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HACETTEPE ÜNİVERSİTESİ
Nükleer Enerji Mühendisliği Bölümü

HACETTEPE ÜNİVERSİTESİ
Fizik Mühendisliği Bölümü

15 KASIM 2024 | Hacettepe Ünversitesi - Beytepe Yerleşkesi - Mehmet Akif Ersoy Salonu

Yenilikçi Küçük Modüler Reaktör Tasarımları ve Gelişmiş Güvenlik Özellikleri

Güncel Durumda Küçük Modüler Reaktörlerin (SMR) Değerlendirilmesi

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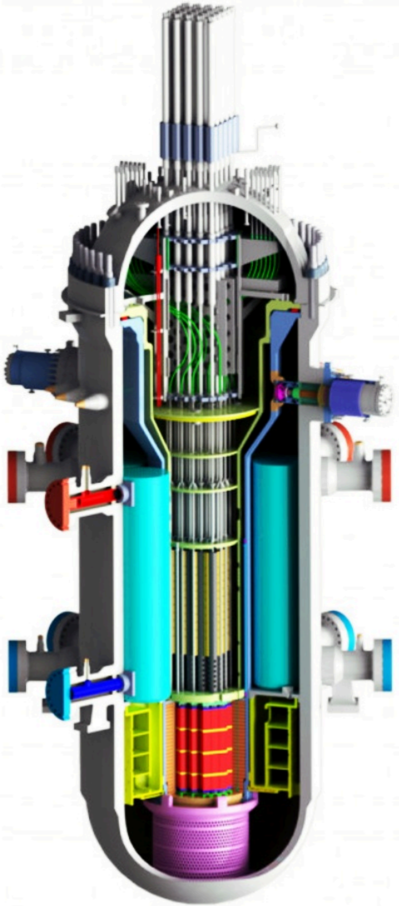
AGENDA

1 INTRODUCTION TO SMRS

2 SMR DESIGNS AND DEVELOPMENT STATUS

3 ADVANCED SAFETY FEATURES IN SMRS

4 FUTURE PROSPECTS AND CHALLENGES



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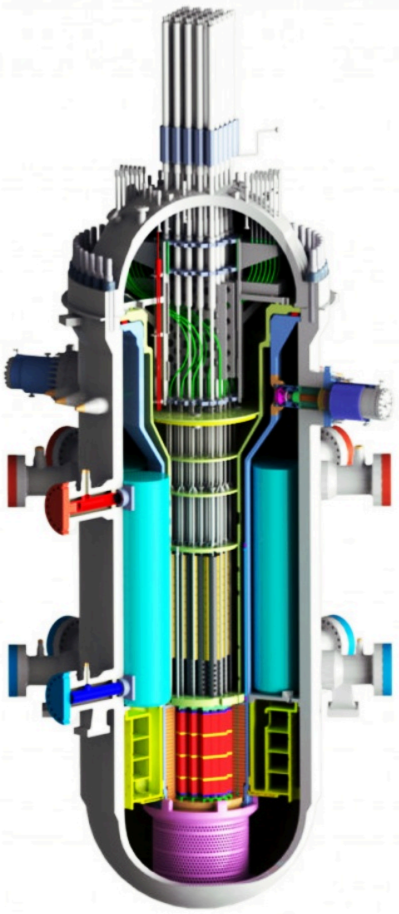
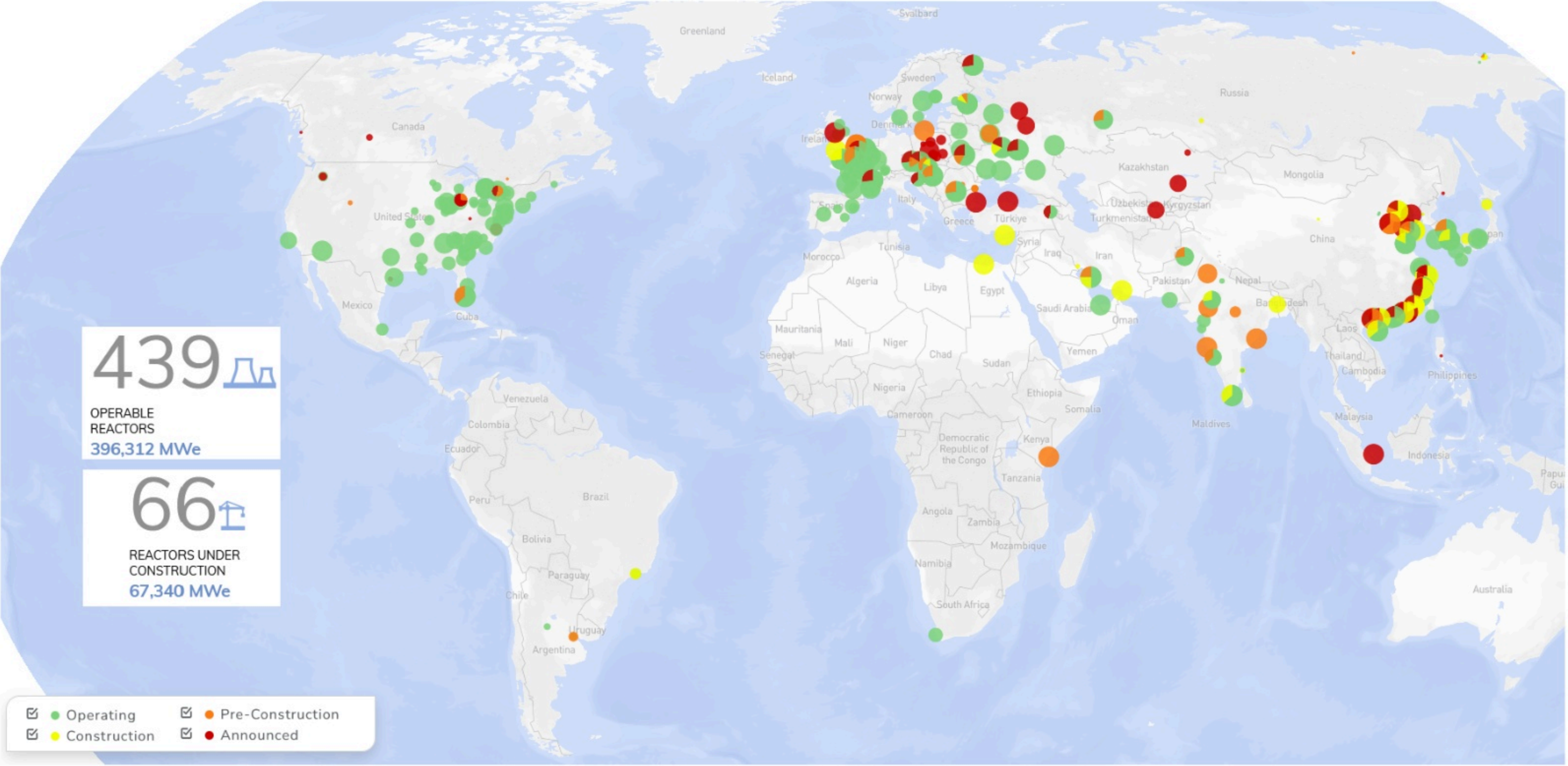


Nuclear Reactor Generations

- **GENERATION I: PROOF OF CONCEPT**
  - Demonstration reactors
- **GENERATION II: ACTIVE SAFETY**
  - Today's LWRs and HWRs
- **GENERATION III: ADVANCED FEATURES**
  - Standard Design
- **GENERATION III+: PASSIVE SAFETY**
  - Rely on natural phenomena
- **GENERATION IV: HIGHER EFFICIENCY**
  - High temperatures, better safety

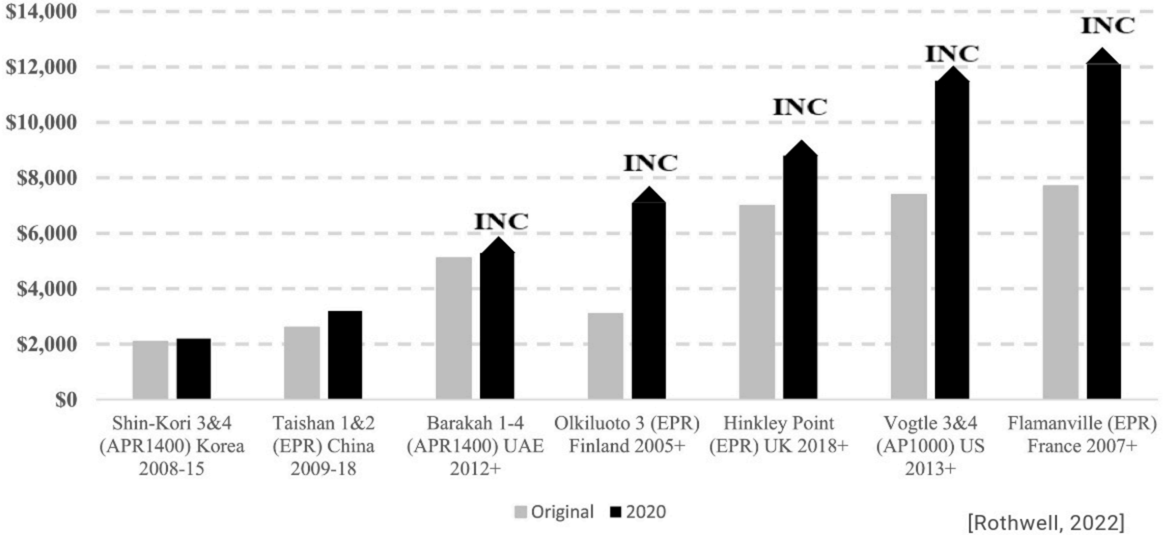
[Foro Nuclear, 2023]

Nuclear Reactor Status



Motivation

- TOO EXPENSIVE
- GRID COMPATIBILITY
- FINANCIALLY RISKY

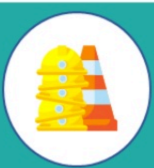


[Rothwell, 2022]

Nuclear Power Paradigm

Comfort Zone	Challenging New Way
• Supply-Leading • Economic Expansion • Long Term Project driven by Government • Maintain Traditional Advantage	• Demand-Leading • Safety and Environment • Surviving and Harmonizing with Renewables • Innovative Technologies

New Way of Nuclear Power



Safety

- Safety and Environment
- Innovative Technologies

→ Public accepted Safety

Economics

- Competitive Price
- Construction and Manufacturing Innovation

→ Cost reduction and Accelerating Deployment

Flexibility

- Demand-Leading
- Surviving and Harmonizing with Renewables

→ Resilience and flexibility of Load-following

SMR Introduction

SMR: Small-sized modularized nuclear reactor with power levels of 10 to 300 MWe

Special sub-section of SMRs called Micro Modular Reactors (MMRs) with power ratings less than 10 MWe (30 MWth)

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)
Up to 300 MWe per module

NUCLEAR ENERGY AGENCY (NEA)
Between 10 and 300 MWe

WORLD NUCLEAR ASSOCIATION (WNA)
300 MWe equivalent or less

NUCLEAR ENERGY INSTITUTE (NEI)
300 MWe or less

NUCLEAR REGULATORY COMMISSION (NRC)
300 MWe or less

DEPARTMENT OF ENERGY (DOE)
Less than or equal to 1,000 MWth per module

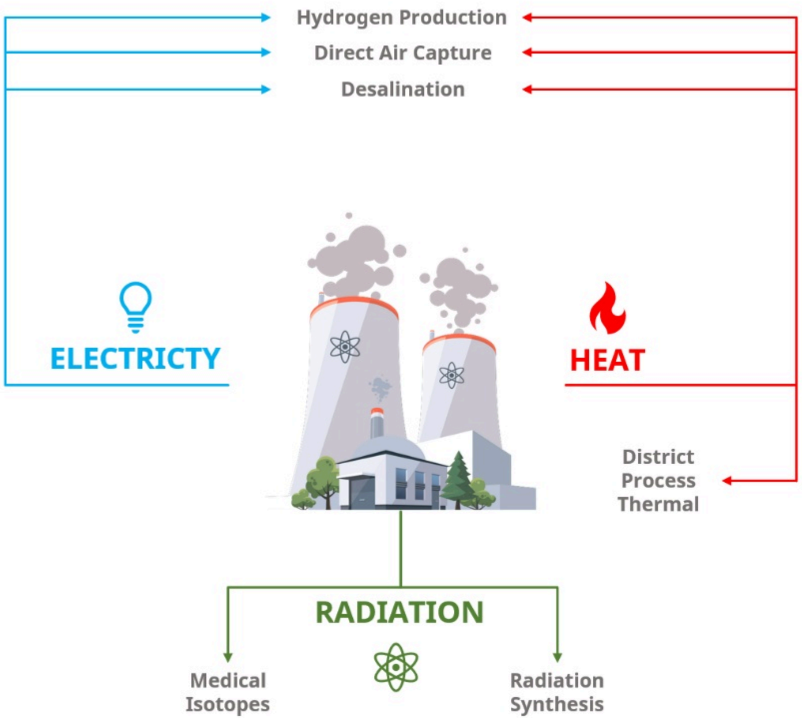
SMR Co-Generation

NUCLEAR CO-GENERATION

Most of the SMR and MMR designs target a specific niche application other than electricity generation where conventional nuclear power plants would be impractical

Integration of SMRs with other systems and applications is often called "nuclear cogeneration" which has certain economic and environmental advantages

As of October 2024, a total of 68 SMR designs have been identified by IAEA with various technology types and stages of designs

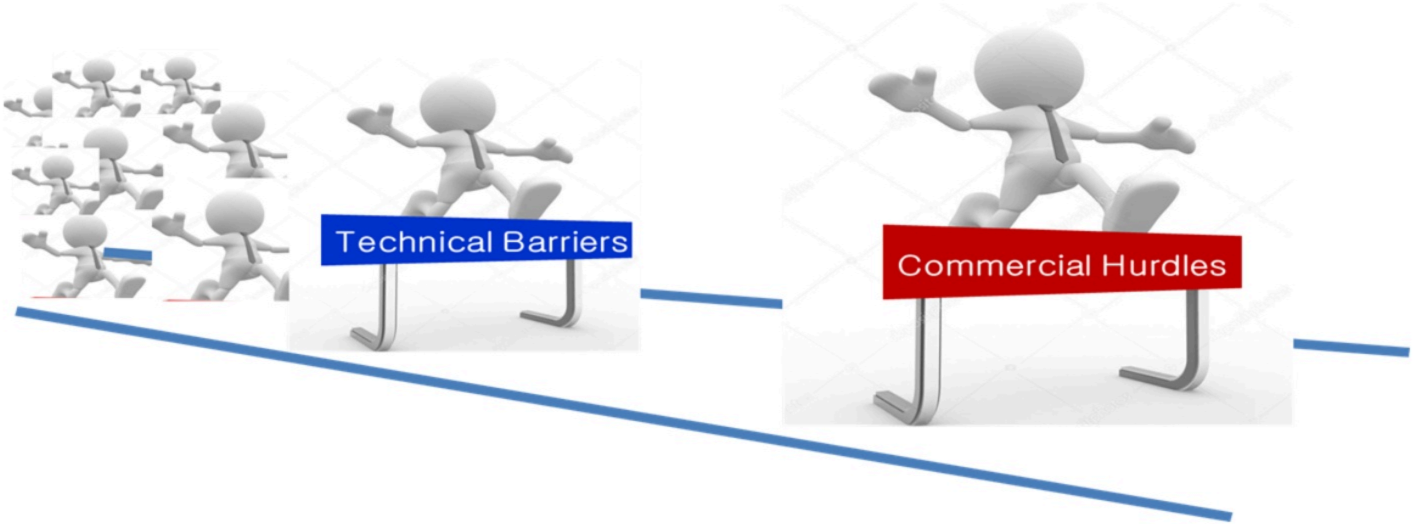


Attractiveness of SMR

- **Enhanced Safety & Security**
  - Inherent safety with additional new safety technologies
  - Small power & source term, Lower CDF
  - Enhanced threat protection
- **Competitive Economics**
  - Lower upfront capital costs
  - Economy of serial production
  - Modularization, Short construction time
- **Flexible Operations**
  - Load-following, Operation during LOOP
- **Smaller Footprint & EPZ**
  - Flexible in siting options & plant cooling options
- **Flexible Applications**
  - Remote regions, Small grids
  - Electric and Non-electric (Desalination, District heating, Hydrogen production)
  - Potential Hybrid Energy System with intermittent renewables

Challenges for SMR Deployment

- **Technical Barriers**
  - Technology Validation through Analysis, Test and Experiments
- **Commercial Hurdle**
  - Economic Justification Compared with Other Energy Sources



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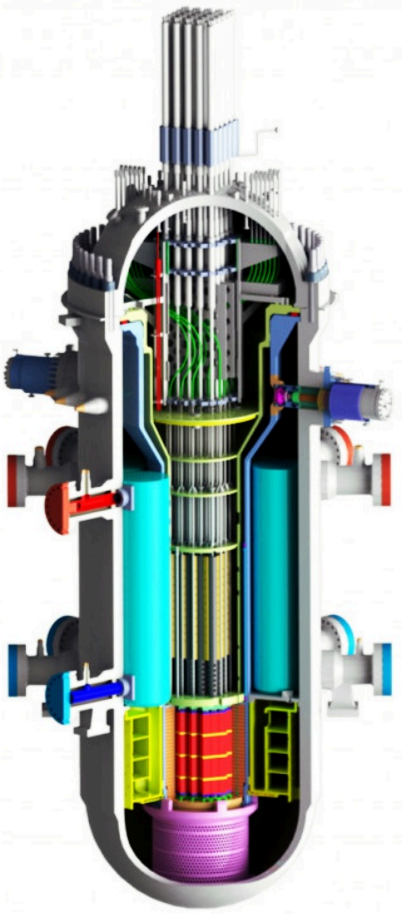
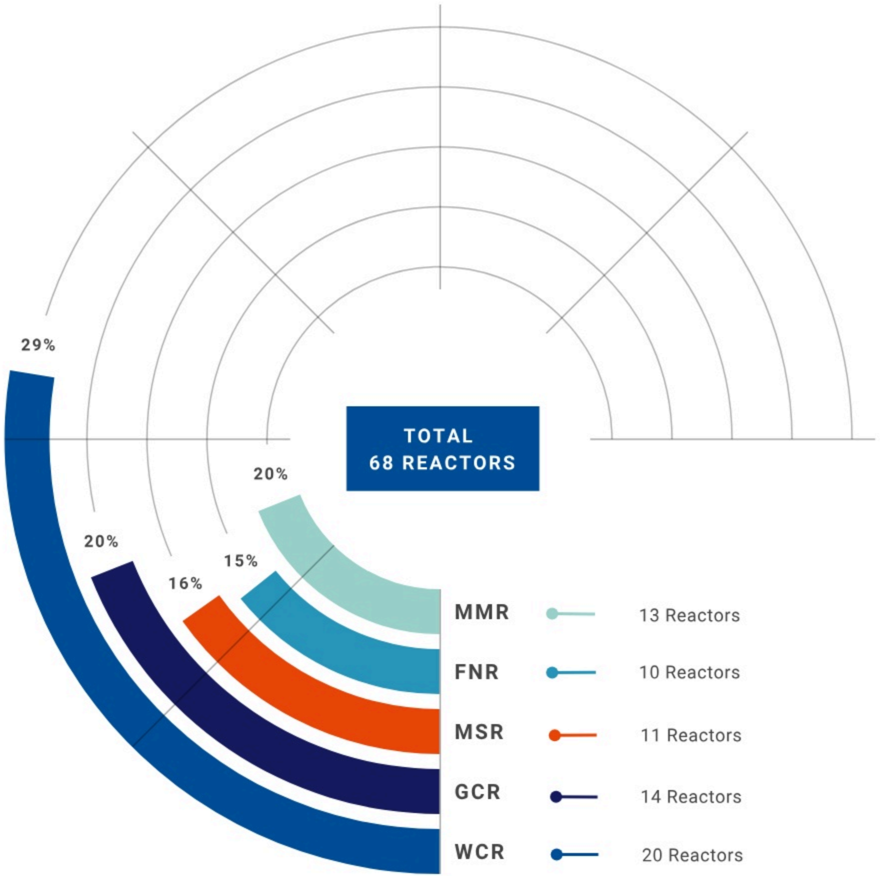
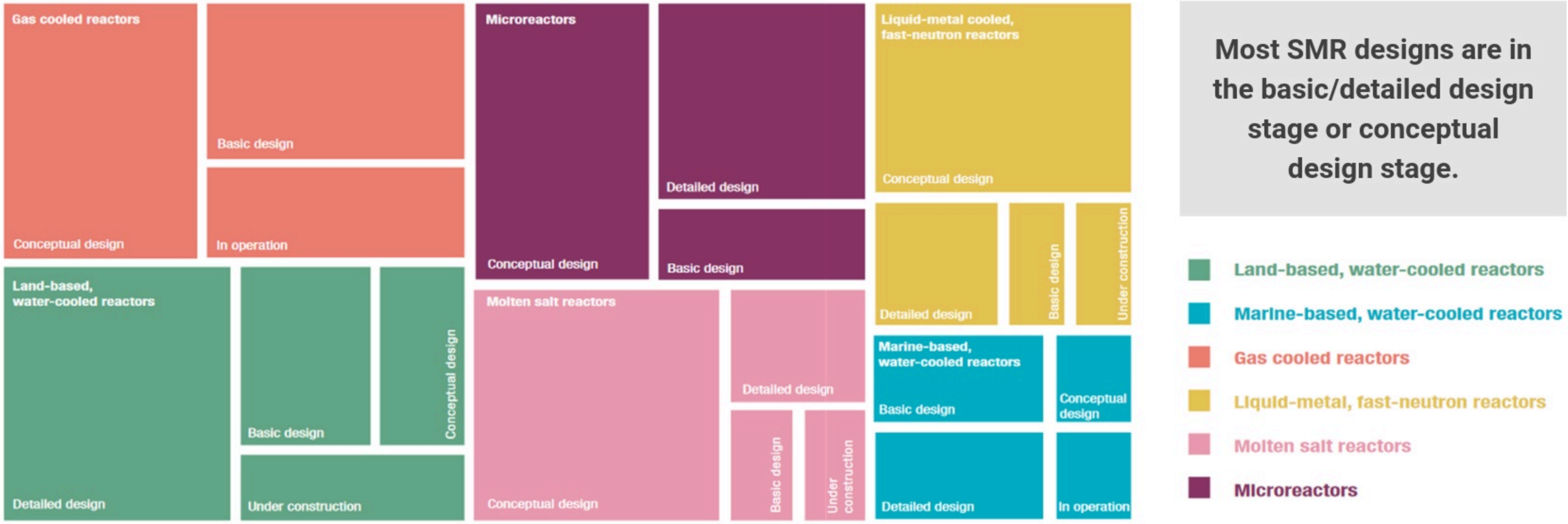




CLASSIFICATION

- **WATER COOLED REACTORS | WCR**
  - Light Water Cooled Reactors | LWR
  - Heavy Water Cooled Reactors | HWR
- **GAS COOLED REACTORS | GCR**
- **MOLTEN SALT REACTORS | MSR**
- **FAST NEUTRON REACTORS | FNR**
- **MICRO MODULAR REACTORS | MMR**

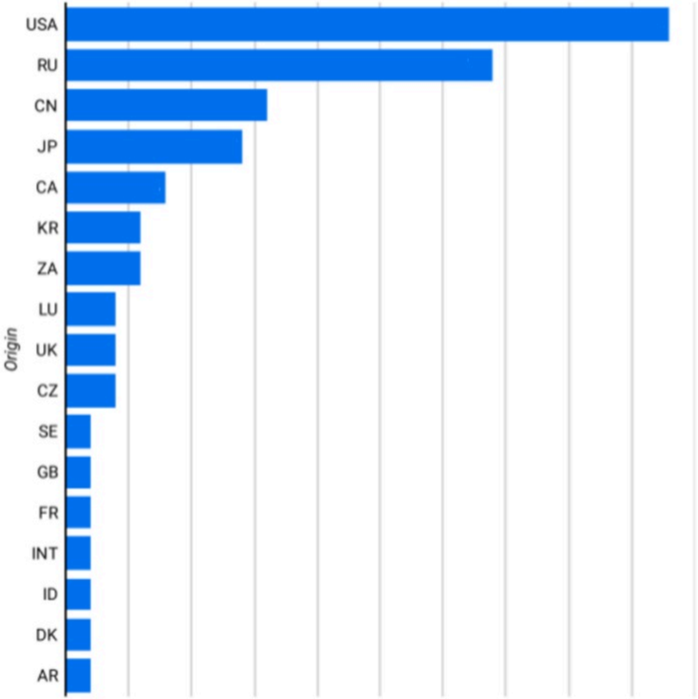
SMR & MMR | Development Status

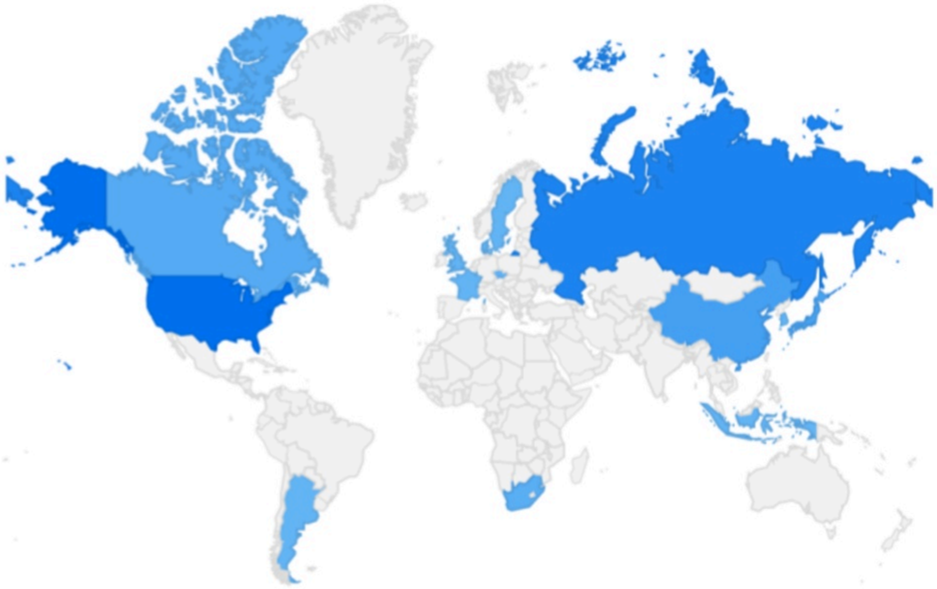


[IAEA, 2024]

Most SMR designs are in the basic/detailed design stage or conceptual design stage.

SMR & MMR | Country of Origin





SMR & MMR | Notable Mentions

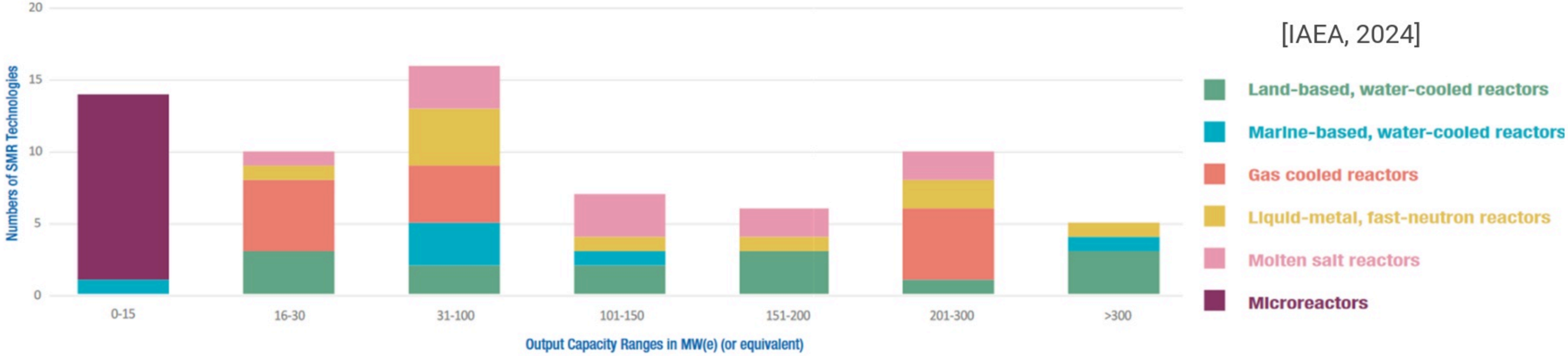
KLT-40S | AKADEMIK LOMONOSOV

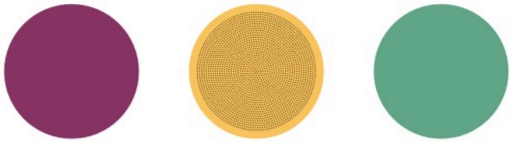
The very first floating SMR by Russian Federation based on WCR has been supplying supplying heat and power to the town of Pevek in the Chukotka region since May 2020 - 35 MWe/unit

HTR-PM | HIGH-TEMPERATURE GAS-COOLED REACTOR - PEBBLE-BED MODULE

The very first land-based industrial demonstration SMR by China was connected to the grid as of December 2021 and started commercial operation in December 2023 - 200 MWe/unit

SMR & MMR | Output, Fuel Cycle and Material



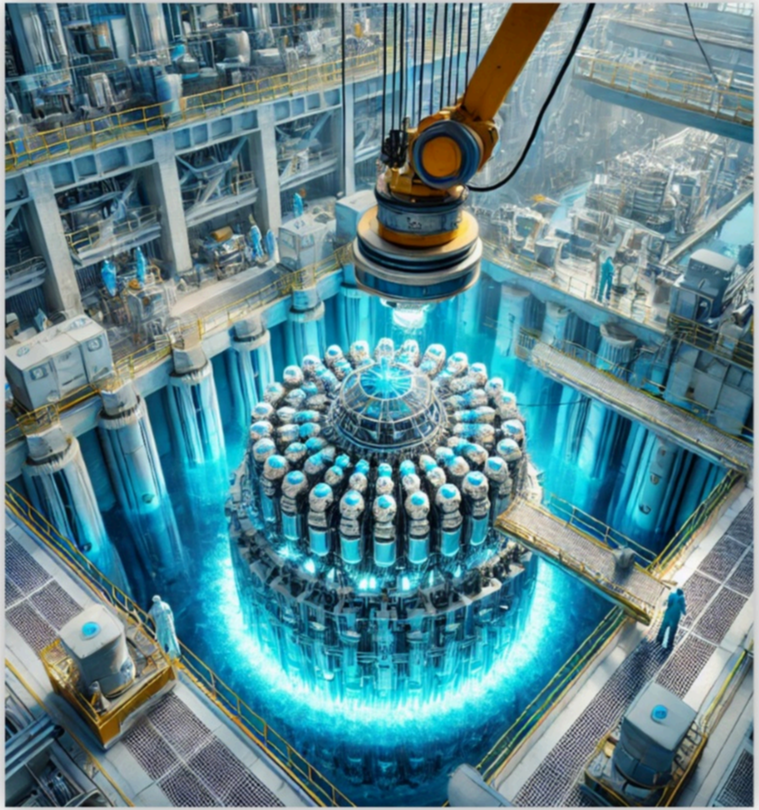


- **Early Life Cycle Planning**: Supports sustainable SMR operation, builds trust, and prevents future liabilities in waste and decommissioning.
- **Innovative Fuel Cycles**: Advanced SMR designs may use new fuel types (e.g., metallic, carbide) requiring new facilities and regulatory adjustments.
- **R&D Needs**: Essential to develop processing, reprocessing, and waste management technologies to support SMR fuel cycle advancements.

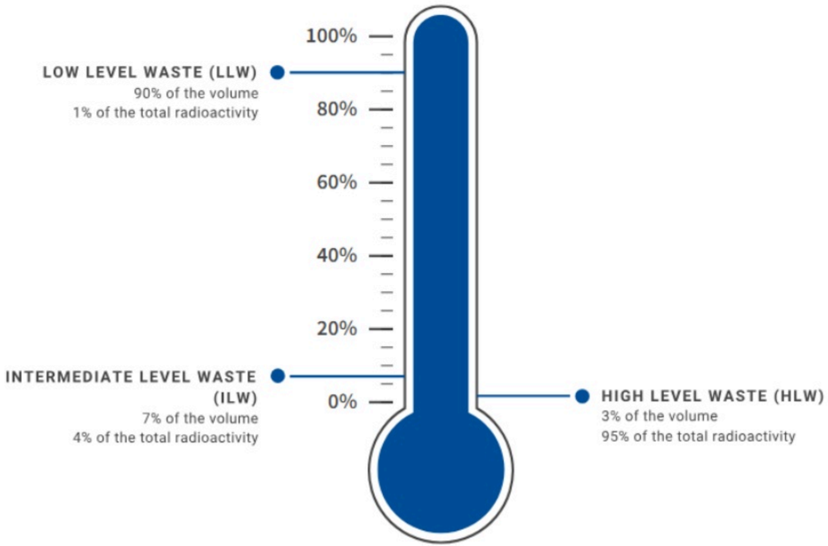
- **HALEU**: Many SMRs need high-assay low enriched uranium fuel, with 5-20% U-235, currently produced commercially only in Russia.:
- **Euratom**: The EU will need 700 kg to 1 ton of HALEU annually by 2035, driving interest in domestic HALEU production for fuel security.
- **Piketon**: The U.S. projects over 40 tons of HALEU by 2030, prompting DOE investments in domestic production to prevent deployment delays.

SMR & MMR | Refueling Cycles

- **Water Cooled Reactors (WCRs)**
  - *Land-based:* Use U-235 enrichment below 5%, with refueling cycles of 18–24 months for cost efficiency and high burnup.
  - *Marine-based:* Higher enrichment (close to 20%) enables refueling cycles of up to 120 months, suitable for remote locations.
- **Gas-Cooled Reactors (GCRs):** Use TRISO particle fuel, supporting high burnup and thermal efficiency, with some designs operating over 30 years without refueling.
- **Molten Salt Reactors (MSRs):** Operate with molten fuel, allowing for refueling cycles up to 150 months and online refueling, which minimizes cladding failure risks.
- **Fast Neutron Reactors (FNRs):** High enrichment levels (14-20%) support fuel cycles up to 30 years, with options for both open and closed fuel cycles.
- **Micro Modular Reactors (MMRs):** Designed for single-use operation without refueling; these reactors are dismantled and replaced after their lifespan



SMR & MMR | Waste Management



- **Water Cooled Reactors (WCRs):** Use advanced dry storage and dose reduction strategies for spent fuel. Waste management aligns with existing water-cooled reactor methods, with integral designs reducing steel embrittlement and waste volume.
- **Gas-Cooled Reactors (GCRs):** Produce less High-Level Waste (HLW) with lower plutonium content and use advanced packaging and waste separation. Disposal solutions for graphite waste are still needed.
- **Molten Salt Reactors (MSRs):** Actively remove and store gaseous fission products. Waste involves off-site reprocessing, with actinides recycled to reduce waste longevity before disposal in geological repositories.
- **Fast Neutron Reactors (FNRs):** Minimize radiotoxicity by burning long-lived plutonium and actinides. These designs support long-term storage for DGR disposal, focusing on waste reduction during decommissioning.
- **Micro Modular Reactors (MMRs):** Typically designed for minimal waste production and centralized waste handling, simplifying spent fuel and radioactive waste management post-operation.

MMR | Main Features

Microreactors are non-conventional plug-and-play type nuclear reactors that are small, compact and modular

FACTORY BUILT

TRANSPORTABLE

SELF REGULATING

MMR | Attributes

KEY CHARACTERISTICS

- Less than 10 MWe generation of electricity
- Smaller footprint with no carbon emission
- Factory fabrication and on-site installation
- Easy to ship and remove
- Self-reliance with inherent safety
- Easier semi-autonomous operation
- Quick deploy-ability during emergency
- Years of operation with no re-fueling
- Easy integration with other applications

POTENTIAL USE CASES

- Remote and rural communities, islands
- Remote mining sites
- Military installations
- Power plant back-up and emergency generations
- Disaster relief and humanitarian assistance missions, load shedding
- Space missions, marine propulsion

MMR | History

1960
The U.S. Army examined MNPPs with vSMR

1963
8 reactors were built for testing, training, and proof-of-concept purposes

2011
DoD concluded reactors <300 MWe have potential but many were larger than needed

2019
Microreactor designs have emerged <20MWth

2027
The first DoD reactor is projected to be online

US Air Force confirms site for first microreactor

"The US Air Force has confirmed the Eielson base in Alaska as the facility planned to host its first small nuclear power plant. A microreactor of up to 5 MWe could be operational there as soon as 2027, according to Eielson." - WNN, 26 October 2021

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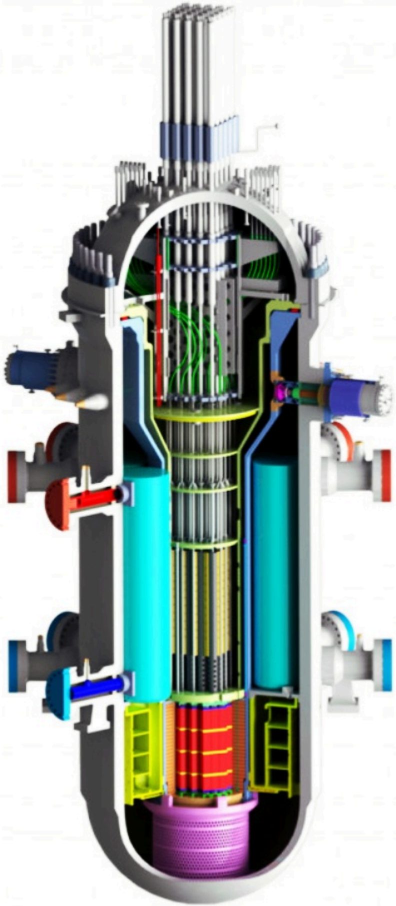


Key System Characteristics

IPWR

- Boron-free operation
- Internal CRDM/RCP
- Multi-unit I&C
- Passive safety systems

HTGR

- HTGR Technology
- Fuel
- Core Design
- Gas Turbine Cycle

MSR

- Molten salt technology
- Fuel
- Corrosion
- Chemical Processing

HPR

- Heat pipe system
- Fuel
- Reflector and shielding
- Power conversion

iPWR - 1/2

- Boron free operation

- **Eliminates the drawbacks of soluble boron**
  - Boron dilution
  - More positive moderator temperature reactivity
  - Corrosion
  - Large CVCS
  - Crud induced power shift
- **Disadvantages**
  - More control rods
  - Redundant and diverse reactivity control issue

- Internal CRDM

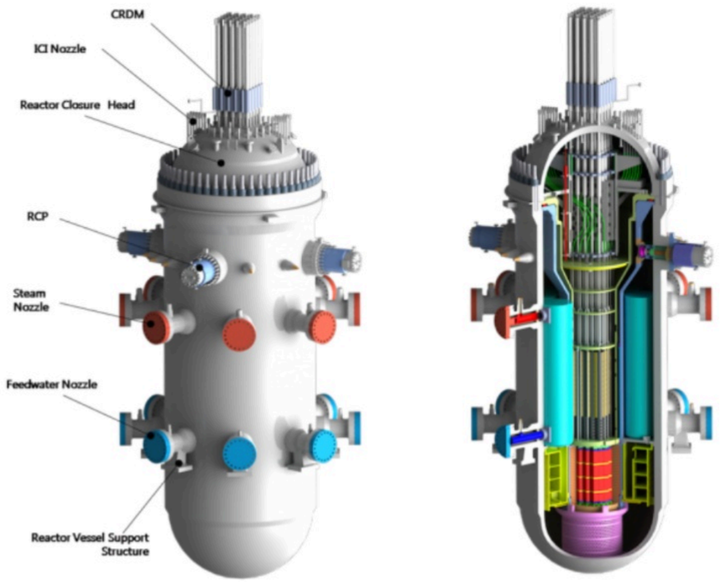
- **Internal CRDM appears to be preferable**
  - Adopted: mPower and Westinghouse SMR
  - Not Adopted: NuScale and SMART
- **Advantages**
  - Highly compact and simple
  - Eliminates RIA
  - Reduces LOCA possibility
- **Disadvantages**
  - High P/T condition of operation

- Internal RCP

- **Adoption**
  - NuScale: No RCP
  - Others: Internal RCPs
- **Free from External RCP**
  - Seal problem
  - Large space
  - Additional system
  - Additional cost
- **Disadvantages**
  - High clean state
  - Low efficiency
  - High cost
  - Lubrication problem

- Multi unit I&C

- **MCR is setup as a single control room**
- **For the design certificate of HSI a simulator was used**



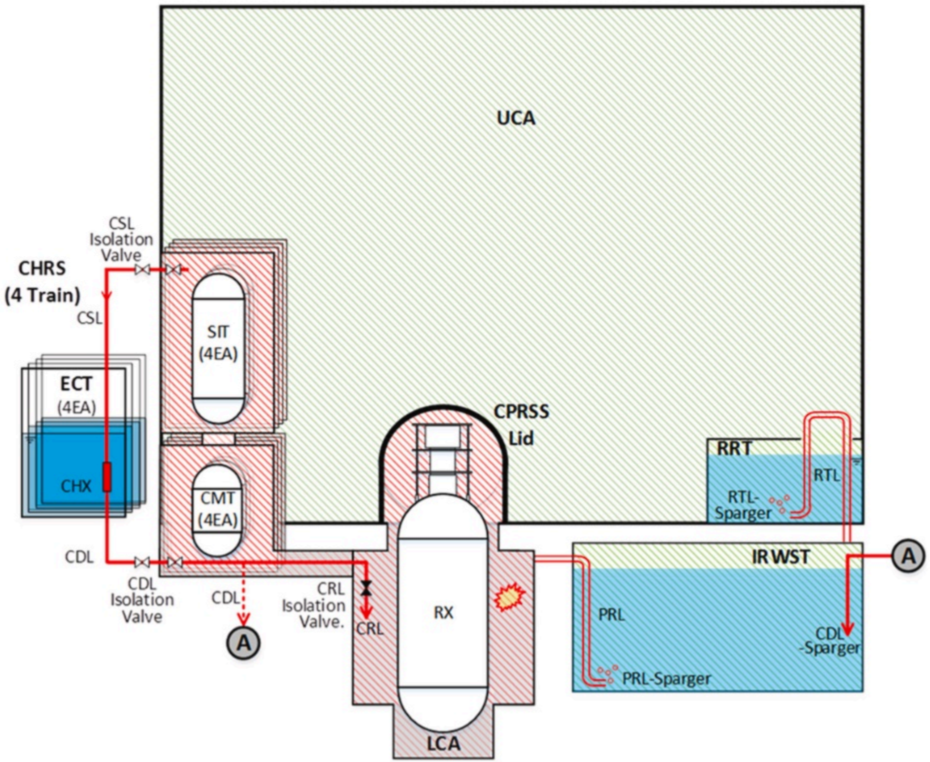
iPWR - 2/2

- Passive Safety System (PSS)

- **Passive heat removal**
  - Passive residual heat removal system
  - Passive emergency core cooling system
  - Passive containment cooling system
- **Important phenomena and their analysis**
- **Specifics in the development of PSS**
  - Activation reliability
  - Dependency on external energy source
  - Environmental conditions to lead functional loss
  - Uncertainty and margin

- Refueling and Waste Management

- **Refueling Issues**
  - Vastly taller reactor and not yet proven technology
- **Not yet proven technology**
  - 'Wait-and-see' policy is deemed appropriate with the large onsite storage strategy as Independent Spent Fuel Storage Installation (ISFSI)



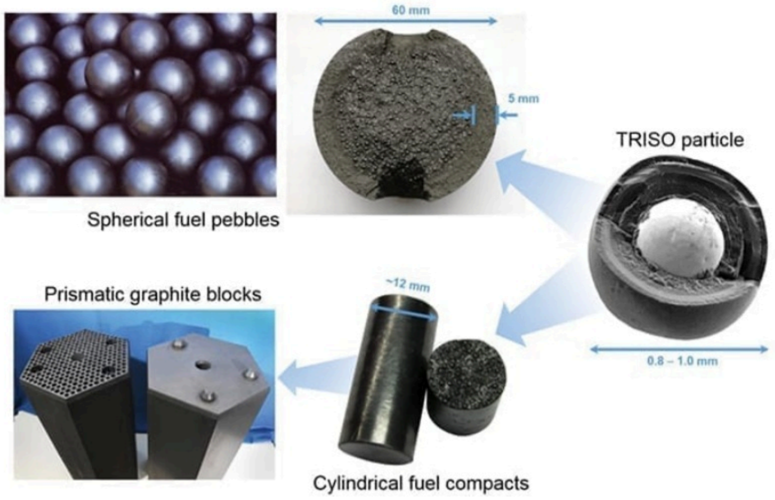
HTGR - 1/2

- TRi-structural ISOtropic [TRISO] Particle Fuel

- **High durable and corrosion-resistant barrier**
  - No additional barriers are required to maintain radioactive substances
  - The particle has its own "containment building" due to triple coated layers which retains the fission products under all operating conditions
- **Low energy density**
  - Sufficient passive air cooling
- **High burn-up**
  - Efficient use of uranium and plutonium
- **Isotopes of spent combustion fuel**
  - Small risk of diffusion
- **Originally developed to be used in HTGRs in the 1950s**
- **DoE's conventional particles have fuel kernel composed of UO2 and UCO**

- Reactor Core Design

- **Pebble bed**
  - Advantage: It can work without interruption for fuel reloads and have a simple structure
  - Disadvantage: Graphite dust can form when the ball moves
- **Prismatic design**
  - Advantage: Immobile fuel operation parameters are more predictable
  - Disadvantage: Reactor must be shut down to replace the fuel



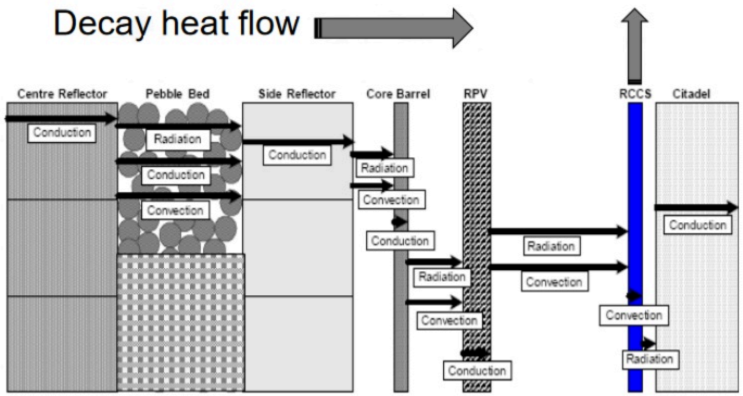
- Project PELE by DoD (March, 2020 kick-off)

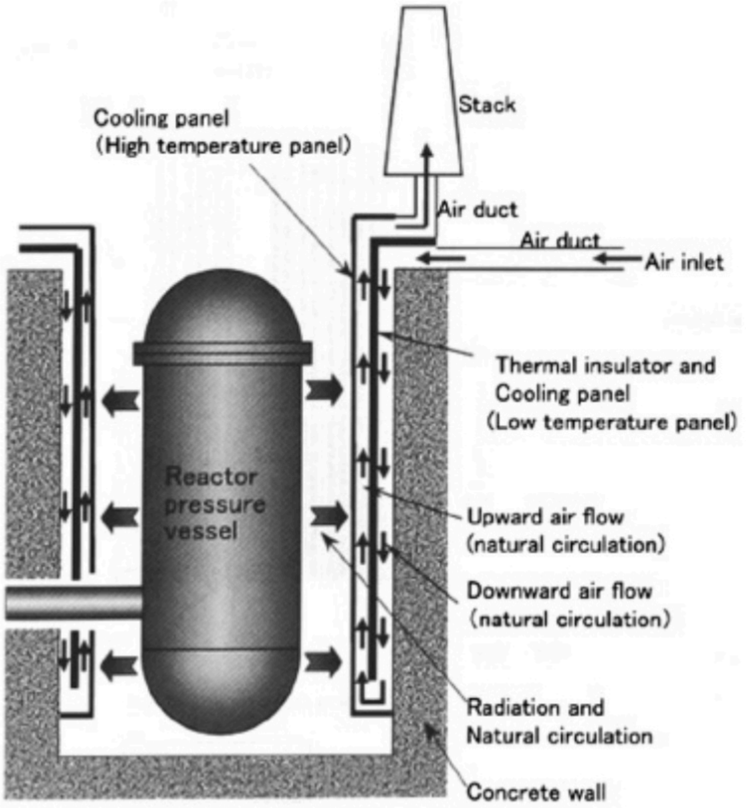
- Two-years competition to design TRISO
- 1-5 MWe, 3+ years lifetime, HALEU fuel, inherently safe
- <40 tons, transportable in a C-17 and by truck
- Assembled in <3 days, dissembled/transportable in <7 days
- $63 million (2020) and $70 million (2021)
- BWXT Advanced Technologies LLC | $13.5 million
- X-energy LLC | $14.5 million ($2.5 billion for XE-100)
- BWXT's design for the microreactor, though in September 2023 X-Energy 1 year

HTGR - 2/2

- Reactor Cavity Cooling System (RCCS)

- Natural convective circulation of air or water during accident conditions
- Redundant and multiple flow paths
- Intake/exhaust structure to mitigate external effects
- Always passive
- Air cooling panels and ducting allow transmission of heat from uninsulated reactor vessel to the atmosphere
- The core gradually heats up and the heat is removed by conduction, radiation, and convection radially to the RV to the RCCS

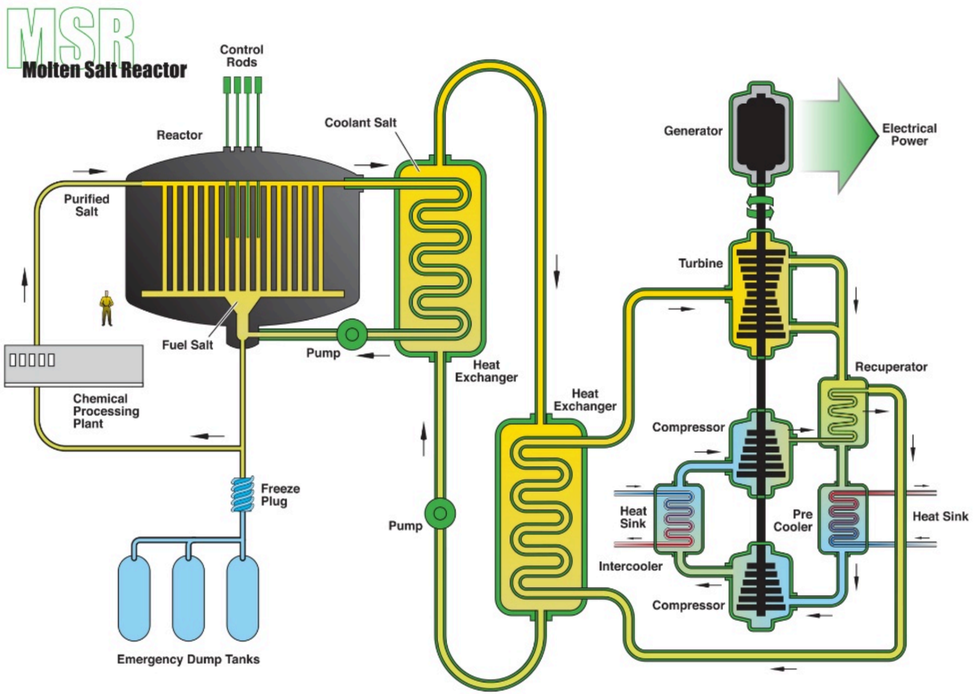




MSR - 1/2

- Distinguished Features

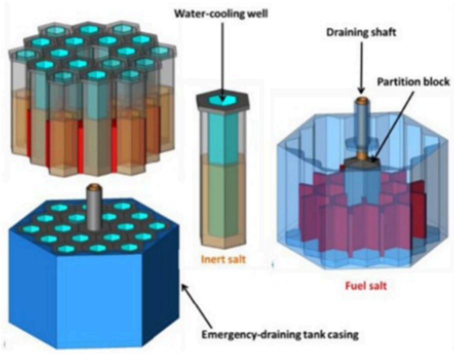
- The conversion ratio of MSRs can be flexibly adjusted by changing the fissile-to-fertile material ratio in the fuel salt
- MSRs eliminate the fuel element fabrication and transport
- Excess reactivity can be minimized by adjusting the fuel salt composition
- Large negative temperature and void reactivity coefficients of the fuel salt ensure the passive safety of MSRs
- High temperature and large power density can be reached without high internal pressures, and thus MSR can be operated under the near atmospheric pressure
- Deep burnup can be achieved in MSRs by removing the fission products from the salt to reduce the parasitic neutron capture and feeding the fissile and fertile materials in either continuous or batch wise operation
- Because of its liquid fuel, no loading pattern strategy is required

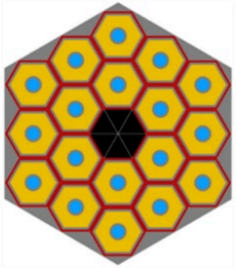


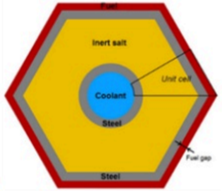
MSR - 2/2

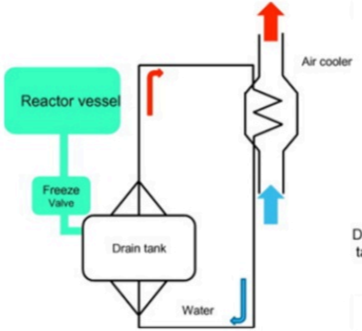
- Emergency Drain Tanks

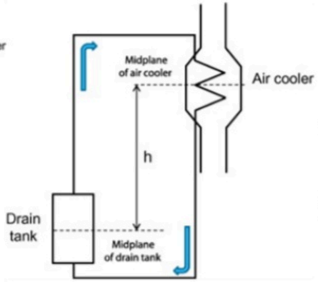
- The passive core drain system is generally considered for improving the safety of MSRs
- Act as a safety feature to handle overheating or emergency shutdowns
- Positioned below the reactor core to allow molten salt to drain by gravity
- A plug kept solid by active cooling; melts in case of power loss, enabling salt drainage
- Operates without external power, relying on gravity and natural convection for cooling
- Drained salt spreads out, reducing heat concentration and lowering meltdown risk
- Salt drains into a subcritical, shielded tank, preventing fission reactions and containing radioactivity
- Emergency tank includes passive cooling features to dissipate residual heat safely over time

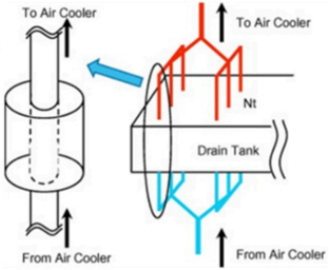








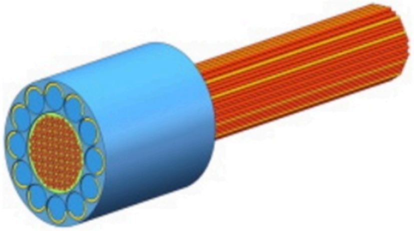




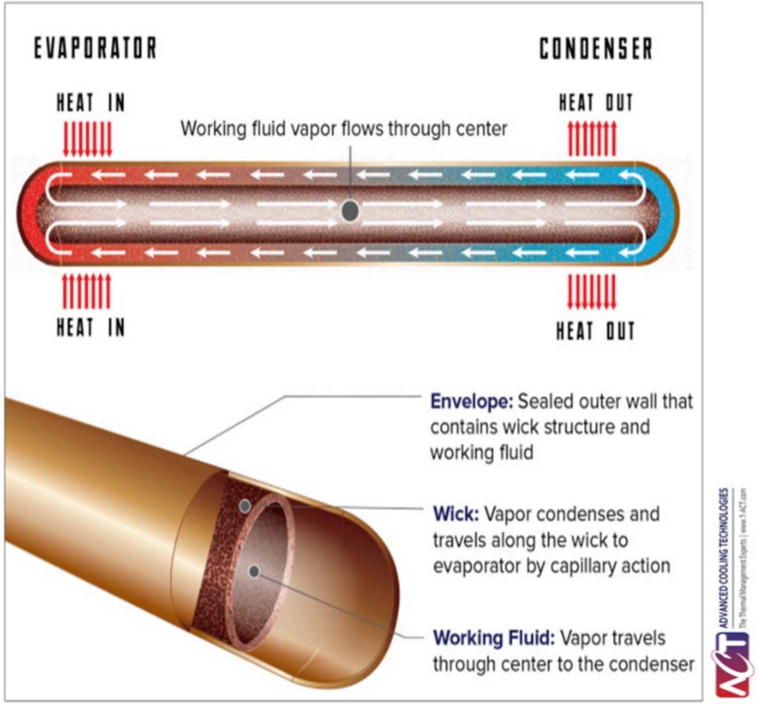
MMR- 1/2

Passive Two-Phase Heat Exchanger

- Invented at LANL in 1963 and analogous to natural circulation loop
- Large heat transfer capability with small temperature difference
- Excellent effective thermal conductivity
- Application Areas
  - Electronics
  - Space
  - Ovens and HVAC
  - Solar, geothermal power
  - **Nuclear microreactors**
    - (KiloPower Program, MegaPower Reactor, SPR)



Yan et. al., 2020



MMR 2-2

- Heat Pipe System

- High performance
- Significant operational limits
- Large thermal gradient
- Startup procedure
- Long term irradiation

- Fuel

- Relatively high enriched fuel preferred
- Monolith Structure
  - Thermal stress issue
  - Size and strength of the monolith and transportation
  - DiD relevant to elimination of direct pathway of radioactive material to environment

- Reflector and Shielding

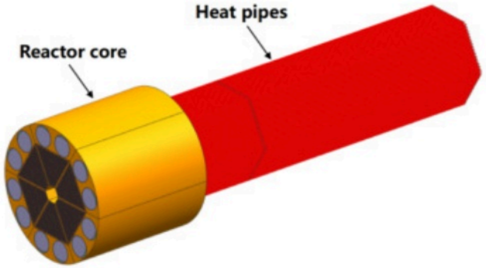
- Sensitive reactivity to geometry and materials
- Highly radioactive core

- Power Conversion

- Brayton cycles are widely selected: No need for water supply
- PCHEs are considered for the microreactor application among the compact heat exchanger

- Refueling and Waste Management

- Will be done in factory by transport
- Fuel together with the monolithic structure are replaced together
- 3~10 year refueling cycle



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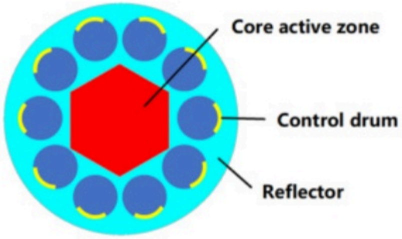
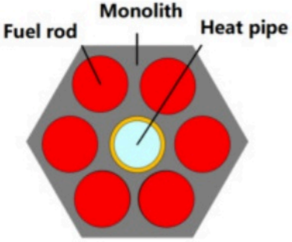


(B)



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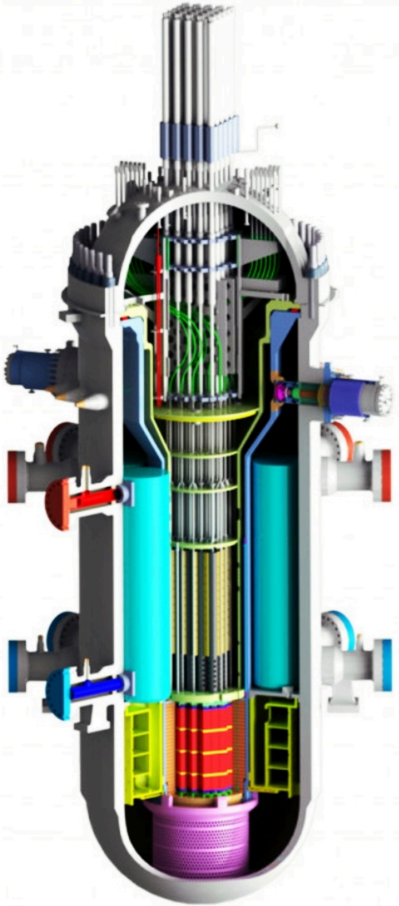
AGENDA



LCOE Calculation

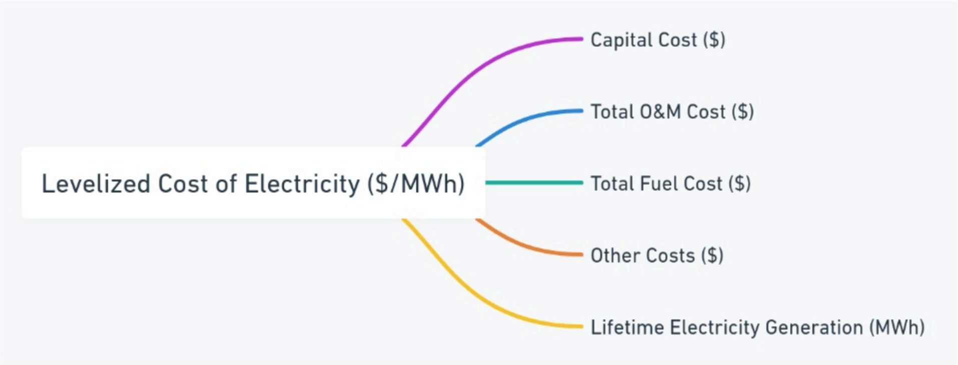
- TOTAL CAPITAL COST | CAPEX
- OPERATING AND MAINTENANCE COSTS | O&M
- FUEL COSTS

$$\text{LCOE} = \frac{\sum_t \frac{(I_t + O\&M_t + \text{Fuel}_t)}{(1+r)^t}}{\sum_t \frac{E_t}{(1+r)^t}}$$

where; I_t : Capital Investment Cost in year t
$O\&M_t$: Operations and Maintenance cost in year t
$Fuel_t$: Fuel Cost in year t
E_t : Amount of electricity produced in year t
r : Annual discount rate

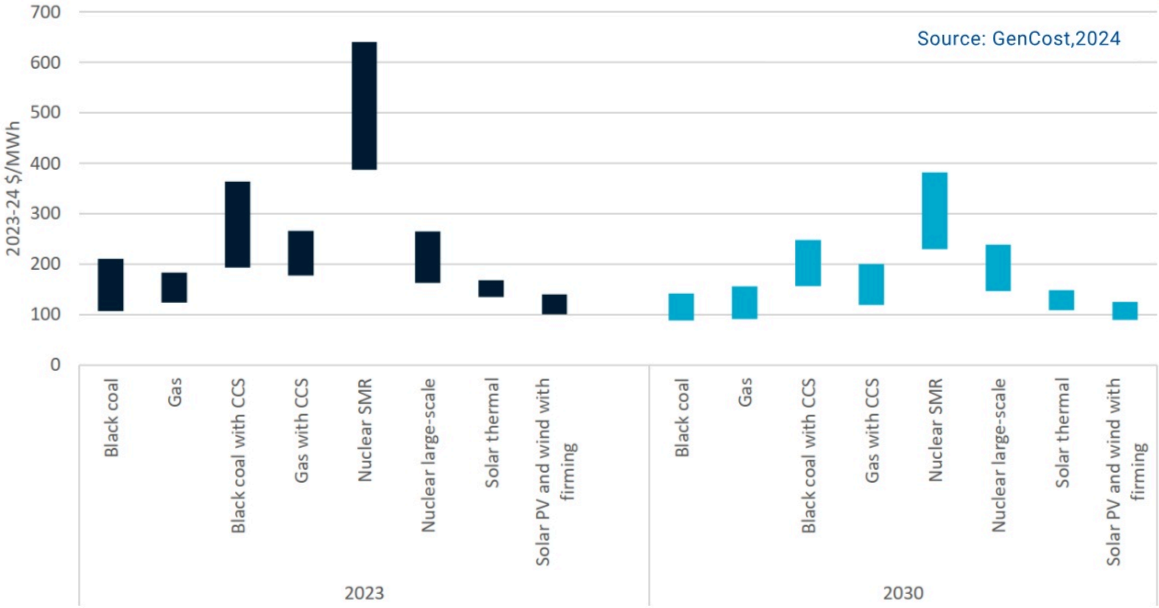
	Labour, Goods and Materials	Weight
1.	Equipment	48%
2.	Labour onsite	25%
3.	Construction materials	12%
4.	Project management services	10%
5.	First fuel load	3%
6.	Other services	2%

	Activity	Weight
1.	Construction and installation works	61%
2.	Site development and civil works	20%
3.	Project engineering, procurement and construction management	7%
4.	Commissioning and first fuel loading	5%
5.	Design, architecture, engineering and licensing	5%
6.	Transportation	2%



Economic Competitiveness

Calculated LCOE by technology and category for 2023 and 2030 in AUD [1 AUD ~ 0.65USD]



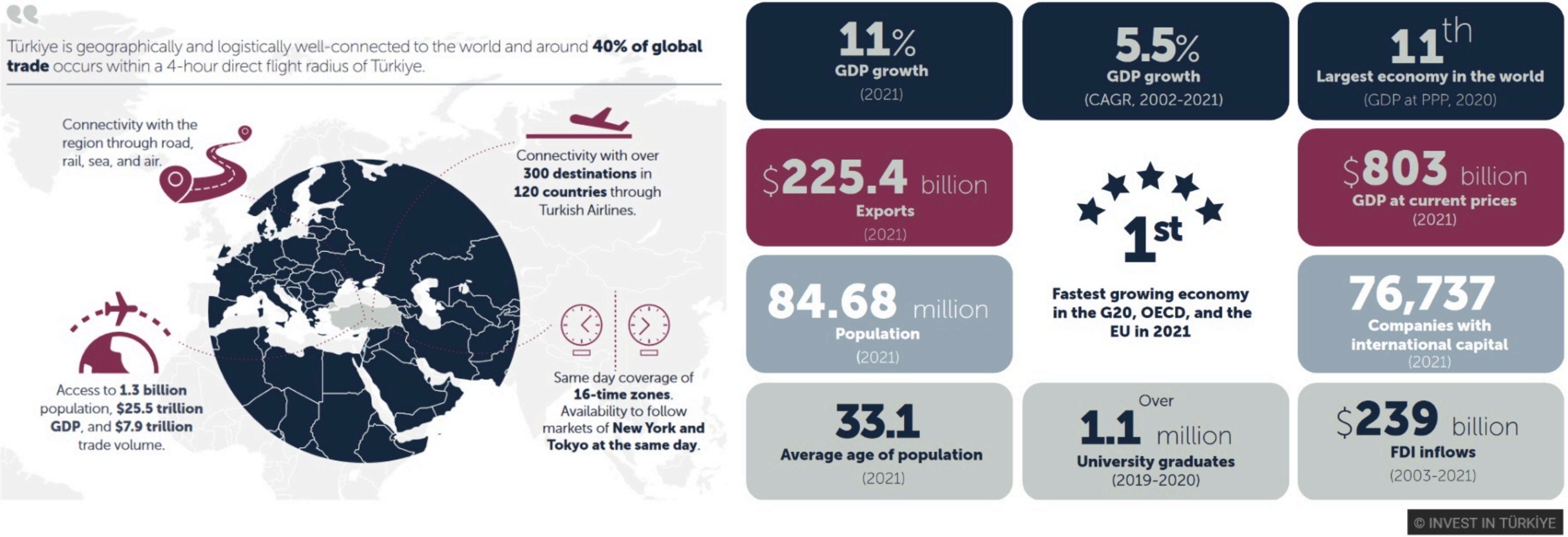
Learning Curve

Unit prices are projected to decrease if SMRs are deployed in series, a process known as economies of scale or learning-by-doing.

LCOE defines the "break-even" cost at a specified rate of return in which the LCOE with the lowest value is identified as the most beneficial option

Turkiye at a Glance

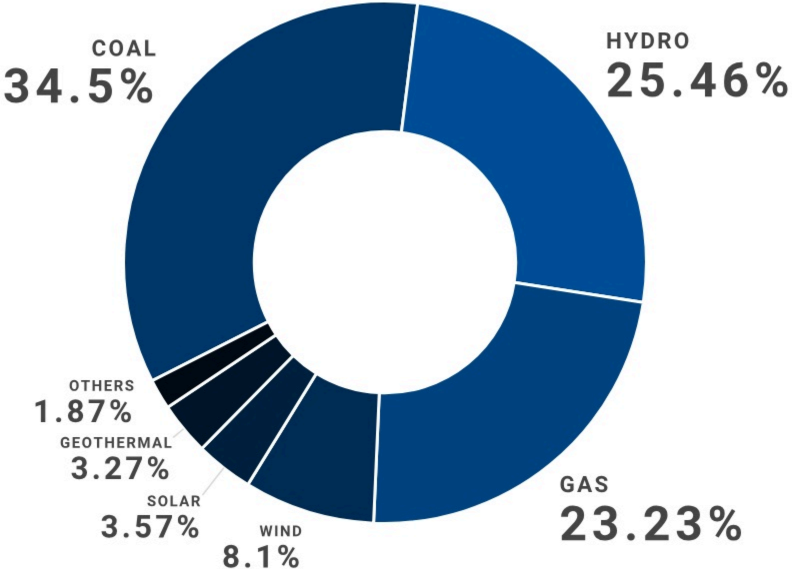
- Turkey's economic and population growth has increased demand for energy and natural resources
- Since 2002, it has experienced the fastest growth in the OECD, with an annual growth rate of 5.5 percent



Turkiye Energy Outlook

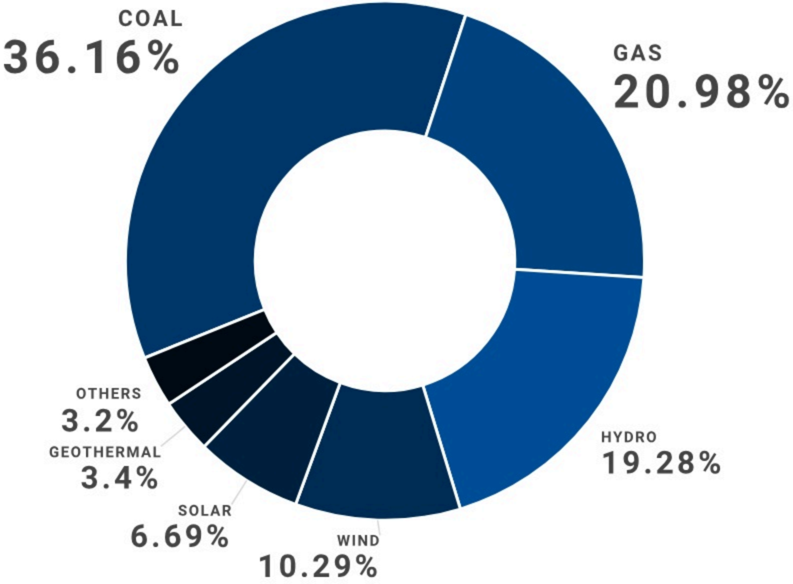
The total installed capacity increased from 31.8 GW to 95.9 GW in 18 years (2002 ~ 2020)

- By 2023, the capacity was expected to reach 125 GW



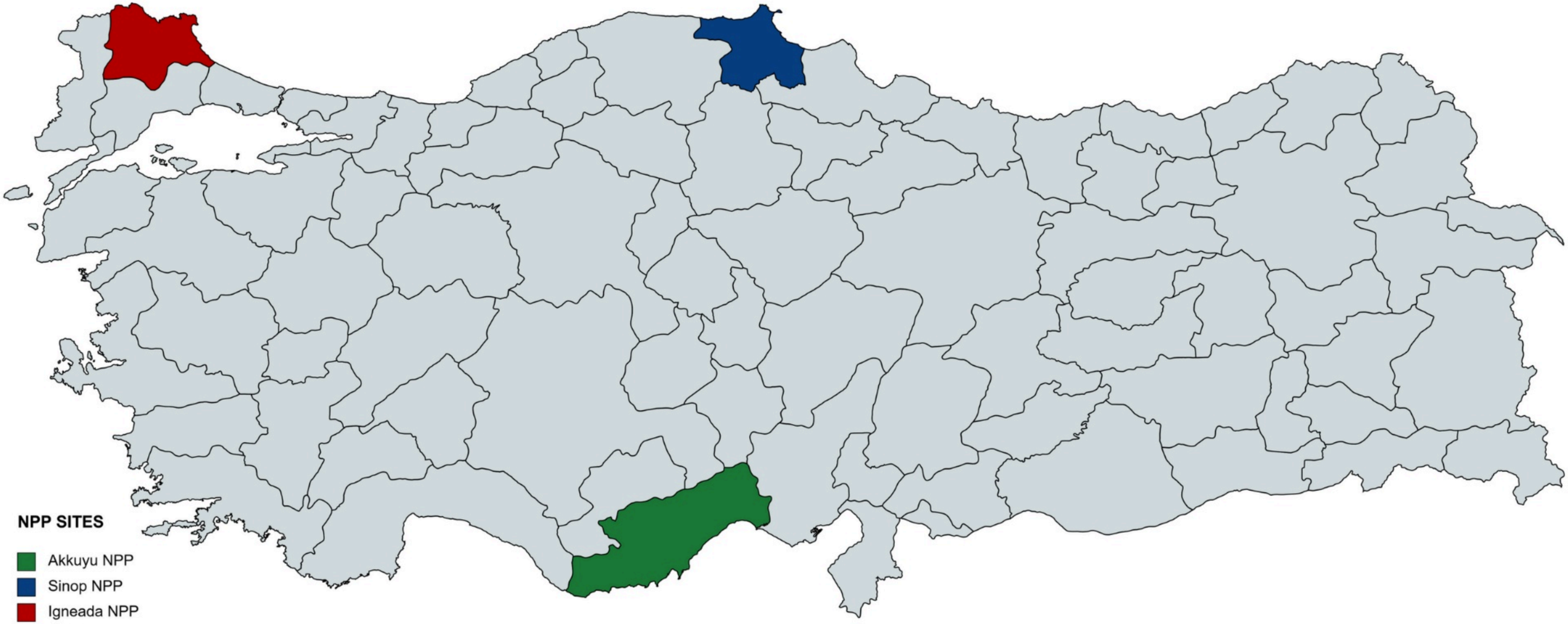
2021

- By 2024, the capacity is 114 GW



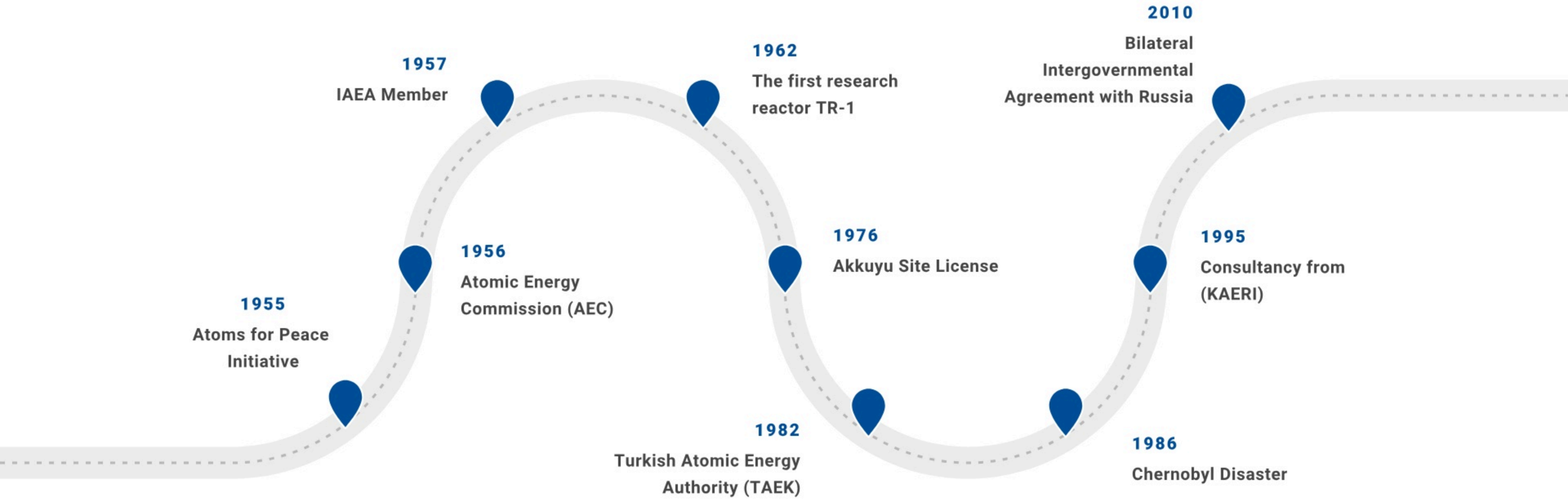
2023

Turkiye Baseload NPP Sites



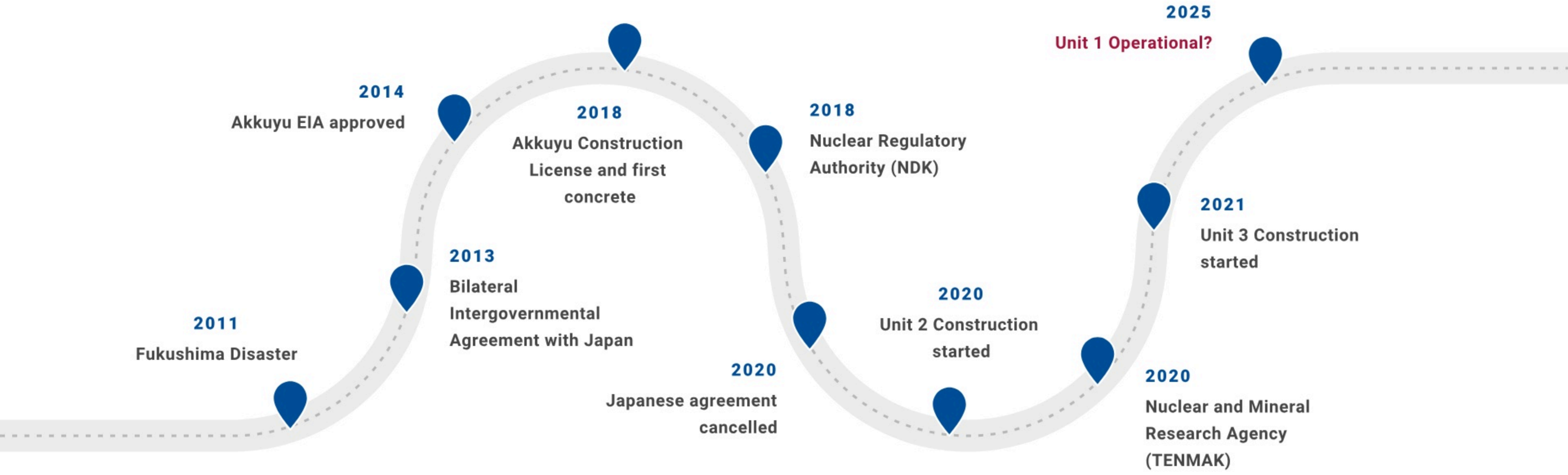
Turkiye Nuclear History 1/2

Since the 1960s, there have been six major attempts to build a nuclear power plant, each lasting roughly a decade



Turkiye Nuclear History 2/2

Since the 1960s, there have been six major attempts to build a nuclear power plant, each lasting roughly a decade



Turkiye Regulatory Framework

FIRST	Turkish Regulations
SECOND	IAEA Safety Standards (Fundamentals and Requirements)
THIRD	Regulations of Designer Country
LAST	Regulations of the Other Countries (Suitable for the Design)

Turkiye | Licensing Process

SITE LICENSE → CONSTRUCTION LICENSE → OPERATING LICENSE

Licensing Basis

- DETERMINATION OF LICENSING BASIS AT THE BEGINNING OF LICENSING PROCESS
- UTILIZATION OF IAEA REQUIREMENTS AND VENDOR COUNTRY REGULATIONS IN LICENSING

Reference Plant

- PROPOSAL OF A SIMILAR DESIGN AS REFERENCE PLANT
- SUBMISSION OF RELEVANT SAFETY ANALYSES AND EVALUATION REPORTS TO FACILITATE THE ASSESSMENT OF NDK

Turkiye SMR Activities

ASO NUKSAK - Umbrella Organization

- Within the Clustering Support Program of the Ministry of Industry and Technology of Turkey, ASO NUKSAK was established in 2016
- Main activities are complex analyses, nuclear quality management, and certification systems, consultancies, research technology training specific to the nuclear sector, R&D studies for stainless steel and infrastructure activities for the technical support organization
- ASO NUKSAK's network is comprised of various chambers, universities, and about 75 companies in Turkey
- **ASO NUKSAK is planning to build an R&D Center for MSR activities**

Turkiye SMR Activities

Türkiye Nükleer Enerji A.Ş. (TÜNAŞ)

Prospective Utility

TÜNAŞ
TÜRKİYE NÜKLEER ENERJİ AŞ

- Türkiye Nuclear Energy Company (TÜNAŞ), a subsidiary of EÜAŞ, a state-owned enterprise (SOE) under the Ministry of Energy and Natural Resources
- It was established in 2022 by transferring the assets of the company EUAS International ICC, which was originally founded abroad in 2015.
- The main target of TÜNAŞ is to realize nuclear power plant new build projects in international partnerships, developing a domestic nuclear supply chain and a local human capital in the quality and quantity capable of meeting the needs of the projects
- While TÜNAŞ is solely responsible for the planning phase of new nuclear power plants, it will share the responsibility during the development, construction and operation phases with its international partners
- **Rolls-Royce and TÜNAŞ have signed an MoU to carry out a study to evaluate both the technical, economical and legal applicability; and also, the possibility of joint production of compact nuclear power stations (SMR) to underpin clean economic growth**

Turkiye SMR Activities

ThorAtom - Nuclear Technology Developer and TSO (Private Company)

ThorAtom
energy forever

- Pioneering engineering company of Turkiye, initiated by FIGES AS
- **Developing a domestic Molten Salt Reactor design**, performing technical support services in the field of nuclear technology, and separating Rare Earth Elements, focusing on producing radiopharmaceutical medication
- ThorAtom is taking the necessary steps to be authorized as a Technical Support Organization (TSO) to support the nuclear safety and licensing works of the regulatory body in Turkiye
- Collaboration has been initiated with the Germany Reactor Safety authority

Concluding Remarks - Challenges

TECHNICAL BARRIERS

- Licensing and regulatory adaptation for new SMR technologies
- Fuel supply challenges, especially with high-assay low enriched uranium (HALEU)
- Development of robust, scalable supply chains for SMR-specific components
- Validation of advanced safety features through testing and simulation
- Long-term waste management solutions for novel fuel types
- Integration with grid systems, especially in flexible or off-grid applications

COMMERCIAL HURDLES

- High LCOE for SMR development, licensing, and manufacturing
- Limited initial market and uncertain demand for SMR technology
- Difficulty attracting investment due to long payback periods
- Establishing viable business models for small-scale reactors
- Competition with other low-carbon energy sources, such as renewables
- Ensuring consistent and competitive pricing for end consumers

Concluding Remarks - Use Cases for Turkiye

RELIABLE ENERGY FOR ANATOLIAN REGION AND KKTC

- Turkey's eastern and southeastern regions face challenges with consistent energy access due to rugged terrain and limited infrastructure. SMRs can provide stable, off-grid power, reducing dependence on long transmission lines and supporting regional development.

DESALINATION FOR COASTAL AND WATER-SCARCE REGIONS

- With Turkey facing increasing water scarcity, especially in regions like the Aegean and Mediterranean, SMRs could be used for desalination. This would support both agricultural and urban water needs, ensuring water security in the face of climate challenges.

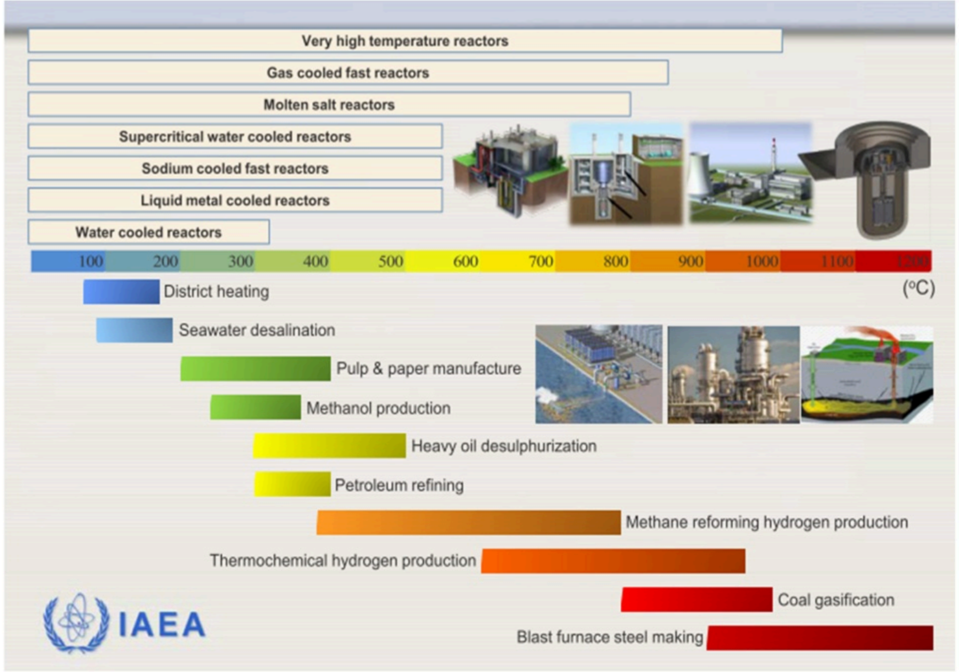
SUPPORTING INDUSTRIAL ZONES IN MARMARA AND AEGEAN

- SMRs could serve as a dedicated power source for Istanbul, Izmir, and Bursa, providing reliable electricity and process heat for manufacturing, chemicals, and petrochemical industries, particularly where large natural gas usage is common.

REPLACEMENT OF AGING COAL PLANTS

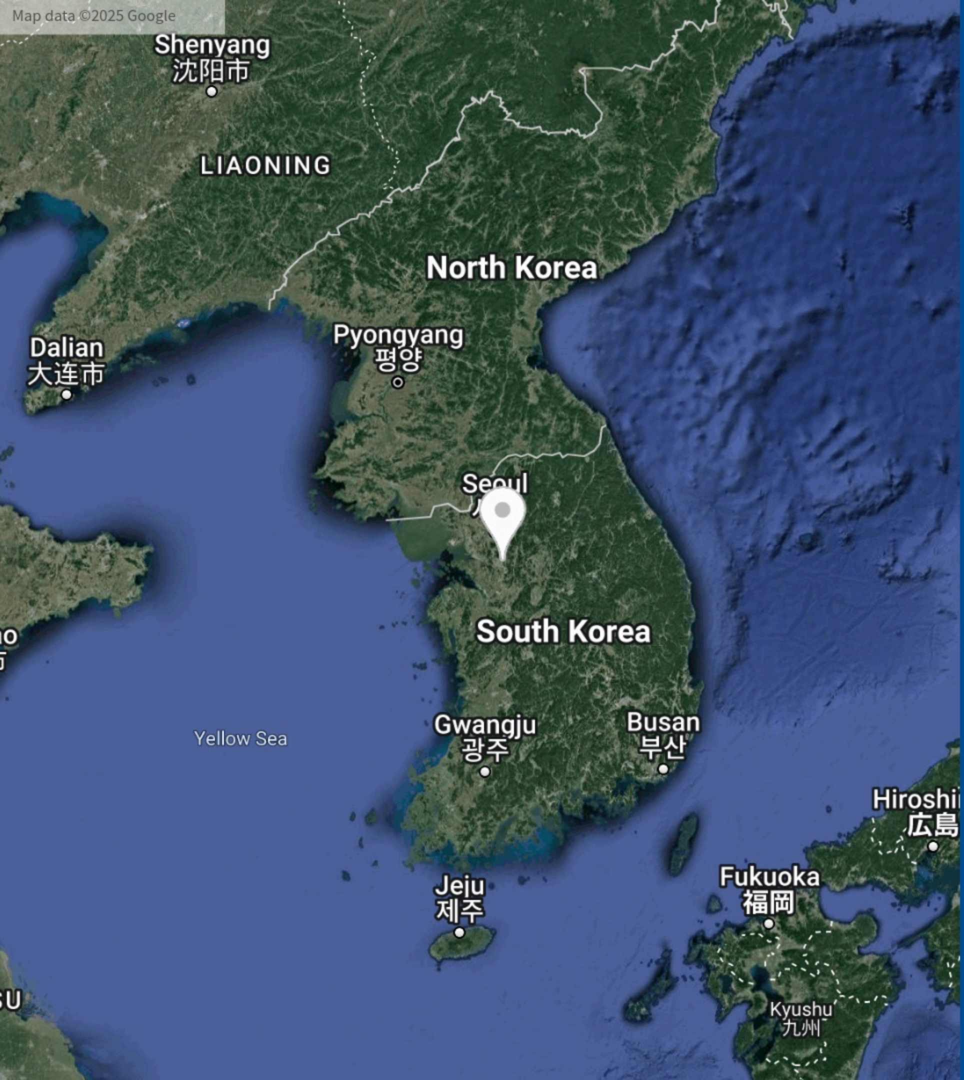
- Turkey's aging coal plants, particularly Afşin-Elbistan,Yatağan, and Kemerköy are due for replacement. SMRs offer a low-carbon alternative, supporting Turkey's goals to reduce emissions while maintaining energy independence.

Concluding Remarks - Application Areas



Exit Temperatures of SMRs for Non-Electrical Applications

- Decarbonization for fulfilling EU's expectation (replacement of fossil fuel)
- Providing stability/flexibility in electricity generations even in urban areas
- Utilization of energy source in;
  - Isolated villages and industrial sites
  - Military operation
- Infrastructure Requirements



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TEŞEKKÜRLER!!
THANK YOU!
감사합니다!