Small Modular Reactor to Contribute in the Future of Grid Decarbonization

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CURENT

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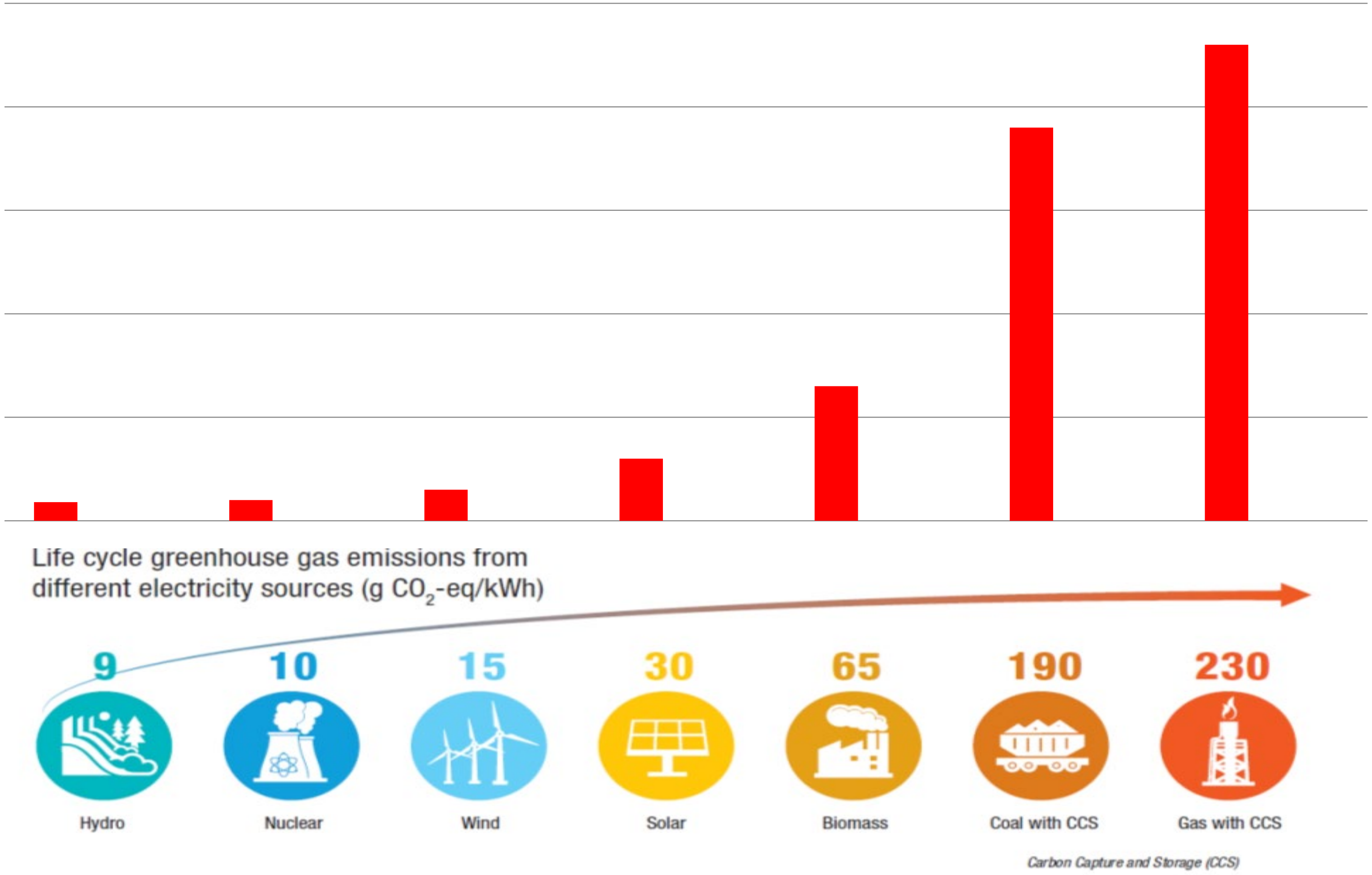
Life Cycle Greenhouse Gas Emissions



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Current U.S. Light Water Nuclear Reactors

- U.S. nuclear electricity is currently generated by light water reactors (LWRs), commercialized in the 1950s and early 1960s, and now used throughout most of the world. LWRs are cooled by ordinary (“light”) water, which also slows (“moderates”) the neutrons that maintain the nuclear fission chain reaction. **Current LWR average 1,000 megawatts for existing U.S. commercial reactors.**

Diagram of a boiling-water nuclear reactor

Source: U.S. Nuclear Regulatory Commission (public domain)

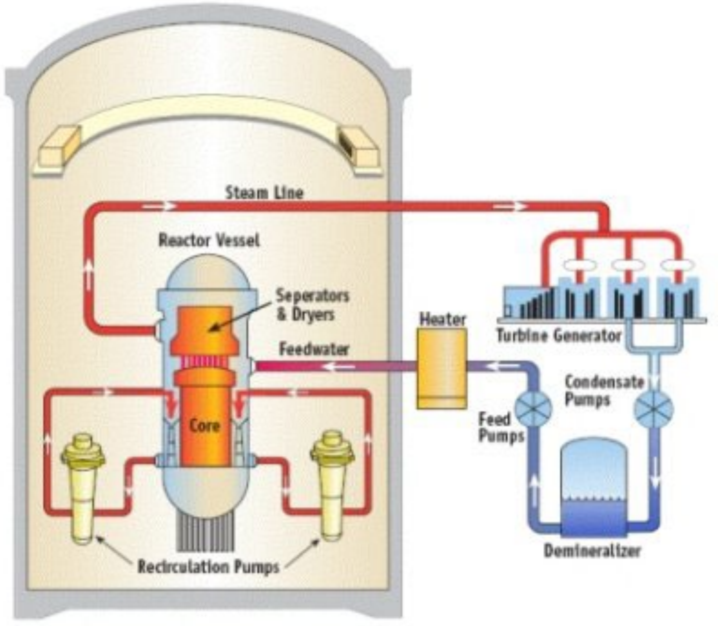
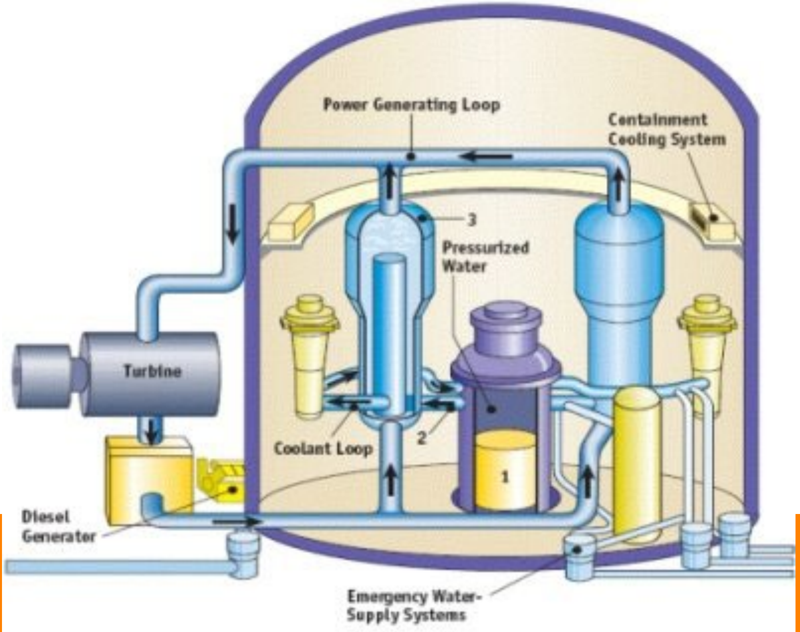
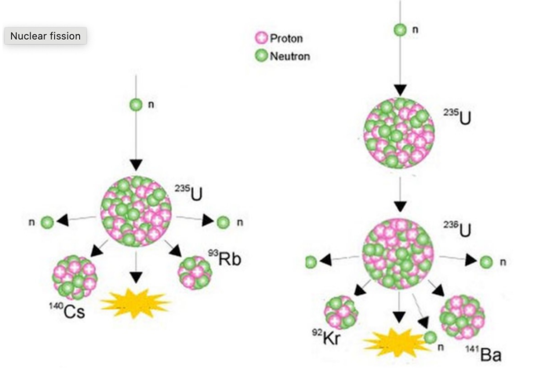


Diagram of a pressurized-water nuclear reactor

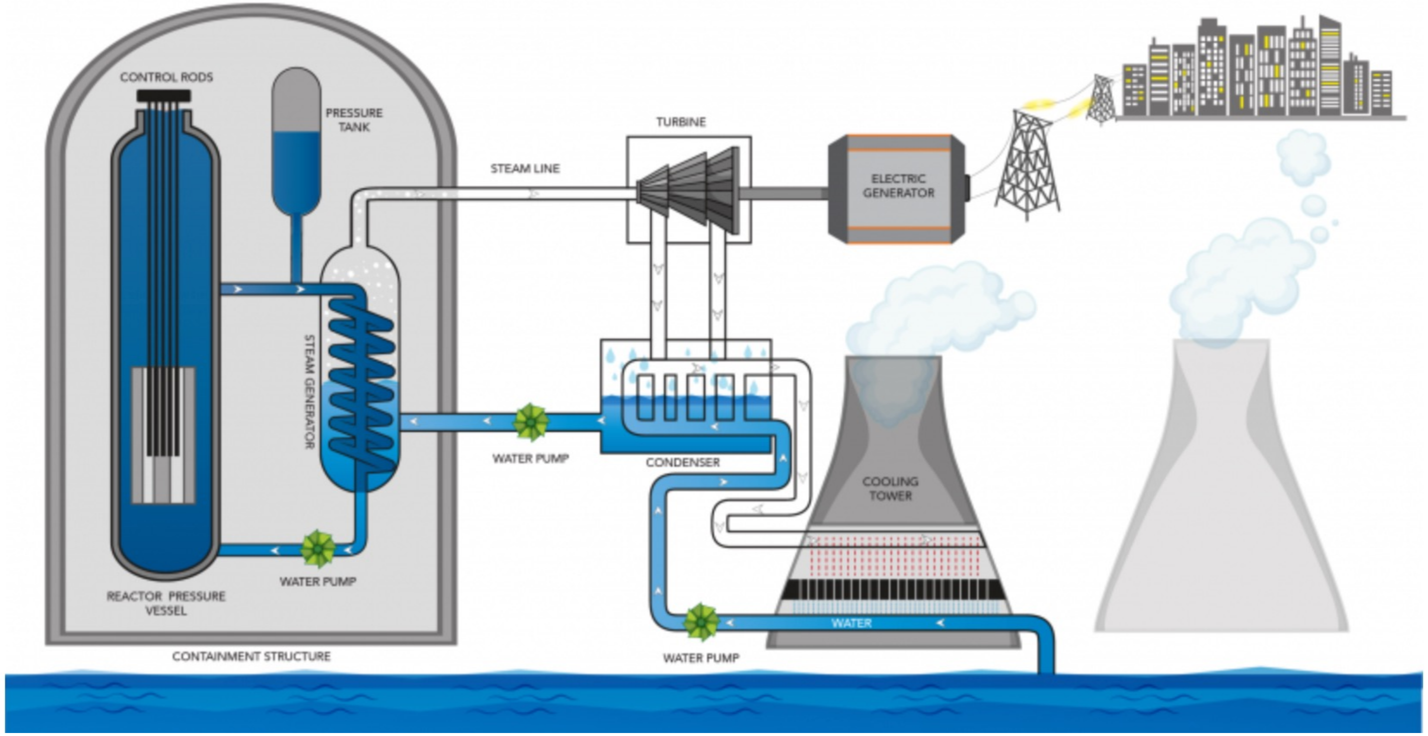
Source: U.S. Nuclear Regulatory Commission (public domain)





Pressurized Water Reactors (PWR)

- More than 65%of the commercial reactors in the United States are pressurized-water reactors or PWRs. These reactors pump water into the reactor core under high pressure to prevent the water from boiling.
- The water in the core is heated by nuclear fission and then pumped into tubes inside a heat exchanger. Those tubes heat a separate water source to create steam. The steam then turns an electric generator to produce electricity.
- The core water cycles back to the reactor to be reheated and the process is repeated.



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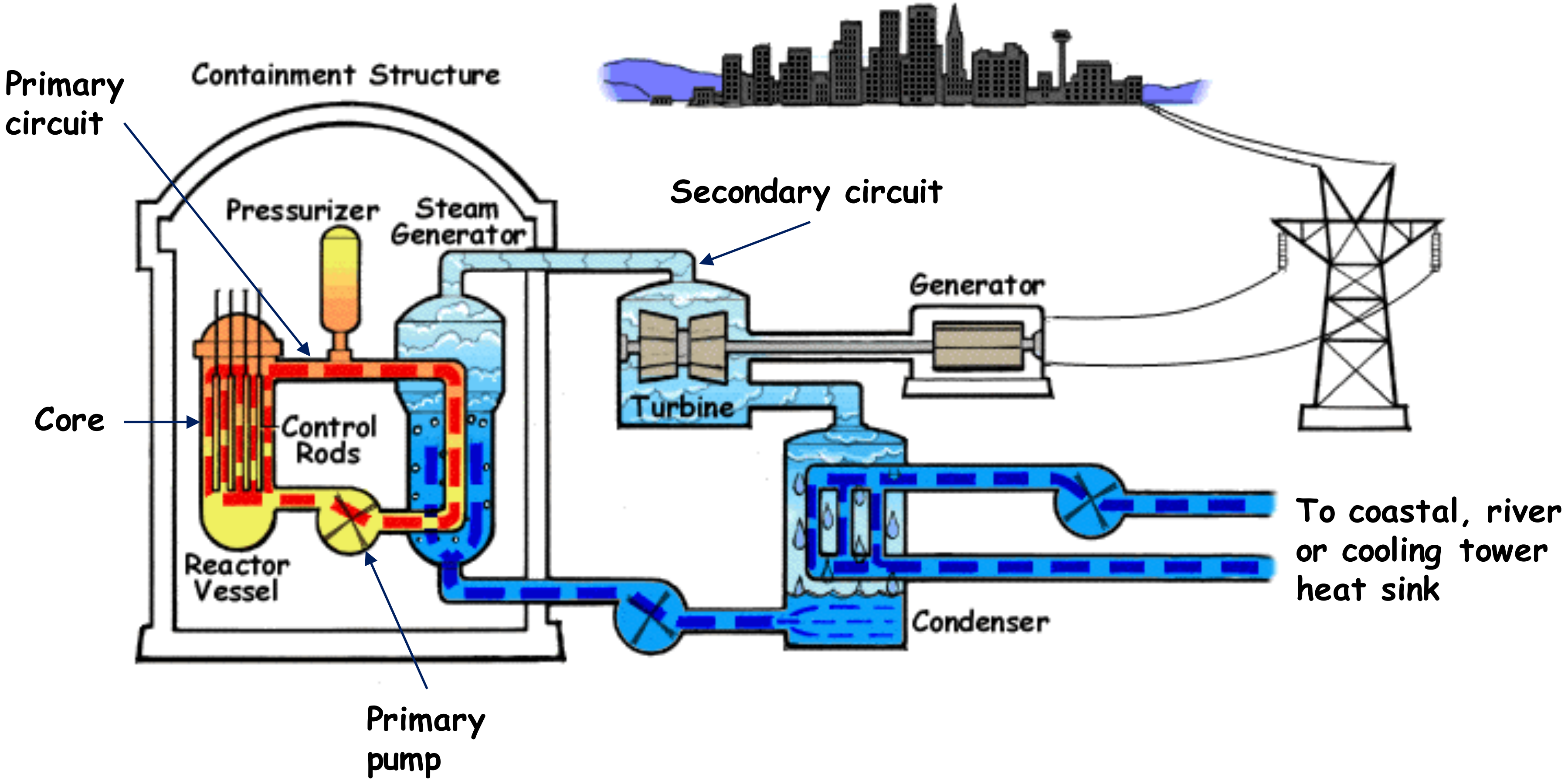
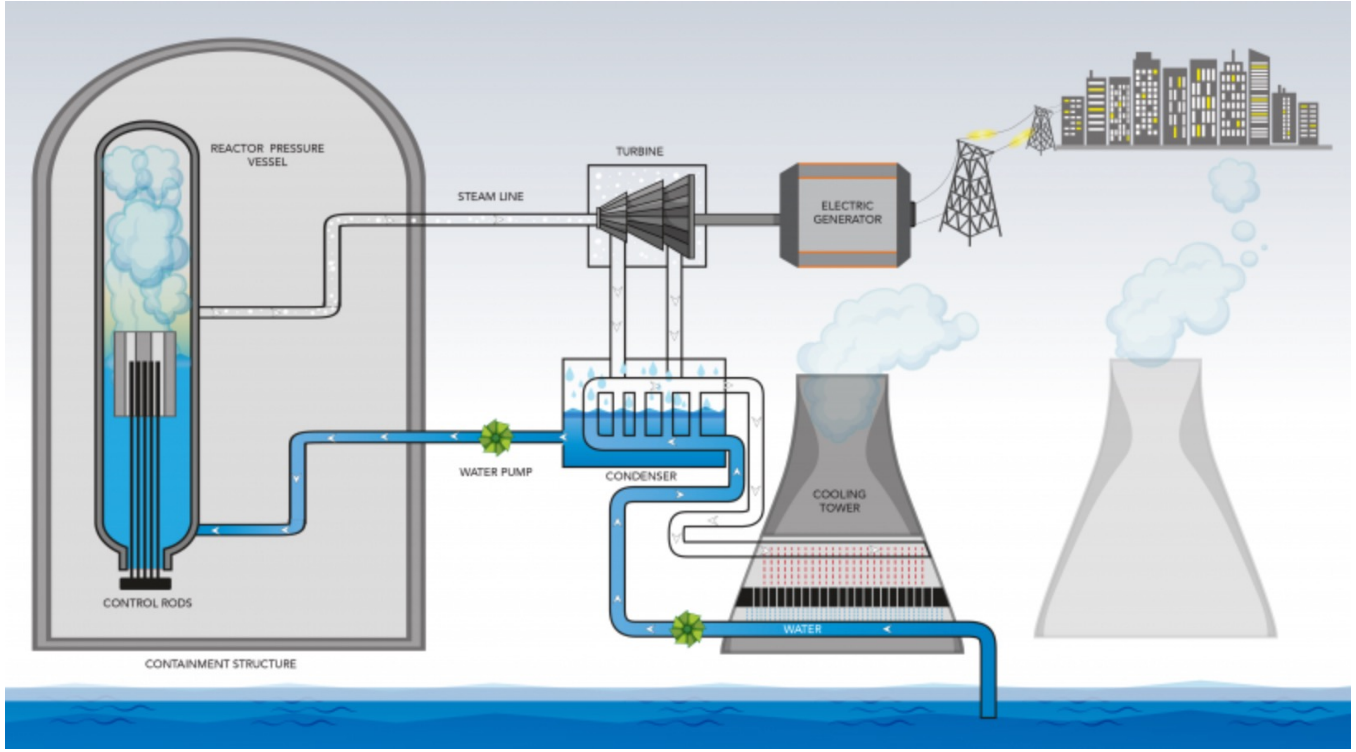
The basic components of a PWR



Boiling Water Reactors

- Roughly a third of the reactors operating in the United States are boiling water reactors (BWRs).
- BWRs heat water and produce steam directly inside the reactor vessel. Water is pumped up through the reactor core and heated by fission. Pipes then feed the steam directly to a turbine to produce electricity.
- The unused steam is then condensed back to water and reused in the heating process.

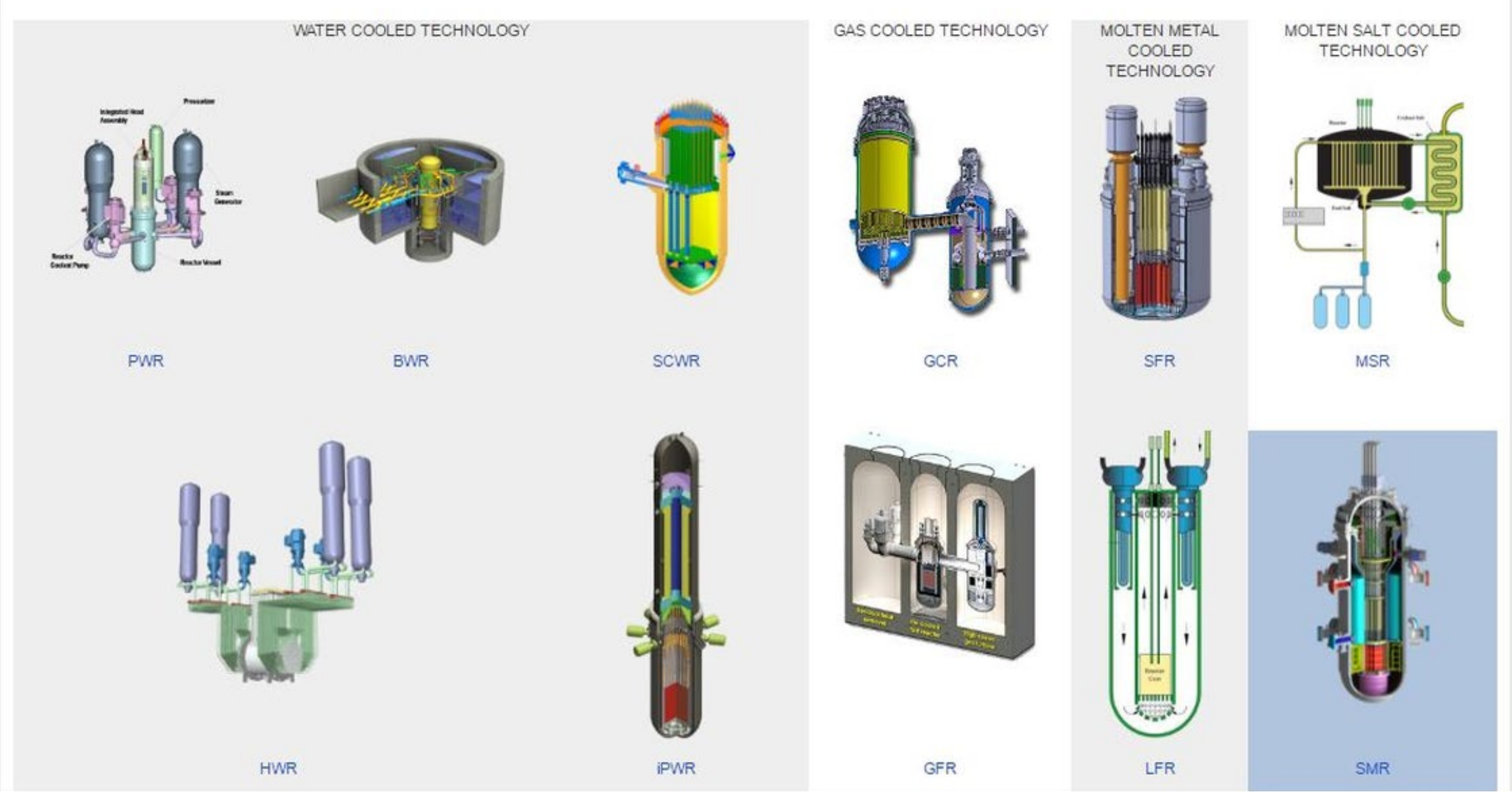


What are advanced Nuclear Reactors?

- **An "advanced nuclear reactor" is defined in 2018 legislation as "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors" or a reactor using nuclear fusion (P.L. 115-248).**
- Advanced nuclear reactors include new **LWR designs; gas-cooled reactors**, which could use **graphite** as a neutron moderator or have no moderator; **liquid metal-cooled reactors**, which would be cooled by liquid sodium or other metals and have no moderator; **molten salt reactors**, which would use liquid fuel; **and fusion reactors**, which would release energy through the combination of light atomic nuclei rather than the splitting (fission) of heavy nuclei such as uranium.
- The Nuclear Energy Innovation and Modernization Act (NEIMA), enacted on January 14, 2019, is intended to promote the commercialization of new nuclear reactor designs that, **compared to current reactors, provide additional inherent safety features, significantly lower levelized cost of electricity, lower waste yields, greater fuel utilization, enhanced reliability, increased proliferation resistance, increased thermal efficiency, or ability to integrate into electric and nonelectric applications.**
- **Most advanced reactor types have never been constructed in the U.S. and require new safety and environmental analyses before licensing; some were last operated in the U.S. several decades ago.**

Advanced Nuclear Reactor technologies

Source: International Atomic Energy Agency 2016



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Advanced Nuclear Reactors

- **Over next 30 years many units of the existing U.S. light water reactor (LWR) fleet will be retired**
- **Light Water Small Modular Reactors (SMRs) are the most mature with ability to immediately contribute to U.S. energy portfolio**
  - Significant work remains to finalize designs and site licensing projects, as well as development of supply chain infrastructure
  - **Need for Government Teaming with Industry**
  - Need new U.S. nuclear builds to regain leadership and global influence
  - **SMRs expected to be a key element of the nation's future electricity generation portfolio**
  - **Historically, all commercial deployments of new reactor technologies preceded by significant private-public partnerships**

What are Small Modular Reactors (SMRs)?

- **SMRs are advanced reactors that have electric generating capacities up to 300 megawatts**
- **Many SMRs would use high-assay low enriched uranium (HALEU) fuel, enriched up to 20 percent uranium-235 (current fuels are enriched up to 5 percent). Availability of U.S. HALEU is currently a major constraint.**
- As of 2022, four companies have submitted license applications to the NRC for light-water advanced SMRs:
  - **NuScale:** 50 MW pressurized water reactor;
  - **General Electric-Hitachi BWRX-300:** 300 MW boiling water reactor;
  - **HOLTEC SMR-160**, a 160 MW pressurized water reactor;
  - **BWXT** mPower 180 MW pressurized water reactor.
- NRC expects to issue new regulations for licensing non-LWR SMRs by July 2025.
  - Including high-temperature gas reactors, gas-cooled fast reactors, sodium-cooled fast reactors, lead-cooled fast reactors, and molten salt reactors - could be deployed in the 2030s.

Small reactor markets: there are essentially two markets for small reactors

Small Modular Reactors (SMRs)

- Sizes from ~20 to 300 MWe
- Designed for grid connection
- Need to compete with other grid generation

Very small reactors (compact reactors)

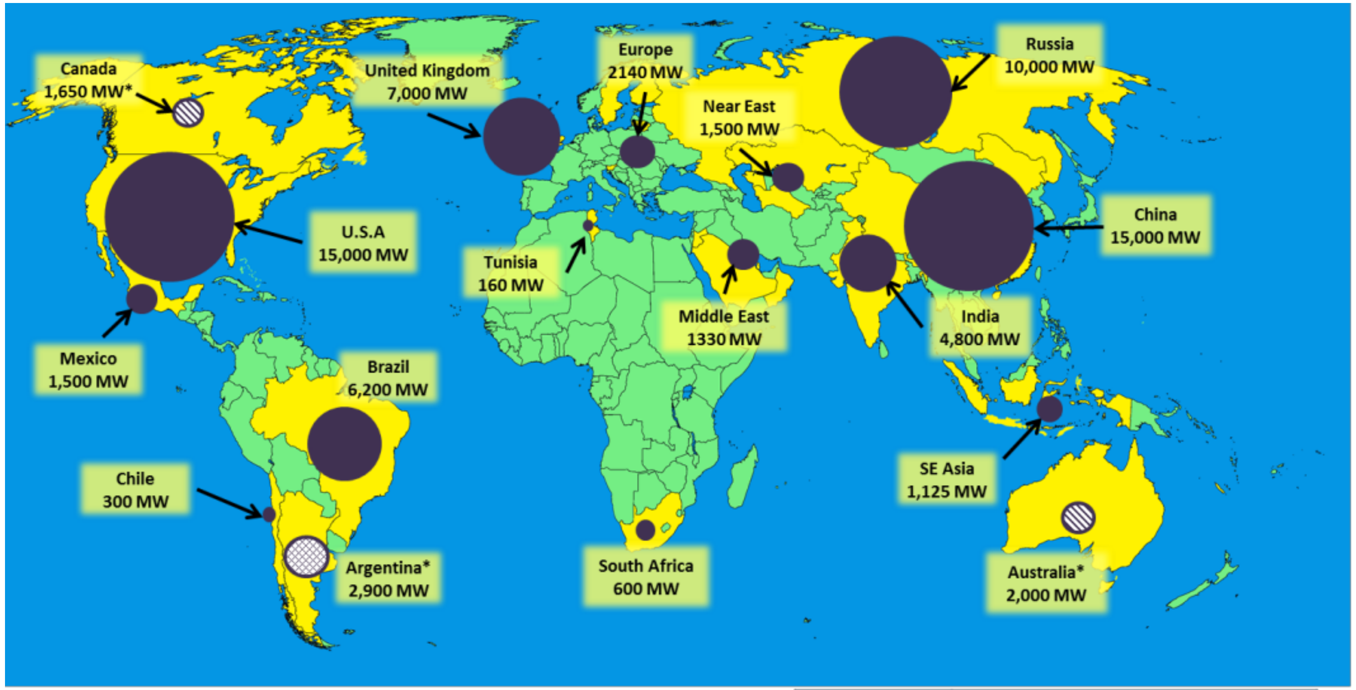
- Sizes from ~1 to 20 MWe
- Designed mainly for off-grid and isolated generation but could be integrated into a grid
- Need to be easily transportable and installed
- Need to compete with diesel and other off-grid generation

Range of SMR concepts

In addition to small versions of current reactors, there are over **60** SMR concepts that have been studied in the last 10 years but few are likely to be built.

- The main thrust of recent SMR development is with ***Integral PWRs*** **– PWRs** where the steam generator is integrated into the reactor pressure vessel (RPV). We will focus on this direction as several designs are close to market
- **High temperature gas cooled reactors** are inherently small reactors to enable heat removal in loss of coolant accidents. The UK U-Battery very small reactor project and China is building a twin 105 MWe pebble bed reactor station. The US Kairos Power Hermes Reactor.
- **A number of small sodium and lead alloy cooled fast reactor designs** – at one time looked like they might be built but currently are seen as a step too far for SMR development.
- There is a recent interest in molten salt reactors, which would be in the SMR range

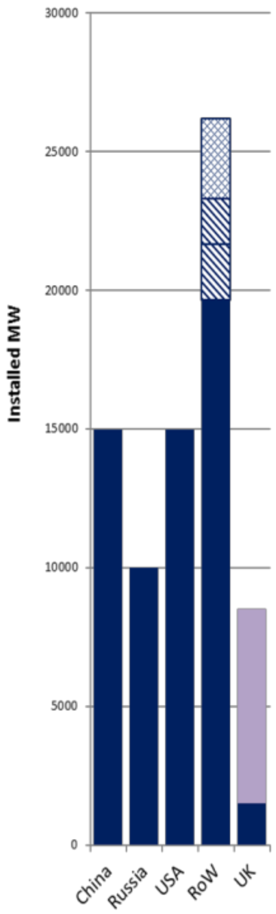
Potential market for SMRs



Region	Nation	Market Potential (2035)
Europe	Finland Lithuania Slovenia Sweden	1,320 MW 400 MW 150 MW 270 MW
Middle East	Bahrain Jordan Oman Qatar Saudi Arabia	75 MW 150 MW 180 MW 225 MW 700 MW

Region	Nation	Market Potential (2035)
SE Asia	Brunei Indonesia New Caledonia	50 MW 1,000 MW 75 MW
Near East	Kazakhstan Turkmenistan	1,000 MW 500 MW

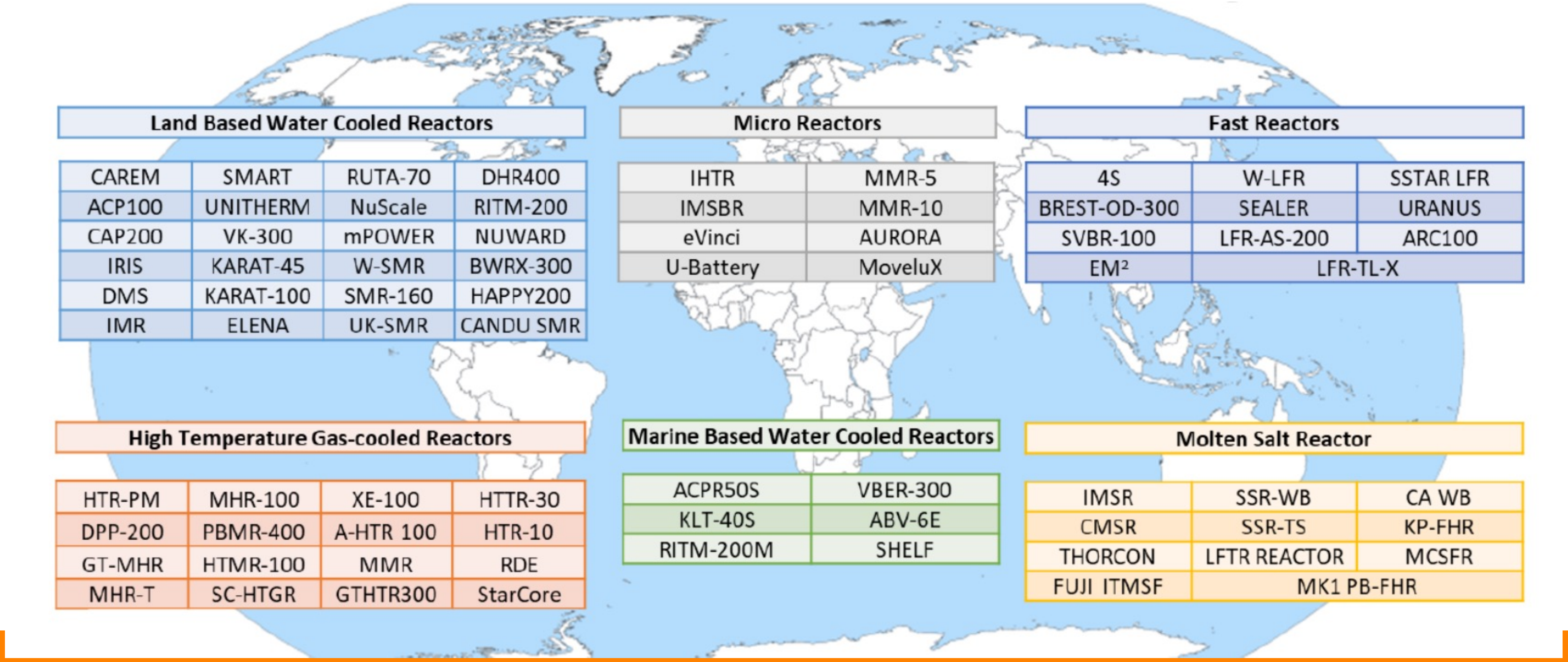
**United Kingdom	1,520 MW based on current policy scenario. 21,000 MW based on ETI ESME model projections for optimised cost of future electricity with large nuclear site limitations
*Argentina	May not be accessible due to nationalised energy sector and indigenous technology (CAREM)
*Canada	Currently a moratorium on new nuclear build
*Australia	Currently a moratorium on new nuclear build



Source: NNL SMR feasibility study 2014

The global international context

- Since the 2010's years, the SMR is a new economic model that has greatly relaunched the trend for nuclear reactors in Anglo-Saxons countries
- A large number of projects have been raised with a mix of start-up, private & public funding => New and innovative situation in the design phase of nuclear reactors



Land Based Water Cooled Reactors

CAREM	SMART	RUTA-70	DHR400
ACP100	UNITHERM	NuScale	RITM-200
CAP200	VK-300	mPOWER	NUWARD
IRIS	KARAT-45	W-SMR	BWRX-300
DMS	KARAT-100	SMR-160	HAPPY200
IMR	ELENA	UK-SMR	CANDU SMR

Micro Reactors

IHTR	MMR-5
IMSBR	MMR-10
eVinci	AURORA
U-Battery	MoveluX

Fast Reactors

4S	W-LFR	SSTAR LFR
BREST-OD-300	SEALER	URANUS
SVBR-100	LFR-AS-200	ARC100
EM²	LFR-TL-X	

High Temperature Gas-cooled Reactors

HTR-PM	MHR-100	XE-100	HTTR-30
DPP-200	PBMR-400	A-HTR 100	HTR-10
GT-MHR	HTMR-100	MMR	RDE
MHR-T	SC-HTGR	GTHTR300	StarCore

Marine Based Water Cooled Reactors

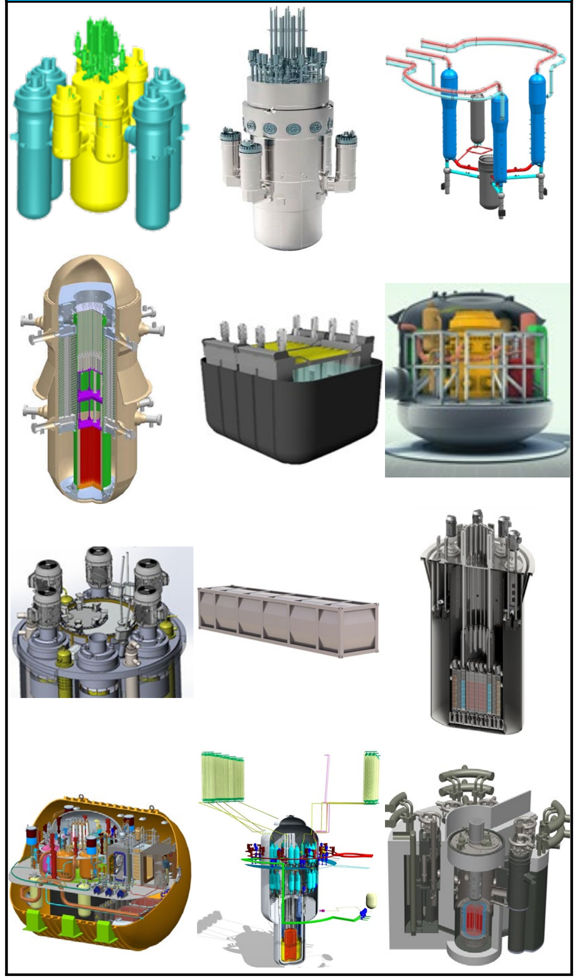
ACPR50S	VBER-300
KLT-40S	ABV-6E
RITM-200M	SHELF

Molten Salt Reactor

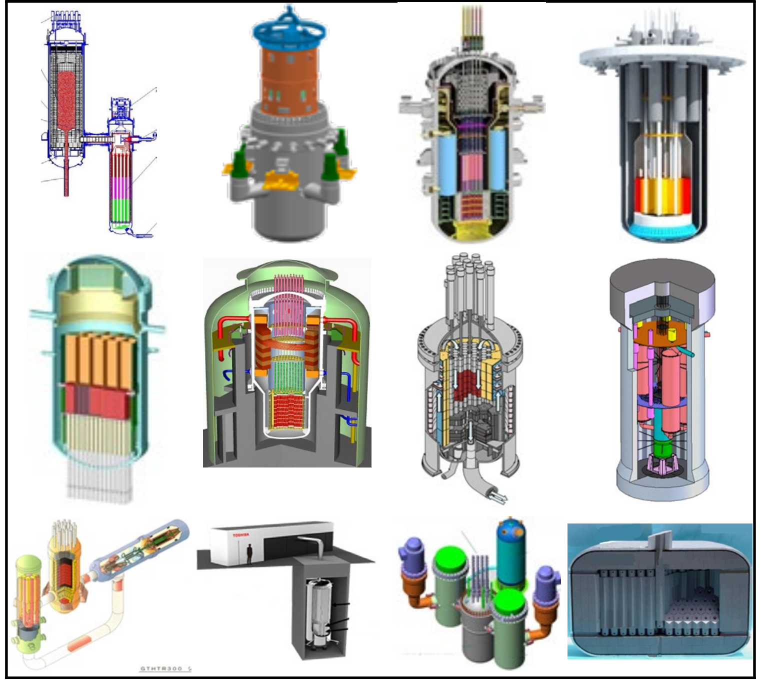
IMSR	SSR-WB	CA WB
CMSR	SSR-TS	KP-FHR
THORCON	LFTR REACTOR	MCSFR
FUJI ITMSF	MK1 PB-FHR	

* Non-exhaustive list

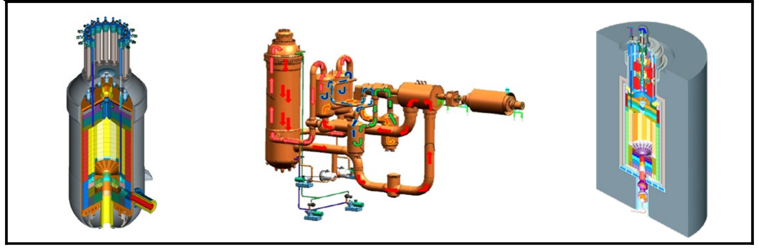
Europe, United Kingdom and Russian Federation



Asia



Africa

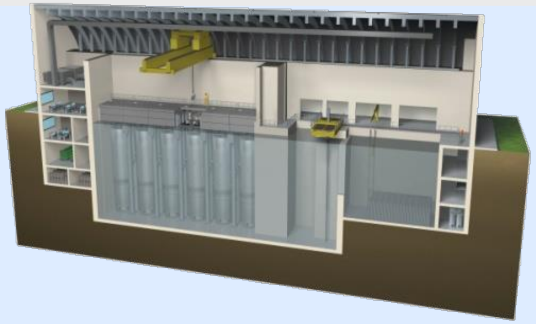


North America and South America

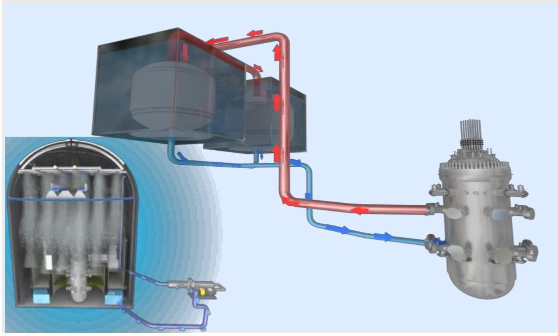
More than 70 designs of all major types in different stage of design development

Driving forces for SMRs

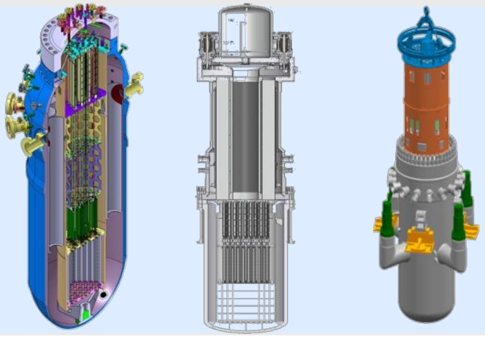
Scalability of Power



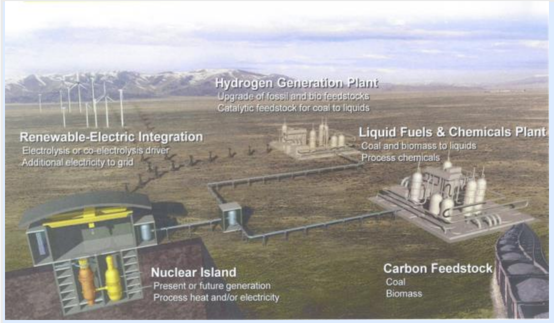
Enhanced Safety



Modularity, Constructability



Flexibility of Utilization



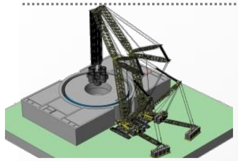
Images courtesy of US-DOE, NuScale, KAERI, CNEA, mPower & CNNC

Key advantages of SMRs

Economic

- Lower Upfront capital cost
- Economy of serial production

Better Affordability



Modularization

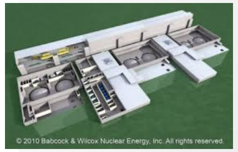
- Multi-module
- Modular Construction

Shorter construction time

Flexible Application

- Remote regions
- Small grids

Wider range of Users



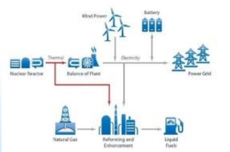
Smaller footprint

- Reduced Emergency planning zone

Site flexibility

Replacement for aging fossil-fired plants

Reduced CO_2 production



Potential Hybrid Energy System

Integration with Renewables

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US-DOE view of SMR benefits

- **Modularity**: in two senses – factory fabrication of modules for a simpler assembly on site and reactor units as modules that can be added to match demand;
- **Lower Capital Investment**: lower unit of investment and lower investment per unit power from factory fabrication and shorter construction times;
- **Siting Flexibility**: smaller footprint, less demanding infrastructure and possibility of siting on existing fossil sites nearer habitation;
- **Gain Efficiency**: use of heat for industry and other applications and coupling with other generation sources for more efficiency;
- **Non-proliferation**: Depending on type of SMR could lead to reduced transport and handling of nuclear materials and longer refueling times, possibility of sealed fuel units;
- **International Marketplace**: Opens a new nuclear market.

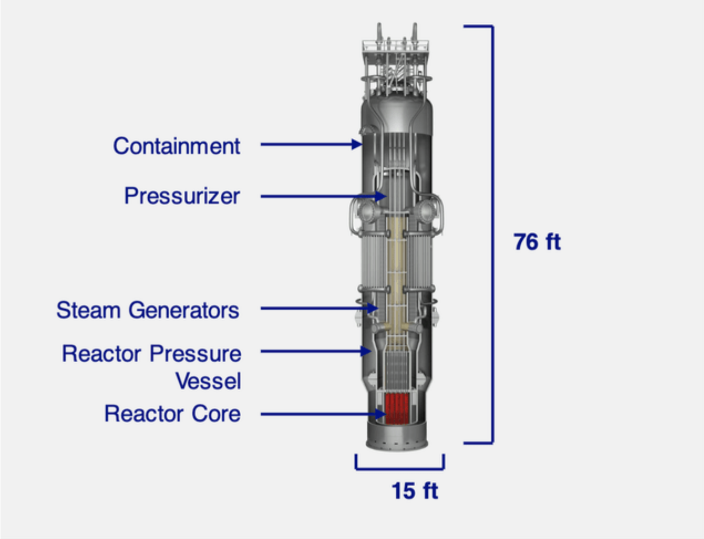
Other potential advantages of SMRs

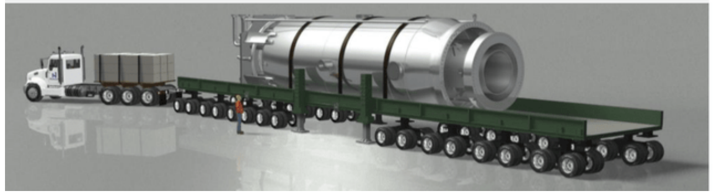
- Multiple build enables reduced costs through learning;
- Enables existing licensed sites to be used where space is limited;
- Small reactors can fit into limited electrical grid in remote regions, islands and in developing countries;
- Small reactors are simpler and more able to use natural convection and passive safety features and to be located underground.

SMR design: NuScale 60 MWe Light Water Reactor for multiple unit installation

Power module comprises integrated reactor vessel, pressurizer, steam generator, and containment vessel

(Seeking Alpha, May 6, 2022)



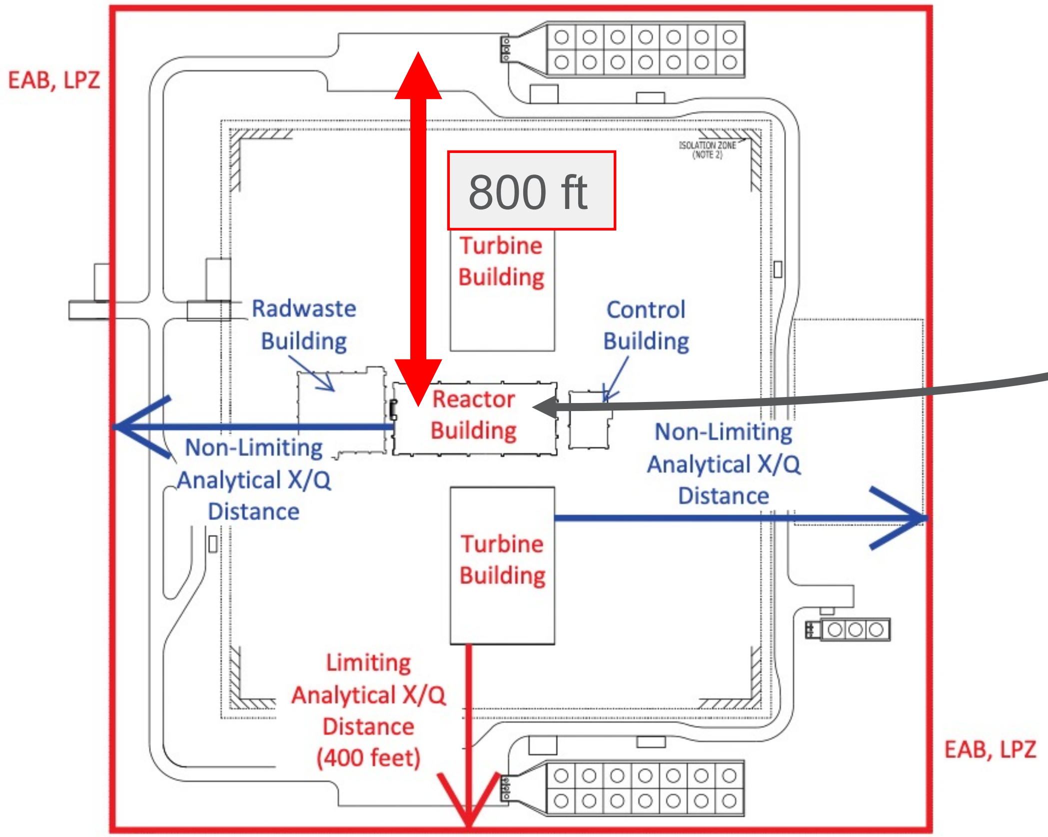


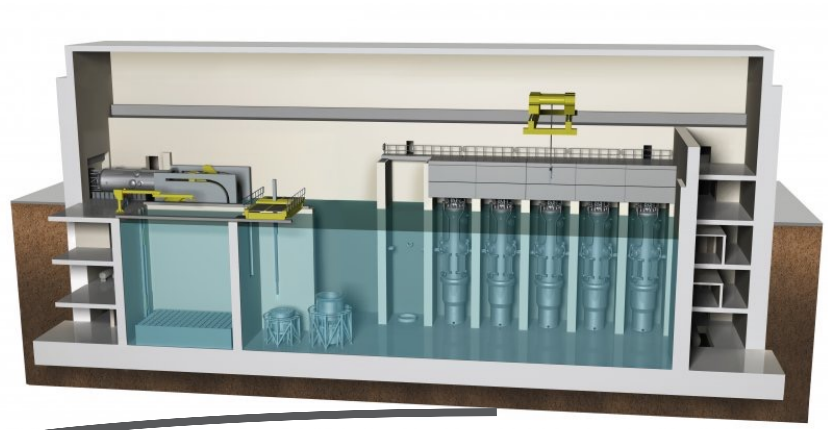
Artist concept of 6-reactor installation

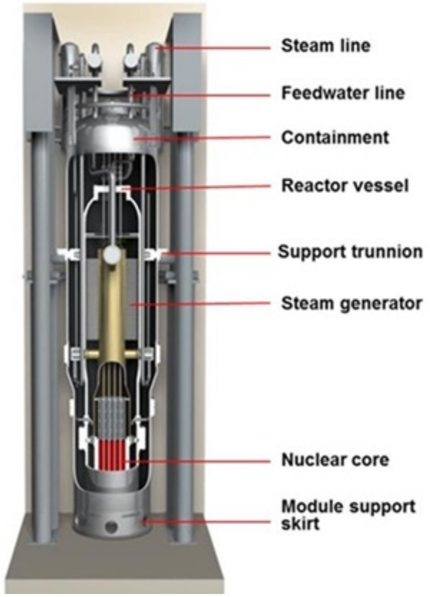
(Dive/Wire December 15, 2021)

NuScale SMR

Figure 2.3-1: Limiting Analytical Distance to EAB and LPZ Outer Boundary





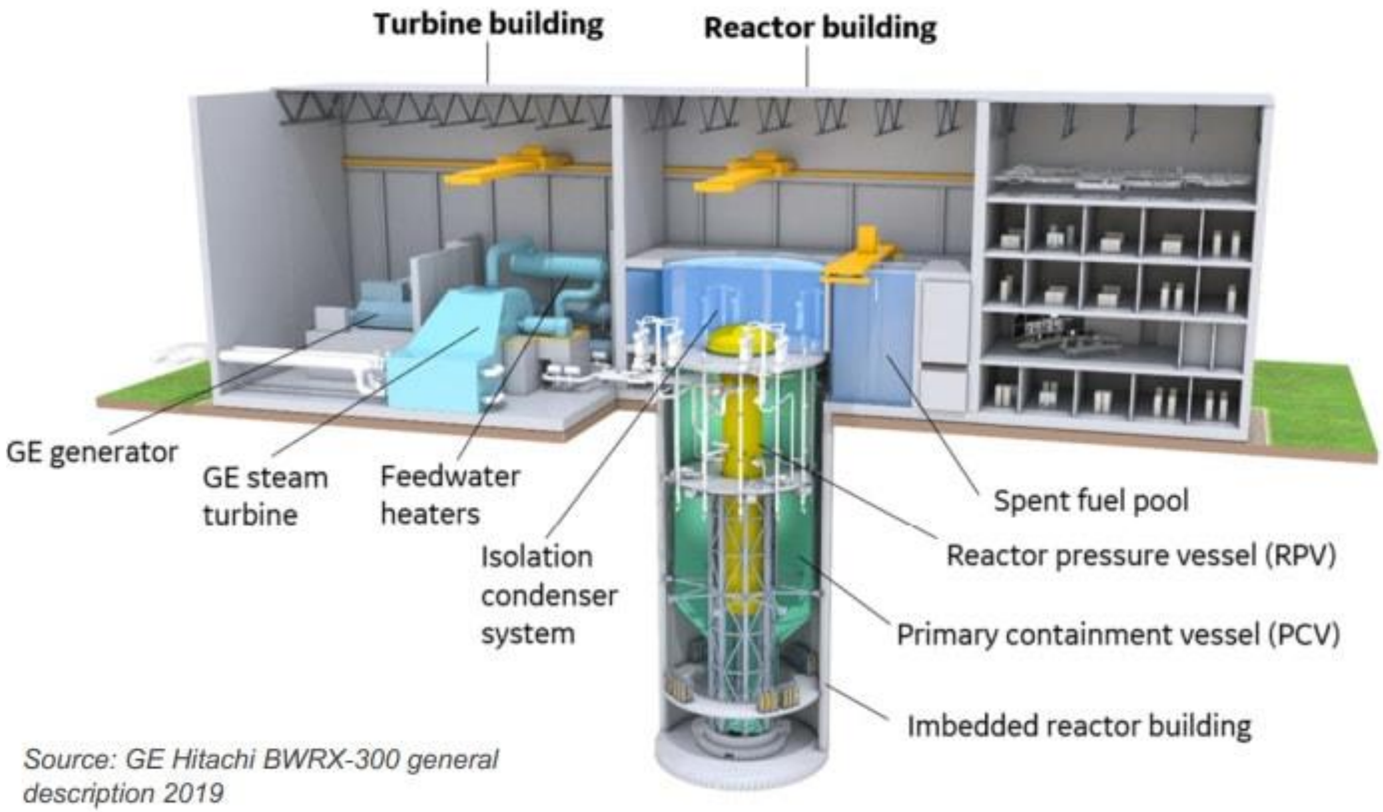


- First Small Modular Reactor to receive NRC design certification approval
- Reactor building ~800 feet form site boundary

- 4, 6, and 12 - cores VOYGR
- 160 MWth per core
- 17 x 17 fuel array
- 24 month cycle length

SMR design: BWRX-300

- TVA agreement with GE to potentially deploy at Clinch River Site Based on Economic, Simplified BWR (ESBWR)
- Utilizes GNF-2 fuel
- Target deployment: 2028
- Enrichments up to 8 w/o U-235



Source: GE Hitachi BWRX-300 general description 2019

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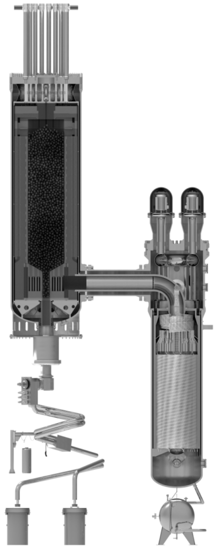
SMR design: XE-100, 320 MWe High-temperature Gas-cooled Reactor

SMR design: XE-100, 320 MWe High-temperature Gas-cooled Reactor

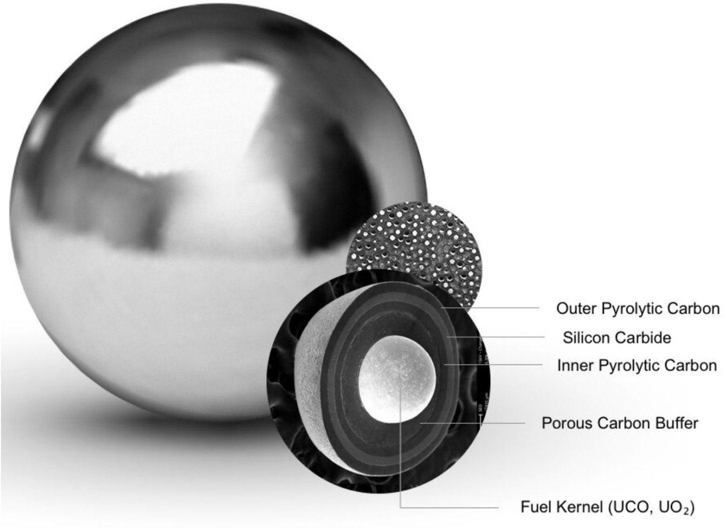
One of four Helium-cooled 80 MWe reactor units for total of 320 MWe

(Frazier, May 2022)



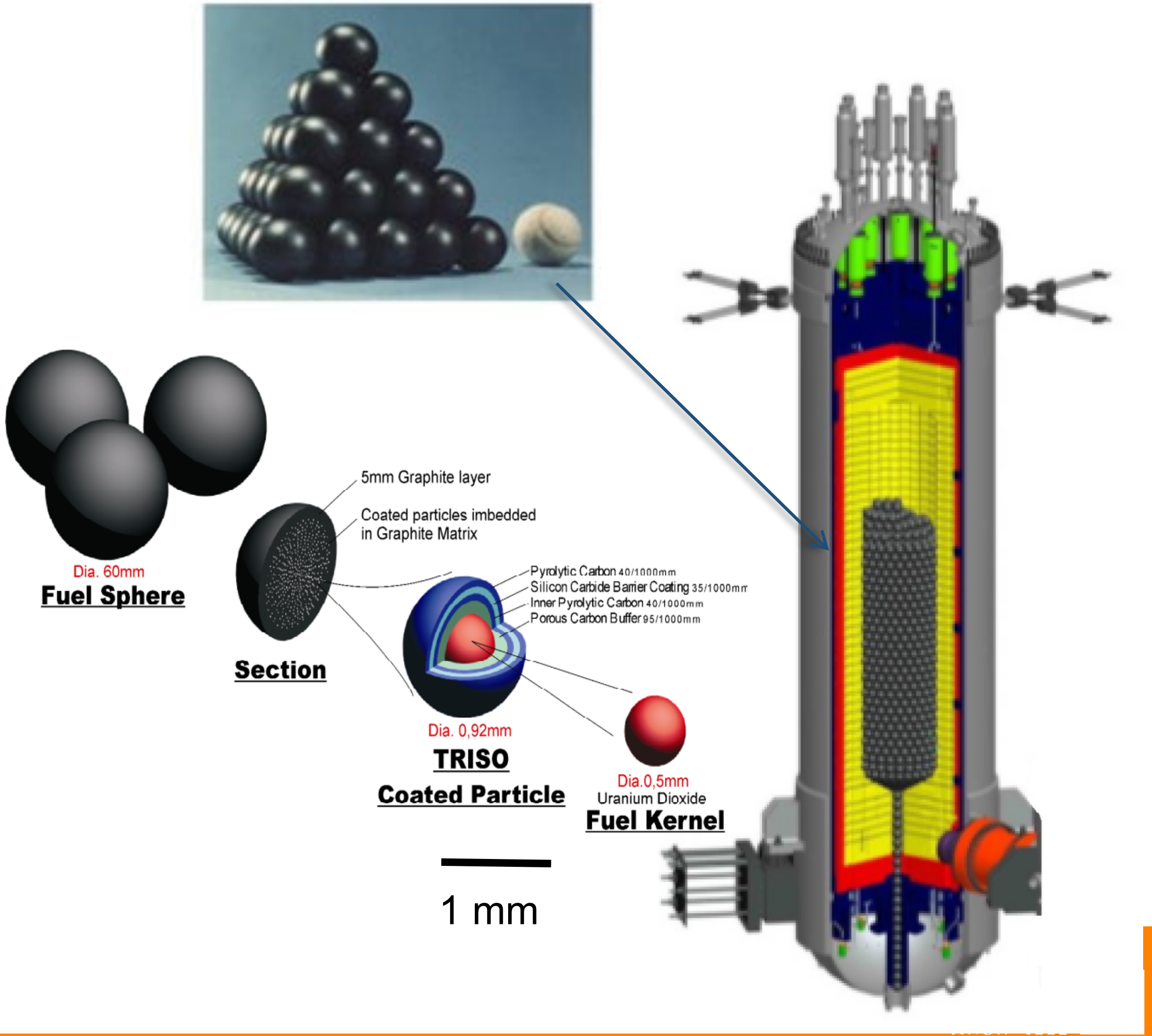
HALEU TRISO-X fuel pebble and TRISO fuel kernel

(Frazier, May 2022)



Pebble type HTGRs

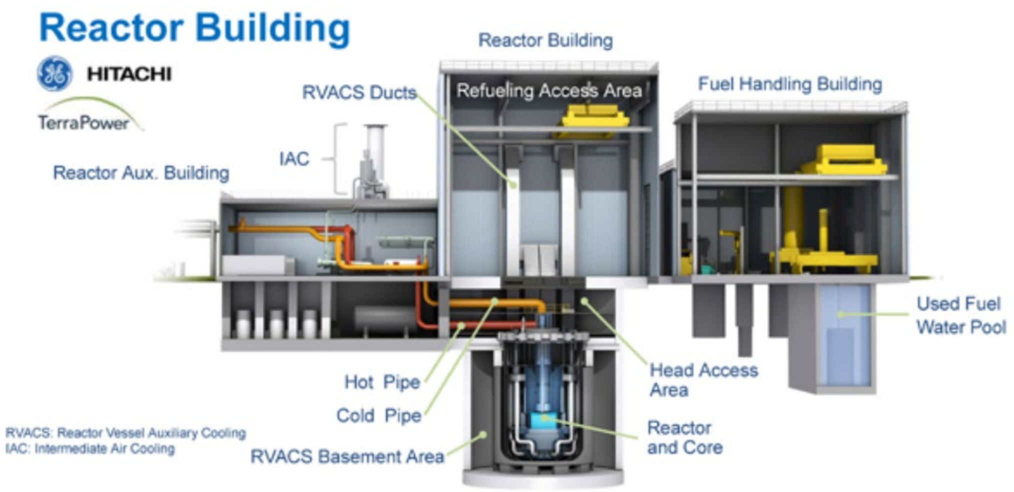
- Spherical graphite fuel element with coated particles fuel
- On-line / continuous fuel loading and circulation
- Fuel loaded in cavity formed by graphite to form a pebble bed



SMR design: Natrium 340 WMe Sodium-cooled pool-type Fast Reactor

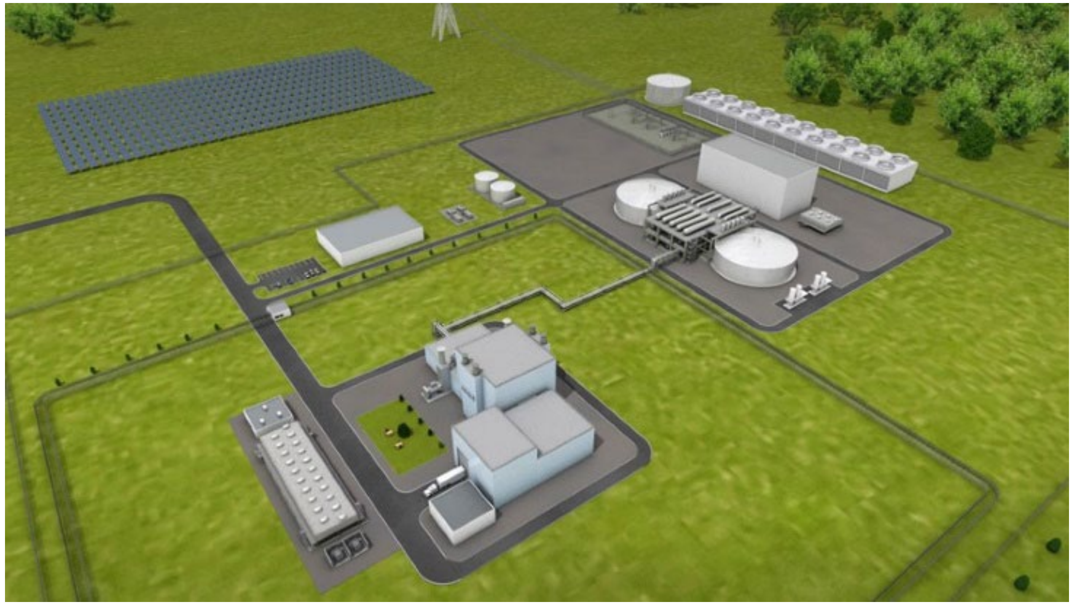
Reactor and Reactor Building

(Frazier, May 2022)



Artist concept of reactor building (lower center) and energy generation and storage (upper right)

(Frazier, May 2022)



Capital costs for SMRs

Key Topics	Prospects	Impediments
Capital component of levelized cost of power	Potential decrease in case of large scale and serial production	Require large initial order *(e.g. 50 – 80 modules)*
Comparison of material quantities	Design saving	Standardization of new structure, system, components and materials
Impact of local labour and productivity	○ Reduced construction time for proven design ○ Lesser work force required with modular construction (case by case)	FOAK deployment of multi-module plant with modular construction technology versus stick-build
Cost of licensing	Based on LWRs technology - easier licensing, but still could take long in established nuclear regulators	First of a kind; Time required for modifying the existing regulatory and legal frameworks
Ensuring all necessary equipment is included in the cost estimate, e.g. there is no 'missing equipment'	Learning curve: the higher the number of SMR built on the same site is, the better the cost effectiveness of construction activities on site	Cost impact by delayed component delivery or defect during shipping
Assurance of reliable estimates of technology holder equipment prices	Similar among vendors	Manufacturing of FOAK components

- **What are the major material quantities?**
- **Do they align with the projection of expected capital costs?**
- **What is the expected capital cost of the *n*th of a kind (NOAK) unit versus the cost of the first of a kind (FOAK) unit?**

We will only know after we build and operate SMRs

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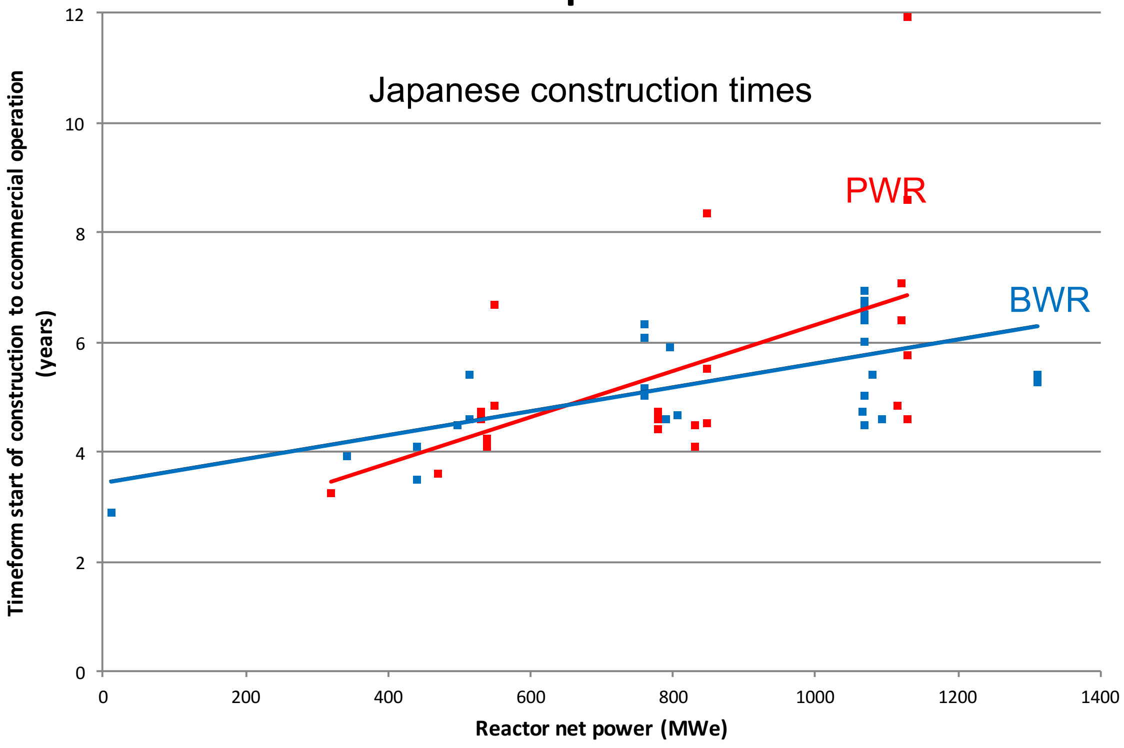
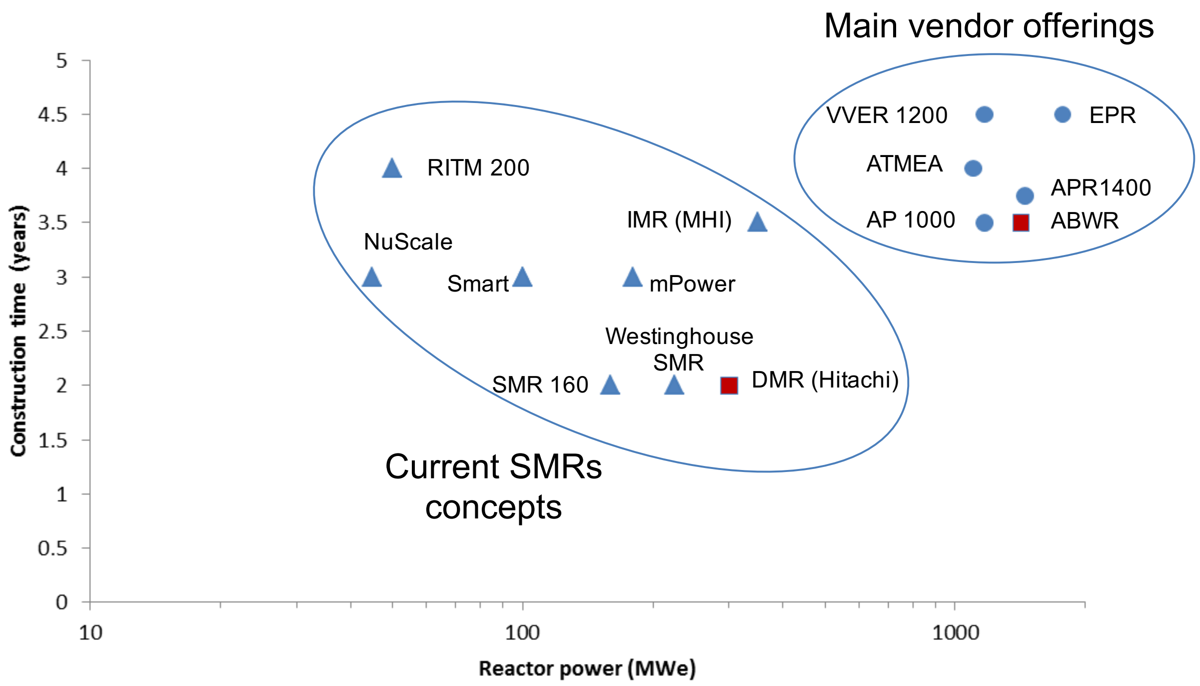
Construction time

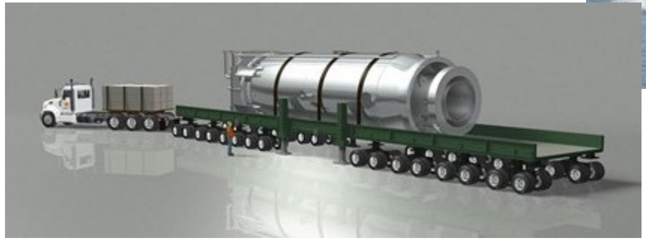
Is reactor construction time related to reactor power?

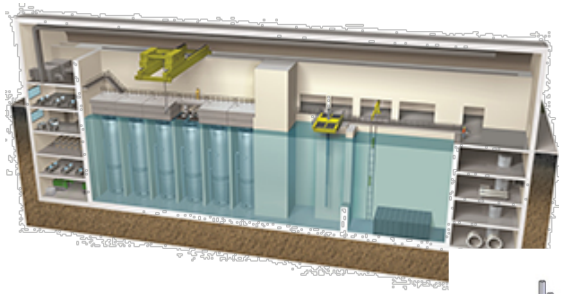


Claimed construction times (from first concrete to grid connection)



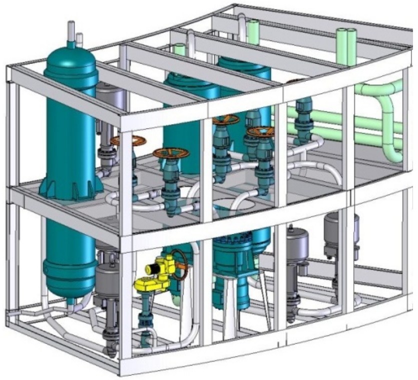
Modularization

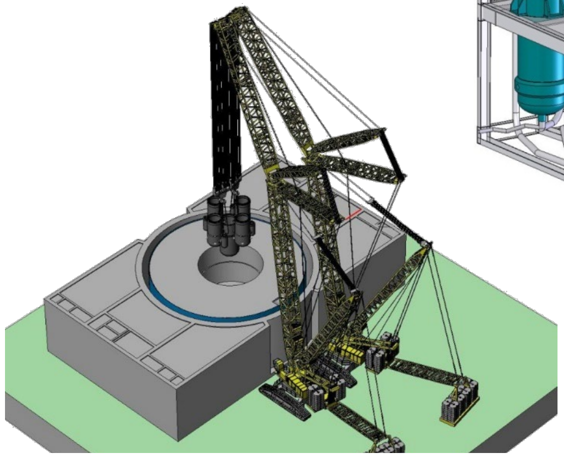




Modularization (construction technology)

- Factory manufactured, tested and Q.A.
- Heavy truck, rail, and barge shipping
- Faster construction
- Incremental increase of capacity addition as needed
- (Construction principle is also applied to large LWRs)





Modular construction

- Modular construction should extend to the whole plant.
- Experience from the aircraft industry shows that complex modules, weighing >100 tons containing multiple services can be made by different factories and assembled on site, but it needs precision.

A380 Module Source: Airbus

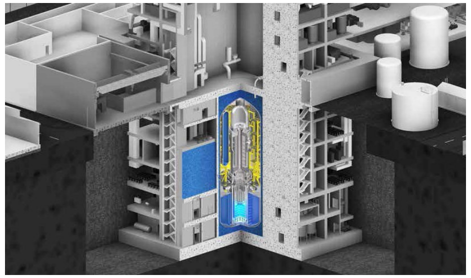
Benefits of SMRs and modularity

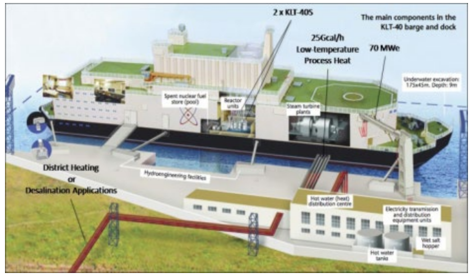
- Less total capital funds at risk during construction period
- Reduced interest during construction expense
- Capability to better match generation capacity to load growth
- Potential to operate fewer modules should load growth not materialize
- Potential to add more modules should load demand increase

Flexible design features offered by SMR

Underground and marine based deployment

- **Underground sites offer:**
  - Better protection against the impacts of severe weather
  - Better seismic strength
  - Enhanced protection against fission product release
  - Improved physical security, aircraft impacts and conventional warfare
- **Marine based deployments offer:**
  - Infinite heat sink (sea)
  - Site flexibility
  - Alternative owner / operator options





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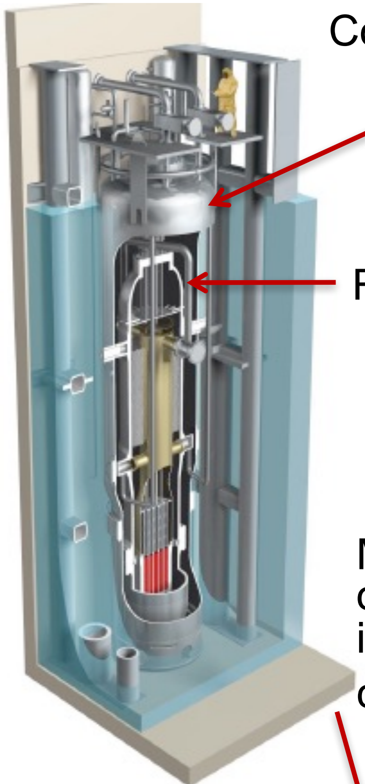
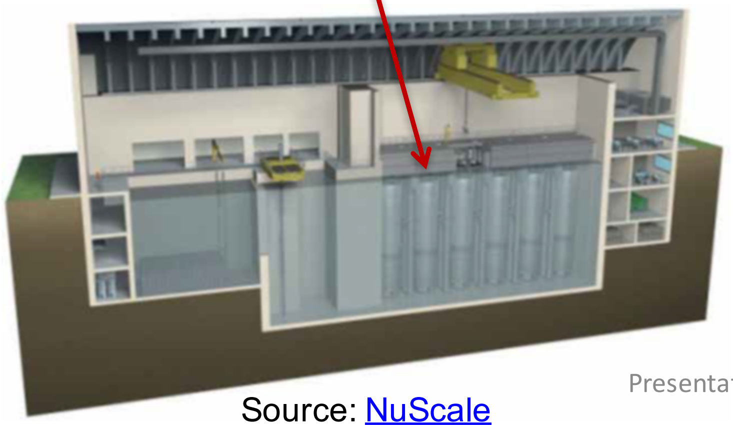
SMR Containment: smaller and safer

- **One of the opportunities for SMR safety design is to choose a small-volume pressure suppression containment more usually found with BWR systems.**
- The NuScale, Westinghouse and ACP-100+ designs have below ground tight steel high pressure containments.
- Westinghouse and NuScale can operate with the containment under vacuum, so that the reactor has no insulation and is easier to cool by flooding the containment in a loss of cooling accident.
- The Westinghouse and ACP-100+ containments have internal water reservoirs for pressure suppression.
- The NuScale design has up to 12 reactors sitting in a large fuel handling pool.



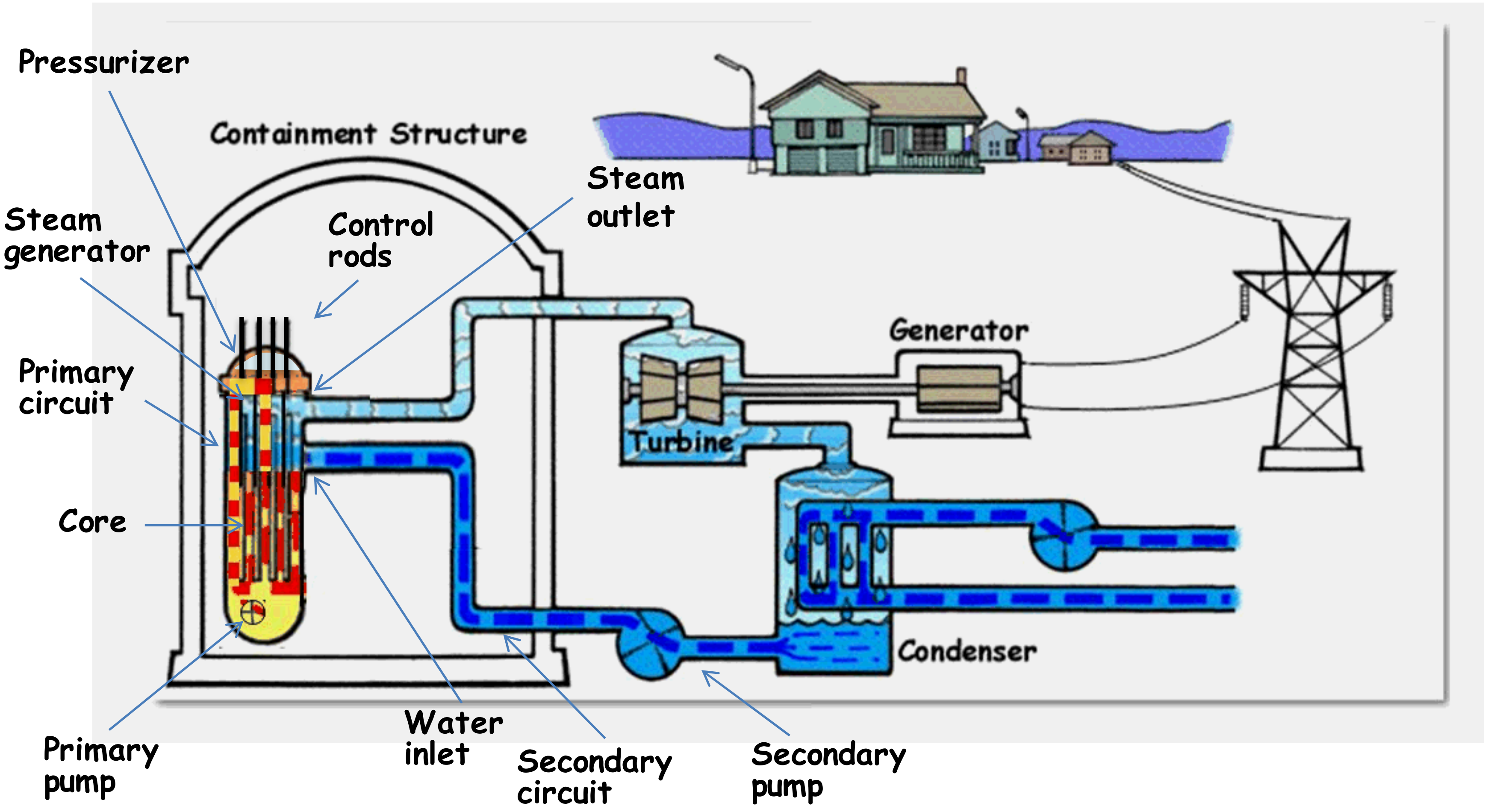
© NuScale Power LLC

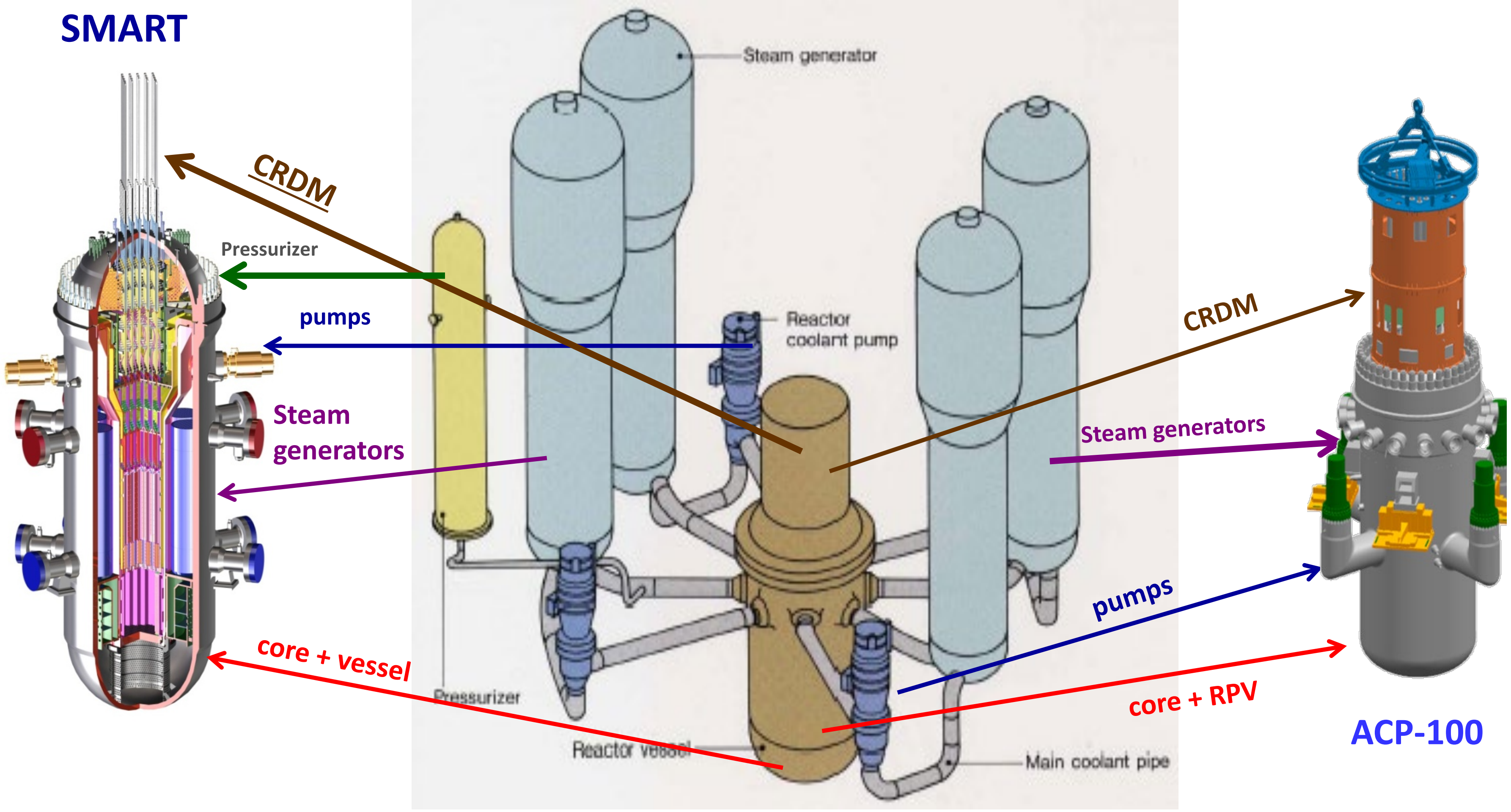


Source: NuScale

Presentati

Integral PWR (origin marine reactors - Otto Hahn, submarines)





Integration of major components to be within the reactor pressure vessel:

– Eliminates loop piping and external components, thus making the nuclear island smaller and compact
– Eliminates the possibility of large break LOCA

Advantages of the integral PWR concept

Careful design will give a considerable reduction in the cost but the main advantages are related to the safety of the system

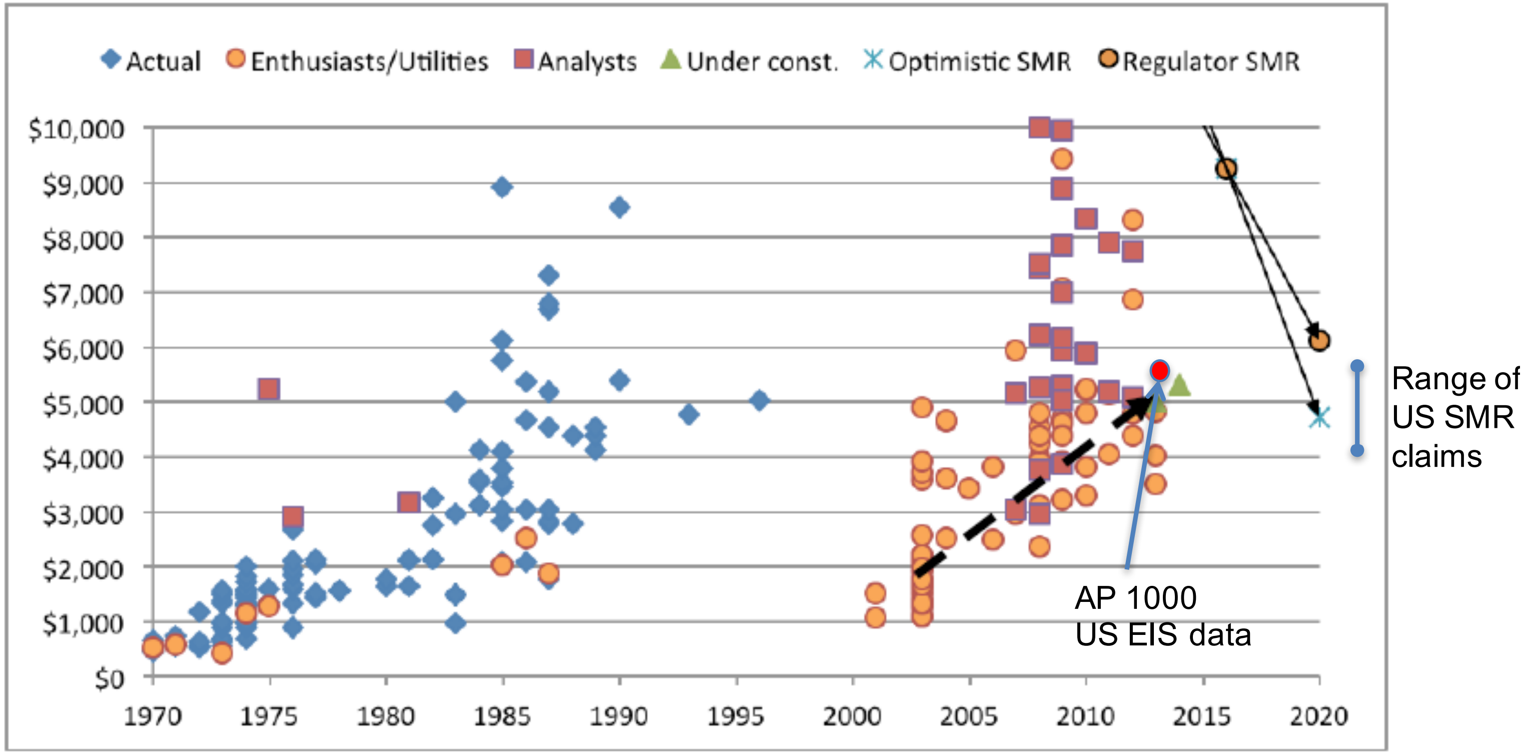
- The primary circuit is kept entirely within the RPV, so no primary pipework and no active circuit outside RPV
- No penetrations of the RPV larger than 50 mm diameter so no large break loss of coolant accidents
- Increased shielding of RPV from fast neutrons
- Lower core power density and larger volume of water in RPV
- Larger surface area to power ratio, making passive decay heat removal easier
- Uses standard PWR fuel, but with shorter fuel rods.

SMR site specific considerations

- SMRs promise much smaller sites
  - **EPZ can possible be reduced**
  - **Located close to population centers / end users**
  - **Located next to heat users / industries**
- The first SMRs currently built / to be deployed has selected existing NPP / nuclear sites (HTR-PM, CAREM, NuScale plan)
- **Important factor is physical security (smaller site and close proximity of other buildings / industries will present new challenges)**

Footprint of SMRs – are they smaller?

- Overnight costs of US nuclear plant



“Great Bandwagon Market” “Nuclear Renaissance” “SMR Hype”

Sources: Mark Cooper, *Nuclear Safety and Nuclear Economics*, Institute for Energy and the Environment, Vermont Law School, 2011; Robert Rosner and Stephen Goldberg, *Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.*, Energy Policy Institute at Chicago, University of Chicago, November 2011, p. 19.

Progress made in applying a graded approach

- Nuclear Regulatory Commission staff agreed with the Tennessee Valley Authority that scalable **emergency planning zones (EPZs)** for small modular reactors are feasible

wnn world nuclear news

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US regulators discuss smaller SMR emergency zones

28 August 2018

Share

CLARIFICATION: NRC staff have concluded the TVA methodology can be used in the future to determine if a reduced emergency planning zones is justified, and has not made a decision on EPZ criteria for small modular reactors.

The US Nuclear Regulatory Commission (NRC) has concluded that Tennessee Valley Authority's (TVA's) methodology can be used in the future to determine if a reduced emergency planning zone is justified for small modular reactors, a spokesman for the Commission told *World Nuclear News* today. It has not yet agreed that an EPZ around small modular reactors can be scaled to reflect their reduced risks rather than the mandatory ten-mile EPZ required for the USA's current light-water reactor fleet.

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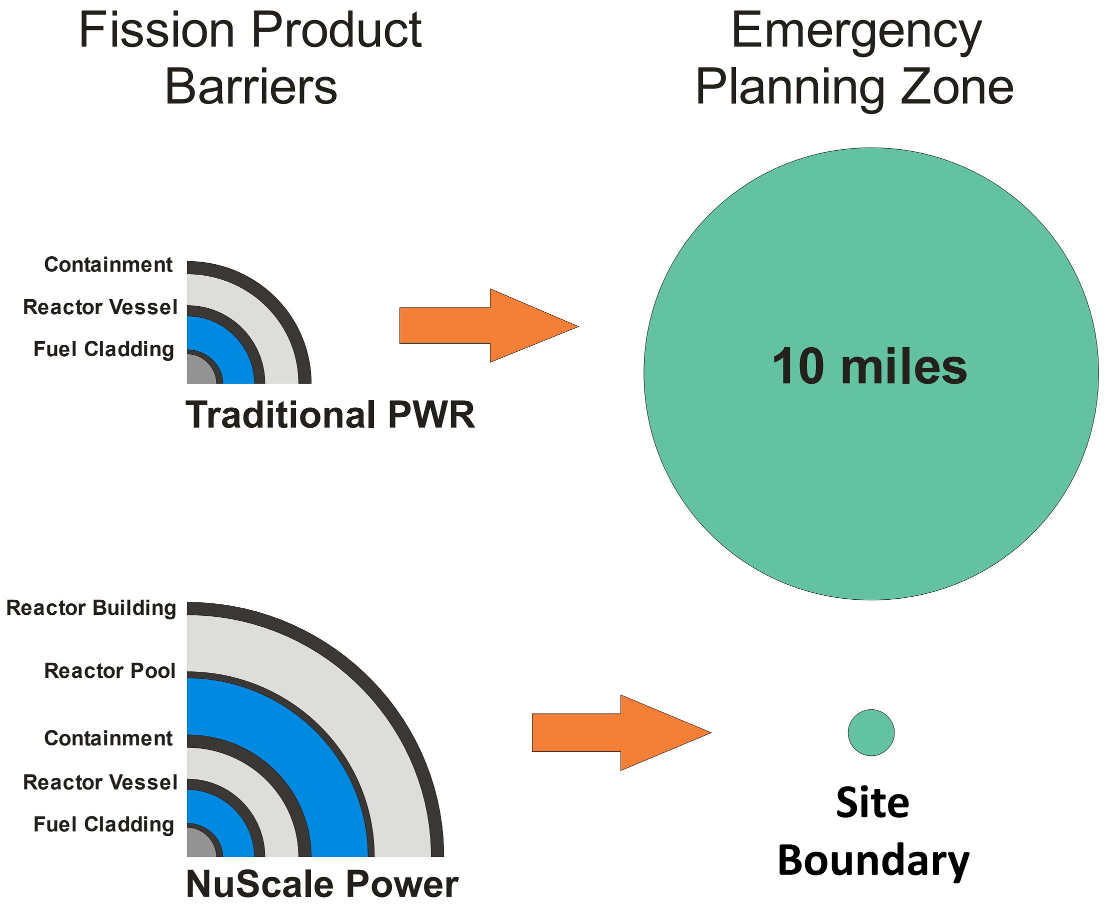
Emergency Planning Zones (EPZs)

- **Greater safety margin**
  - Elimination of many accident initiators
  - Passive and active accident prevention
  - Low power density
- **Slower event sequences**
  - Larger water inventory
  - Larger pressurizer volume
  - Huge core graphite mass
- **Reduced core damage frequency**
  - >3,000 times lower than operating reactors
  - Risk-informed design process
  - No core melt (mHTGRs)
- **Better accident mitigation**
  - Smaller fuel inventory
  - More design features to reduce and delay radionuclide release

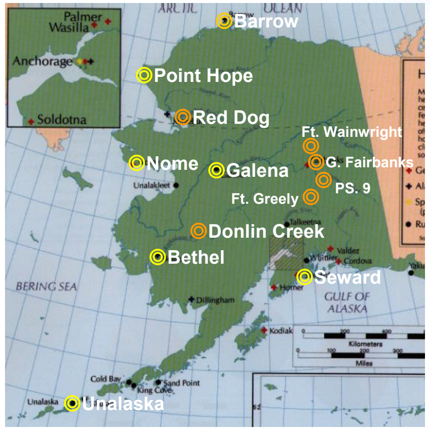


NuScale SMR: now nuclear goes ‘Off the Grid’

- **NuScale Power’s design has an additional characteristic that deserves attention, and will allow it to fill new roles: uniquely among power reactors, it does not have to be on a grid. Nuclear reactors in service today add stability to the grid, but this new model will go a step beyond that. These reactors would be among the first generators to re-start in an emergency, and could sustain critical loads for extended periods if the recovery time were drawn out.**
- The ability to operate without outside electricity is important because nuclear reactors now in service must shut down if the power on the surrounding power grid is lost, and they cannot start up again until the grid is running. But special features in the design of NuScale Power’s SMR will let it continue operating smoothly even if an outside event like a storm, an earthquake or human error takes transmission lines out of service. And if a NuScale plant comprising several SMRs does shut down, it can start up independently of the grid and take the lead in helping to re-establish normal grid operations.

NuScale SMR: in remote areas

- Many plants running on natural gas can start up independently, but these operate mostly with a “just-in-time” fuel delivery system, and weather or other events can disrupt fuel supplies. Some natural gas units have oil backup, but not for very long.
- **SMRs can change their output to meet varying levels of demand. And in normal operation on the grid, this capability will help them mesh well with intermittent renewables.**
- Typical NuScale plant will be a cluster of 12 small reactors, if a catastrophic event knocked out the grid for an extended period, the NuScale plant could run a micro-grid and provide power to first responders following a natural disaster, or provide critical community services, or power a military base that must maintain operations for national security, for several years without outside support.



(Map: State of Alaska, Japan Office)

Current electricity price
at remote area
in Alaska
$0.30 – over $1 per kwh

(Doyon, Limited Report, January, 2009)

(Map: http://www.threecordministries.org/ArcticMaps.htm)

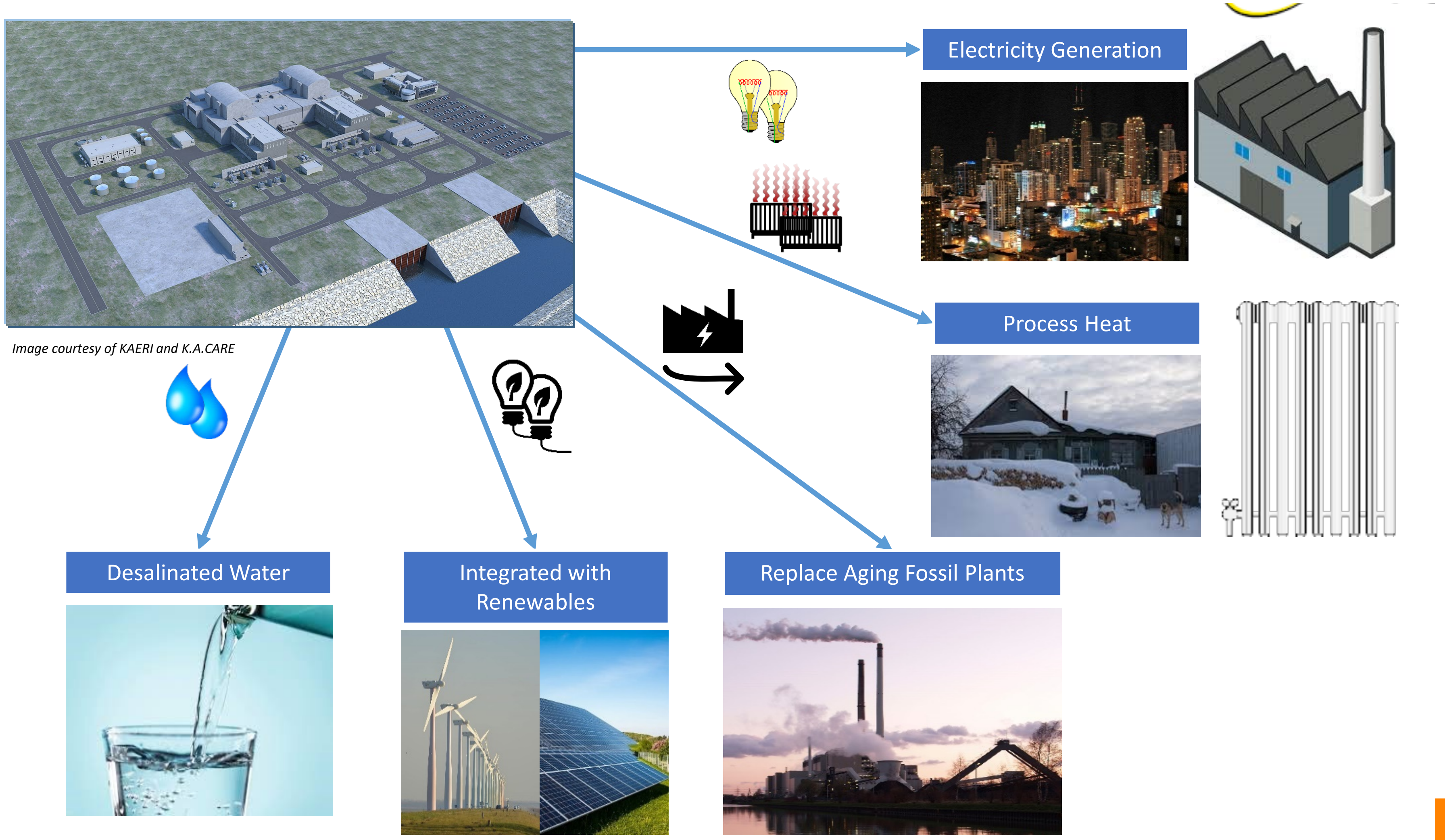
Current electricity price
at Nunavut Communities
In Canada
$0.39 - $0.94 per kwh

(Radix Corporation, ANS annual meeting 2010, San Diego)

Beyond the grid: SMR could deliver direct power

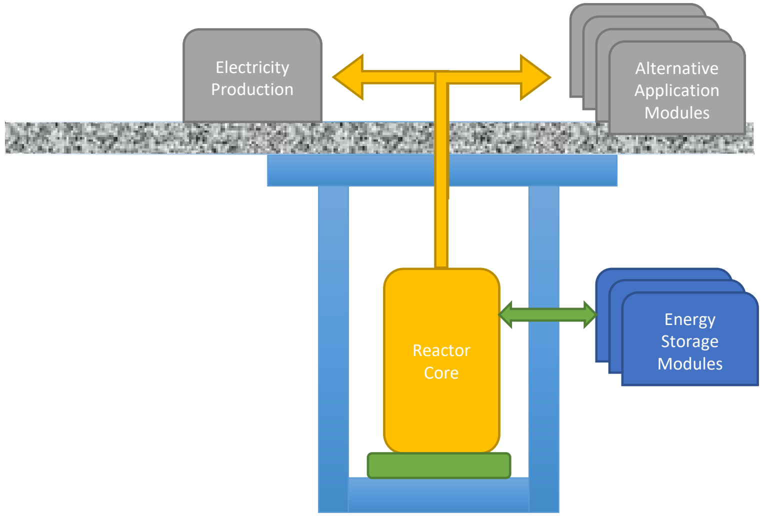
Small modular reactors have found a niche powering industrial equipment directly, rather than feeding energy into a national grid system. From seawater desalination to powering mining vehicles, we look at how small modular reactors could be used in more ways than previously thought.

Viable applications of SMRs

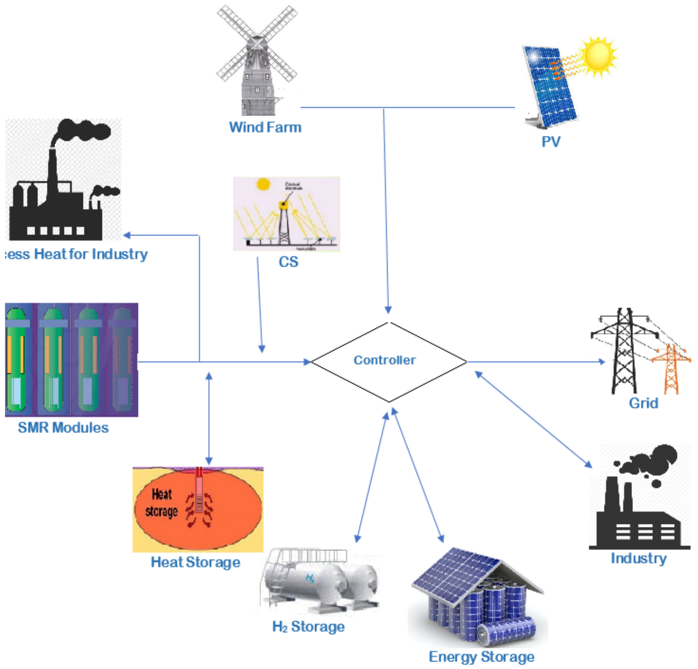


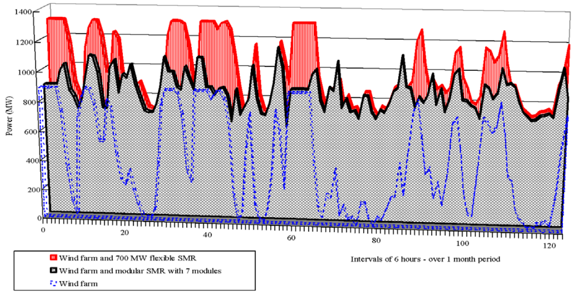
A viable option to contribute to Climate Change Mitigation

Hybrid energy system to reduce GHG emission



Modules:
- Electricity production
- Process heat
  - Petro-chemical industry
  - Desalination plant
  - Oil and gas reforming
  - Hydrogen production
  - Ammonia production
  - District heating / cooling
  - Waste reforming
- Energy storage
- Load follow capabilities
  - Switch between applications





Example of load follow with renewables

TECDOC:
Options to Enhance Energy Supply Security using Hybrid Energy Systems based on SMR;
being finalised in 2020

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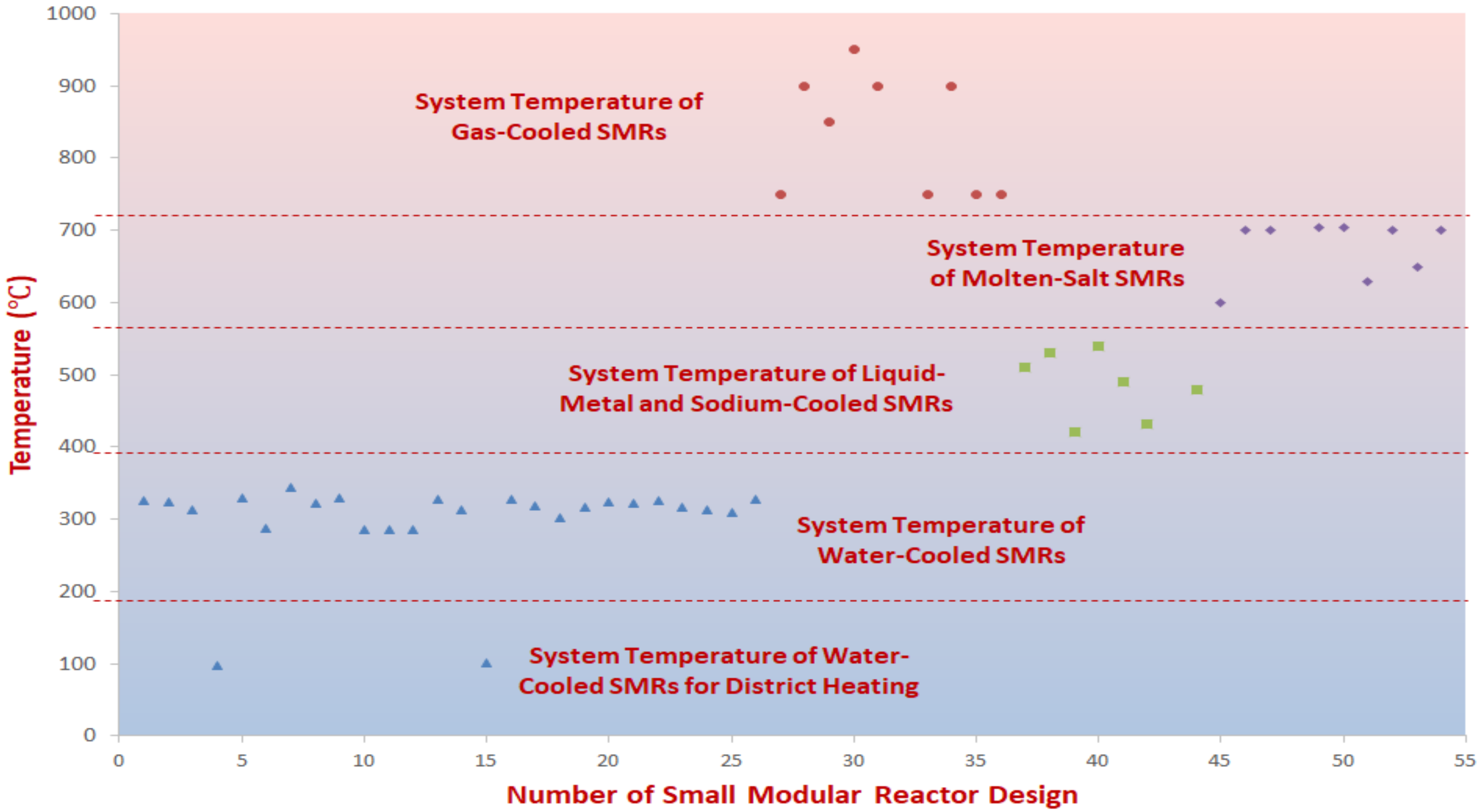
SMR designs based on core exit temperature



Value of non-electric applications

- **Better Efficiency**

Over 80% energy efficiency
Open new sectors for nuclear power

- **Better Use of energy**

Optimize energy efficiency
Match industrial application needs at the right temperature

- **Better Flexibility**

In future energy planning
In operating nuclear power plants/and electrical Grid
In diversifying energy outputs

- **Reduced environmental impact**

Reduced waste heat dumped to the environment
Additional heat sink

Save Energy

Recover waste heat
Open new utilization of nuclear power

Save Environment

Reduce CO_2 emissions
Reduce nuclear waste

Save Money

Get cheaper energy
Reduce the need for fossil fuels

- **Feasible**

On all reactor types
Existing nuclear reactors can be retrofitted

- **Safe**

Minimal impact on reactor safety
Product outputs is free of radioactive contamination

- **Value added**

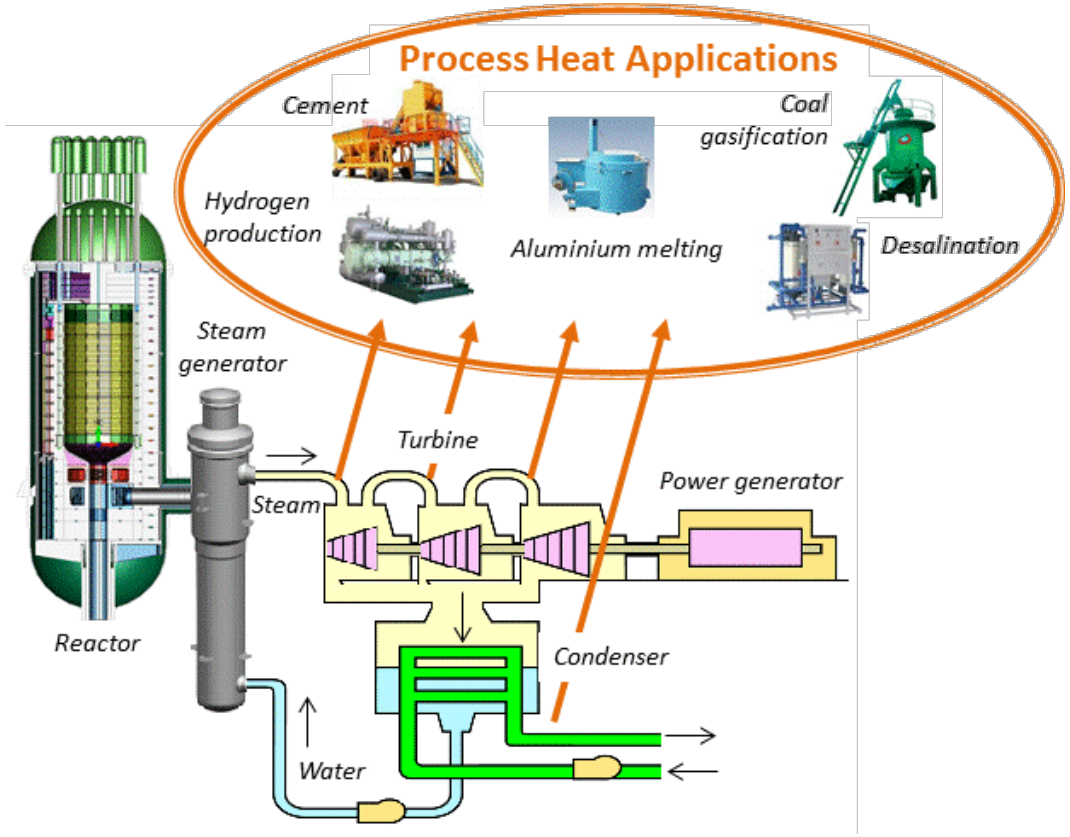
For pubic use: Drinking Water, District heating/cooling
For industrial use : Steam, Synthetic Fuels, Hydrogen

Process heat / co-generation

- Near term market potential

North America / USA only:

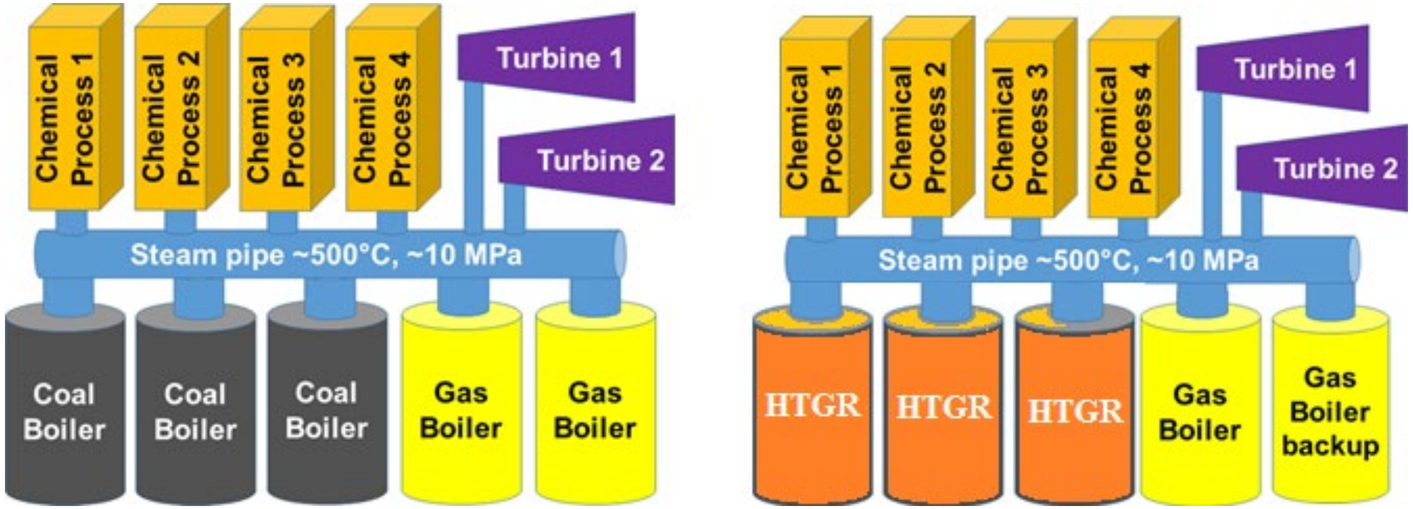
- 250-500C = 75,000MWt (or 150-300 reactors)
- Mostly Petroleum products: 500-700C = 65,000MWt (or 130 – 260 reactors)
- (Petroleum + Ammonia)
- Easily achievable today



Allows flexibility of operation switching between electricity and process heat

HTGRs and Poland

- **Industrial Heat Market in Poland**
  - 13 largest chemical plants need 6500 MW of heat at T=400-550°C
  - Construction of experimental reactor of ~10 MWth in Swierk
  - Target to construct the first commercial reactor of 150-300 MWth (165 MWth was determined to be optimum size for Poland)
- Huge potential: Foresee 10, 100, 1000 reactors for Poland, Europe and the world …



Benefits from SMR and HTGR deployment for economy & society in Poland*

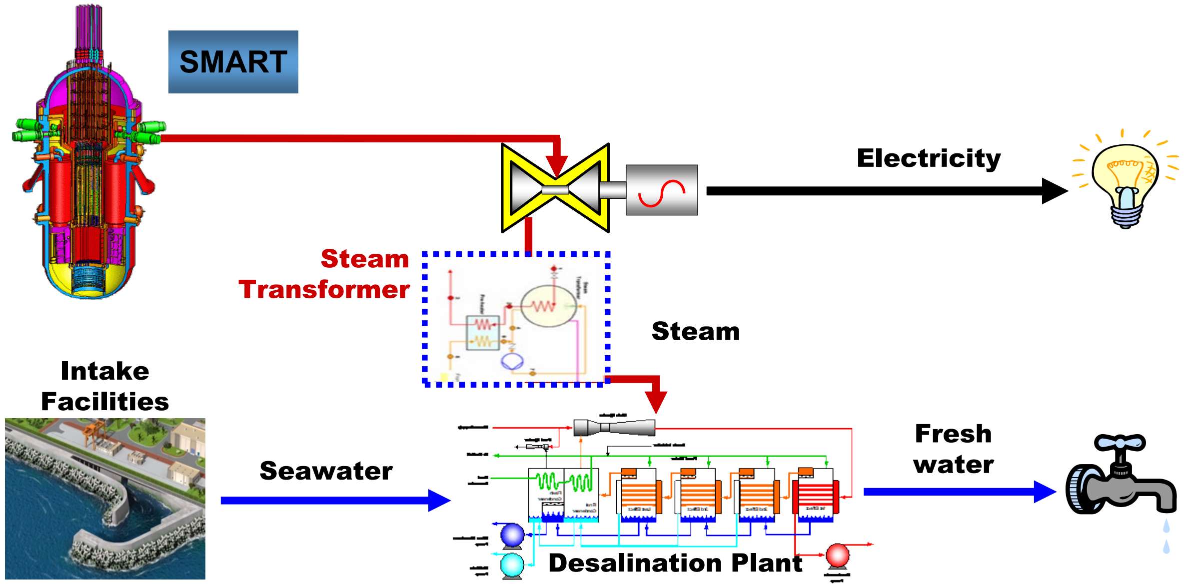
- Decreasing dependence on fossil fuel import: HTGR is the only practical alternative to replace fossil fuels for industrial heat production. With expected growth of CO_2 tax and low discount rate, the cost of the steam from HTGR could be comparable to that from gas, while having more secure availability and more predictable prices.
- Decreasing sensitivity of economy to environmental regulations . Industry dependent on fossil fuels might become less competitive in case of stronger environmental regulations (CO2 tax, emission limits, etc.). HTGR being a zero emission technology is immune to that.
- Boost for economy growth based on high added value. HTGR deployment is a large, innovative project, opening a new branch of economy, leading to high-tech reindustrialization and creating more attractive jobs.
- Increasing scientific and industrial potential, upgrading the regulatory framework, developing human resources and creating a supply chain, will be beneficial for both HTGR and LWR projects.
- Large export potential. Very high safety level, favorable output parameters (>500°C) and relatively small size makes HTGR a very attractive export product.
- Most of those benefits are valid for other countries.

* From 2017 IAEA GC Side Event – Poland Ministry of Energy

Cogeneration concept of SMART

$330\,MW_{th}$ integral-PWR

Electricity Generation, Desalination and/or District Heating



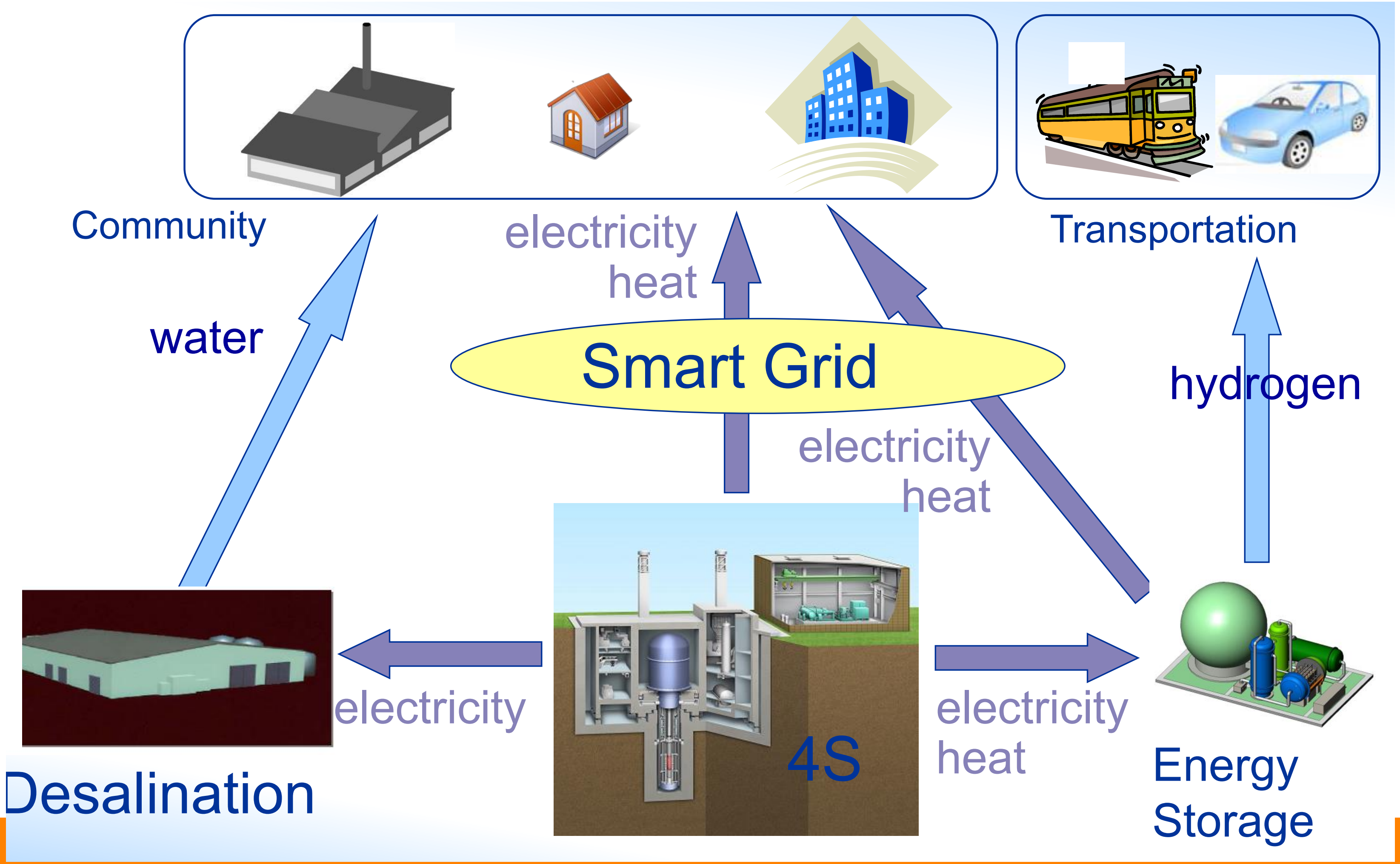
Plant Data
● Power : 330 MWt
● Water : 40,000 t/day
● Electricity : 90 MWe

System-integrated Modular Advanced ReacTor

- ❑ Electricity and Fresh Water Supply for a City of 100,000 Population
- ❑ Suitable for Small Grid Size or Distributed Power System

Images courtesy of KAERI, Republic of Korea

Hybrid system (4s + smart grid + energy storage)



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More World SMR applications: Rolls-Royce to power UK with SMRs

- **In February, Rolls-Royce, as part of a localized, private joint venture, revealed plans to install and operate SMRs built in the UK by 2029.**
- Rolls-Royce is leading a consortium for the UK SMR project, which also involves Assystem, Atkins, BAM Nuttall, Laing O'Rourke, National Nuclear Laboratory, Nuclear AMRC, Wood, and The Welding Institute.
- While the SMR designs are much smaller than traditional nuclear reactors, they are expected to produce about 450MWe, compared with 600MWe at each of the two reactors at the Dungeness B plant in Kent, England.
- The consortium is aiming to roll out 10-15 SMRs while planning for an export market, which is estimated at $328bn according to the company.
- Along with investments from the consortium members, and £18m signed off in November 2019 from the UK Government, private equities have also expressed interest.
- With Britain's eight large-scale nuclear power plants approaching the end of their collective lifespan, and most due to be decommissioned after 2030, Rolls-Royce joins the ambition to help shrink the UK's energy footprint and increase the safety of nuclear power.

Russia's floating SMR for water desalination

- Successfully deployed in 2019, the floating SMR nuclear power plant Akademik Lomonosov provides heat to residents in the Chaun-Bilibino region of Russia as well as powering water desalination.
- **The unique nuclear plant, which generates up to 50Gcal of heat per hour can desalinate up to 240,000 cubic meters of fresh drinking water every day, according to its developer – state-owned atomic energy corporation Rosatom.**
- Despite opponents raising concerns over safety and the possibility of nuclear waste pollution in the Arctic region, Akademik Lomonosov has been operating successfully. Rosatom is currently working on the second-generation design-optimized floating power units, which will be built in a series and become available for export.
- **Future plants could be connected directly to desalination plants, making it possible for future island states to benefit from the production of fresh water.**
- **According to the IAEA, nuclear desalination is a viable option to meet the growing demand for fresh water, especially in remote regions.**
- With this project, Russia has joined the list of countries, along with Saudi Arabia, Argentina, China, South Korea, and Egypt, that have constructed nuclear powered desalination plants.

Finland’s SMR district heating project

- **In February 2020, state-owned company VTT Technical Research Centre in Finland announced the launch of a project to develop a small modular reactor for district heating, as the country is planning to phase out its use of coal in energy production by 2029.**
- VTT has said that it will rely on in-house calculation tools to develop the SMR and model the reactor core. The company will also apply high-fidelity numerical simulation methods, supported by the advances in high-performance parallel computing.
- The model for this case study, conducted in Helsinki, consists of future annual energy use in district heating at 8TWh, electricity at 12TWh, and 4TWh of hydrogen for transport fuels. The selected reactor models for consideration include the HTR-PM pebble-bed reactor, currently being constructed in China, and Terrestrial Energy’s Integral Molten Salt Reactor, developed in Canada.
- **VTT has recently been involved in projects for research and deployment of SMRs and it coordinated the European Licensing of Small Modular Reactors project in 2019; it also led one of the work packages of the European Research and Innovation project McSAFE in 2017.**

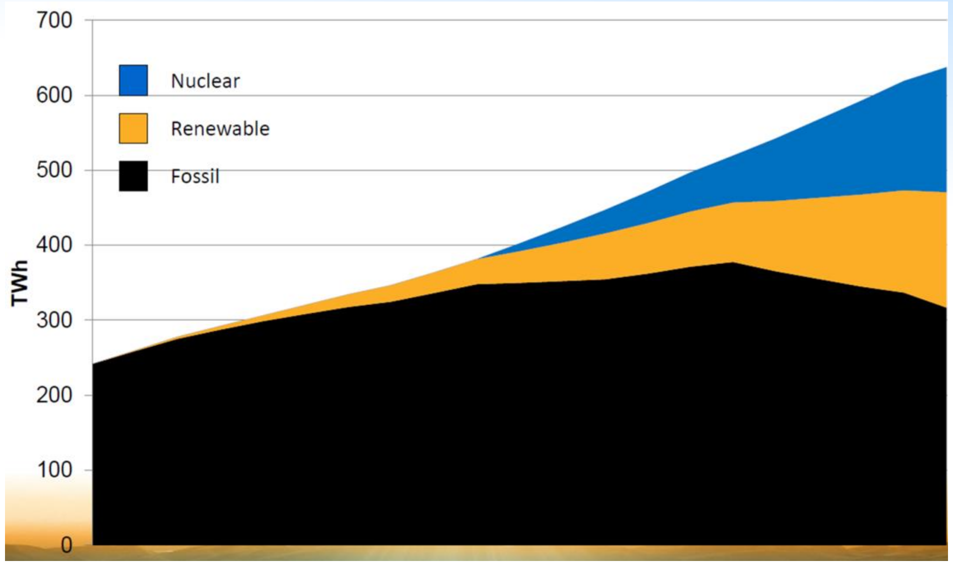
Canada to power mines with SMRs

- **Canadian Nuclear Laboratories has recently dedicated a team to pursue the development of SMRs. At the heart of Canada's venture is the idea to incorporate SMRs into the mining industry.**
- The company introduced the idea of modular reactors as a clean energy solution for the mining industry during the Prospectors & Developers Association of Canada 2019 convention in Toronto. As industrial mining sites in remote locations usually rely on diesel, the modular approach to construction, deployment, and decommissioning of SMR technologies could provide an emission-free alternative for the mining and resource extraction sector.
- Small modular nuclear technologies are also thought to provide economic advantages to Canada in addition to environmental benefits. For example, 'Canada's SMR Roadmap' report, which included input from stakeholders and industries from across Canada, indicates that SMRs could offer significant cost savings compared to diesel generation, particularly for remote industrial operations.
- As 40% of a mine's energy usage is related to heating and ventilation, the application of SMRs can make a difference by providing the electricity needed to power equipment and vehicles, reduce ventilation requirements, and deliver passive local area heating to the mine operations.

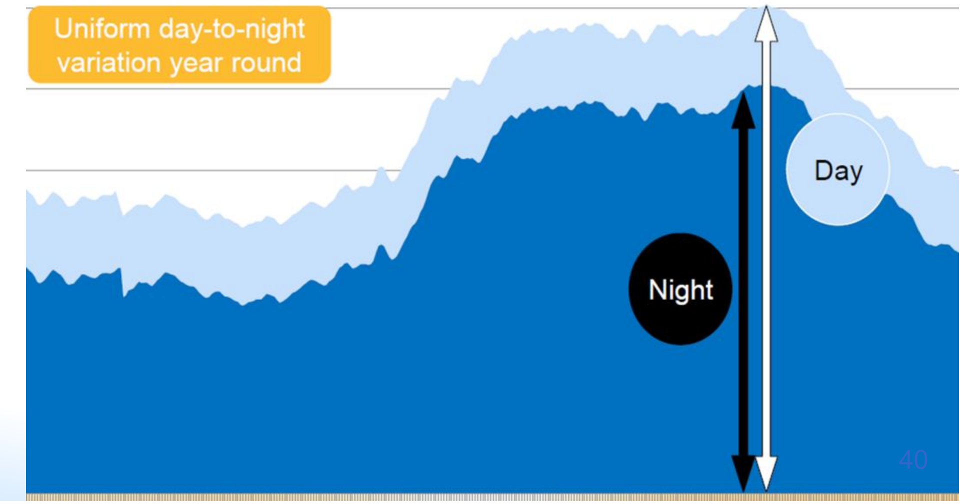
SMR for Saudi Arabia

- Bilateral nuclear cooperation agreement signed between governments of Saudi Arabia and Republic of Korea in November 2011
- Pre-Project Engineering for 2x100 Mwe **SMART** plant construction
- An on-going cooperation between K.A.CARE and KAERI; MoU signed in September 2015
- **Desire for full IP ownership of NSSS technology**
- **Future SMR export market in MENA**
- **Nuclear cogeneration for remote cities & industry**
- **Coastal and inland SMR site availability**

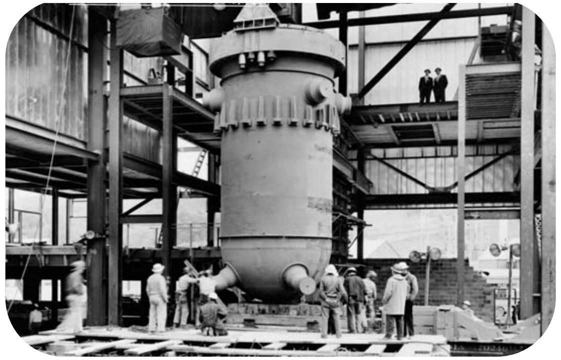
Gradual Offsetting of Fossil 50% by 2040



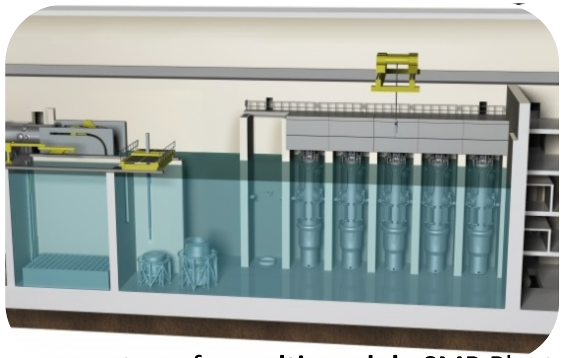
Day-night load variation for Saudi Arabia



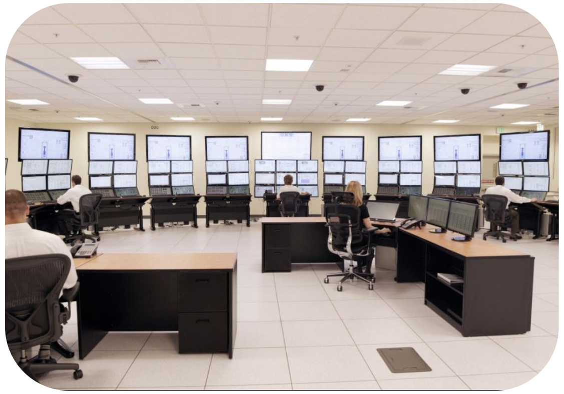
SMR challenges



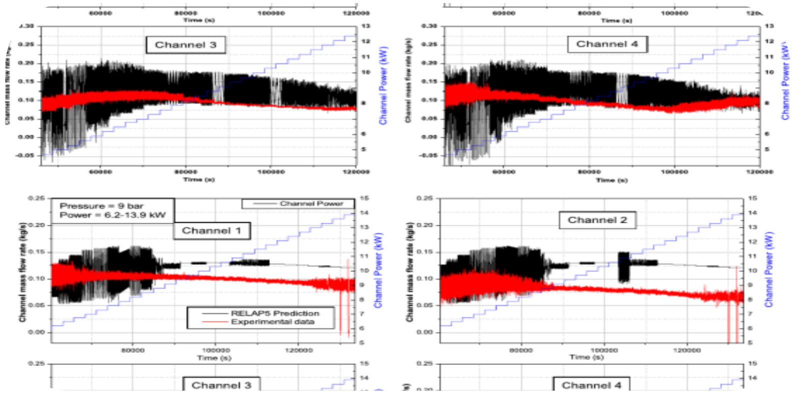
Standardization of first-of-a-kind engineering structure, systems and components



Defining source term for **multi-module** SMR Plants with regards to determining **emergency planning zone**



Control room staffing for **multi-module** SMR Plants



Rational **start-up procedure** for **natural circulation** integral PWR designs

Key barriers/challenges to deployment

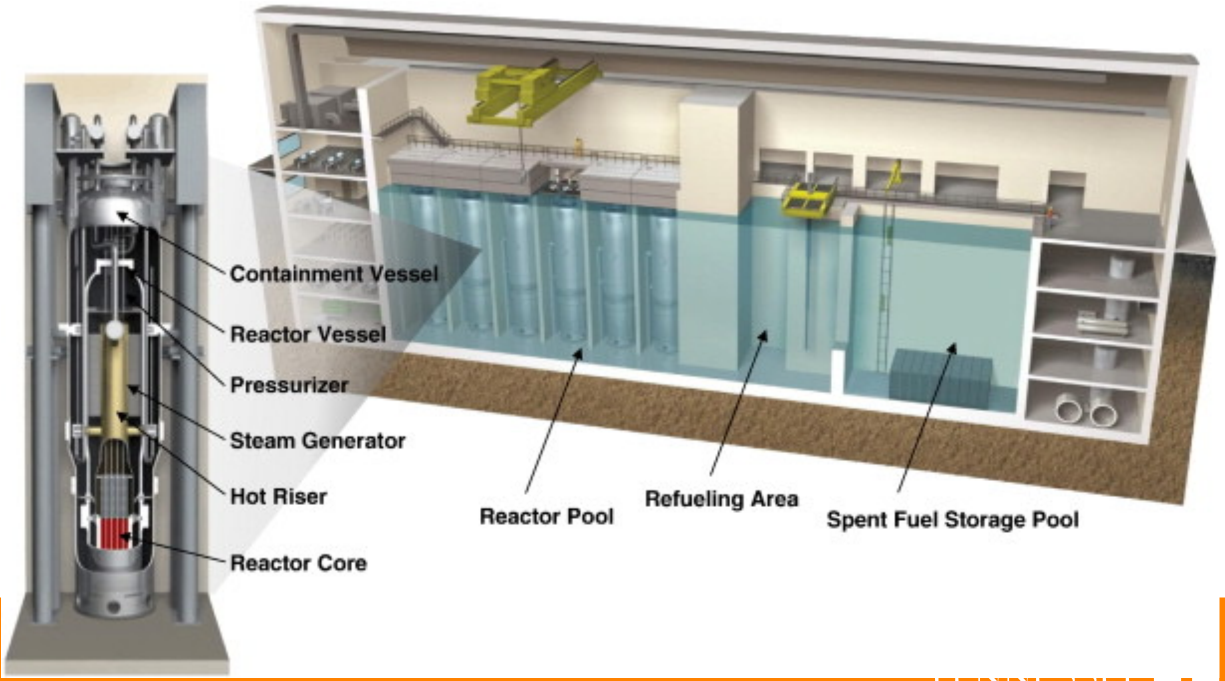
- **Limited *near-term commercial availability***
  - Technology developers ability to secure investors for design development and deployment: *first domestically, then international markets may be an opportunity to cooperate*
- **Economic competitiveness**
  - Need economy of numbers (vs economy of scale) …
- **Regulatory, licensing and safety issues.**
  - *FOAK, passive features, integrated designs, different technologies*
- **Technology Maturity**
  - Water cooled SMRs (iPWR and BWRs) based on mature technology
  - HTGR mature technology (with steam generator and Tout < 850 C)
  - MSR has limited operation experience –some challenges to be solved

NEED GOVERNMENT COMMITMENT TO REALIZE DEMONSTRATIONS PROJECTS!

Challenges on Safeguard for SMRs

- Construction of these SMRs in remote locations add to the burden on IAEA
- More cores per site mean more inspections per site
- Cores are co-located: Refueling may occur inside the reactor building while other cores are operating

Pros	Cons
Smaller targets for diversion	Higher Enrichment
Sealed Designs	Increased Deployment
Infrequent Refueling	Breeder Technologies
Remote Monitoring	Lack of Core Access for Verification



Conclusions on SMRs

- Today nuclear reactor building projects in the world are still with large power reactors
- But in parallel there is today a worldwide new dynamism around all type of SMRs
- The economical logic of SMRs remains to be demonstrated => a challenge, one of the major external event in this international race
- SMRs can propose larger services than electricity production. It is one of their main asset in a new energy paradigm seeking for a decarbonized society

General Conclusions on Nuclear Energy

- Nuclear energy has the potential to acquire a major role in a context where reduction of CO_2 emissions, reduction of fossil fuels use, and energy supply security are pursued by Governments.
- About reduction of CO_2 emissions, substantial efforts have to be undertaken to decarbonize the electricity generation sector. Nuclear energy is key to meet this objective. But nuclear energy production will have to be integrated in electricity generation schemes with increasing shares of intermittent renewables.
- The decarbonation of the electricity production alone will not be sufficient to meet the CO_2 emissions reduction targets. Non-electric industry and transports offer significant potential for further emissions reduction through the direct use of nuclear heat and/or via hydrogen vector. Thus the economics of nuclear energy production has to be reinvestigated.
- The reactors technologies, especially in their SMR versions, may be suitable to address both the environmental and economic challenges for their potential to be integrated in energy mix with high shares of renewables and through cogeneration approaches. Designs of cogeneration systems for different purposes exist and are already available in the literature.