Prospects and Challenges of Small Modular Reactor Deployments as Option to Enhance Energy Supply Security

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IAEA
International Atomic Energy Agency
Advanced Water Cooled Reactors
Indispensable Solution to meet the Increasing Energy Demand

State-of-the-Arts:
- Newer generations
- Improved robustness
- Advanced design features
- Enhanced safety performance
- Economically more competitive
- More resilient toward external events

Meet IAEA Safety Standards and URDs
Incorporates lessons-learned from major accidents

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State-of-the-Arts:
- Solar
- Nuclear
- Wind
- Fossil
- Hydro
Regional Distribution of NPPs

Source: IAEA Power Reactor Information System (PRIS), March 2016

- 442 nuclear power reactors operational
- 384,194 MW(e) total net installed capacity
- 66 nuclear power reactors under construction
Advanced Water Cooled Reactor Design and Technology Developments: Progress Milestones

- IAEA Power Reactor Information System (PRIS) as of 1 March 2016:
  - 66 NPPs under construction in 15 Member States

**Advanced Reactors under construction:**
- ABWR: 2 units in Japan, 2 in Taiwan
- EPR: 3 units: in China, Finland, France
- APR1400: 4 units in Korea, 2 units in UAE (+2 units just approved)
- AP1000: 4 units in USA, 4 units in China
- VVER1000/1200s deployments in Russian and foreign markets
- CAP1400 completed safety review by the nuclear regulatory authority in China
- South Korea’s first **APR1400** Shin Kori-3 connected to grid on 15 January 2016

**China constructing:** 24 NPPs (incl. 1 SMR: HTR-PM)

**Russia constructing:** 9 VVERs (+ planned constructions in embarking countries (Turkey, Vietnam, Bangladesh, Belarus, Jordan, ..) + KLT-40s a Floating NPP
SMRs Estimated Timeline of Deployment

Immediate Deployable
- CAREM
  - CNEA, Argentina
- HTR-PM
  - INET, China
- KLT-40S
  - OKBM Afrikantov, Russian Federation

Near-term Deployable
- ACP100
  - China
- SMART
  - Republic of Korea
- NuScale
  - USA

Mid to Longer-term Deployable
- IMR
  - Japan
- HTMR100
  - South Africa
- SMR160
  - United States of America

Under Construction
- SMART
  - KOKR, Republic of Korea
- RITM-200
  - CRDM, Russian Federation
- PRISM
  - GE-Hitachi, USA
- PBMR-400
  - PBMR, South Africa
- BREST300-OD
  - NIKIET, Russian Federation
- 4S
  - Toshiba, Japan

Certified or at Advanced Design Stage
- ACP100
  - China, China
- UNITHERM, VK-300
  - NIKIET, Russian Federation
- NuScale Power
  - United States of America
- mPower
  - B&W, United States of America
- GTTHR300
  - JAEA, Japan
- SVBR-100
  - AKME Engineering, Russian Federation

Conceptual Design for Mid to Long Term Deployment
- AHWR300
  - BARC, India
- Flexblue
  - DCNS, France
- IRIS
  - IRIS International Consortium
- DMS
  - Mitsubishi, Japan
- VVER-300
  - OKO Gidropress, Russia Federation
- Westinghouse SMR
  - United States of America
- SMR150
  - HCLTAC, United States of America
- Th-100
  - STL, South Africa
- SC-HTGR
  - AREVA, France
- G4M
  - Gen4 Energy, United States of America

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### SMRs for immediate & near term deployment

**Samples for land-based SMRs**

#### Water cooled SMRs
- Carem
- SMART
- ACP100
- NuScale

#### Gas cooled SMRs
- HTR-PM
- GTHTR300
- HTMR100
- EM²

#### Liquid metal cooled SMRs
- PFBR
- PRISM
- SVBR
- 4S

- **Land-based, marine-based, and factory fuelled transportable SMRs**
- **Estimated power limit to be modular/transportable ≤ 180 MW(e)**
### SMR: Motivation – Driving Forces…

Advanced Reactors that produce electric power up to 300 MW, built in factories and transported as modules to utilities and sites for installation as demand arises.

| The need for **flexible** power generation for wider range of users and applications |
| Replacement of aging fossil-fired units |
| Cogeneration needs in remote and off-grid areas |
| Potential for enhanced safety margin through inherent and/or passive safety features |
| Economic consideration – better affordability |
| Potential for innovative energy systems: |
| - Cogeneration & non-electric applications |
| - Hybrid energy systems of nuclear with renewables |
Synergy of Nuclear and Renewables

Source: US DOE
Application of Hybrid Energy System of SMRs with Cogeneration and Renewable Energy Sources

Max Output of 1061 MWe to the power GRID ►►

Composite Wind Farms

Node

Variable Electricity

1018 MWe

Offsetting SMR Electricity

Reactor Heat

Nuclear reactor 347 MWe (755 MWth)

Dynamic Energy Switching

Hydrogen Electrolysis

Regional Biomass

(80 Km radius or ~2 million hectares)

1.000.000 t/DM/yr

104 GWh heat at 200°C

1169 GWh heat at 500°C

Drying and Torrefaction Processes

Torrified Product

+ Pyrolysis

Pyrolyzed oil + char + offgas

+ Synfuel Production

753 m³/day bio-diesel

597 m³/day bio-gasoline

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Issues of Integrating SMR + Cogeneration + Renewable (Wind)

- Challenge in finding the optimal ratio of the wind farm capacity to nuclear capacity, while providing adequate heat to support biomass processing while matching power demands
- Variability of power to grid relative to instantaneous demand should be minimized
- If nuclear is sized too large, variability of power production may be reduced, however, process heat and electricity are wasted
- Biomass availability is a key constraint

## Economic Trade-offs

<table>
<thead>
<tr>
<th>Nuclear Hybrid System with RES</th>
<th>Conventional System with RES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compensates variable RES</td>
<td>Highly intermittent RES</td>
</tr>
<tr>
<td>Electricity price in balancing/peaking markets</td>
<td>Electricity price in base-load electricity market</td>
</tr>
<tr>
<td>Value from Synfuels</td>
<td>Cost to remove waste heat</td>
</tr>
<tr>
<td>Additional capital and operating costs, some loss of thermal efficiency</td>
<td>Addition of grid upgrades and energy storage for balancing, subject to fuel price volatility</td>
</tr>
<tr>
<td>Little or no backup capacity needed, no carbon emitted</td>
<td>100% backup for RES, using natural gas, subject to C-tax</td>
</tr>
</tbody>
</table>

### SMRs Under Construction for Immediate Deployment – the front runners …

<table>
<thead>
<tr>
<th>Country</th>
<th>Reactor Model</th>
<th>Output (MWe)</th>
<th>Designer</th>
<th>Number of units</th>
<th>Site, Plant ID, and unit #</th>
<th>Commercial Start</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>CAREM-25</td>
<td>27</td>
<td>CNEA</td>
<td>1</td>
<td>Near the Atucha-2 site</td>
<td>2017 ~ 2018</td>
</tr>
<tr>
<td>China</td>
<td>HTR-PM</td>
<td>250</td>
<td>Tsinghua Univ./Harbin</td>
<td>2 mods, 1 turbine</td>
<td>Shidaowan unit-1</td>
<td>2017 ~ 2018</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>KLT-40S (ship-borne)</td>
<td>70</td>
<td>OKBM Afrikantov</td>
<td>2 modules</td>
<td>Akademik Lomonosov units 1 &amp; 2</td>
<td>2016~2017</td>
</tr>
<tr>
<td></td>
<td>RITM-200 (Icebreaker)</td>
<td>50</td>
<td>OKBM Afrikantov</td>
<td>2 modules</td>
<td>RITM-200 nuclear-propelled icebreaker ship</td>
<td>2017 ~ 2018</td>
</tr>
</tbody>
</table>
SMR Design Characteristics (2)

- Multi modules configuration
  - Two or more modules located in one location/reactor building and controlled by single control room
    - → reduced staff
    - → new approach for I&C system
SMR Design Characteristics (3)

- Modularization (construction technology)
  - Factory manufactured, tested and Q.A.
  - Heavy truck, rail, and barge shipping
  - Faster construction
  - Incremental increase of capacity addition as needed
SMR Site Specific Considerations

- Site size requirements, boundary conditions, population, neighbours and environs
- Site structure plan; single or multi-unit site requirements

- What site specific issues could affect the site preparation schedule and costs?
- What is the footprint of the major facilities on the site?
## Perceived Advantages & Potential Challenges

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology Issues</strong></td>
<td></td>
</tr>
<tr>
<td>• Shorter construction period (modularization)</td>
<td>• Licensability (first-of-a-kind structure, systems and components)</td>
</tr>
<tr>
<td>• Potential for enhanced safety and reliability</td>
<td>• Non-LWR technologies</td>
</tr>
<tr>
<td>• Design simplicity</td>
<td>• Operability and Maintainability</td>
</tr>
<tr>
<td>• Suitability for non-electric application (desalination, etc.)</td>
<td>• <strong>Staffing for multi-module plant;</strong> Human factor engineering;</td>
</tr>
<tr>
<td>• Replacement for aging fossil plants, reducing GHG emissions</td>
<td>• Post Fukushima action items on design, safety and licensing</td>
</tr>
<tr>
<td></td>
<td>• Advanced R&amp;D needs</td>
</tr>
<tr>
<td><strong>Non-Techno Issues</strong></td>
<td></td>
</tr>
<tr>
<td>• Fitness for smaller electricity grids</td>
<td>• Economic competitiveness</td>
</tr>
<tr>
<td>• Options to match demand growth by incremental capacity increase</td>
<td>• Plant cost estimate</td>
</tr>
<tr>
<td>• Site flexibility</td>
<td>• Regulatory infrastructure</td>
</tr>
<tr>
<td>• <strong>Reduced emergency planning zone</strong></td>
<td>• Availability of design for newcomers</td>
</tr>
<tr>
<td>• Lower upfront capital cost (better affordability)</td>
<td>• Post Fukushima action items on institutional issues and public acceptance</td>
</tr>
<tr>
<td>• Easier financing scheme</td>
<td></td>
</tr>
</tbody>
</table>
# Elements that facilitate SMR deployment

<table>
<thead>
<tr>
<th>Large Reactors (&gt;700MWe)</th>
<th>SMRs (&lt;700MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow to Deploy</td>
<td>Faster Construction (factory produced modules)</td>
</tr>
<tr>
<td>Expensive to Build</td>
<td>Smaller Capital Layout (stagger construction)</td>
</tr>
<tr>
<td>Large Capacity</td>
<td>Small to Medium Capacity (replace high-C plants)</td>
</tr>
<tr>
<td>Baseload Power</td>
<td>More Flexible Power (demand-follow)</td>
</tr>
<tr>
<td>Electric Only</td>
<td>Diverse applications, Non-Electric (desalination, process heat)</td>
</tr>
<tr>
<td>Large EPZ</td>
<td>Smaller EPZ allowing new siting opportunities</td>
</tr>
</tbody>
</table>
An example of SMR: NuScale (1)

- **Full name**: NuScale
- **Designer**: NuScale Power Inc., USA
- **Reactor type**: Integral Pressurized Water Reactor
- **Coolant/Moderator**: Light Water
- **Neutron Spectrum**: Thermal Neutrons
- **Thermal/Electrical Capacity**: 165 MW(t)/45 MW(e)
- **Modules per plant**: (1 – 12) modules
- **Fuel Cycle**: 24 months
- **Salient Features**: Natural circulation cooled; Decay heat removal using containment; built below ground
- **Design status**: Design Certification application in 4th Quarter of 2016
An example of SMR: NuScale (2)

Overview of NuScale Design

NuScale Power Module

- reactor building crane
- biological shield
- pool water
- refueling machine
- reactor building
- spent fuel pool
- weirs
- containment vessel
- steam generator
- reactor vessel
- core
- NuScale Power Modules
- containment vessel flange tool
- reactor vessel flange tool
An example of SMR: KLT-40S (1)

- **Designer:** OKBM Afrikantov – Russian Federation
- **Reactor type:** PWR – Floating Nuclear Cogeneration Plant
- **Coolant/Moderator:** H₂O
- **Neutron Spectrum:** Thermal Neutrons
- **Thermal/Electric capacity:** 150 MW(t) / 35 MW(e)
- **Fuel Cycle:** Single-Loading of LEU fuel with initial uranium enrichment <20% to enhance proliferation resistance
- **Salient Features:** based on long-term experience of nuclear icebreakers; cogeneration options for district heating and desalination
- **Design status:** 2 units finalizing construction aims for commissioning in Q4 of 2016
An example of SMR: KLT-40S (2)

(Source: http://www.uxc.com)
IAEA is engaged in SMR Deployment Issues

Nine countries developing ~40 SMR designs with different time scales of deployment and 4 units are under construction (CAREM25, HTR-PM, KLT-40s, PFBR500)

Commercial availability and operating experience in vendors’ countries is key to embarking country adoption

Countries understand the potential benefits of SMRs, but support needed to assess the specific technology and customize to their own circumstances

Indicators of future international deployment show positive potential