Small Modular Reactors – Challenge for Nuclear Energy

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2. Present energy sector at Europe

- **2.1 Present energy crisis at Europe**
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Olkiluoto 3 – started to produce electricity

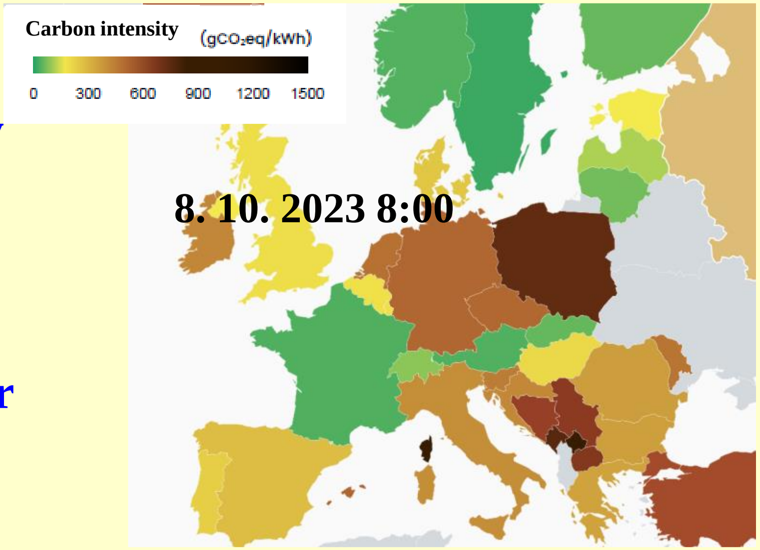
SMR ACP100 construction is in progress

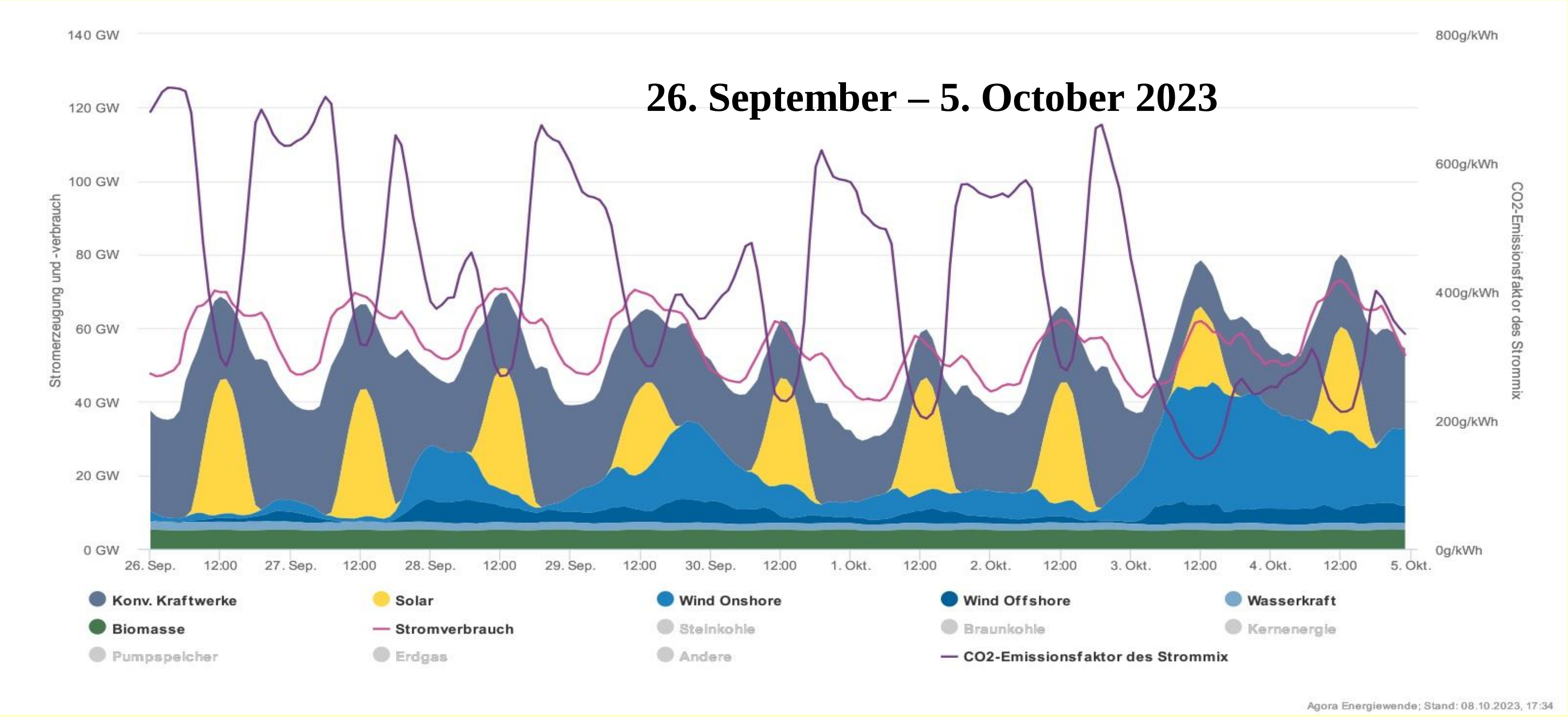
Introduction

Decommissioning of the last reactors in Germany

Start-up of the Olkiluoto 3 and Mochovce 3 reactors

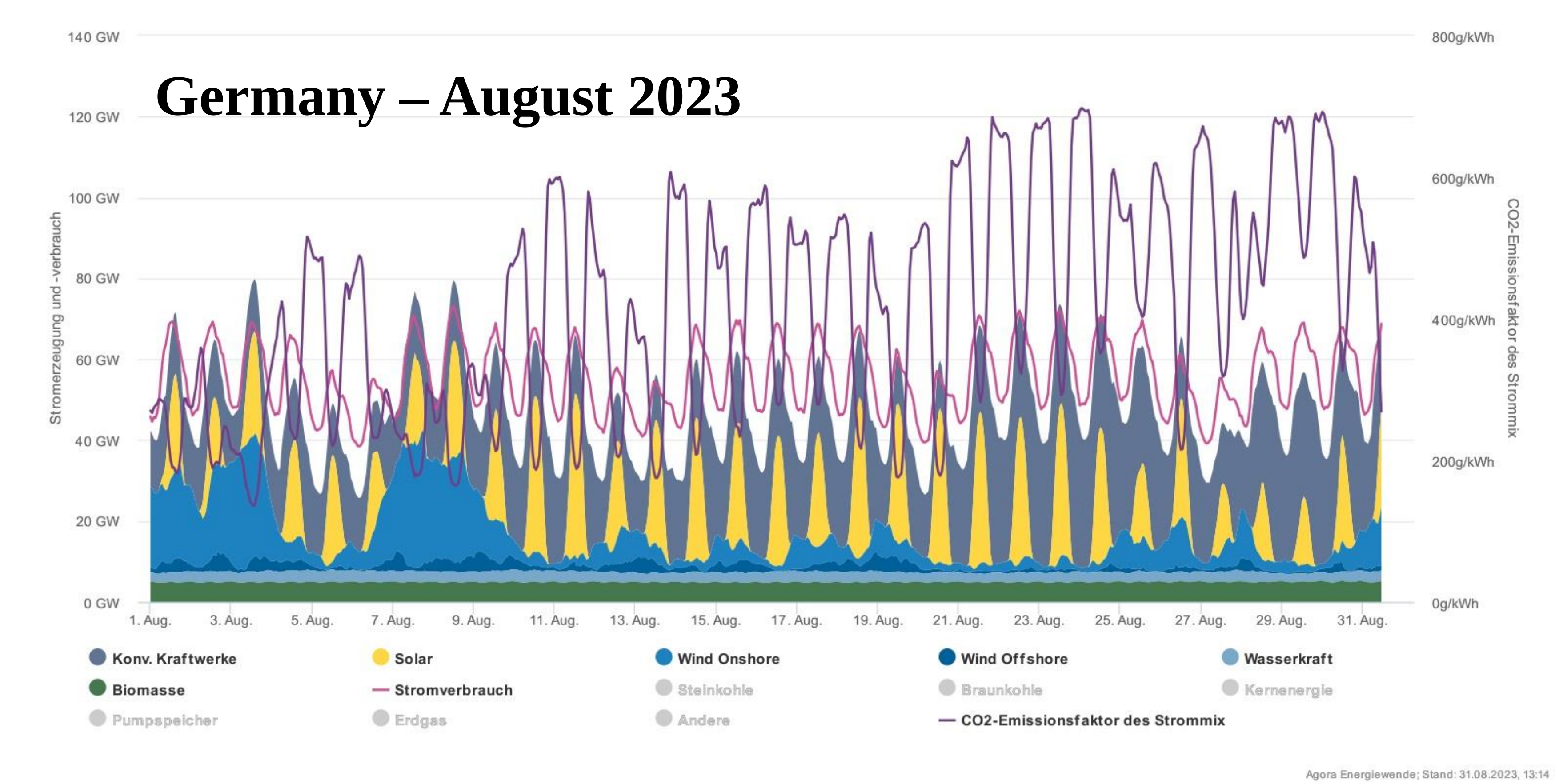
France, Sweden and Switzerland have a low-emission electric power industry based on nuclear and RES, and now also Slovakia, Finland is working on it





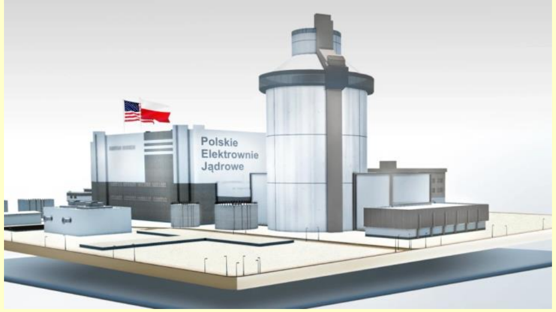
European energy – current situation

1) **France is again the largest exporter of electricity (followed by Sweden and Czechia).**
2) **Germany has become a net importer (although it still has enough power in coal, but for economic reasons it prefers to import from France and the Czech Republic).**
3) **Surpluses grow in ideal times for sun and wind and shortages in times without wind and sun.**



Europe - great interest in new blocks

1) A number of countries have decided to operate existing nuclear units for as long as possible. In the Czech Republic, Dukovany has been operating for 60 years, possibly even more.
2) The whole series of countries want to build new blocs: France, Great Britain, Sweden, the Netherlands, Slovenia, Bulgaria, Hungary, the Czech Republic … the first to build in Poland, and Italy is considering this option.
3) In many cases smaller blocks are suitable for smaller economies (Czech Republic, Slovenia, the Netherlands, Slovakia) → EDF a KHNP license smaller versions of their reactors, even if they do not plan to build them in France and South Korea.
4) It would be sensible to build the blocks in series, now it seems that there could be rather a shortage of supplier capacity and everyone will apply.
5) Interest in small modular reactors is growing – their construction is also being planned by private investors, not only those sponsored by the state.




Nuclear power – present chalanges

The basic tasks:

1) **Long term operation of Generation II reactors**
2) **Transition to Generation III reactors**
3) **Introduction of Small Modular Reactors**
4) **Nuclear heat for heating**
5) **Development of Generation IV reactors**

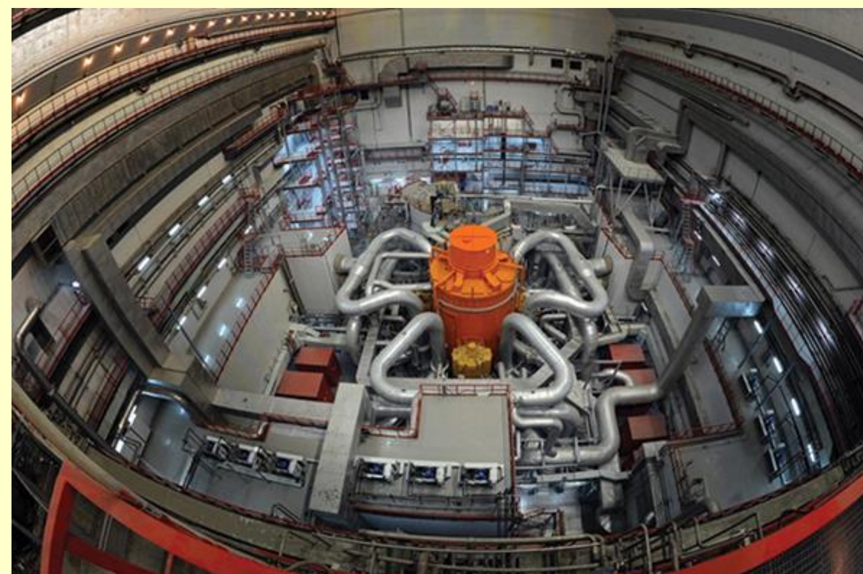
Renaissance in China, stagnation in Europe and USA

USA and Europa – extending the life of blocks

The renewal of competence and knowledge in this sector is crucial for Europe

Small Modular Reactor HTR-PM at China

Reactor EPR (Olkiluoto 3)



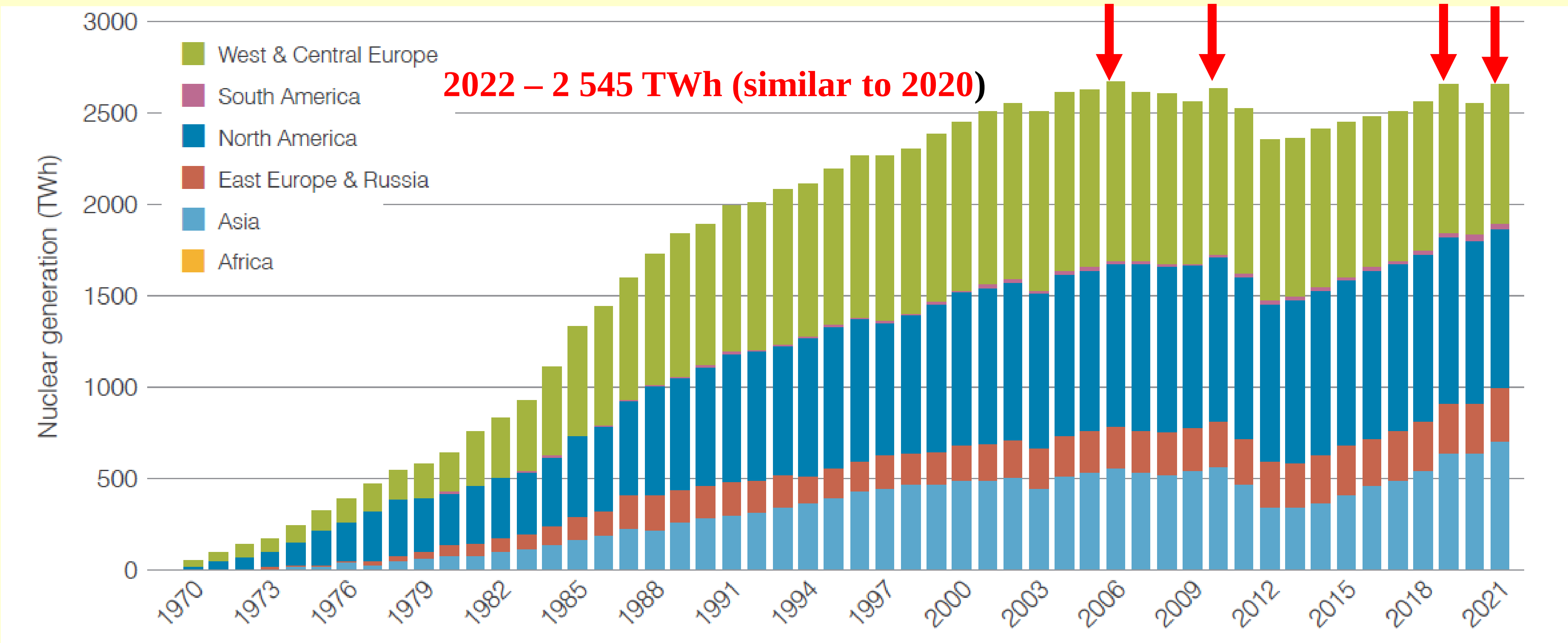
Fast sodium reactor BN-800 –Beloyarsk 3

Nuclear sources – current situation - statistic

Safe long term operation of existing units and the transition Generation II to III.

Number of blocks: 436   Installed power: 392 GWe (halfway through 2023)
Under construction: 60 blocks with power 67 GWe

The nuclear share of electricity production is slightly over 10 %
Future development depends on the resumption of the work of Japanese blocks and two trends, the shutdown of old blocks and the start-up of new ones (China has overtaken France and is in second place)

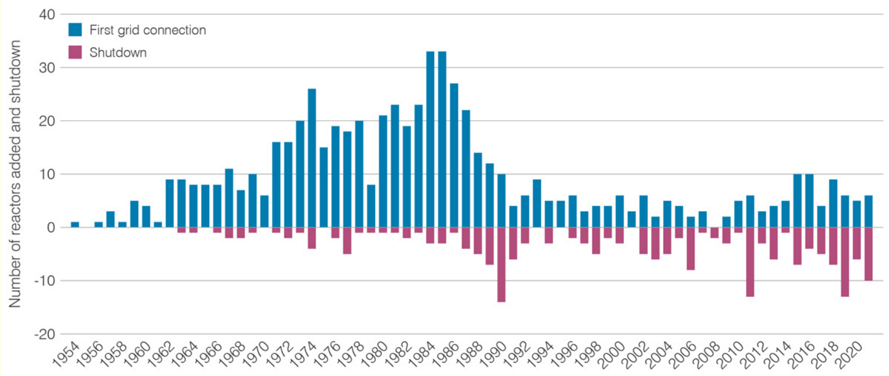


Extending the service life of existing nuclear units

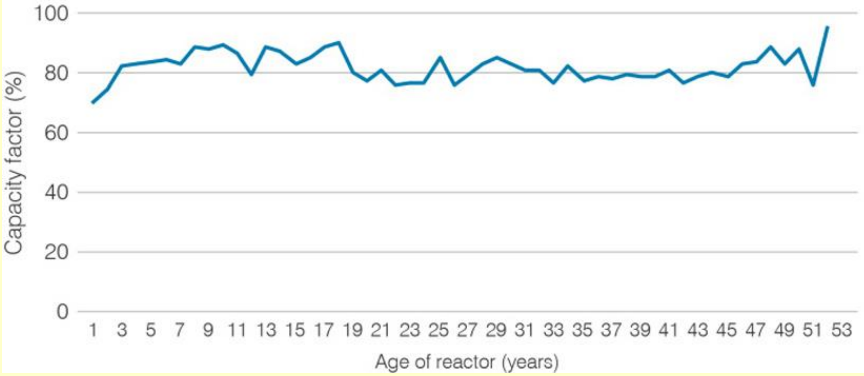
1) Europe has over 20 % of its electricity nuclear, operation as long as possible is needed.
2) Belgium is extending the operation of its more modern nuclear reactors beyond 2025.
3) A number of countries anticipate operating their reactors for sixty years or more
4) Europe needs to provide both service and fuel for these units
5) The importance of taking care of the reactors was shown (the welds at France)

Beznau 1 a 2 (Switzerland) belong to the oldest Blocks (more then 50 years), Beznau 1 start of operation 1969

Loviisa 1 and 2 (VVER440) has been running for over 40 years, license application for 80 years



Started and stopped blocks



Capacity factor (2017 -2021), dependency on age of reactor

Reactor AP1000 (Westinghouse USA)

Four reactors in operation in China:

	Power	Commercial Operation	Cumulative Load Factor
Sanmen 1	1150 MWe	September 2018	89,2 %
Sanmen 2	1150 MWe	November 2018	69,9 % (89,3 %) Problems - 2019
Haiyang 1	1130 MWe	October 2018	90,0 %
Haiyang 2	1130 MWe	January 2019	92,8 %

Two reactors are launching in USA:

Vogtle 3	1120 MWe	July 2023
Vogtle 4	1120 MWe	Fuel loaded

Four CAP1000s under construction (Sanmen 3 a 4, Haiyang 3 a 4), construction of additional units approved at Lianjing and planned for Lufeng

APR1000 (APR1400) (KHNP, South Korea)

Three in operation and three under construction in South Korea:

	Power	Commercial Operation	Cumulative Load Factor
Sauel 1 (Shin Kori 3)	1340 MWe	December 2016	80,1 %
Sauel 2 (Shin Kori 4)	1340 MWe	August 2019	79,4 %
Sauel 3 (Shin Kori 5)	1340 MWe		
Sauel 4 (Shin Kori 6)	1340 MWe		
Shin Hanul 1	1340 MWe	December 2022	
Shin Hanul 2	1340 MWe		

Three in operation and one is being completed in the UAE:

Barakah 1	1310 MWe	April 2021	76,9 %
Barakah 2	1310 MWe	April 2022	
Barakah 3	1310 MWe	February 2023	
Barakah 4	1310 MWe	Launch in 2024	

Reactor EPR (EDF France)

Two reactors in operation in China:

	Power	Commercial Operation	Cumulative Load Factor
Taishan 1	1660 MWe	December 2018	57,0 % (66,3 %)
Taishan 2	1660 MWe	September 2019	74,4 % (81,1 %)

One operational, one close to completion and two under construction in Europe:

Olkiluoto 3	1600 MWe	May 2023
Flamanville 3	1630 MWe	Startup 2024
Hinkley Point C 1	1630 MWe	
Hinkley Point C 2	1630 MWe	
Sizewell C 1 a 2	just before start of construction	

The growing share of blocks of Generation III per production

Other types of reactors of Generation III:

VVER1200	6 + 10 + 6	(in operation + under construction + planned)	75 – 80 %
ACPR1000	6		76 – 89 %
Hualong One (HPR1000)	5 + 11 +		
ABWR	4 + 2	(shut down since the Fukushima accident)	

Already 31 units in operation, 33 under construction and many in preparation, are beginning to have a significant share in the production of low-emission electricity and heat. China, Russia and South Korea, which continuously build blocks, have a construction period of les than 10 years – the tendency is to shorten, operating experience positive.

VVER1200 reactors at the Ostrovec NPP (Belarus)

HPR1000 reactors at the Karachi NPP (Pakistan)

Nuclear energy for district heating and industrial heat

Large part of emissions – heating and industry

1) Heating (very important for northern territories):

- **Electric heating – the way of France, the opportunity to use in regulation**
- **Heat pumps – electricity is needed**
- **Cogeneration at large units – construction of a heat pipeline from Temelin, a number of projects in Russia and China (Leningrad 2-1 a 2-2, Hongyanhe 1-4)**
- **Use of Small Modular Reactors – cogeneration ad pure heating (ACP100)**

2) Heat for industry:

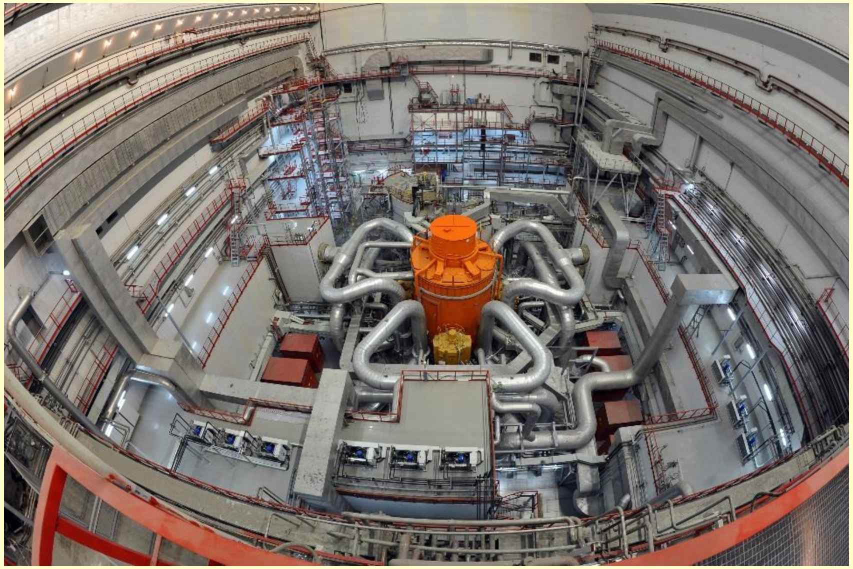
- **Use of current reactors – lower temperature only (Tianwan 3 a 4)**
- **Use of high temperature reactors (large and small modular) – HTR-PM**
- **Efficient hydrogen production.**

Tianwan 3 a 4 – steam supply for chemical plant ACP100 reactor construction TRISO fuel

Generation IV reactors

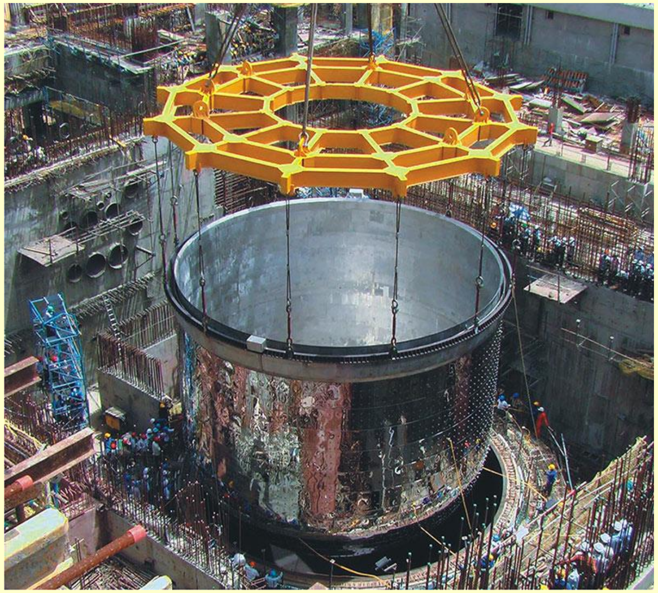
Why do we need them?

1) Increasing the efficiency of the use of uranium and thorium (fuel stocks for many millennia) – fast reactors
2) Reduction of the volume and danger of radioactive waste (closing the fuel cycle)- exotic types with liquid fuel and continuous separation
3) Increasing the efficiency of electricity and heat production for industry (high-temperature reactors for industry and hydrogen production.
4) Completely new concepts, sometimes quite exotic – six classes of concepts



Sodium cooled reactor BN800

Sodium Cooled Reactors – Fast reactor, successful commercial units BN600 and BN800 (Russia), experimental CEFR and now large prototype CFR600 (China), Kalpakkam 500 MWe unit being completed (India)



Sodium reactor Kalpakkam (India)

Lead-cooled Reactor – Fast reactor, cooled by liquid metal, experience on submarines, BREST-300 – prototype reactor (Russia)

BREST 300 reactor fuel assembly and construction site

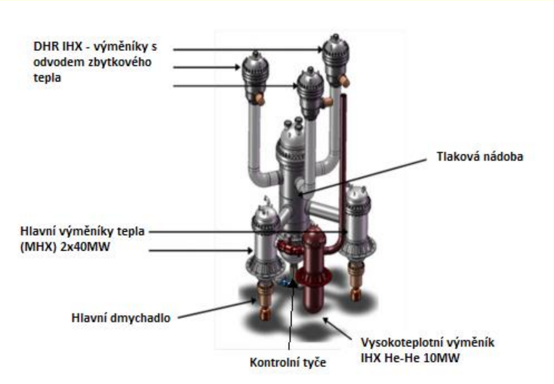
Russian submarine with a lead-cooled reactor

Gas-cooled fast reactor – helium cooling, unmoderated, European ALLEGRO project, considerations for its construction in Central Europe, helium loop in ÚJV a.s.

Reactors using liquid salts – use of fluorine salts with lithium, liquid fuel – the most innovative principle, different types of moderation (energy spectrum). Suitable for converting thorium 232 to uranium 233. Farthest in China. Involvement of CVŘ and ÚJV a.s.

High Temperature Gas Cooled Reactor – Helium (or other gas) cooled, graphite moderated, high fuel burn-up, passive safety, completed pebble fuel reactor in China – HTR-PM, collaboration with Saudi Arabia

Reactor cooled by supercritical water – supercritical units with classical moderation, very high efficiency of heat to electricity conversion. Loop with supercritical water in ÚJV a.s.



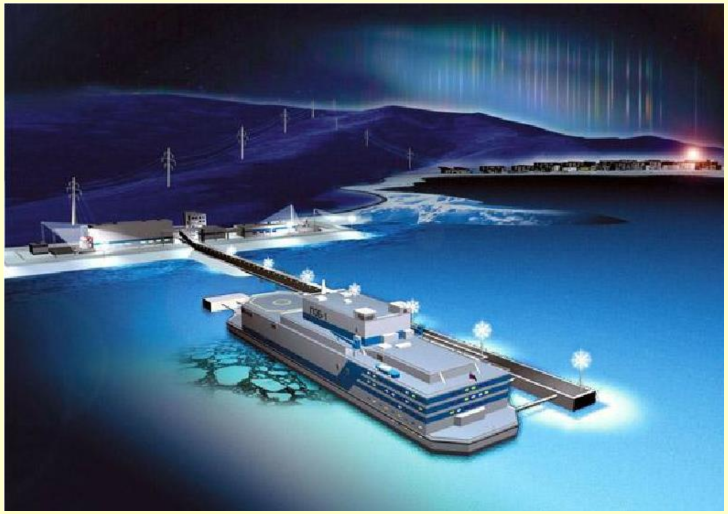
Scheme of the Allegro reactor project

Installation of the HTR-PM reactor (China)

Pebble fuel for the HTR-PM reactor (China)

Small Modular Reactors (SMR)

1) The main problem – only a very large source, high initial investment
2) Solution – Small Modular Reactors (power less than 300 MWe, 500 MWe)
3) They allow: a) Build a large power plant gradually
   . b) Build a small unit, for example, for heating purposes
4) Possible variants: a) Based on a classic concepts
   . b) Small Modular Reactors of generation IV
   . c) „Battery“ with a long fuel change period
5) So far more exoticism for specific purposes (mostly only project preparations)



Akademik Lomonosov floating power plant

Architectural vision of the StarCore Nuclear compact „battery“

Present classic light water SMR

KLT-40S (Russia) – PWR, 2 units of 35 MWe, floating power plant Akademik Lomonsov replaces old Bilibin power plant (4 units 11 MWe)

Serial floating power plants – reactors **RITM-200**
50 MWe from icebreaker

Serial small power plants – same reactors

ACP100 (China) – first „standard“ SMR

ACP100 (Linglong One)

Floating power plant Akademik Lomonosov will replace the Bilibin power plant

Proposal for the use of the RITM-200 reactor for a small Yakutia power plant

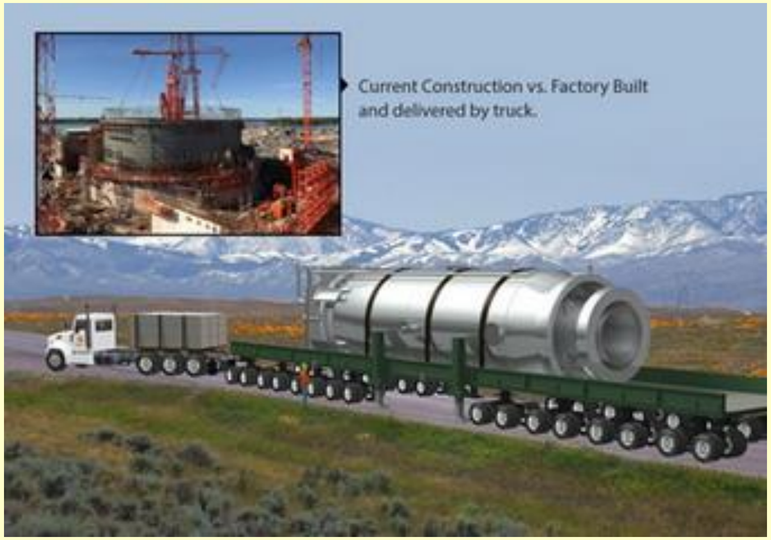
Classic light water types

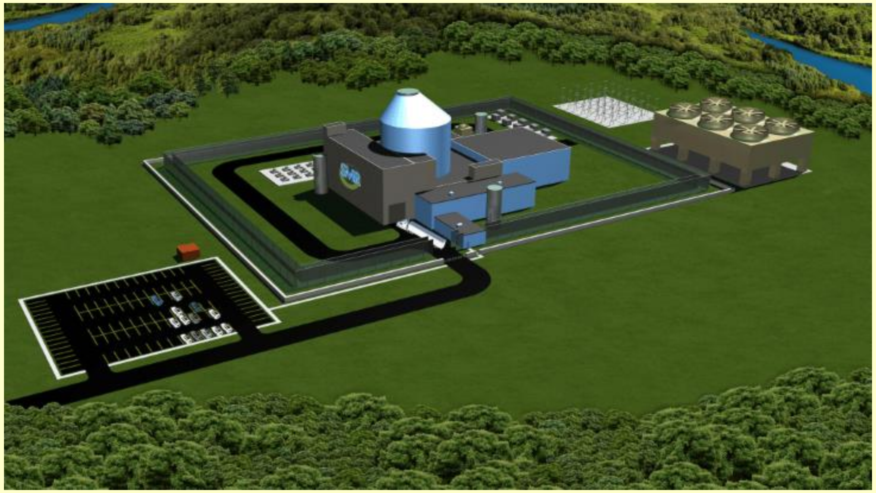
Pressurized - VBER-300 (Russia), SMR-160 (USA), Rolls Royce (Great Britain)

Integral pressurized – NuScale (USA), ACP100 (China), SMART (South Korea)

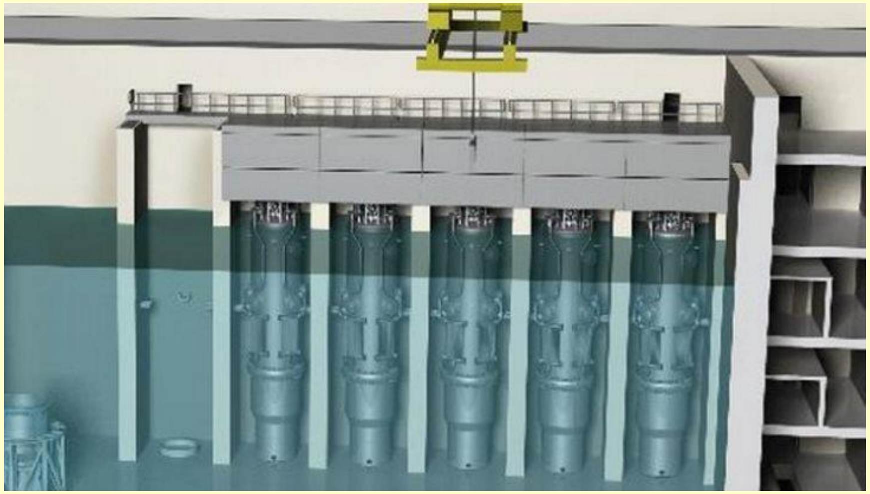
Boiling – BWRX-300 (Japan)

NuScale – 50 -77 MWe, USA license 2020, Prototype (12 modules) (Idaho) - construction beginning – 2025?, operation – 2030?





SMR 160



NuScale (probably closest to implementation)

Innovative Small Modular Reactors

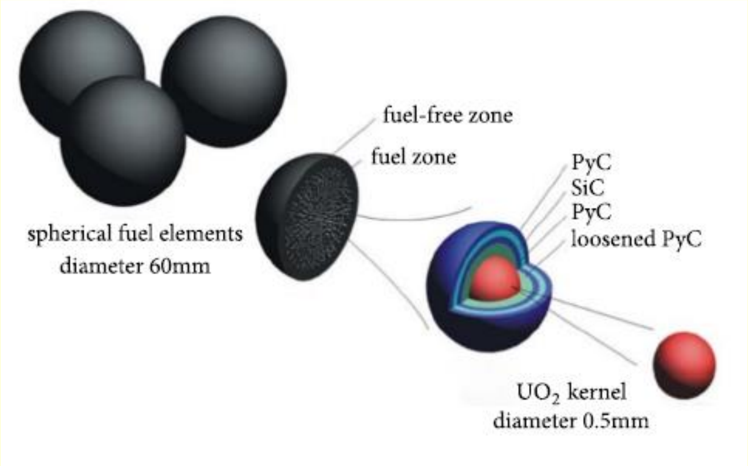
Running HTR-PM – high temperature gas cooled reactor with pebble bed, helium is used and temperature 750°C, graphite moderation, TRISO fuel, two units with single turbine 210 MWe

Beginning of 2021 – completion of hot tests, start-up phase started

Important experience with the use of helium and TRISO fuel – efficiency and economy

Preparation of larger unit consisting of six modules with a common turbine HTR-PM600

Small Modular Reactor HTR-PM in Shidaowan



TRISO fuel for HTR-PM units

SMR as battery – long burning time

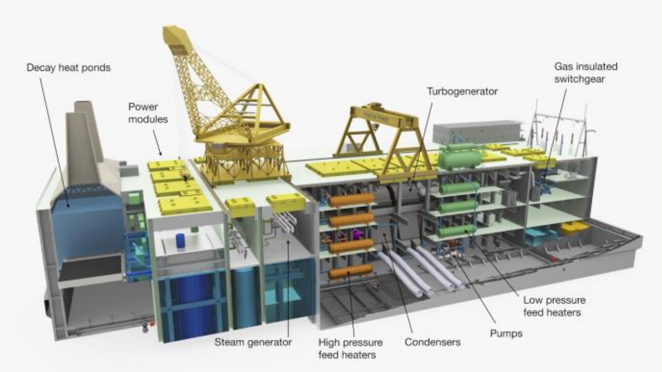
Long burning time (10 – 20 years, even more),

ThorCon reactor TMSR Molten Salt Reactors

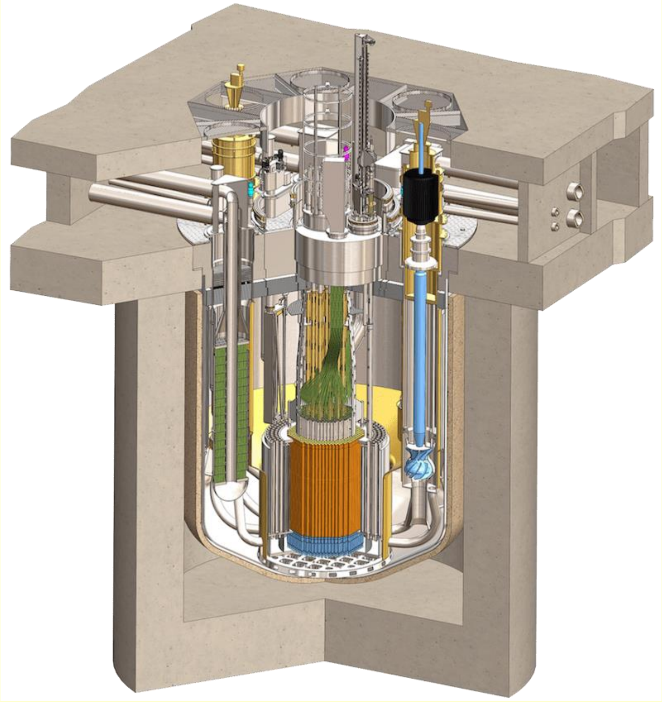
Molten Salt cooling, liquid molten salt fuel

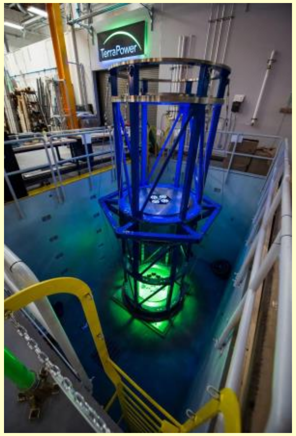
Two modules (power 500 MWe)

Terrestrial Energy company - reactor IMSR (Integral Molten Salt Reaktor) (power 195 MWe



Bill Gates TerraPower is TWR (Traveling Wave Reactor) type – fast reactor, natrium cooling, HALEU fuel (enrichment 19.75 %)
Power: ~ 345 MWe





Minireactors and microreactors

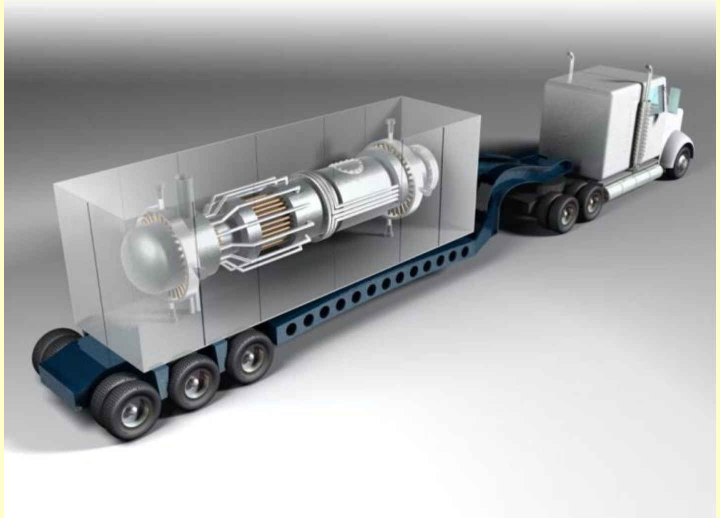
Power output fractions and units of MWe
up to 20 MWe

Dominantly for Island Mode

Project Pele high temperature gas cooled microreactorwith power from 1 up to 3 MWe, HALEU fuel

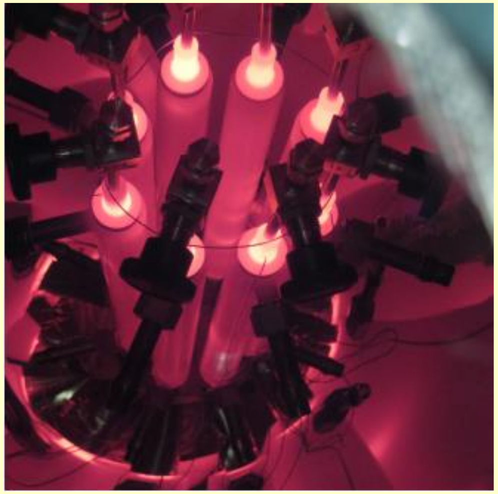
Reactor eVinci with power 5 MWe will use heat pipes

Space reactors – Kilopower – heat pipes



Concepcion of reactor Pele

Vizualization of μMR eVinci™ of company Westinghouse



Heat pipes for Kilopower

Small Modular Reactor - summary

1) By spreading the investment, you can overcome the problems with the price of money.
2) Serial production of modules in the factory.
3) It does not replace large units, but complements them.
4) Penetration into decentralized energy and heating – cogeneration, large range of regulation.
5) The need to simplify licensing conditions.
6) The question of when serial commercial units will still be open in the market, not before 2030s.

Reactor NuScale (visualization of the power plant and its scale model)

Present time – great interest in SMR

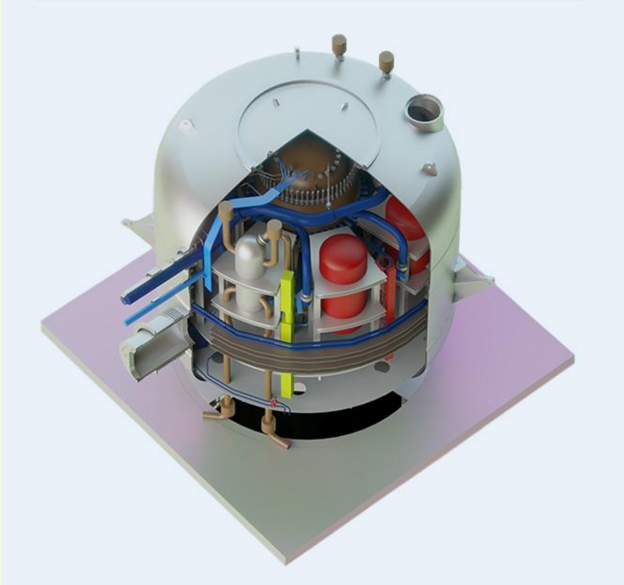
also large well-known companies are preparing their SMR projects

Company KHNP: SMR SMART with power 330 MWt (up to 100 MWe)

Company Westinghouse: SMR with power 300 MWe based on AP1000 reactor knowledge

Company Holtec: SMR SMR-160 with power 160 MWe first prototype at Oyster Creek, Prototype ready at 2030

Company EDF: SMR NUVARD™. Compact system with two independent reactor modules each with power 170 MWe. First concrete at France at 2030



ACP-100 (Linglong One)

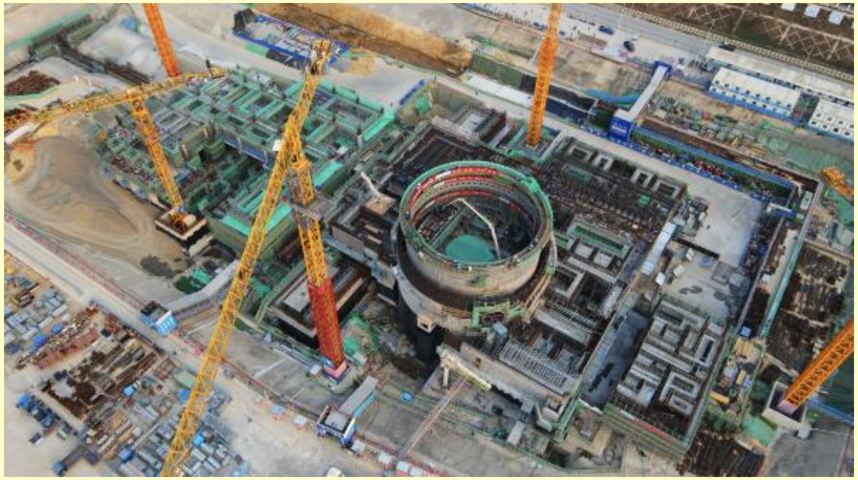
Construction continues apace - completion 2026

July 2023 – central module completed.

A comparison of the economics and efficiency of China´s large reactors and SMR will be very useful

Construction and completion of the first small modular reactors

1) The first SMR are being put into operation, so far in Russia and China. Experiences from their operation will be interesting.
2) A number of projects as NuScale, BWRX-300 and more are entering advanced project preparation and prelicensing and licensing stages.
3) A number of states are already selecting specific locations for their construction and coordinating licensing procedures (Temelin in the Czech Republic).
4) The broad and intensive cooperation of as many future users as possible will be very important.



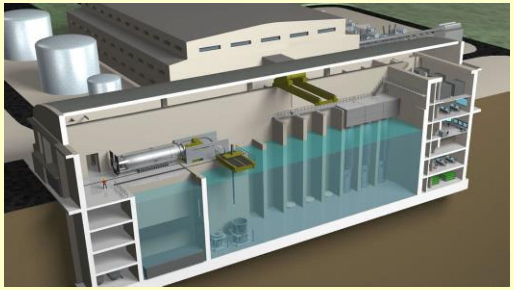
Small modular reactor ACP100 (Linglon One)

First experience with HTR-PM

Huge potential for the construction of SMR in Europe and the Czech Republic

1) **Pressure to move away from fossil fuels (efforts to reduce emissions and dependence on their imports**
2) **The necessity of using nuclear sources to regulate and ensure network stability (decentralization)**
3) **The necessity of providing heating – a suitable model of less centralization and smaller sources closer to the point of consumption**
4) **A more suitable financial model for private local investors**
5) **The number of states that are considering the use of SMR is growing (more selected locations are added)**
6) **Large and small reactors could complement each other appropriately**
7) **The Czechia has selected a location for the first SMR prototype, work is underway on a selection of other suitable locations (appropriate seismological assessment procedures …)**


Aurora


NuScale


BWRX-300


Rolls Royce

Czech concepts of Small Modular Reactors

1) Three classic (usage of VVER fuel assemblies):

DAVID (Witkowitz) – two active zones on top of each other, very compact, fuel change in the central plant

Teplátor - „only“ heating source, heavy water reactor (use of also spent fuel assemblies)

CR 100 (UJF a.s. CVŘ s.r.o.) - SMR based on VVER fuel

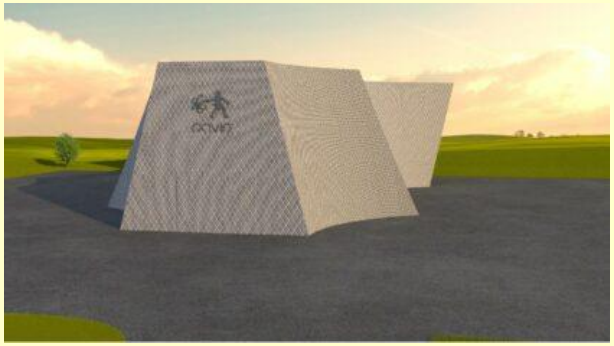
2) Innovative types (generation IV reactors) ÚJV a.s. (CVŘ s.r.o.):

EnergyWell – cooling by liquid salt, long term burning …

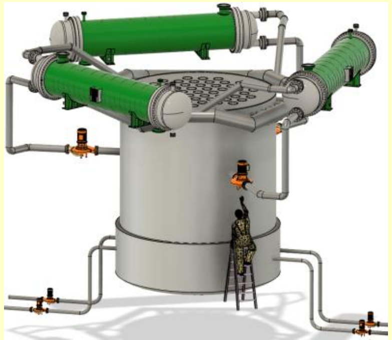
HeFASTo – fast helium cooled reactor

Involvement in a number of international projects– NuScale, Rolls-Royce, BWRX300 …

Potential for expert education, development of industrial base and synergies with other nuclear technology areas – first proposed place Temelin

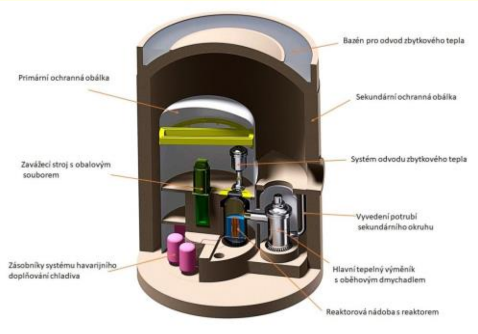


DAVID



Teplátor

EnergyWell



HeFASTo

Summary

1) Necessity to solve our dependency on fossil fuel, mainly Russian gas
2) Nuclear power has proven the possibility of a very efficient transition to low-emission electricity production (France, Sweden, Ontario, …).
3) Five main challenges of nuclear power industry
4) Transition to generation III reactors – question of succes still open.
5) Great potential in SMR, need to develop a compact model with mass production (classic and innovative types)
6) Classic types are closest to implementation, later this innovative
7) The Czech Republic is counting on Small Modular Reactors.
8) The necessity of developing adequate education, research and industry.
9) No solution is ideal – there is always a trade-off.

APR1400 Generation III. reactor

BWRX300 SMR