소형모듈원자로 기술조사보고회

부제: SMR 개발 및 사업화의 길을 묻다

수냉각형 소형모듈원자로 기술개발 및 사업 현황

강 한 옥
SMART개발단
2023년10월25일(수)

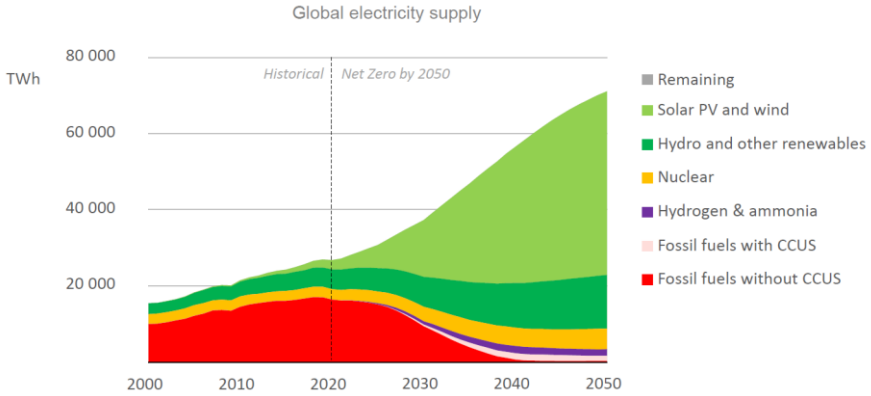
KAERI Korea Atomic Energy Research Institute

1-1 On Carbon Neutrality

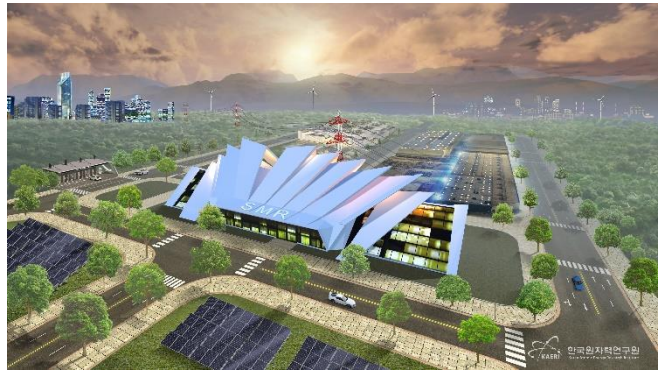
Korea Atomic Energy Research Institute

(Electrification) Energy transition to renewable electricity for achieving carbon neutrality

- The share of nuclear energy rises along with the growth of renewable energy.



Brent Wanner, Korea Atomic Power Annual Conference, 27 April, 2022

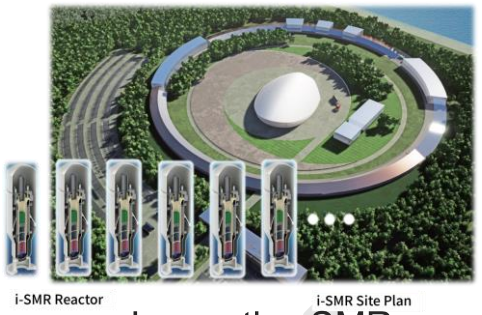


< SMR Net Zero City >

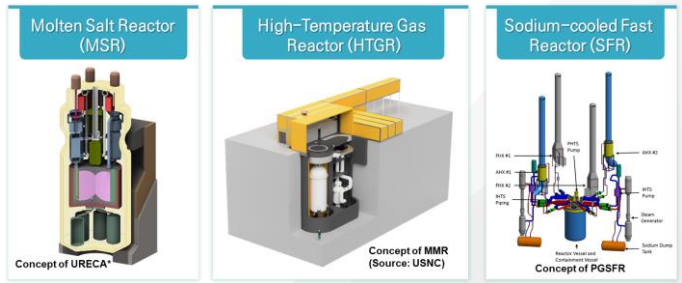
(SMR) Roles of SMR in Net Zero Emissions

- Replacement of coal plants to supply on-grid power
- Replacement of fossil fuels in heavy industry, off-grid mining and district heating
- Hydrogen production, desalination and merchant shipping

< SMART for Heat Supply >



< Innovative SMR >

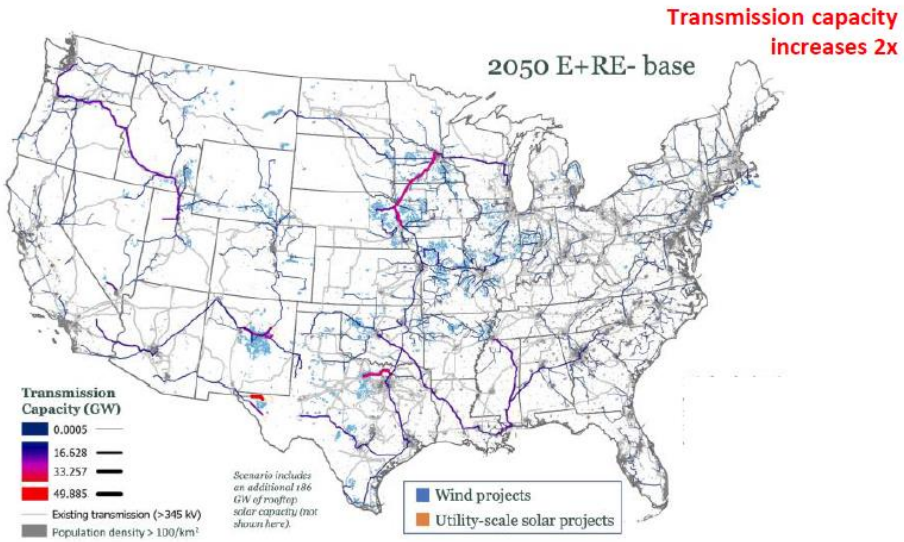


< Generation IV SMR >

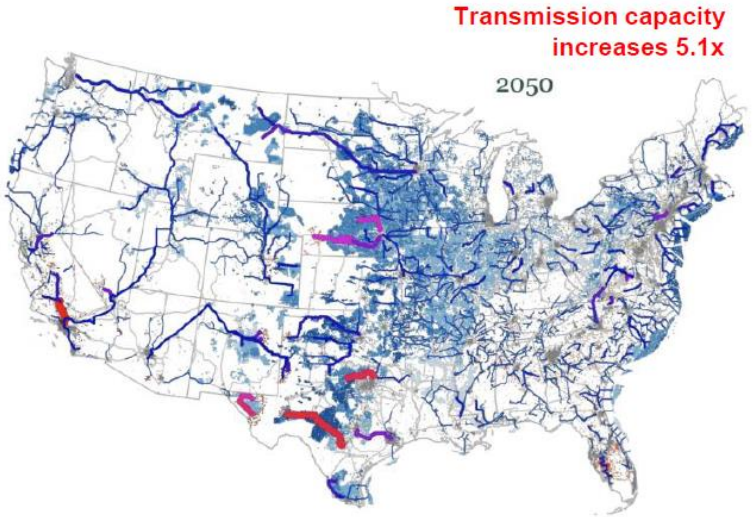
미국의 탈탄소화 평가

Transmission is a potential decarbonization bottleneck: 5x more transmission needed in 2050 for 100% renewable scenario vs only 2x with new nuclear nuclear builds

Transmission in E+RE- scenario, 2050; nuclear expands to 250 GW



Transmission in E+RE+ scenario, 2050; no nuclear



Matt Bowen, 37th Korea Atomic Power Annual Conference, April 28, 2022
(Source) Princeton (2021), "Net-Zero America: Potential Pathways, Infrastructure and Impacts

SMR이란?

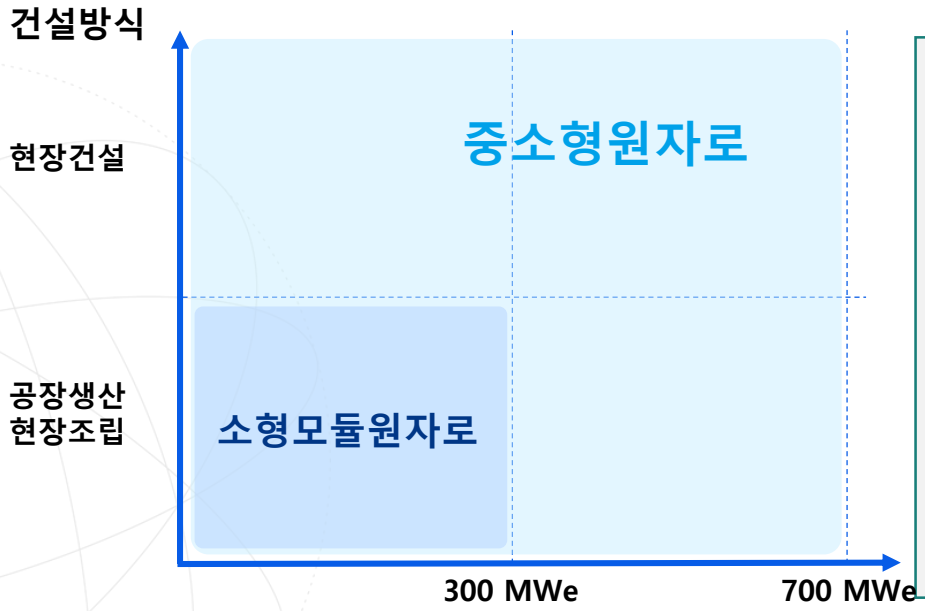
소형모듈원자로(SMR)는 원자로의 부품을 공장에서 모듈형으로 생산하여 현장에서 쉽게 조립할 수 있도록 설계한 300 MWe이하 출력의 원자로

중소형원자로(Small and Medium sized Reactor)

대용량 발전원자로와 대비되는 개념으로
전기출력 규모 700 MWe 이하의 원자로를 통칭

소형모듈원자로(Small Modular Reactor)

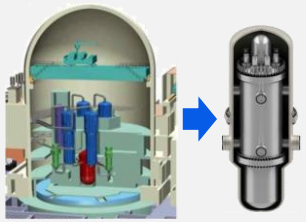
300 MWe이하의 출력을 가지며,
원자로 부품을 공장에서 모듈형으로 생산하여 현장에서 쉽게 조립할 수 있도록 설계한 원자로



(참고) 'Modular'의 중의(重義)

1 Modular design

증기발생기, 원자로냉각재펌프, 가압기 등의 원전 주요기기들이 일체형으로 설계/제작
→ SMR을 설명하는데 사용되는 의미



2 Modular construction

공장에서 부분적으로 제조되고 시험을 거친 Component Module을 현장에서 설치
→ 공기단축등을 위해 사용되는 건설공법

* 출처 : IAEA, Advances in Small Modular Reactor Technology Developments, 2020
IAEA, Technology Roadmap for Small Modular Reactor Deployment, 2021

1-4 SMR 장점

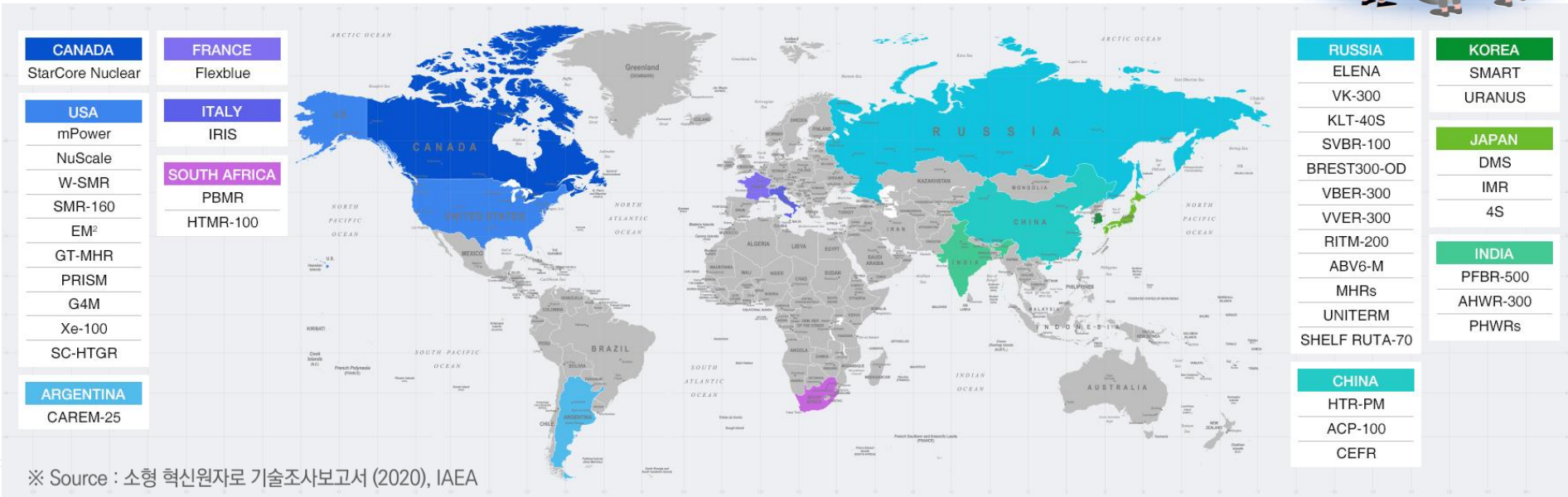
Korea Atomic Energy Research Institute

1-5

세계 SMR 개발 현황

Korea Atomic Energy Research Institute

한국, 미국, 러시아, 중국 등 에서 80종 이상의 SMR 개발 중

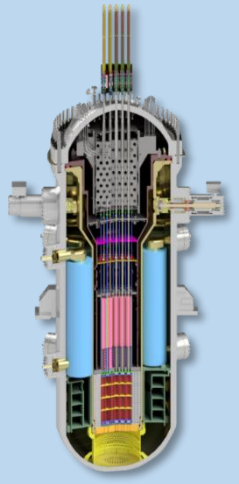


※ Source : 소형 혁신원자로 기술조사보고서 (2020), IAEA

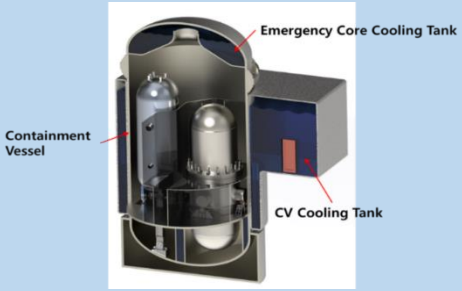
국내 SMR 개발 ← → 해외 SMR 개발

SMART	BANDI-60S	NuScale	BWRX-300	NuWard	UK SMR	KLT-40S	ACP100
KAERI	한전기술㈜	NuScale(미)	GE-Hitachi(미)	EDF(프)	Rolls-Royce(영)	OKBM(러)	CNNC(중)
'12년 7월 표준설계 인가	해수담수화 개념설계 단계	자연순환 표준설계인가('20년 8월)	BWR 노형 NRC예비심사중	블록형, 개념설계 '30년 건설계획	440MWe, 루프형 '30년 건설계획	블록형, 해상원전 상업운전중('19)	원전부지 선정 '25년 준공 계획

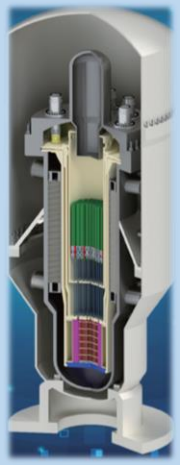
K-SMRs



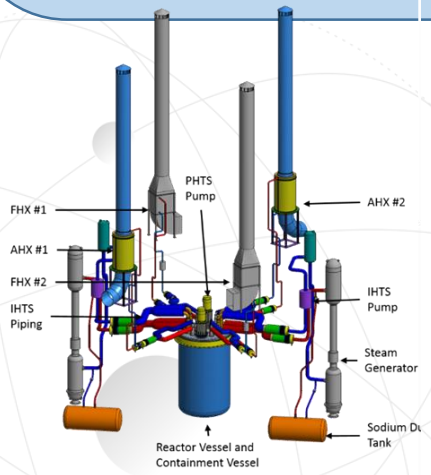
SMART



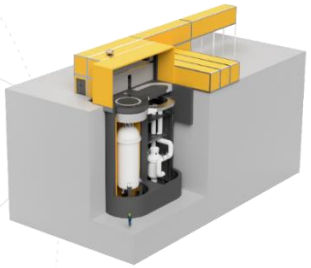
BANDI



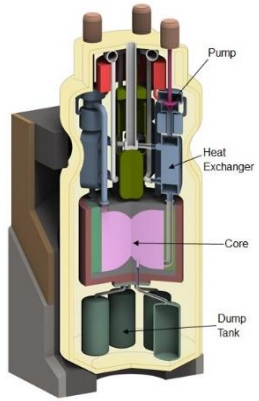
i-SMR



PGSFR



USNC MMR



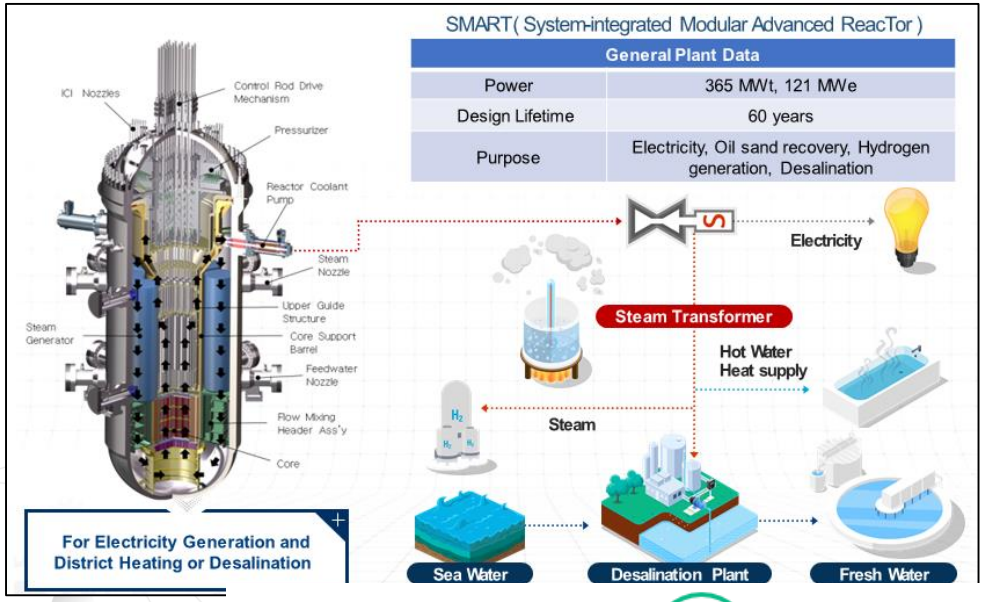
K-MSR

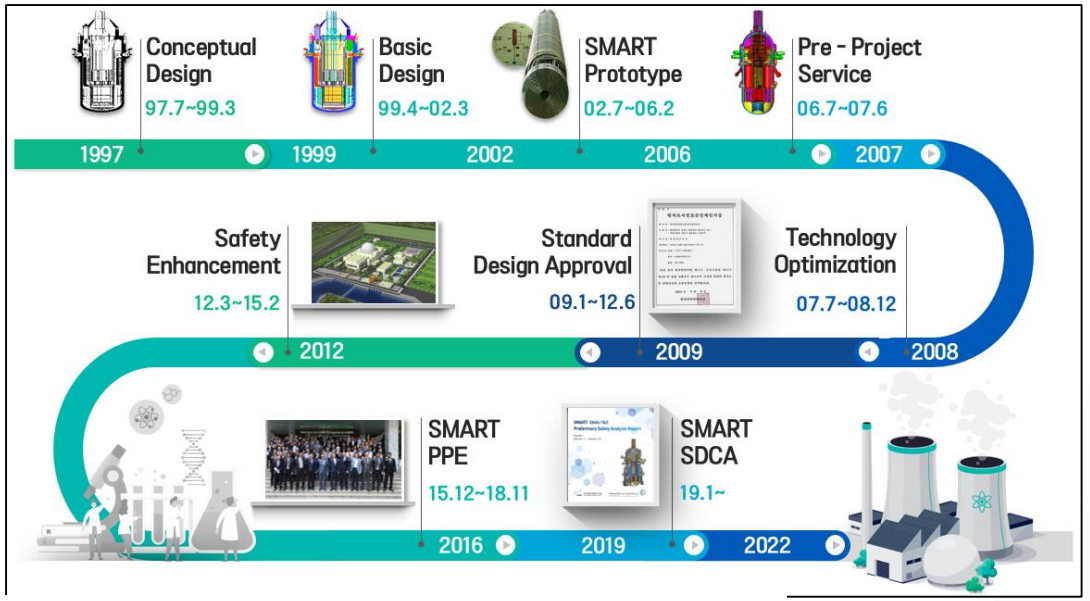
1997	• SMART Project Initiation
2012	• SMART Standard Design Approval
2014	• SMART Safety Enhancement Project
2015	• Korea-Saudi Arabia SMART partnership
2016	• BANDI Conceptual Design
2018	• MMR CNL Demonstration Project (USNC)
2020	• PGSFR Basic Design
2021	• i-SMR Project Initiation
2022	• i-SMR Conceptual/Basic Design
2023	• SMART100 Standard Design Approval
	• K-MSR National Program Initiation

2-1 SMART Technology Concepts

Korea Atomic Energy Research Institute

ALL-IN-ONE: Significant safety enhancement has been achieved with passive heat removal as well as an advanced LOCA mitigation concept





Innovative Concept

- All Major Components in Rx Vessel
- Modularization for Field Installation and Maintenance
- Passive Safety System
- Fully Digitized Control System

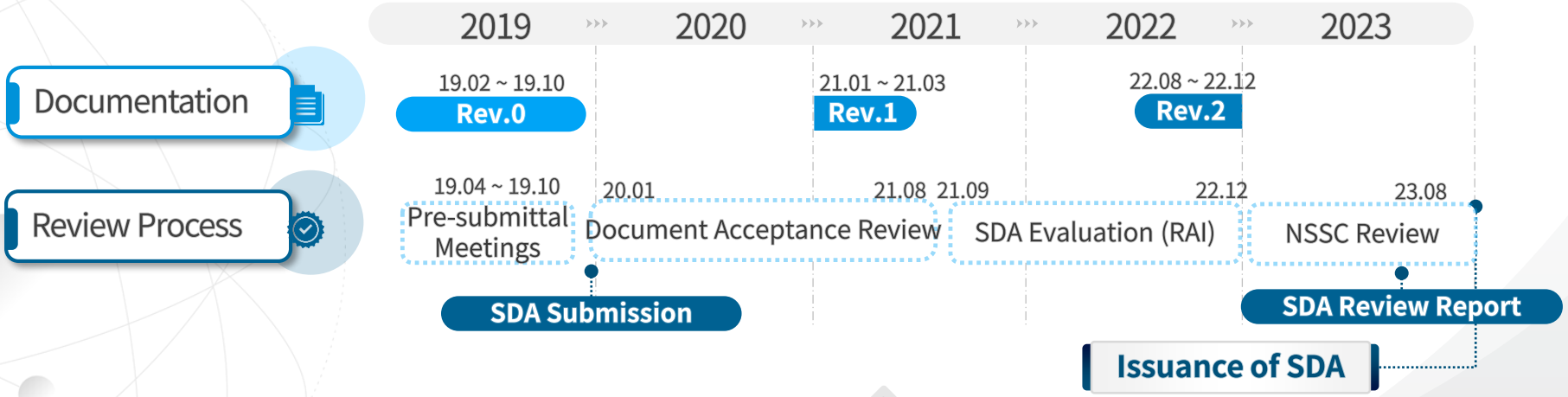
Proven Technologies

- 17 x 17 UO_2 Proven Fuel Technology
- Control Rod Drive Mechanism
- Reactivity Control Concepts Using BP and Soluble Boron

2-2 Current Status of SMART

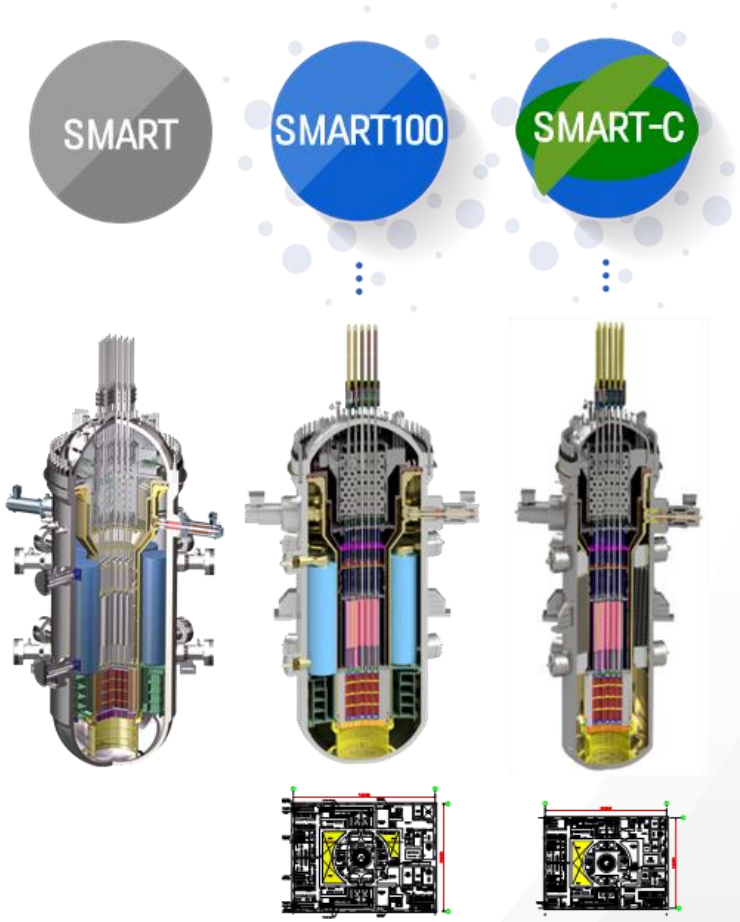
Korea Atomic Energy Research Institute

- (R&D) **Development is complete, while further improvements for various applications are still on-going.**
  - Little risk in terms of **safety, operation, licensing, supply chain and fuel supply** (technical maturity is comparable to other PWRs, such as VOYGR and BWRX-300)
  - Targeting different markets, **design improvements are still on-going** (e.g. SMART-C for SAGD process in oil sands)
- (Licensing) **Validated twice in Korea and ready for license application in Canada**
  - **Standard Design Approval** (with partially passive safety system) **in 2012**
  - **Standard Design Approval** (with fully passive safety system) **to be complete by the end of 2023**
  - **Licensing documentations** are already **written in English**, ready for the licensing process in Canada.



Evolution of SMART Technology

	• SMART	• SMART100	• SMART-C
Thermal Output	330 MWt	365 MWt	365 MWt
Electrical Output	100 MWe	110 MWe	110 MWe
Reactor Type	Integral PWR	Integral PWR	Integral PWR
RV Diameter	Appr. 6 m	Appr. 6 m	Appr. 4.5 m
Refueling Cycle	36 Months	30 Months	30 Months
SG Type	8 Helical OTSG	8 Helical OTSG	1 Helical OTSG
Safety System	Partially Passive	Fully Passive (4 Trains)	Fully Passive (2 Trains)
Emergency Power	EDG	Battery	Battery
Driving Forces	AC + Natural	DC + Natural	DC + Natural
Grace Time	30 Min.	72 Hours	72 Hours
Core Damage Frequency	< $1.0X10^{-6}$ / RY	< $1.0X10^{-7}$ / RY	< $1.0X10^{-7}$ / RY
Containment Building	Dome/Cylinder	Arch / Rectangular	Reduced[1] Arch / Rectangular



1) Due to Reduction in IRWST & HVAC and Integration of CMT & SIT

※ IRWST (In-Containment Refueling Water Storage Tank)

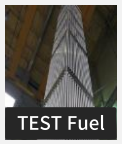
HVAC (Heating, Ventilating & Air Conditioning)

2-4 Comprehensive SMART Technology Validation Program

Korea Atomic Energy Research Institute

Fuel TH Tests

- Fuel Performance Tests

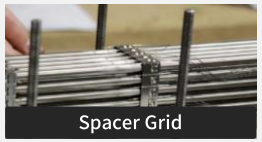

TEST Fuel


Vibration TEST


Measurements


TEST Section

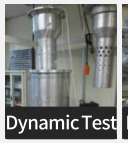
- CHF Measurement Test


Spacer Grid


TEST Section

Mechanics and Components

- RPV Dynamics Test, RCP Mockup Test and Helical ISI Test

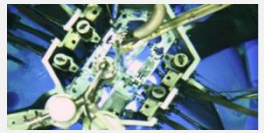

Dynamic Test


RCP TEST Loop

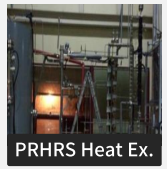

Low Friction Cable

- SG Tube Material (A690) Irradiation Test


Test Facility



Thermal - Hydraulics Experiment


PRHRS Heat Ex.

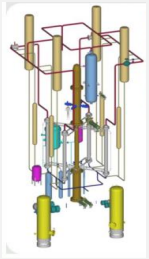

Safety Injection


Pressurizer

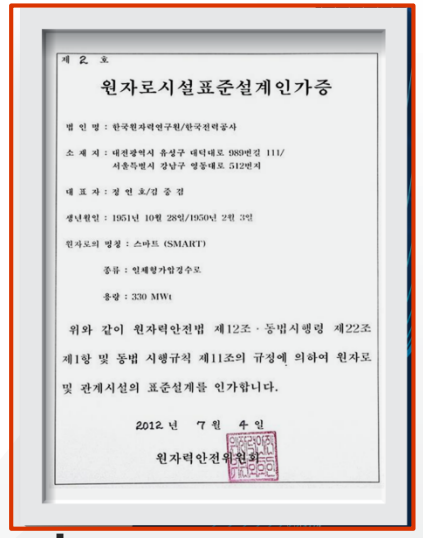

VISTA Integral Test Facility

SMART – ITL [1)]

- World's Unique and Largest Full Scope Accident Simulation
  1:1 Height, 1/49 Volume



SMART - MCR [2)] Simulator



제 2 호

원자로시설표준설계인가증

법 인 명 : 한국원자력연구원/한국전력공사

소 재 지 : 대전광역시 유성구 대덕대로 989번길 111/
서울특별시 강남구 영동대로 512번지

대 표 자 : 경 언 호/김 중 겸

생년월일 : 1951년 10월 28일/1950년 2월 3일

원자로의 명칭 : 스마트 (SMART)

종류 : 일체형가압경수로

용량 : 330 MWt

위와 같이 원자력안전법 제12조 · 동법시행령 제22조 제1항 및 동법 시행규칙 제11조의 규정에 의하여 원자로 및 관계시설의 표준설계를 인가합니다.

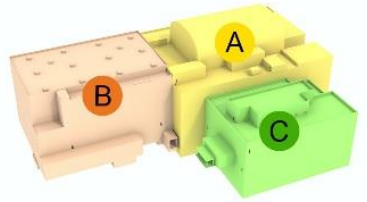
2012 년 7 월 우 일

원자력안전위원회

- Systems, Component, and Design Tools have been fully Developed and Licensed.
- SMART Standard Design Approval in 2012 (Meet the Most Country's Licensing Requirements)

SMART Plant Layout

KAERI Korea Atomic Energy Research Institute

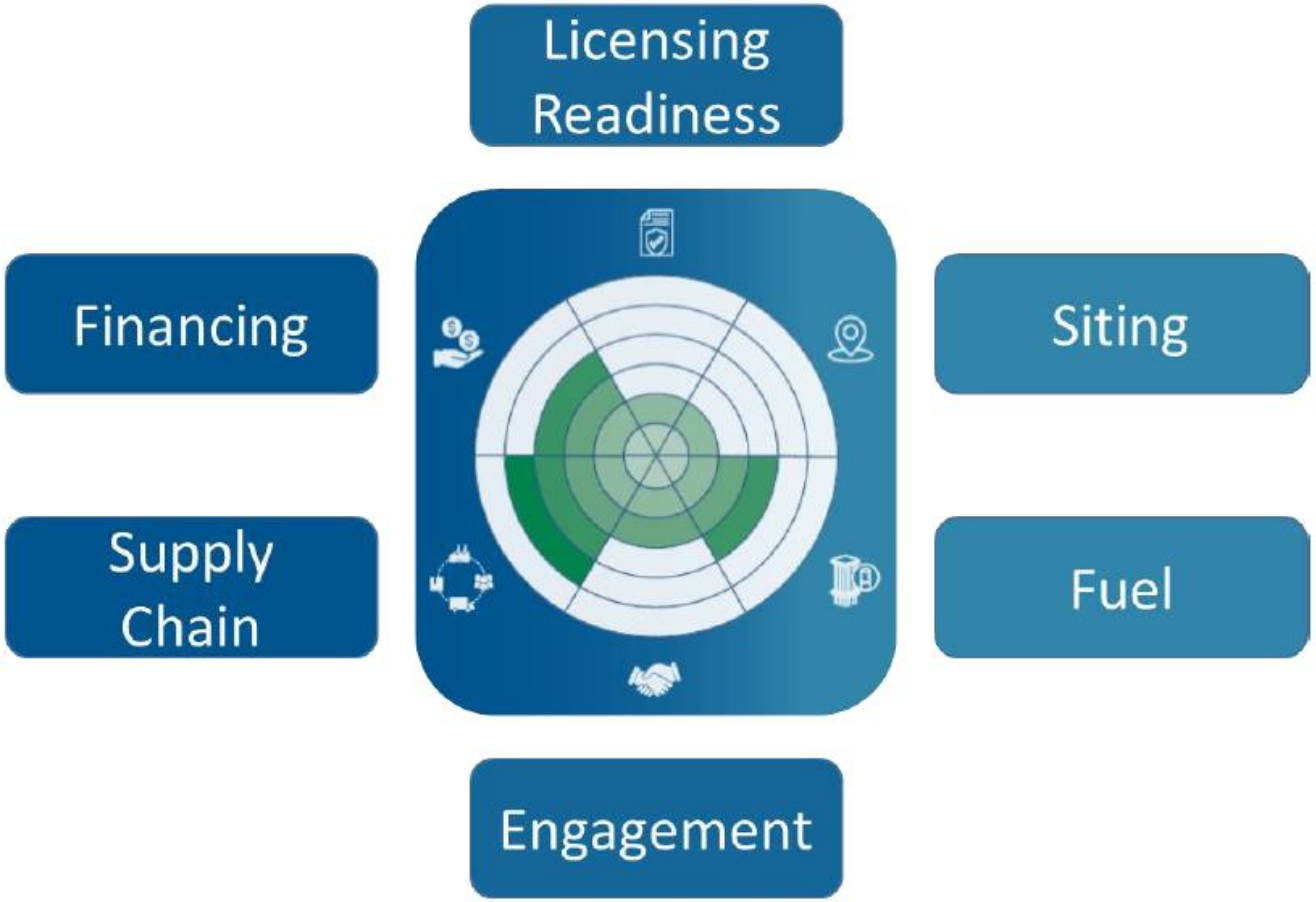


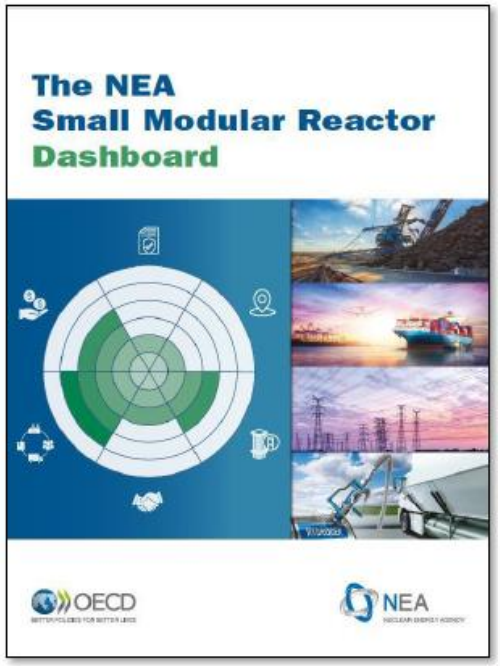
A. Reactor Containment and Auxiliary Building
B. Turbine Building
C. Compound Building

NEA SMR Dashboard (I)

Korea Atomic Energy Research Institute

- "Technology readiness level" is useful, but only reveals part of the picture
- **NEA defined six additional indicators of progress**
- With the NEA indicators, the picture becomes clearer

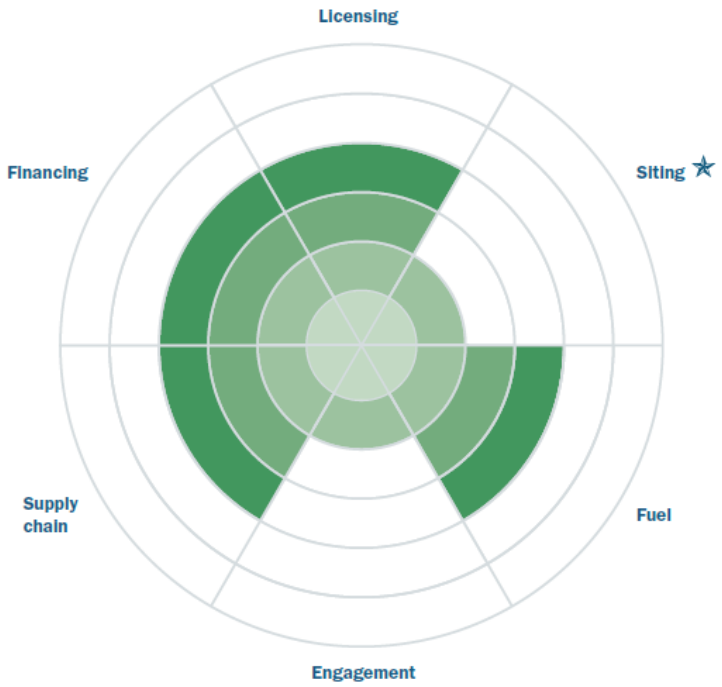




From W. D. Magwood, *Nuclear Energy: The Future is Now* , KNS Presentation, Spring 2023

2-7 NEA SMR Dashboard (II)

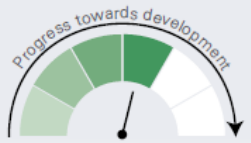
Korea Atomic Energy Research Institute



★ Active in multiple jurisdictions or countries.

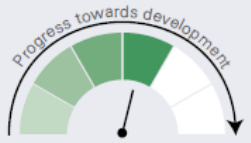
Design organisation	Korea Atomic Energy Research Institute (KAERI)
Thermal power (MWth)	365
Outlet temperature (°C)	322
Spectrum (thermal/fast)	Thermal
Fuel type	UO_2 pellets
Fuel (LEU/HALEU/HEU)	LEU

Licensing

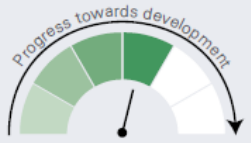


Siting ★

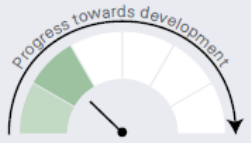
Financing



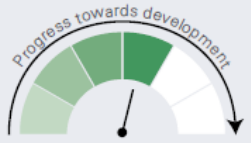
Supply chain



Engagement



Fuel



Licensing

The System-integrated Modular Advanced ReacTor (SMART) SMR developed by the Korea Atomic Energy Research Institute (KAERI) is a 365 MWth land-based pressurised light water reactor. KAERI received a Standard Design Approval for the SMART SMR from the Korean Nuclear Safety and Security Commission (NSSC) in 2012.

Siting ★

In 2015, KAERI signed a Memorandum of Understanding (MoU) with King Abdullah City for Atomic and Renewable Energy (K.A.CARE) in Saudi Arabia to assess the potential of siting multiple SMART SMRs at K.A.CARE. In 2023, KAERI signed a MoU with the Government of Alberta, Canada to collaborate on the possible deployment of SMART SMR technology in the Canadian province.

Financing

The Government of Korea, Korea Electric Power Corporation (KEPCO), and various others, including POSCO, Daewoo and STX Heavy Industries have contributed KRW 310 billion (USD 270.9 million) in financing the development of the SMART SMR plus an additional KRW 170 billion (USD 148.6 million) to support the Standard Design Approval process. In 2015, the South Korean Ministry of Science and ICT announced that KAERI was partnering with K.A.CARE on pre-project engineering (PPE) to construct SMART units in Saudi Arabia, supported by investments by the two partners totalling USD 130 million (USD 100 million from Saudi Arabia and USD 30 million from South Korea).

Supply chain

KAERI and K.A.CARE have established the joint venture "SMART EPC". Korea Hydro & Nuclear Power (KHNP) is leading this project, which intends to involve both Korean and Saudi enterprises. KHNP also signed an MoU with KEPCO Engineering & Construction (E&C) to jointly develop SMART units in Saudi Arabia. For the SMART reactor: KEPCO E&C and POSCO conducted the balance of plant design; KEPCO Nuclear Fuel designed the fuel; Hyosung Goodsprings developed the reactor coolant pumps and conducted reactor coolant pump performance testing; BHI designed the fuel handling system; Soosan ENS verified the reactor protection system and engineered the safety feature component control system; and Doosan Enerbility is providing design and engineering services for major components.

Engagement

The Korea Atomic Energy Cultural Foundation and KAERI signed an MoU to collaborate on enhancing public understanding and awareness of nuclear technology, including the SMART SMR, in 2009. KAERI and Government of Alberta signed an MoU to utilise SMRs, including SMART, for emissions reduction in Alberta.

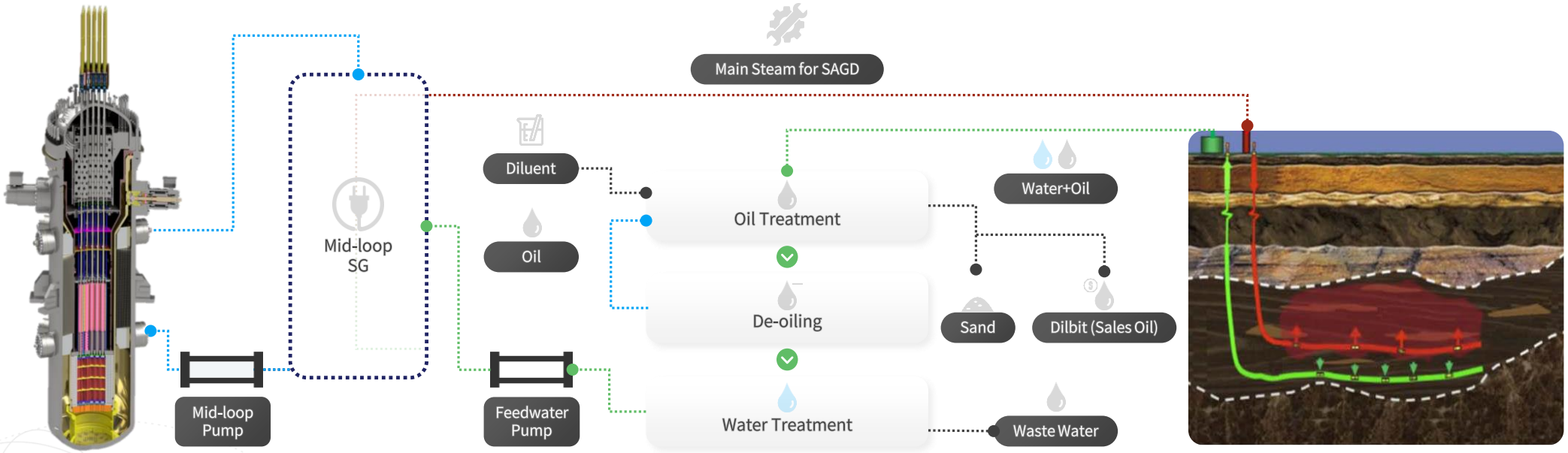
Fuel

SMART utilises the same fuel as the current industry standard for similar design water-cooled reactor technologies. Given this, no barriers are expected in the fuel supply chain for this SMR.

Note: The exchange rate applied is the currency relevant average for 2021. In this case, the price of KRW 1 143.952 equals the price of USD 1.000.

Application of SMART in SAGD* Process

(*Steam Assistant Gravity Drainage)



Design Enhancement

- Slimmer reactor vessel, Optimized steam generator for steam supply

Two or Single Phase Mid-loop

- Heat transfer through mid-loop SG without fluid connection
- Separated water treatment
- Closed secondary system (additional barrier for radioactive materials)

Two-Track Strategy in Canada

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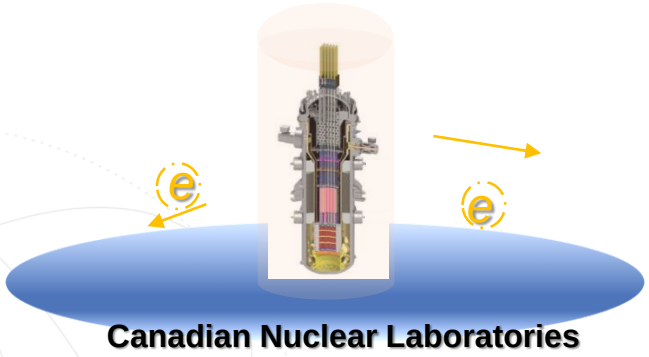
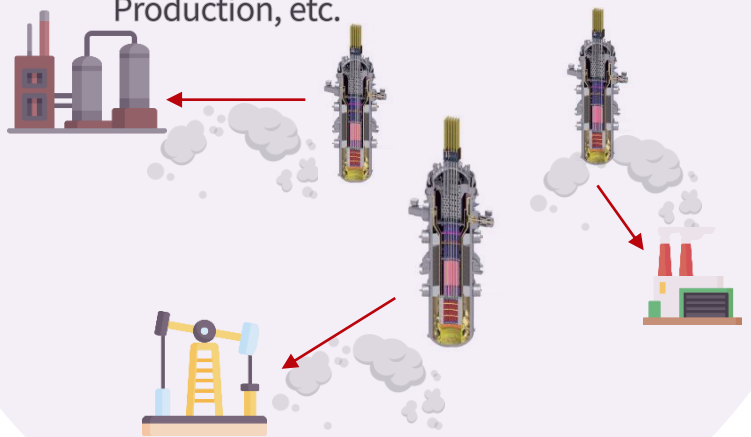
First of a Kind (FOAK)

- FOAK Plant in Ontario
  - Demonstration of the first SMART at CNL site (Chalk River, Ontario)
  - The established nuclear industry is the strength of Ontario as a FOAK site
  - The MOU between KAERI and AECL



Nth of a Kind (NOAK)

- NOAK Plants in Alberta
  - The MOU between KAERI and the Government of Alberta
  - Alberta is the major market for SMART
  - Marketing in Alberta in parallel with demonstration in Ontario
  - SAGD process, Chemicals, Hydrogen Production, etc.



The KAERI-Hyundai Engineering partnership for SMART demonstration and further SMART applications

- Korean companies are invited to join the partnership as either investor or business partner

3-1 i-SMR Deployment Depending on the Demand

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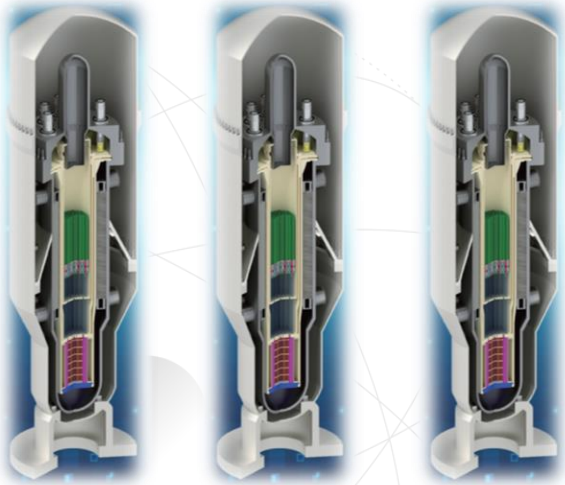
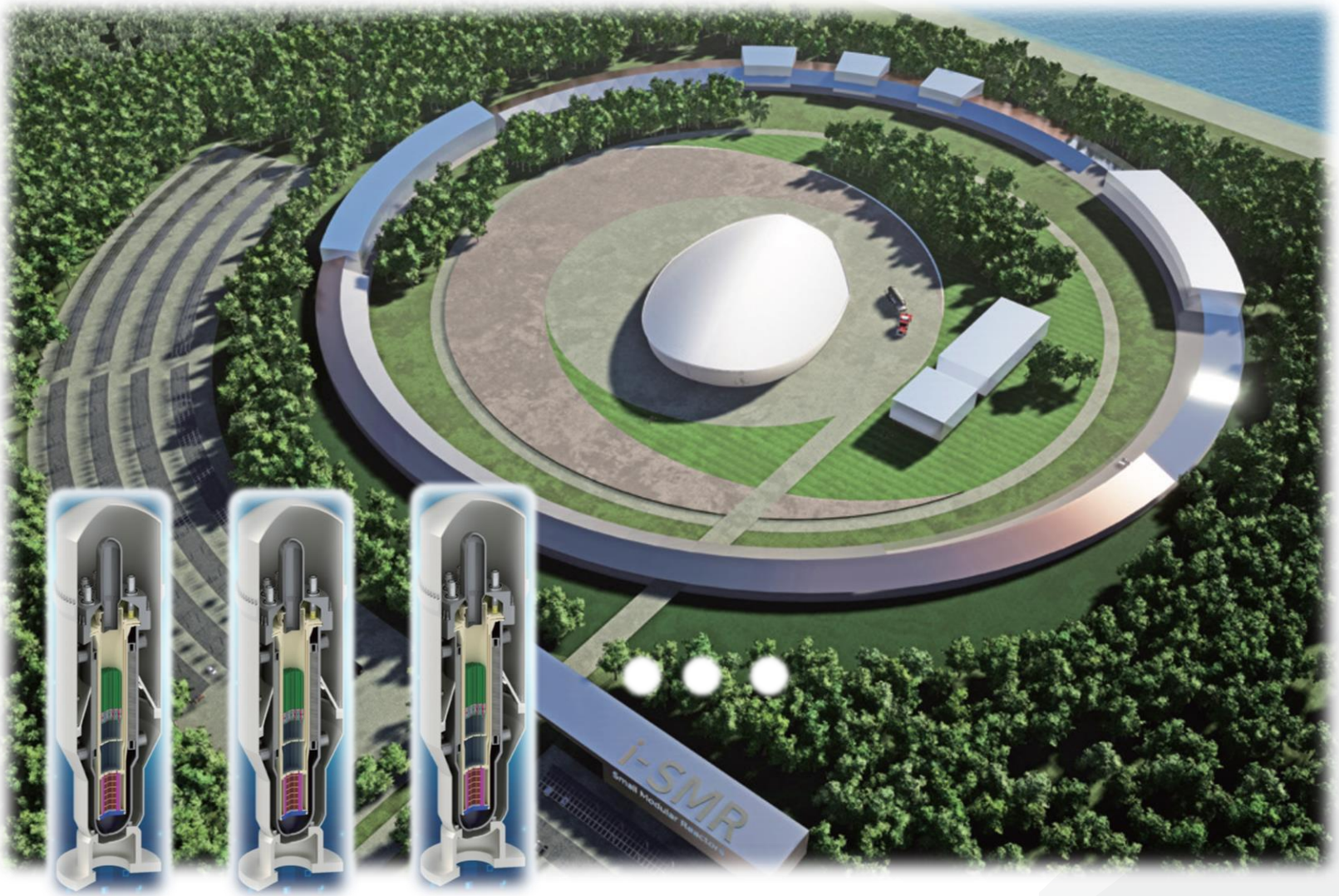


i-SMR Reactors



i-SMR Site Plan

3-2 i-SMR Development Target

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General

- PWR
- Power : 170 MWe
- Design Life : 80 years
- Site : site envelope seismic design (0.5g)

Safety

- CDF : 1.0 × 10^{-9} /M·Y
- EPZ : Within EAB
- Grace time : over 72 hrs (Minimum)
- Fully passive safety system without AC/DC power

Economic

- Overnight cost : $3,500 /kWe, LCOE : LCOE $65 /MWh
- Modualization and factory manufacturing
  - component design optimization considering inland transportation
- Construction time ≤ 24 month (First module)
- Plant construction time ≤ 42 month (4 modules)

Flexibility

- Boron free operation
- Load following operation
- Multipurpose utilization

3-3 i-SMR Design Characteristics - RCS

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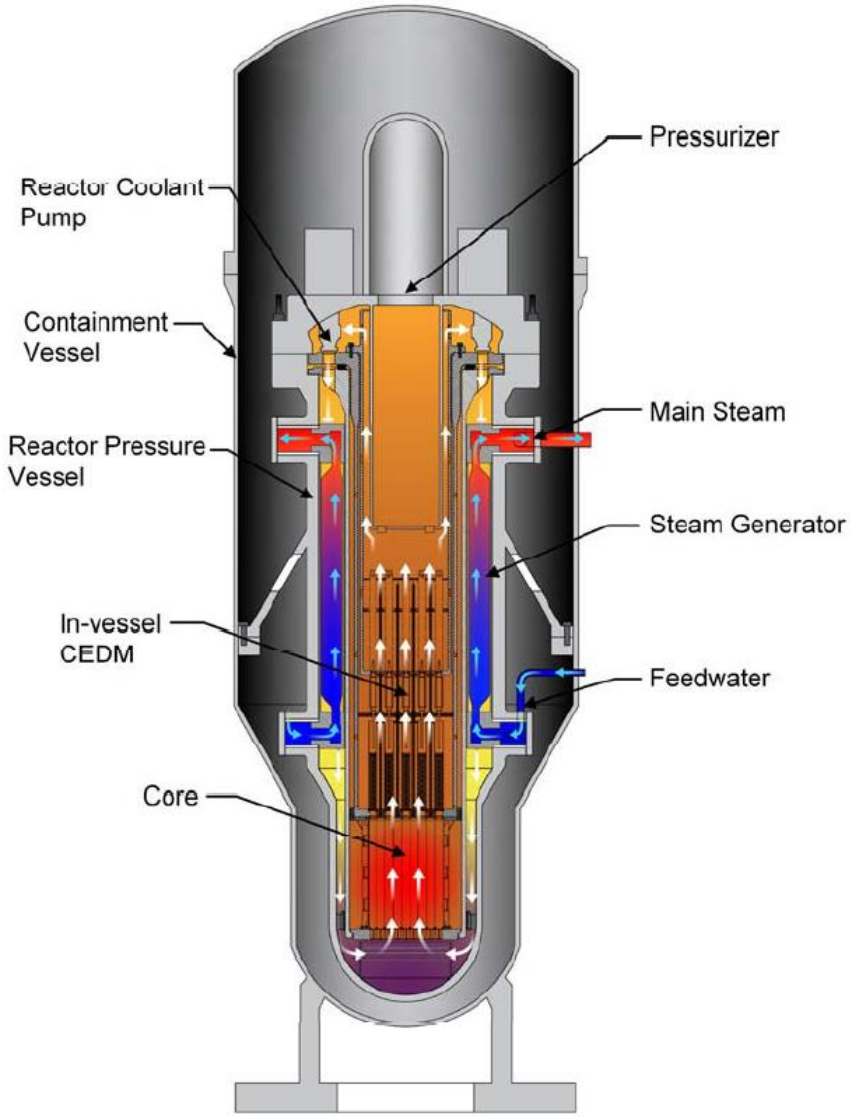


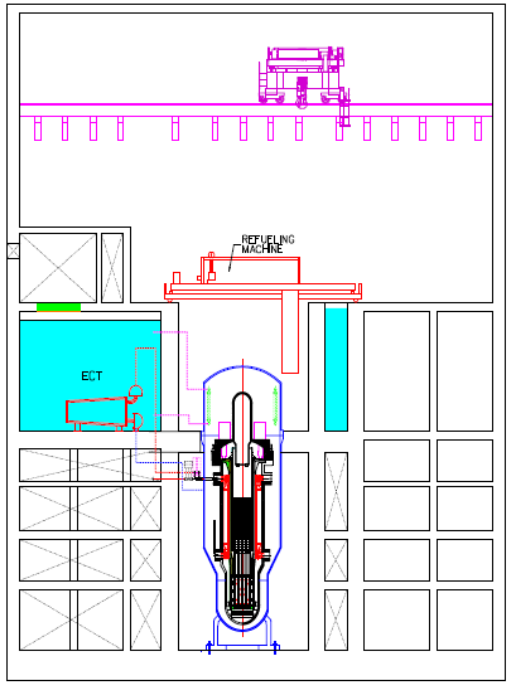
< Reactor Coolant System and Containment Vessel >

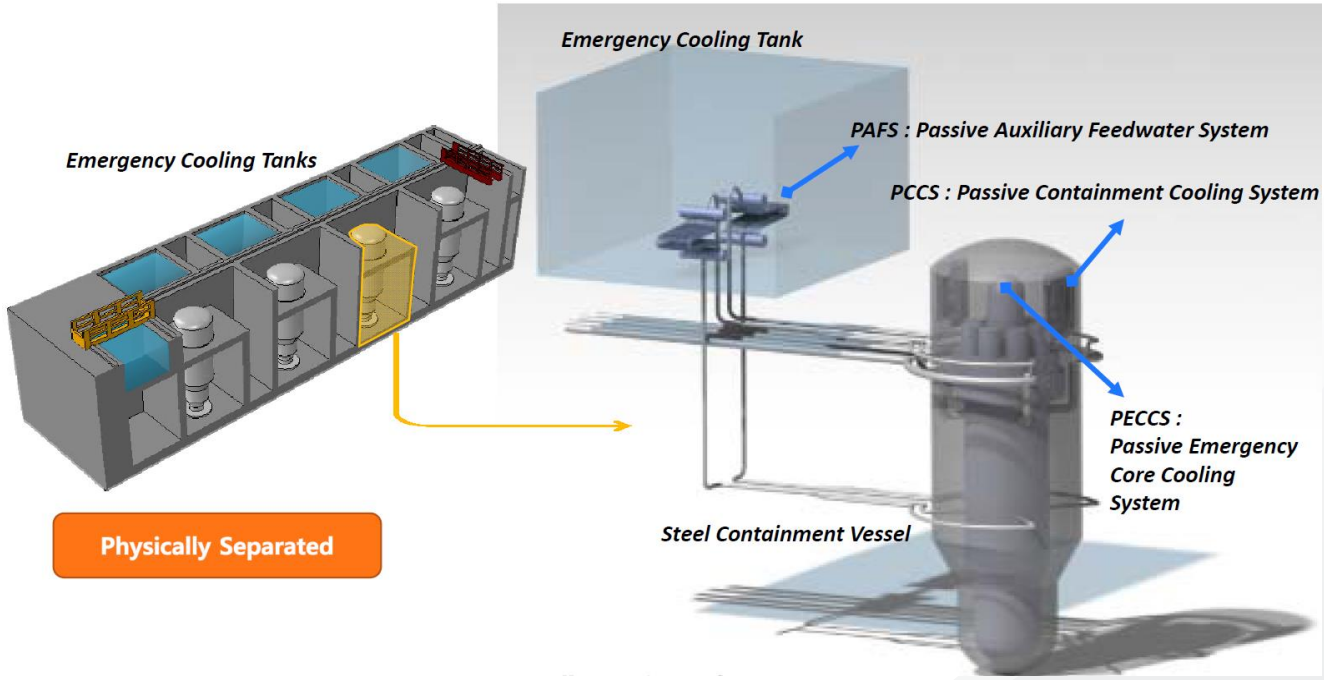
NSSS Design Characteristics

- Electrical output per module : 170 MWe /Module
  - 680 MWe in case of 4 modules
- Core : UO_2, 69 FAs, (active length : 2.4 m)
- Reactivity control : Control rod, Burnable Position, MTC (Boron-free)
- Control rod derive mechanism : In-Vessel
- Steam generator : Helical, Once-through
- Canned motor RCPs

i-SMR Safety Systems

- Passive Auxiliary Feedwater System (PAFS)
- Passive Emergency Core Cooling System (PECCS)
- Passive Containment Cooling System (PCCS)

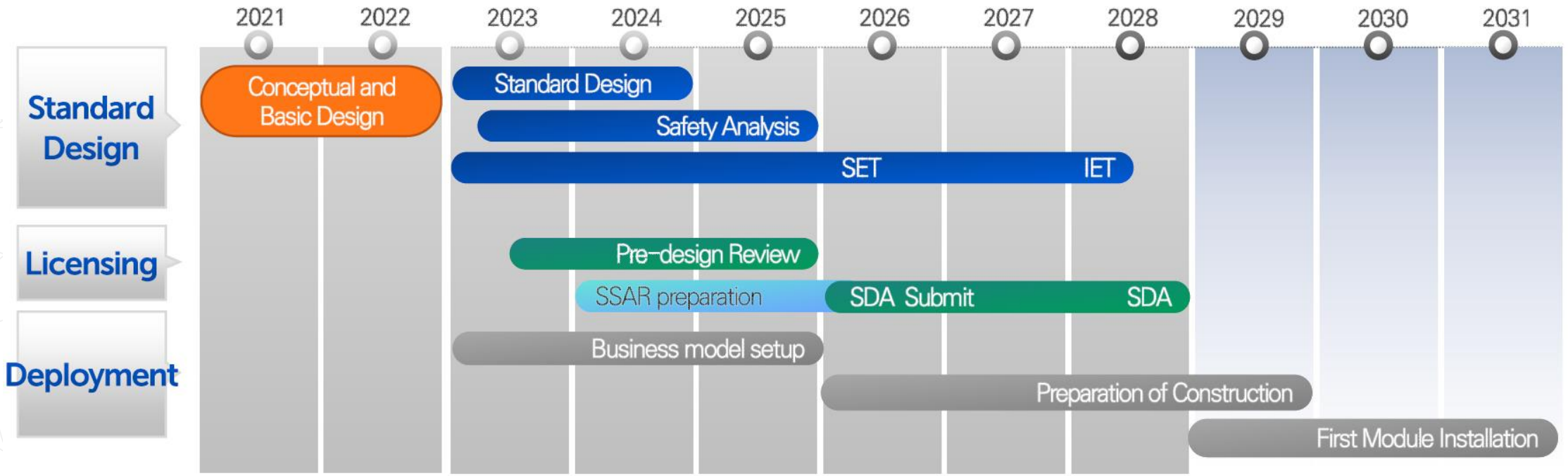




i-SMR Development Roadmap

Standard Design Approval (in Korea) by 2028

- Government funding has been started for standard design program this year.
- Pre-design review of Korean regulatory body has been already started in July.
- SDA acquisition by 2028 and first module installation by 2031



i-SMR 상용화 (I)

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세계적으로 71기[1] 개발 중. NuScale은 실증로 없이 자금, 부지, 파트너 등 사업기반 확보

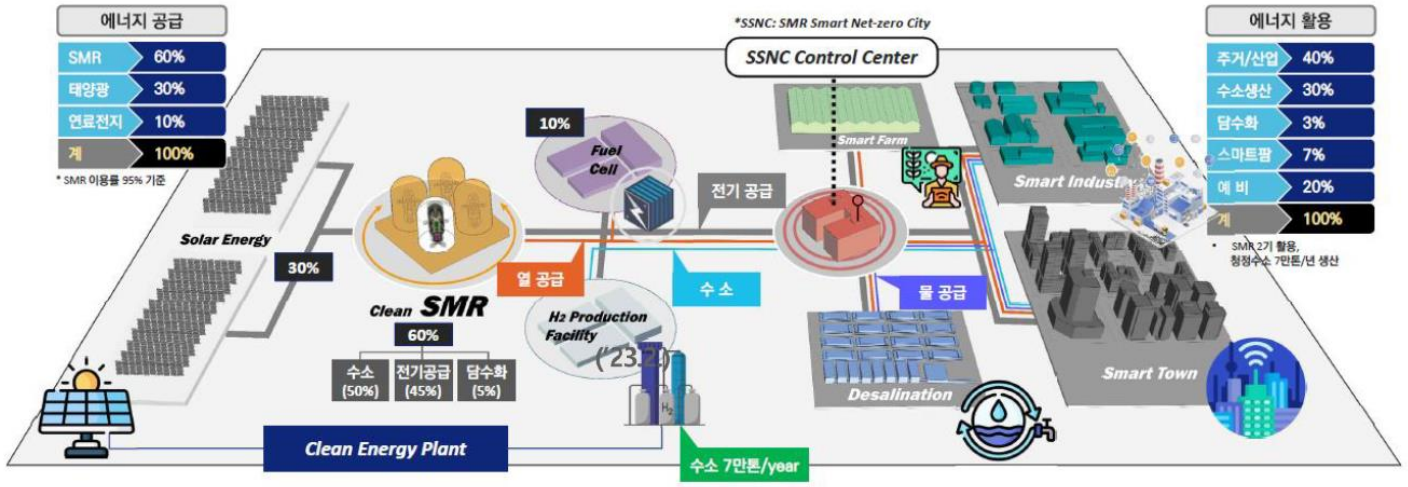
SMR 개발 현황

개념 단계	설계 단계	인허가 전 단계	건설 전 단계	건설중	운영중
HTGR/VHTR	HTGR/VHTR	SFR	SFR	SFR	SFR	SFR	LFR	SFR	HTGR/VHTR
HTGR/VHTR	HTGR/VHTR	HTGR/VHTR	HTGR/VHTR						
MSR	MSR	MSR	MSR	HTGR/VHTR	MSR				
MSR	LFR	LFR	GFR	MSR	LFR	LFR			

● 미국 ● 한국 ● 캐나다 ● 러시아 ● 룩셈부르크 ● 일본
● 중국 ● 남아프리카 ● 스웨덴 ● 덴마크 ● 네덜란드 ● 영국

고객 니즈 관점의 확장성을 고려한 혁신형 SMR 개발, 사업화 병행 추진 필요

SMR 스마트 넷제로 시티



출처: 황주호, 원자력 다시보기, 춘계학술대회 특별강연, 2023

3-7 i-SMR 상용화 (II)

Korea Atomic Energy Research Institute

서울경제

증권 부동산 경제 · 금융 산업 정치 사회 국제 오피니언 문화 · 스포츠 영상 · 포

경제동향 정책 공기업 경제분석 금융정책 은행 카드 보험 제2금융 재테크 금융가 경제·금융일반

홈 경제·금융 경제동향

한수원, SMR 정조준…스웨덴서 수주 도전장

입력 2023-07-11 17:50:52 수정 2023.07.11 17:50:52 세종=유현욱 기자

뉴스듣기 가

국영 전력사서 입찰 요청서 반아
서해안 링할스에 최소 2기 추진

오늘의 핫토픽

기준금리 6연속 동결

서경·갤럽 여론조사

이스라엘·팔레스타인 접쟁

국정감사

글로벌 발전플랜트 Solution Provider

전기신문

에너지Biz 전기경제 시공·인전 피플 오피니언 e-딘독 전기문화 2023 국정감사

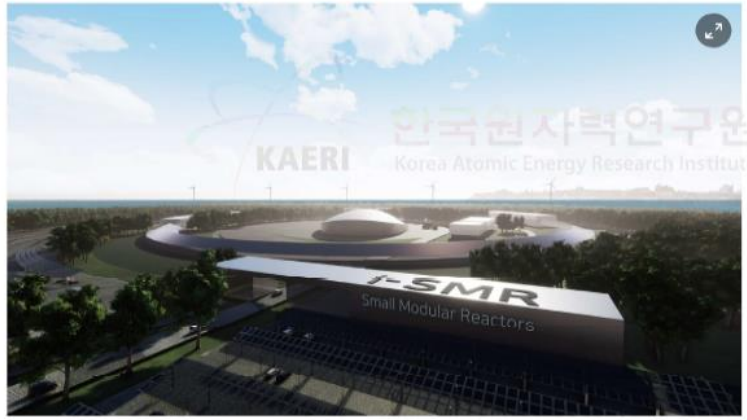
에너지BIZ 원자력

혁신형 SMR 첫 호기는 스웨덴?...한수원 전담 TF 구성

정세영 기자(cschung@electimes.com) 제보

입력 2023.07.13 16:26 호수 4156 지면 1면

9월 중순까지 의향서 제출...내년초 우선협상대상자 선정
영국 롤스로이스 등 5~6개 경수로 SMR 노형 경쟁 구도
변수는 혁신형 SMR 기술개발 속도, 양국 인허가 리스크



많이 본 뉴스

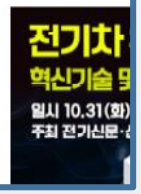
1 지멘스 가메사 두산에너빌리

2 미래먹거리 '' 도경쟁 '치열'

3 코맥스, 1000 부 '국민 생체

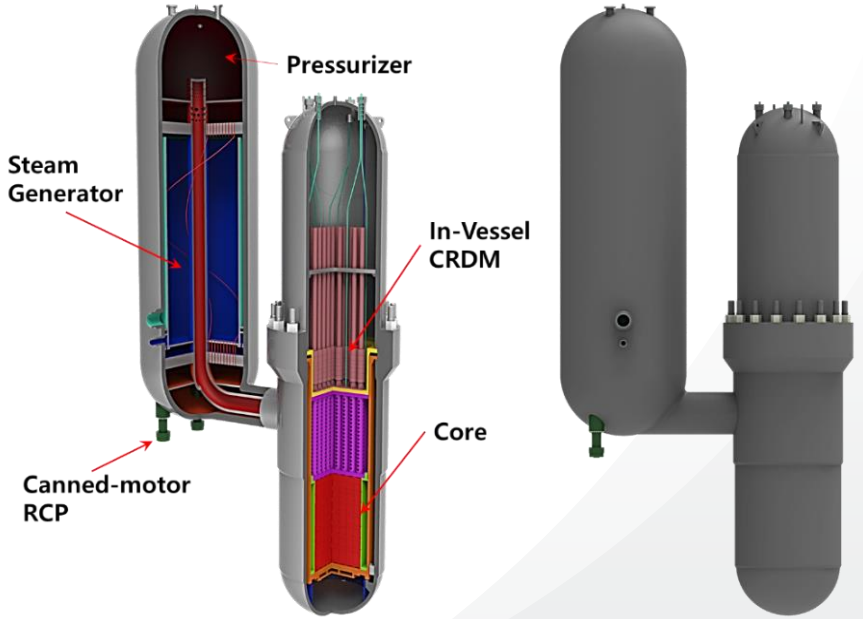
4 태양광 장기계 임...갈리는 업

5 '2.5조원' 루마 성큼...한수원



BANDI – Marine-based NPP

- ‘Block-type’ reactor coolant system where the reactor vessel and the steam generator are ‘nozzle-to-nozzle’ connected to each other without big pipes.
- The first phase of BANDI project, concept development , was started in 2016 and completed in 2022. The second phase of basic design will be continued from 2023 to 2028.



5-1 For New Nuclear Energy to be Successful, Key Challenges Must be Addressed

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Industrial Challenges

- **Execution**—industry must take breakthrough technologies from the drawing board to commercial reality and deliver projects as promised
- **Operations Models**—industry must present realistic models to operate large numbers of SMRs and microreactors
- **Supply Chain**—past experience demonstrates that the global nuclear supply chain is neither broad nor deep and suppliers are not always as prepared as might be expected

Regulatory Challenges

- **Adaptation to New Technologies**—regulators must not view Gen IV technologies through a Gen II lens and must be prepared to address digital technologies
- **Global Thinking**—regulators must act nationally but think globally; otherwise there cannot be a true global market for new technologies
- **Accept New Paradigms**—new technologies may be game-changers in as EP and security, but regulators must be truly risk-informed

Policy and Market Challenges

- **Outdated Electricity Markets**—today's markets don't support long-term environmental and energy security goals; dispatchability has value!
- **FOAK**—governments must put policies in place to address FOAK risks; industry cannot/will not absorb all the risks
- **Financing**—government policies are needed to support financing of new nuclear construction and other high-capital investments needed to reach Net-Zero

re Challenges

- **HALEU**—the lack of a clear path to provide high assay LEU is already a barrier to new technologies
- **Codes and Standards**—industry, governments, regulators and other stakeholders must commit to strive toward simplified and harmonised nuclear standards
- **Human Resources**—more must be done to promote a new generation of nuclear experts while promoting greater diversity and gender balance

From W. D. Magwood, *Nuclear Energy: The Future is Now* , KNS Presentation, Spring 2023

5-2 맺음말 (1)

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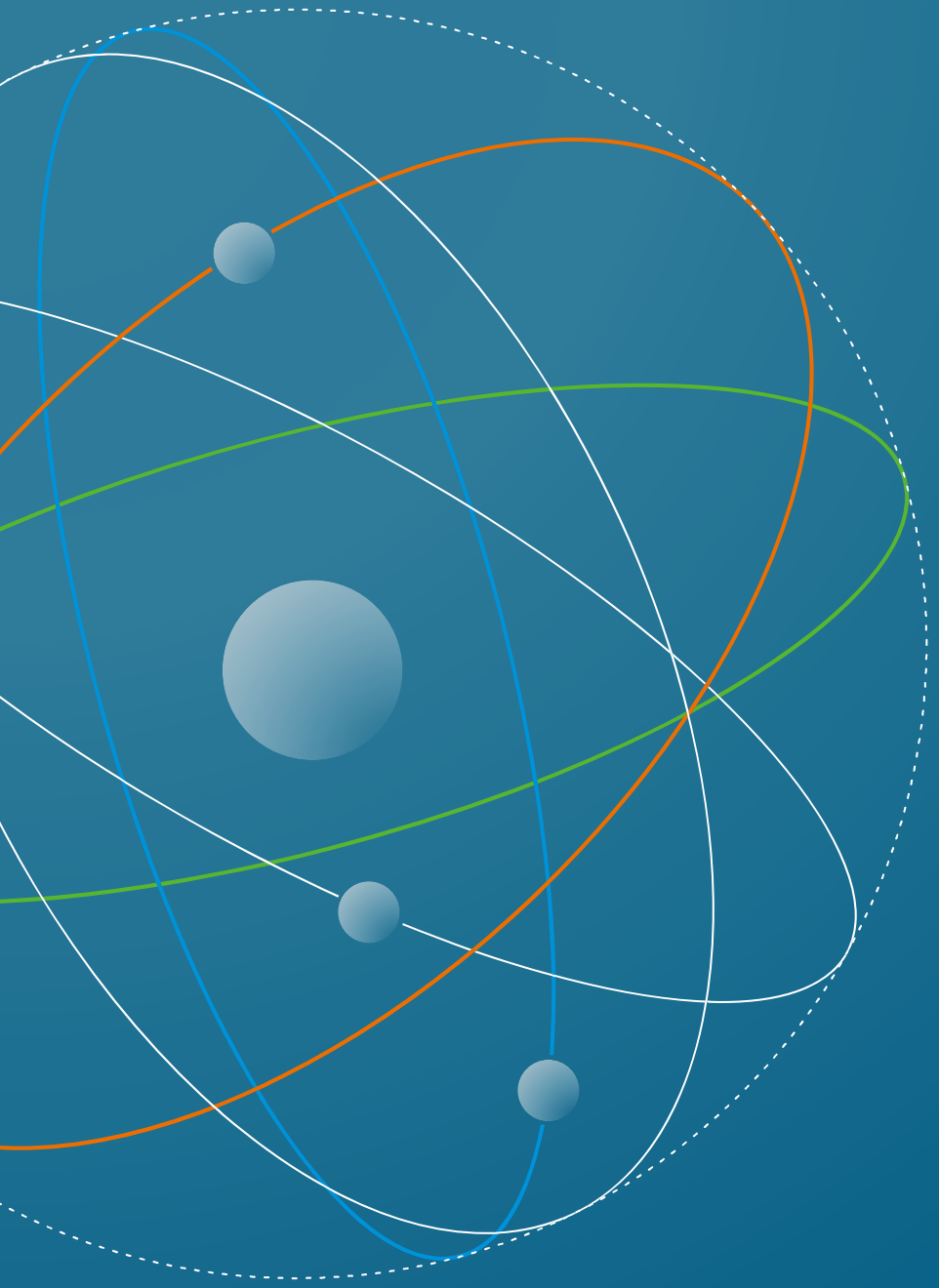
- 우리나라는 꾸준한 국내 원전건설과 해외수출을 통해 대형원전 분야에서 세계 최고 수준의 경쟁력을 가지고 있으며, ‘97부터 개발에 착수하여 세계최초로 표준설계인가를 획득한 SMART와 최근 개발에 착수한 i-SMR 등을 통해, 글로벌 SMR 분야에서 우수한 경쟁력 확보
  - (1) AI, 혁신제조, 디지털트윈과 같이 수출경쟁력을 향상시키기 위한 연구개발 및 (2) 민간기업들이 개별적으로 확보하기 어려운 대규모 시험설비의 구축/운영을 위한 정부의 적극적이고 지속적인 지원이 필요
- 국내 민간기업의 SMR 해외수출 역량 강화를 위해 (1) 단기적으로는 정부-공기업-민간부분 SMR 얼라이언스를 활용하고 (2) 장기적으로는 민간부분의 주도적인 SMR 사업 추진을 위한 체계 구축
- 민간기업이 자체적으로 SMR을 활용하여 열증기 공급과, 수소생산을 할 수 있도록 제도적인 장치 마련 필요

5-3 맺음말 (2)

Korea Atomic Energy Research Institute

- KAERI는 경수형 SMR인 SMART, i-SMR 뿐만 아니라, 4세대 SMR에 대한 원천기술을 확보하고 있으며, 혁신기술을 실증하기 위한 대규모 인프라 설비 또한 구비하고 있으므로 이를 적극적으로 활용하는 것이 필요
- 소형·모듈형·다목적의 SMR 설계특성을 고려한 규체체계 정비와 함께 안전규제기술 개발 추진이 필요하며, 원안위는 최근 SMR 설계개념과 규제요건 등에 대한 상호 이해를 제고할 수 있는 절차를 정립
  - SMR을 미래 원자력안전분야의 도전과제로 인식하고 SMR 개발 수요에 적극적 대응을 위해 규제방향을 선제적으로 제시하고, 다양하게 개발중인 SMR의 설계특성을 포괄할 수 있는 규제체계를 만들어 나가야 할 시점



A nuclear energy reshaping the future based on **peoples trust**

THANK YOU

KAERI Korea Atomic Energy Research Institute