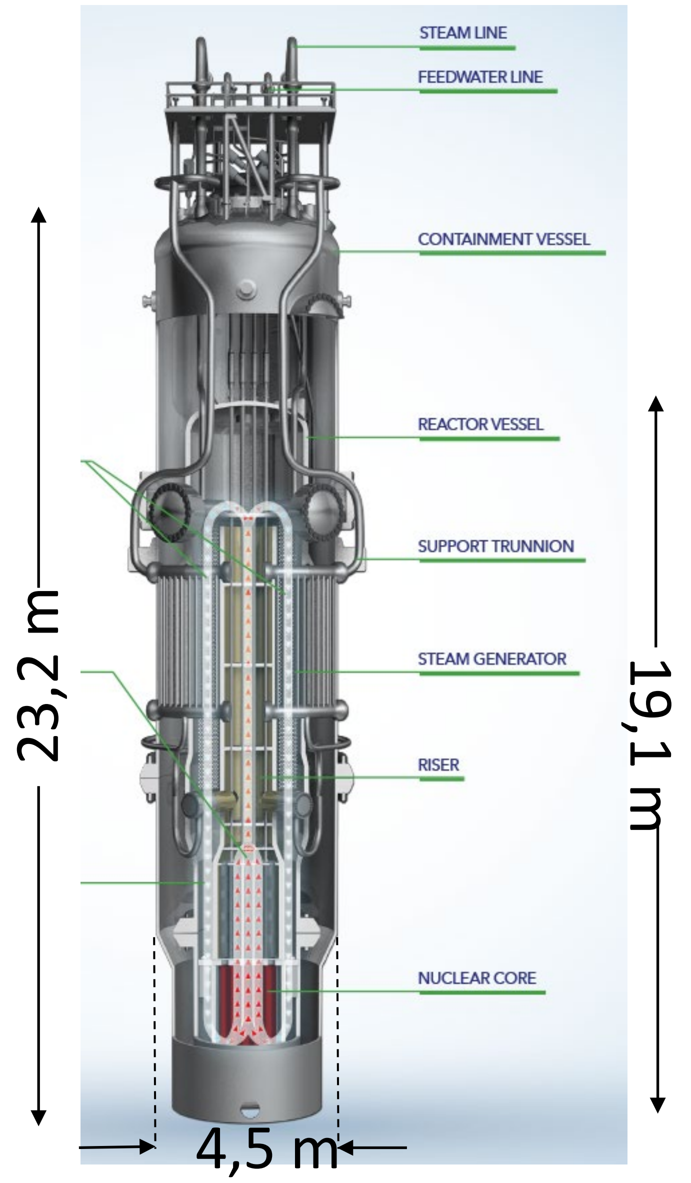
** 2021 economics, 2 unit plant, range dependent on financing mechanism

AP300 (Westinghouse, US)

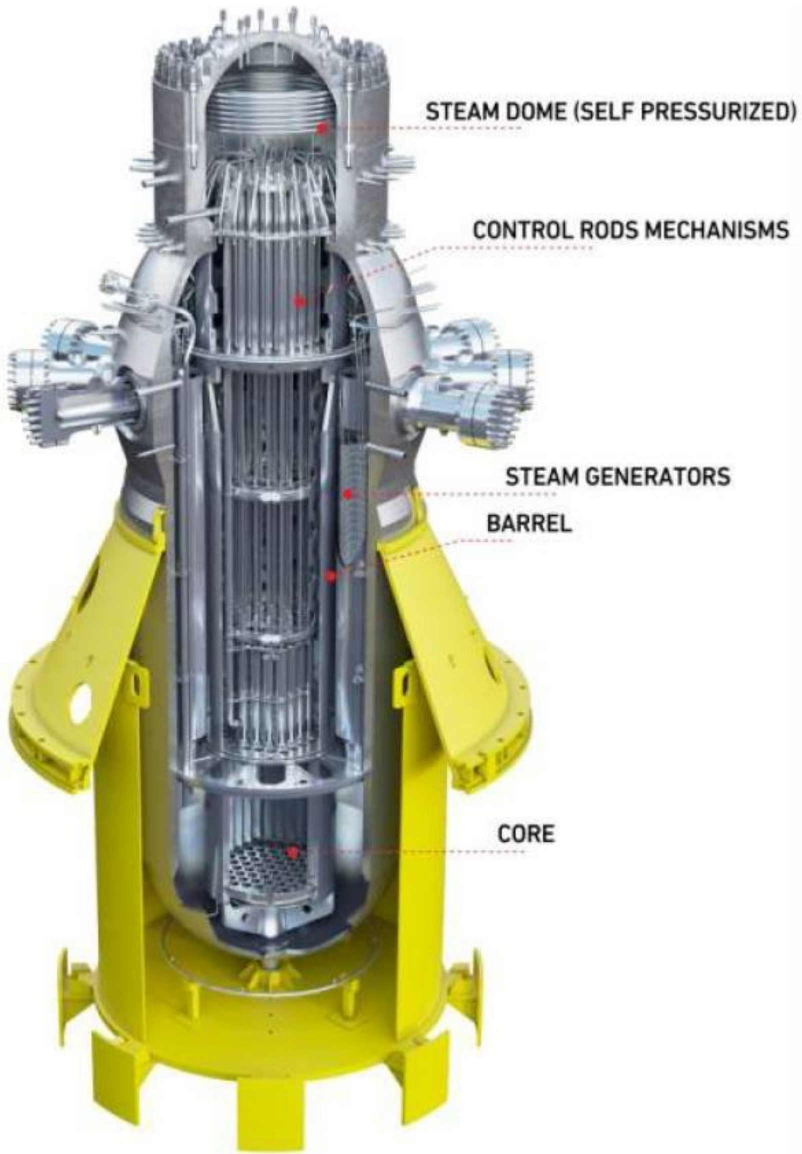
Small Modular Reactors (LWR-SMR): Integral Modules



Westinghouse Small Modular Reactor 225 MWe



NuScale 77 MWe Module



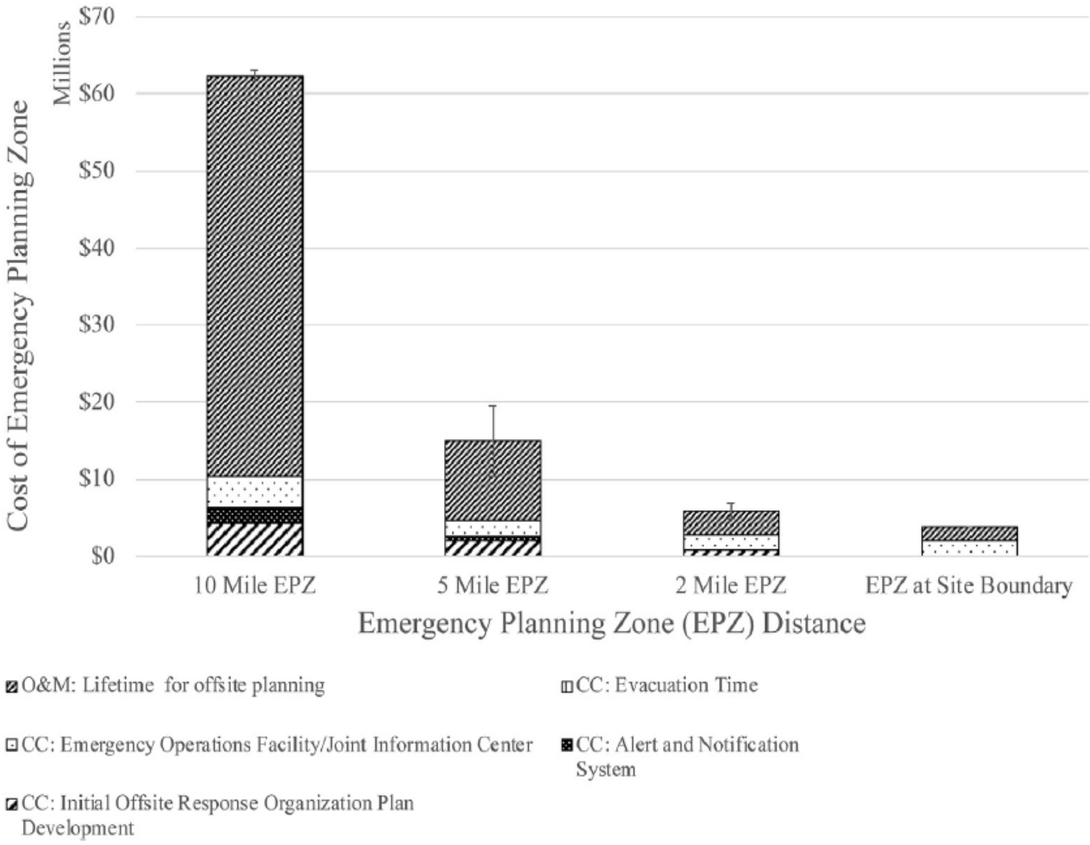
CAREM-25MW (3.2 x 11 m)

Reduced EPZ Size for Small Modular Reactors (USA)

US NRC has been very strict on the 10/50-miles EPZ, with very few exceptions (one gas-cooled reactor, PWR < 250 MW with 5 miles plume exposure pathway)

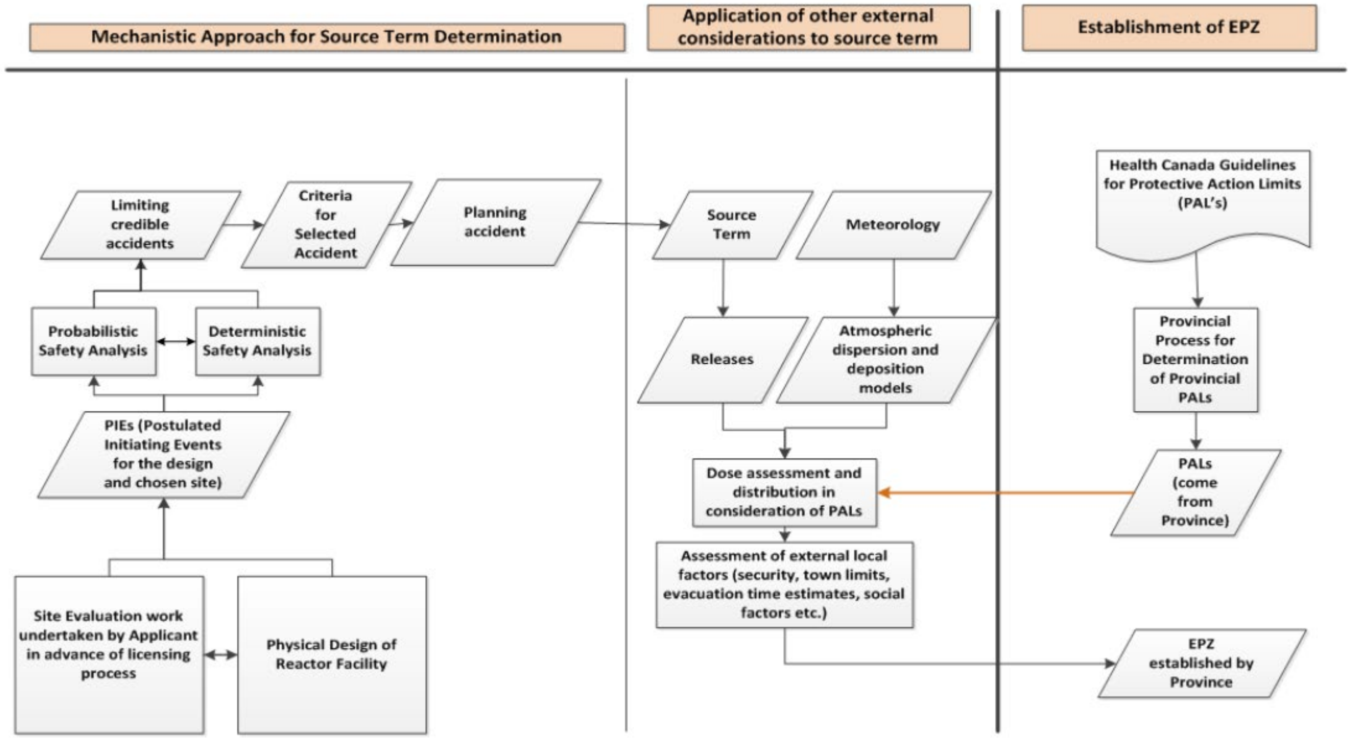
SMR vendors push for reduced EPZ:

- **Strongly decreased cost** of maintaining emergency preparedness
- **Siting closer to densely populated areas,** particularly important for district heating applications
- **New SMR can replace older coal-fired power stations,** with little additional siting requirements



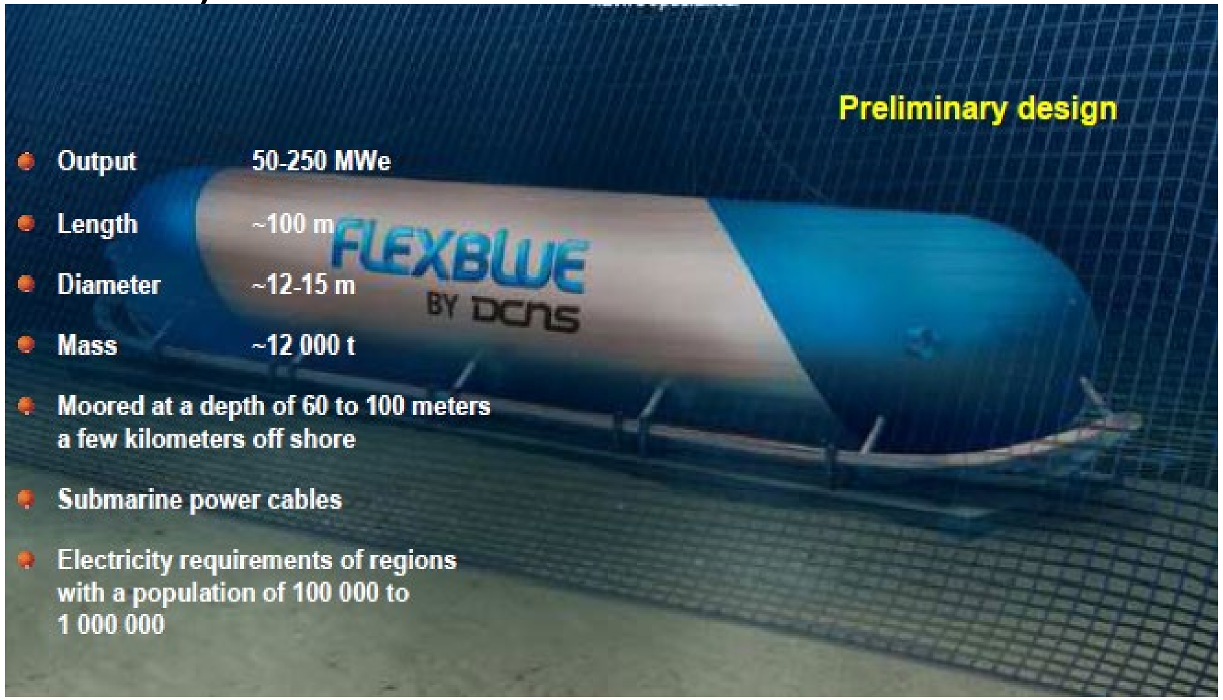
Reduced EPZ Size for Small Modular Reactors (USA)

NuScale submitted a "Methodology for Establishing the Technical Basis for Plume Exposure Emergency Planning Zones," TR-0915-17772-NP, Revision 2, August 2020. ADAMS Accession Number ML20217L422.

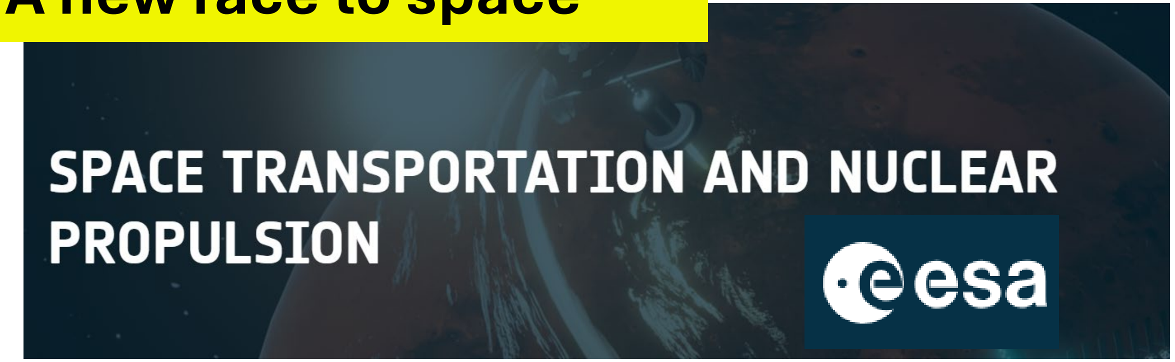


- The EPZ should encompass areas in which projected dose from design basis accidents (DBAs) could exceed 10 to 50 mSv TEDE (requiring evacuation and sheltering, respectively).
- Oct 2022: NRC / ACRS approves NuScale Methodology for SMR EPZ, resulting in an EPZ of approx. 500 meters radius (for a specific site in Utah)

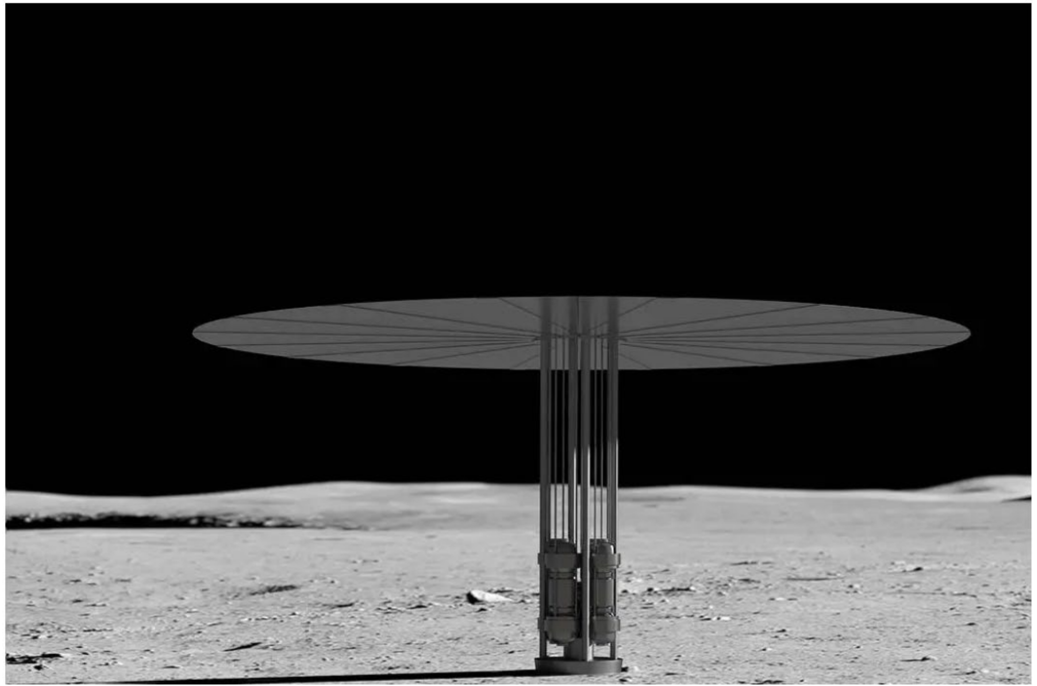
- **FLEXBLUE (Design: DCNS): Konzept 50-250 MW_e für einen DWR in 100 m Wassertiefe**
  - Kleiner DWR mit passiven Sicherheitssystemen ähnlich dem AP-1000
  - Vollständig ferngesteuerte Anlage (keine Betriebsmannschaft an Bord)
  - Notkühlsystem ca. eine Woche autark, bis menschliches Eingreifen (Notfallmaßnahmen) erforderlich wird



A new race to space



NASA Announces Artemis Concept Awards for Nuclear Power on Moon



Russia and China planning nuclear power plant on Moon by 2035

The joint project between the two countries could be a step towards establishing future lunar settlements.

March 6, 2024

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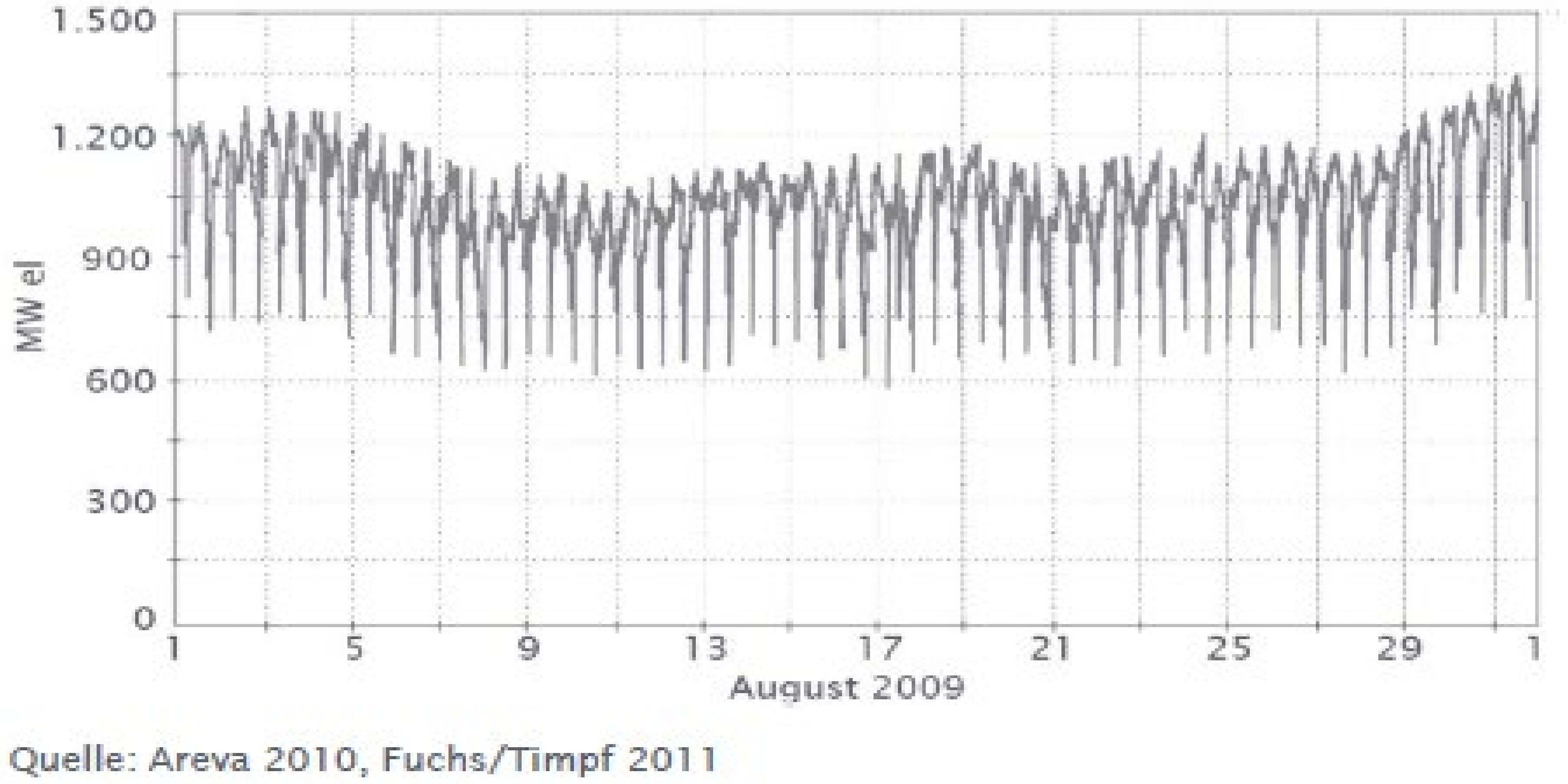
Lastfolgebetrieb von Kernkraftwerken



Lastfolgenbetrieb eines norddeutschen Kernkraftwerks im August 2009