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SMR projects: an experience and a perspective

21st INPRO Dialogue Forum on the Deployment of Small Modular Reactor Projects and Technologies to Support the Sustainable Development Goals, Sankt-Petersburg, 28 August - 01 September 2023

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Center for Analytical Research and Developments (CARD)

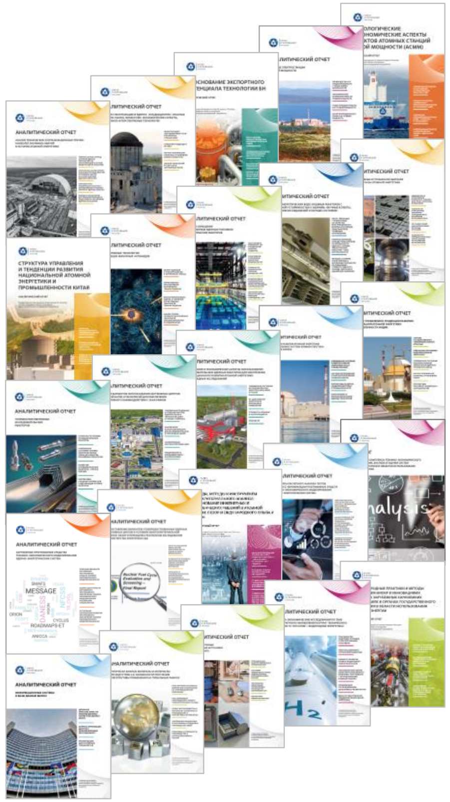
30 August 2023

CARD Analytical Reports

CARD annually issues **analytical reports focused on key directions of SC Rosatom technological development**.

Objective – to provide the SC Rosatom management and expert community with relevant, and objective analytical information.

Reports are reviewed by industry experts, discussed at hearings, deposited and published.



34 analytical reports issued

Relevant Reports Published:

"Analysis of technical and organizational causes of the most severe accidents in the history of nuclear power" (2021)

"Technical and Economic Aspects of SMR projects" (2019)

"Medium Power NPPs" (2022)

“Technical and Economic Aspects of SMR Projects” (2019)

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An analytical study “Technical and Economic Aspects of SMR Projects” has been issued by CARD in 2019.

The study included:

- **statistical analysis** of 54 foreign and 38 domestic SMR projects by their power, reactor technology, readiness level and vendor;
- identifying **effects of scale, “learning” and reactor technology** on the economic characteristics of SMRs;
- analysis of **requirements of potential SMR markets** – “Grid” market (the basic generation in medium and large grids) and “Off Grid” market (the energy supply for remote communities);
- preliminary **multiple-aspect assessment** of the SMR projects competiveness based on different reactor technologies.

The study emphasized that **the multiple-aspect** (including technical and economic considerations) **approach is necessary to compare and select SMR projects.**

The revision of the study is planned to be issued in 2023 and will include approaches and methodologies of economic analysis with application to the RITM-200 project.

SMRs as a Tool to Mitigate Risks of Nuclear Power Projects

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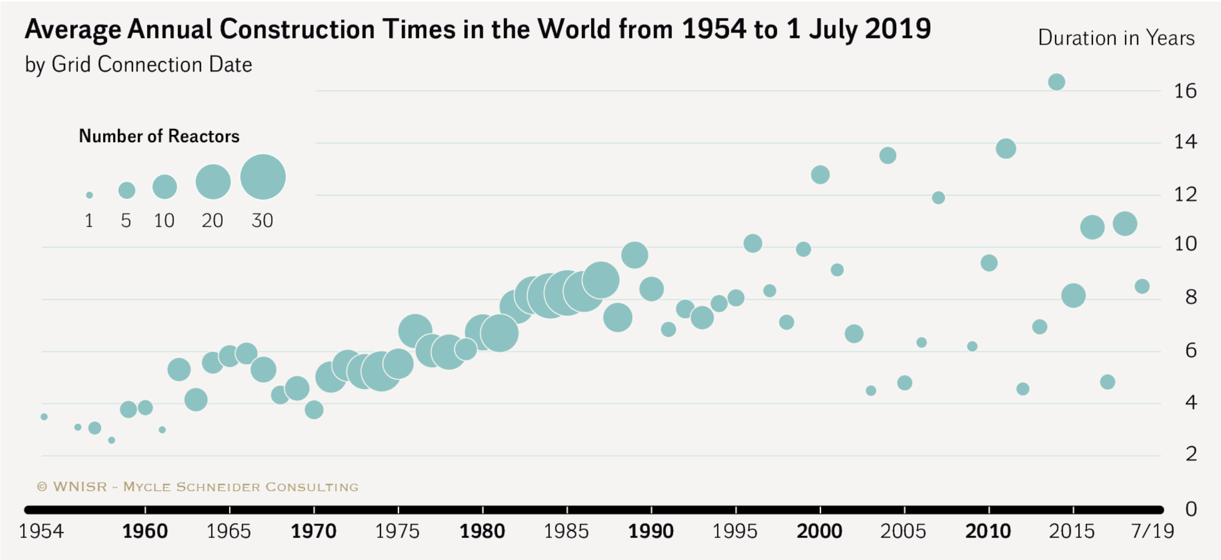

In addition to increase in the construction time of NPPs' units (by about 3 years in 20 years), there is a growing "turbulence" - the uncertainty in the timing of the construction, which should be considered as a factor of risk.

In order to mitigate risks a possible path of nuclear power plants evolution (similar to evolution in the animal kingdom) - from large "types" to smaller ones.

Russia's Experience in SMR

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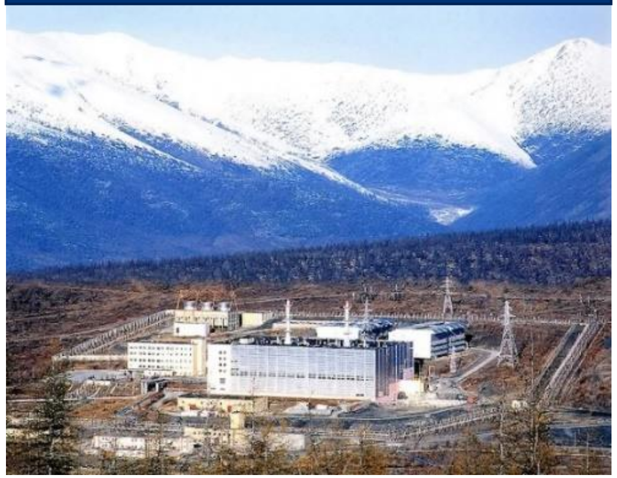
Bilibino NPP



4*EGP-6 (3 in operation now)
(LWGR, 3*12 MW(e)),
in operation since 1974 at
**strong weather conditions –
-60 in winter!**

"Akademik Lomonosov" FNPP

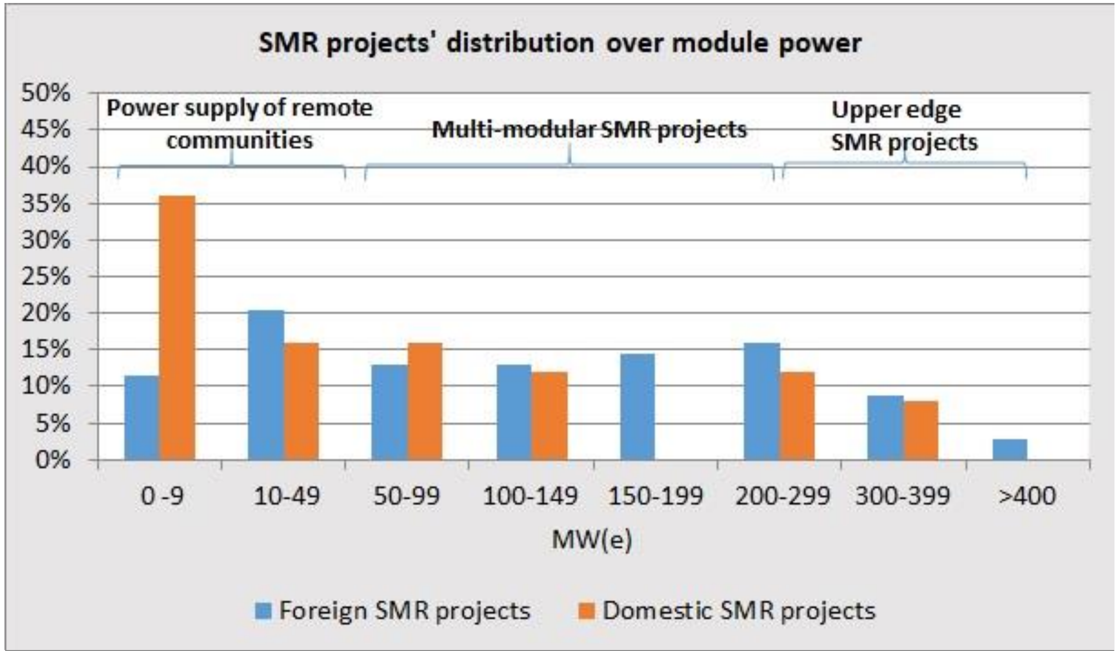
2*KLT-40S
(PWR, 77 MW(e)),
Commissioned in 2019.

RITM-200

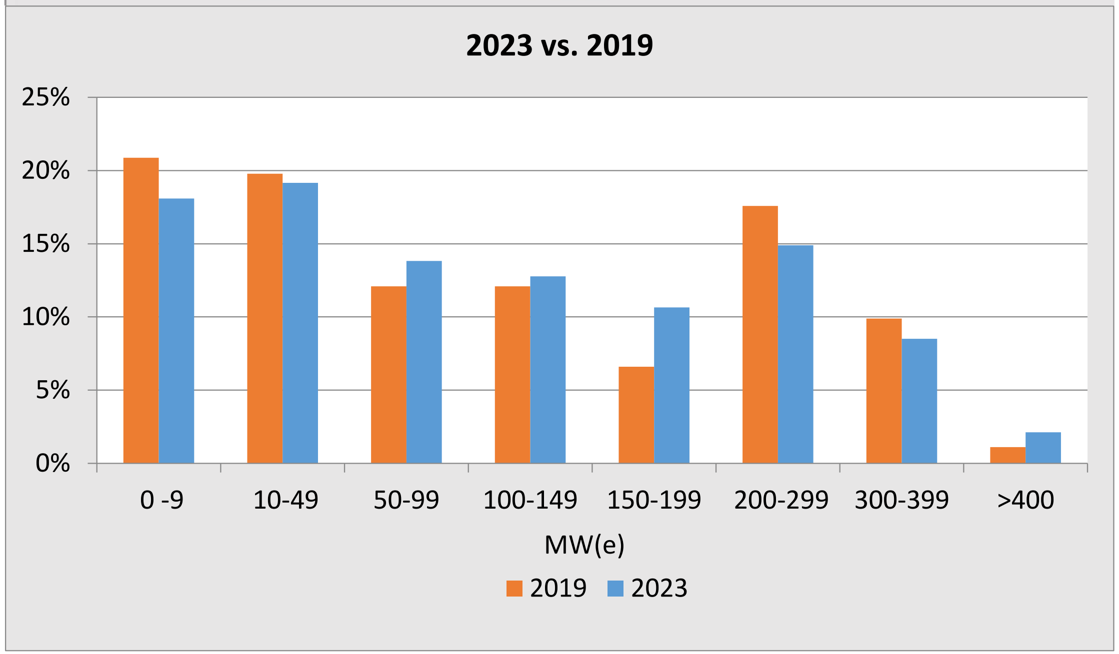
Installed on icebreakers
(iPWR, 40 MW(e))
Six reactors manufactured
since 2019.
45% less in dimensions and
35% less in mass compared to
KLT-40S.

SMR Projects' Distribution over Module Power

Distribution of RF SMR projects over module power shows a maximum at range <10 MW(e) – developers are focused mainly on the power supply of remote communities in north regions.

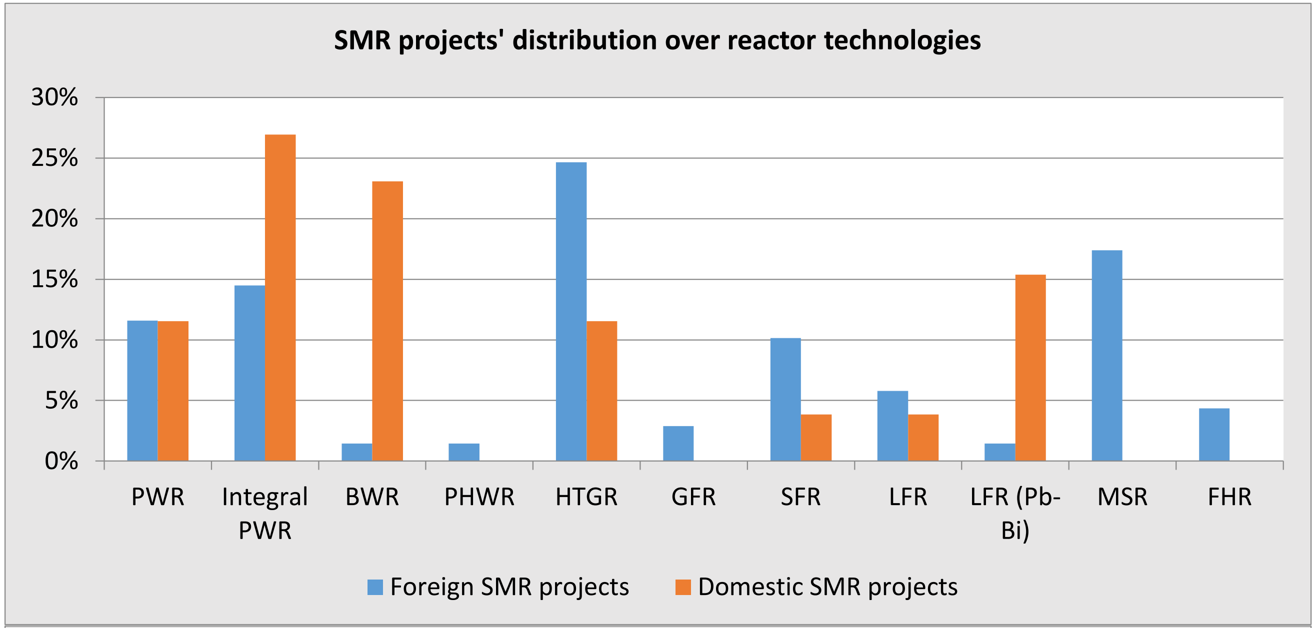


Maximum increase in SMR projects number from 2019 to 2023 is observed in power range of 150-200 MW(e).

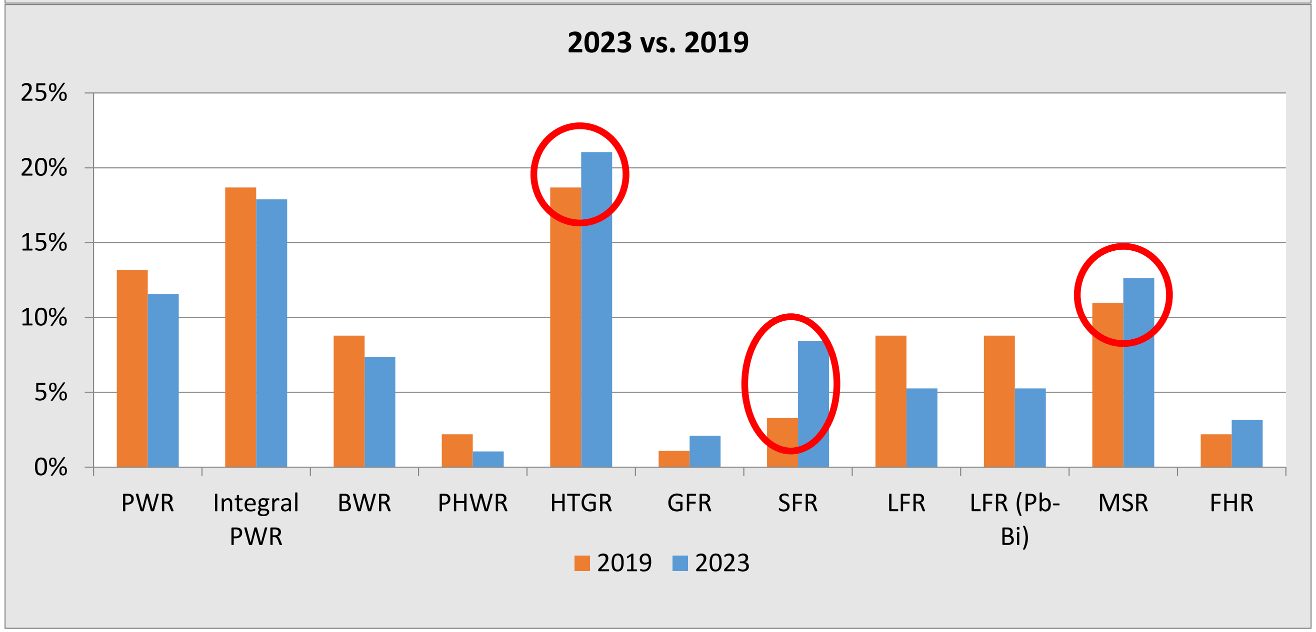


SMR Projects' Distribution over Reactor Technologies

Most of RF SMR projects are based on proven reactor technologies – integral PWR and BWR.



An increase in quantity of SMR projects based on innovative reactor types (SFR, HTGR and MSR) is observed in 2023.



Anticipated Requirements to SMR Projects on “Grid” and “Off-Grid” Markets

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Parameter	“Off-Grid” market: remote communities	“Grid” market: generation in medium and large grids
LCOE (at WACC=5%), $/MWh	≤ **100** Competition with: Diesel generation ~ 300-500[1]; Renewables ~ 150-200[1] at strong weather conditions; LNG ~ 90 – 150[1] (including transportation).	≤ **50** Competition with: Coal ~75-100[2] (120 with CCS); Gas combined cycle ~35-80[2] (75-100 with CCS); Large power nuclear ~50-100[2]; Wind, onshore ~35-70[2]; Wind, offshore ~110-170 (85-130 with tax credit)[2]; Solar: ~35-100[2].
Power of SMR module	~ 30-50 MW; Up to 4-5 modules on site.	~ 100-200 MW; Up to 10-12 modules on site for replacement of coal and large power nuclear generation.
Applications	1. Communal heat 2. Electric power 3. Water desalination	1. Electric power 2. Water desalination 3. Communal heat 4. Industrial heat.
Load following	100-30-100% within 24 hours, otherwise a support by diesel/energy storage system will be required that increases LCOE.	100-50-100% in grids having a power reserve.
Fuel cycle	Refueling once in 5 years (or more) on site with centralized service by vendor.	Refueling once in 12-24 moths by operator.

[1]Calculated LCOE [2]NEA OECD (2022).

Potential of Advanced Reactor Technologies in LCOE Reduction

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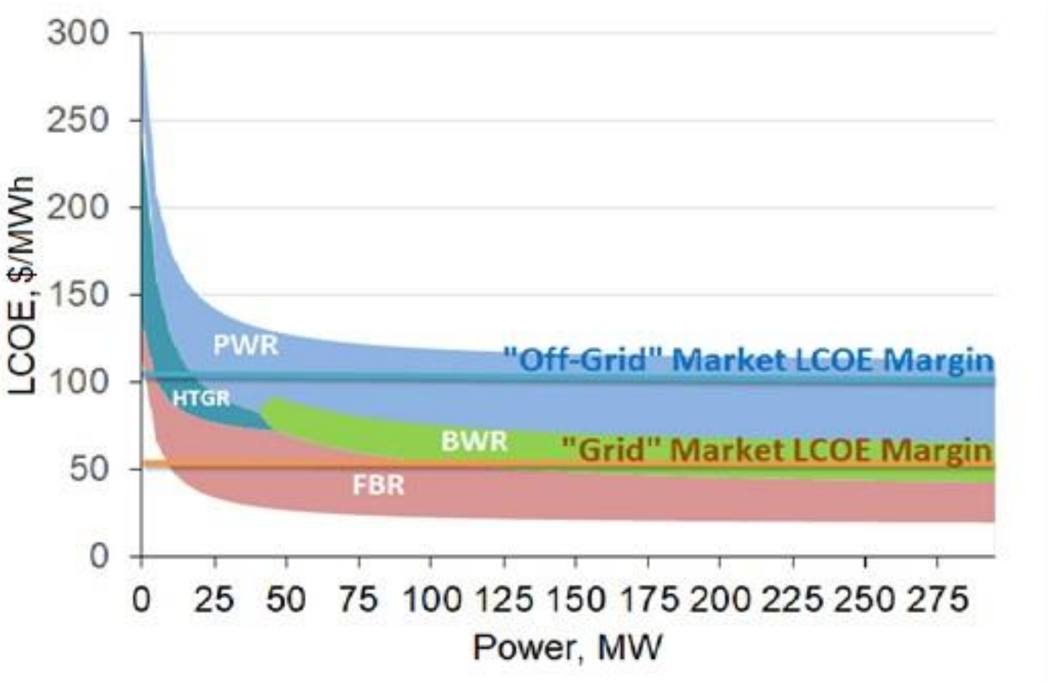
According to results of CARD SMR study:

- maximal potential of LCOE reduction have SMRs with liquid metal cooled reactors (Na, Pb/Bi) but non-proliferation issues need to consider;
- HTGR with Brayton cycle have certain potential to reduce LCOE, but their deployment requires a deep R&D.



SMR Concepts expected to be completed up to 2030

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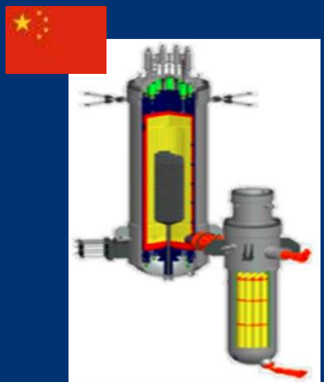
Recently commissioned SMRs

"Akademik Lomonosov", 2*KLT-40 (PWR), 77 MW(e) – since 2019



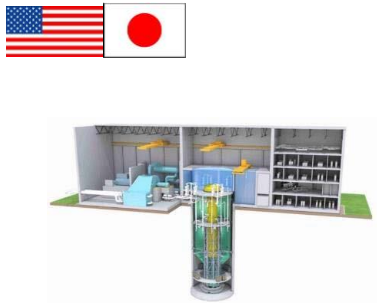
HTR-PM, HTGR, 2*250 MW(th)/210 MW(e) – since 2021

LWR based SMR projects

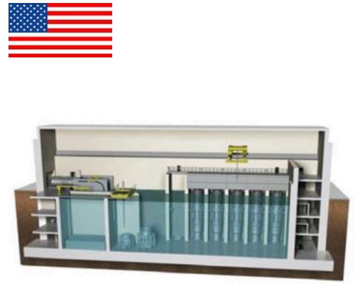
APC100 (CNNC), iPWR, 125 MW(e) **2026**

CAREM (CNEA), iPWR, 32 MW(e) **2028**

RITM-200N (Rosatom), iPWR, 55 MW(e) **2028**



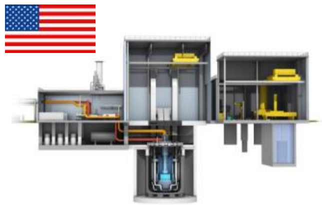
BWRX-300 (GE-Hitachi), BWR, 300 MW(e) **2028**



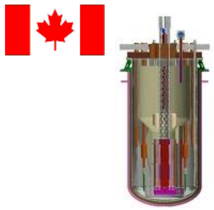
VOYGR™ (NuScale Power), iPWR, (6-12)*77 MW(e) **2029**

SMR projects based on advanced reactor technologies

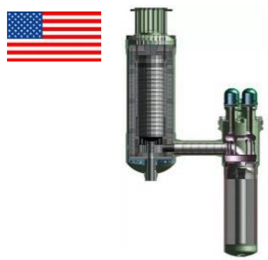
BREST-OD-300 (Rosatom), LFR, 300 MW(e) **2026**



Natrium (TerraPower), SFR, 345 MW(e) **2028**



ARC-100 (ARC Clean Energy), SFR, 100 MW(e), **2029**



Xe-100 (X-Energy), HTGR, 80 MW(e) FOAK to **the end of 2020s**.

CMSR (Seaborg Tech.), MSR, 100 MW(e) **2028**

Licensing Statuses of SMR Projects (LWR SMRs)

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<table>
<tr><th>Vendor, country</th><th>SMR project</th><th>Technology</th><th>Power, MW(e)</th><th>Country of review</th><th>Review beginning</th><th>Status of review</th></tr>
<tr><td rowspan="2">NuScale Power, LLC, USA</td><td>NuScale</td><td>iPWR</td><td>12*50</td><td>USA</td><td>March, 2017</td><td>Standard Design Approval received from the NRC in September 2020</td></tr>
<tr><td>VOYGR™</td><td>iPWR</td><td>6*77</td><td>USA</td><td>January, 2022</td><td>Pre-Application for a Combined License</td></tr>
<tr><td rowspan="2">SMR, LLC (Holtec), USA</td><td rowspan="2">SMR-160</td><td rowspan="2">iPWR</td><td rowspan="2">160</td><td>Canada</td><td>July, 2018</td><td>Review completed</td></tr>
<tr><td>USA</td><td>2020</td><td>Pre-Application</td></tr>
<tr><td>KAERI, Korea</td><td>SMART</td><td>iPWR</td><td>107</td><td>Р.Корея</td><td></td><td>Standard Design Approval Applied (2020)</td></tr>
<tr><td>CEA & EDF, France</td><td>NUWARD</td><td>iPWR</td><td>2*170</td><td>Франция</td><td>July, 2023</td><td>Prelicensing process begun</td></tr>
<tr><td>CNNC/NPIC, China</td><td>ACP100</td><td>iPWR</td><td>125</td><td>КНР</td><td></td><td>PSAR planned to submit to National Nuclear Safety Authority in 2023</td></tr>
<tr><td rowspan="3">GE-Hitachi Nuclear Energy, USA-Japan</td><td rowspan="3">BWRX-300</td><td rowspan="3">BWR</td><td rowspan="3">300</td><td>USA</td><td>Decembrt, 2019</td><td>Pre-Application</td></tr>
<tr><td>Canada</td><td>January, 2020</td><td>Phase 2 of VDR completed</td></tr>
<tr><td>Великобритания</td><td></td><td>Pre-Application</td></tr>
</table>

Licensing Statuses of SMR Projects (non-LWR SMRs)

Vendor, country	SMR project	Technology	Power, MW(e)	Country of review	Review beginning	Status of review
ARC Nuclear Canada Inc., Canada	ARC-100	SFR	100	Canada	September, 2017	Phase 2 VDR
Ultra Safe Nuclear Corporation, USA	MMR-5 и MMR-10,	HTGR	5-10	Canada	December, 2016	Phase 2 VDR
X-Energy, USA	Xe-100	HTGR	80	Canada	July, 2020	Phase 2 VDR
				USA		Pre-Application
Westinghouse Electric Company, LLC, USA	eVinci Micro Reactor	HTGR	<5	Canada	January, 2023	Phase 2 VDR planned to begin in 2023
Terrestrial Energy Inc., Canada	IMSR (Integral Molten Salt Reactor)	MSR	200	Canada	November, 2017	Phase 2 of VDR completed
				USA		Pre-Application
Moltex Energy, UK	Moltex Energy Stable Salt Reactor	MSR	300	Canada	December, 2017	Phase 2 VDR

Comparative Assessment of Generation 4 Reactor Technologies

1 - Based on Ongoing Reactor Projects

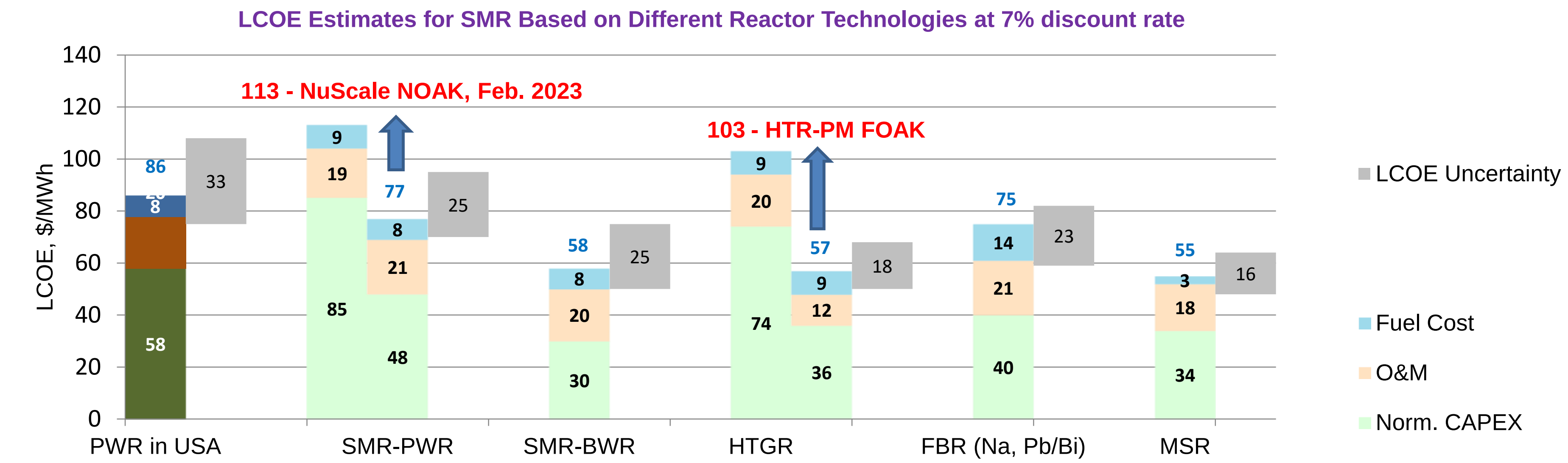
Areas	Criteria	Reactor technologies						
		PWR	SFR	VHTR	LFR	SCWR	GFR	MSR
Sustainability	Neutron spectrum	Thermal	Fast	Thermal	Fast	Intermediate / fast	Fast	Thermal / Intermediate
	Burnup, MWd/kg U	~40-60	~100-120	>100	~90	~60	>100	–
	Type of fuel	Oxide	Oxide / metal/ nitride	TRISO	Oxide / nitride	Oxide	Ceramic matrix (ZrC, TiN)	Molten salt
	Efficiency of MA incineration	-	Medium	High	Medium	Low	High	High
	Refuelling period, months	12-24	18	Online refuelling / 18-24	12-18	12-18	12-18	Online refuelling
Safety and Reliability	Coolant	H_2O	Na	He / CO_2	Pb / Pb-Bi	H_2O	He	Fluorides/ Chlorides
	Pressure in the primary circuit, MPa	16	0,1	7,0	0,1	22,5	7,0	0,1
	Quantity of safety barriers	4	4	4	4	4	4	2
Proliferation Resistance and Physical Protection	Non-attractiveness of nuclear fuel materials	1	2	3	2	2	3	1
Economics	Expected CAPEX, $/MW	1	~0,9	~0,8	~0,9	~0,8-0,9	~0,8	~0,7
	Quantity of circuits	2	3	1-2	2	1-2	1-2	2
	Thermal efficiency, %	33	40	>55	41-43	45-50	>50	45-50
	Potential for non-electrical applications	Low (298-329 °C)	Medium (500-550 °C)	High (750-950 °C)	Medium (480-570 °C)	Medium (510-625 °C)	High (850 °C)	High (700-800 °C)
	Potential for load following	Use is limited	Use is limited	Wide range	Use is limited	Use is limited	Wide range	Wide range

Comparative Assessment of Generation 4 Reactor Technologies

2 - Based on Current Development Level

Criteria	Reactor technologies						
	PWR	SFR	VHTR	LFR	SCWR	GFR	MSR
	World						
Availability of large-scale experimental stands	In operation	In operation	In operation	In operation	Lack	In operation	Lack
Research/experiment. reactors using this technology or loop facilities	In operation	In operation	In operation	Lack	Lack	Lack	Lack
Expected date of power reactors commissioning	In operation	Until 2025 (Generation III+ reactor under In operation)	In operation (prototype)	2025-2030	After 2030	After 2030	~ 2030
Level of the fuel development	Mastered	Mastered	Mastered	Reactor research	Laboratory tests	Laboratory tests	Bench testing
Level of the coolant development	Mastered	Mastered	Mastered	Full-scale tests	Bench testing	Mastered	Bench testing
Level of the structure materials development	Mastered	Mastered	Mastered	Full-scale tests	Laboratory tests	Laboratory tests	Bench testing
	Russia						
Availability of large-scale experimental stands	In operation	In operation	Lack	In operation	In operation	--	Lack
Research / experiment. reactors using this technology or loop facilities	In operation	In operation	Lack	Lack	Lack	--	Lack
Expected date of power reactors commissioning	In operation	After 2030 (Generation III+ reactor under In operation)	After 2030 г.	2026-2030	After 2030	--	After 2030
Level of the fuel development	Mastered	Mastered	Reactor research	Reactor research	Laboratory tests	--	Bench testing
Level of the coolant development	Mastered	Mastered	Bench testing	Bench testing	Bench testing	--	Bench testing
Level of the structure materials development	Mastered	Mastered	Bench testing	Bench testing	Bench testing	--	Bench testing

A Correlation between LCOE and TRL



According to a Report of Energy Technology Institute (UK), 2018

The question for further studies is: how strong the economical characteristics (CAPEX and LCOE) of SMR projects are correlated with their readiness levels, and **how much the economics of SMR projects can change with increase of TRL in reality.**

Beyond Economics: A Multiple-aspect Approach Required

The above margin on LCOE for the “Off Grid” market may not be an imperative.

1 kWh of energy from AA battery costs ~**166$ ($166000/MWh).**
But no one refuses batteries, because their purpose is **not to sell electricity to the network**, but to power the corresponding devices.
Similarly, the probable purpose of SMR on the “Off Grid” market is **the local and regional energy supply** of individual communities and industries that are not covered by centralized energy supply (currently subsidized).
This is the difference between SMRs and LP NPPs, the defining quality of which are economic indicators.

The economic aspects should be weighted with:
- social aspects – enhance a living conditions for residents of remote and isolated territories;
- environmental aspects – to solve the problem of the negative impact of the fossil fuels use on the environmental situation (especially in the Arctic region, where the cost of eliminating the accumulated environmental damage is measured in hundred millions USD).

The deployment of SMRs for “Off Grid” market assuming these aspects should be supported by government.

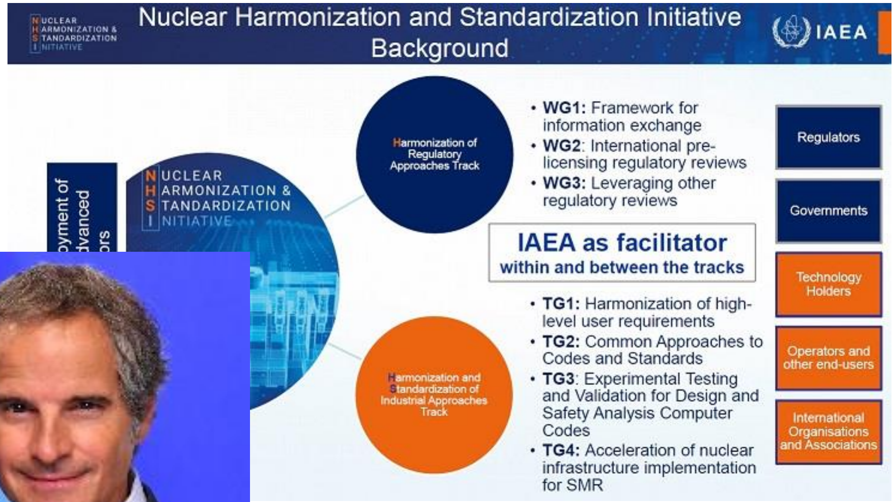
Optimization of SMR Licensing

A “guaranteed safety” in case of SMRs means an elimination of reactor vessel rupture during any anticipated accident since the surface to volume ratio is increasing with decrease of the power as 1/Power.

It is necessary to develop safety standards for SMRs based on scaling down in proportion to the power, volume of nuclear materials, requirements for safety systems and the radius of the protective measures planning zone, for their further approval by regulatory bodies.

The initiative on harmonization and standardization of a regulatory framework and licensing mechanisms for SMRs (NHSI) being formed currently in different countries has been launched by IAEA in 2022, Rosatom is supporting it (CARD is participating).

22.03.23 Scientific and Engineering Centre for Nuclear and Radiation Safety and CARD held a workshop on the information and analytical support of safely operation of nuclear power plants including SMRs.



Nuclear Liability Insurance

Is intend to decrease the charge paid by nuclear operators.

- Vienna convention on Civil Liability for Nuclear Damage of 1963:

  The liability of the operator for one nuclear incident may be limited not less than $5 M in terms of gold on 29 April 1963 ($ 35 per one troy ounce of gold) – is about $250 M now.

  National laws in most of member countries established limits of civil liability on nuclear operator close to that amount (~$300 M).

  But it is **1000 times lower** than the possible damage caused by major nuclear accident like Fukushima or Chernobyl **(~$200-300 Billion**).

- Revised Paris Convention of 2004:

  Basic limit of liability of the operator is established as Minimum €700 M.

The Nuclear Liability Insurance is not effective in terms of coverage of the damage caused by the severe accident on a large power NPP.

The solution is **Hedging the Nuclear Risk by Reducing the Unit Power**.

Hedging the Nuclear Risk by Reducing the Unit Power

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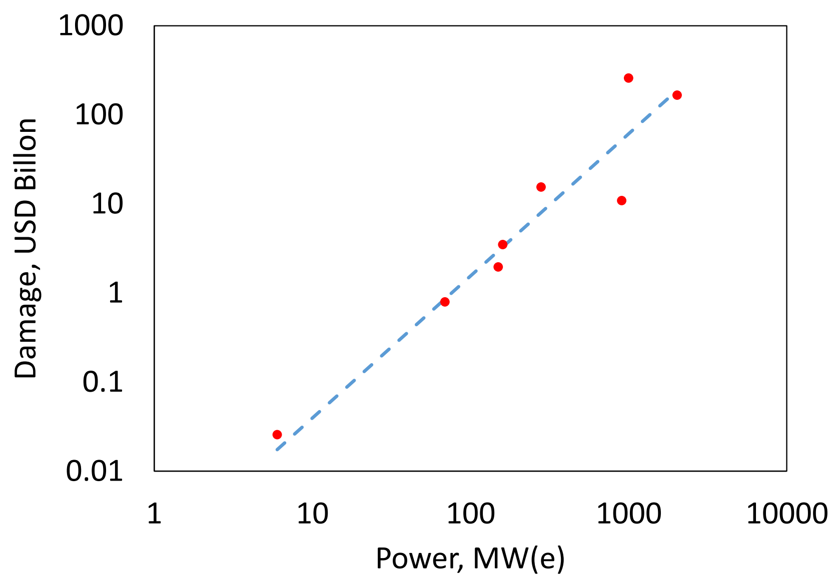
Date	Accident	Damage, USD MM (2013)	Power, MW(e)	INES Level
26.4.1986	Chernobyl NPP, Unit 4 (USSR)	259 336	1000	7
11.3.2011	Fukushima-I, Units 1-3 (Japan)	166 089	2028	7
8.12.1995	Monju reactor (Japan)	15 500	280	-
28.3.1979	Three Mile Island NPP, Unit 2 (USA)	10 910	906	5
22.2.1977	Bohunice A-1 (Czechoslovakia)	1 964.5	150	4
5.10.1966	Fermi-1 reactor (USA)	793.9	69	4
21.01.1969	Lucens reactor (Switzerland)	25.7	6	5

Empirical dependence of maximum damage caused by severe accidents from the reactor power is proven to have a power law with exponent equal to 1.6.

It means, even the number of SMRs modules will increase, the aggregated damage decreases.

Thus, **the nuclear insurance becomes realistic in case of SMRs.** It seems to be important for governments in “newcomer” countries facing extension of operators’ community while implementing SMRs.



More details available at: http://link.springer.com/article/10.1007/s10512-020-00693-5

Conclusions and proposals (1/2)

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- Development of a comprehensive set of criteria for comparing various SMR projects with each other is proposed.
- It is recommended to develop a comprehensive set of requirements to SMR projects for "Off-grid" and "Grid" SMR markets, specified for each power level within the entire range of module power for SMRs.
- In a perspective, attention should be paid to the potential of reactor technologies other than PWR (BWR, liquid metal cooled reactors). Depending on the future severity of non-proliferation issues, either SMRs with thermal spectrum HTGRs (the most proliferation-resistant due to the use of TRISO fuel) or SMRs with fast neutron reactors can receive priority.
- The question for further studies is: how strong the economical characteristics (CAPEX and LCOE) of SMR projects are correlated with their readiness levels, and how much the economics of SMR projects can change with increase of TRL in reality.

Conclusions and proposals (2/2)

- A “guaranteed safety” can be achieved for SMRs due to elimination of reactor vessel rupture during any anticipated accident since the surface to volume ratio is increasing as 1/power.
- It is necessary to develop safety standards for SMRs based on scaling down in proportion to the power, volume of nuclear materials, requirements for safety systems and the radius of the protective measures planning zone, for their further approval by regulatory bodies.
- The regulatory framework and licensing mechanisms for SMR projects may be to a certain extent harmonized with international requirements and standards.
- The realistic nuclear liability insurance is possible for SMRs due to the empiric non-linear relation between the damage caused by a severe accident and the reactor power.
- Allowance of real insurance of nuclear liability is important for governments in “newcomer” countries facing extension of operators’ community while implementing SMRs and seems to be appropriate for further consideration at international level within the INPRO.

Thank you
for your attention

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