What Role for Nuclear Energy in Energy Transition: SMRs – a game changer for nuclear energy?"

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2nd Cycle of concurrent sessions – 15.30-17.00

16. Nuclear Energy: some experiences

18th IAEE European Conference: The Global Energy Transition Toward Decarbonization

Milan, 24-27 July, 2023

The role of Nuclear Energy (NE) in the world's energy transition

Is NE an indispensable part of the response to climate change?
Will SMRs take the lead in any serious NE expansion?

- **If Paris Agreement aims to keep rise in temperature below 1.5 C,**
  - **Then in all plausible pathways, NE is necessary**
  - **Is NE likely to play an important role by 2050?**
  - **Not assured yet! but increasingly likely; However, it must overcome major lingering concerns/challenges**
  - **Before COP26: rising interest; But not mentioned in COP26 official statement**
- **NE was discussed in COP27 as part of the main debate**
  - **Mentioned only indirectly (as part of low carbon technologies),**
- **All indicators are that NE will major role at COP28**
  - **NE will likely be mentioned explicitly this time**
  - **SMRs will very likely take centre stage of possible Nuclear Renaissance**

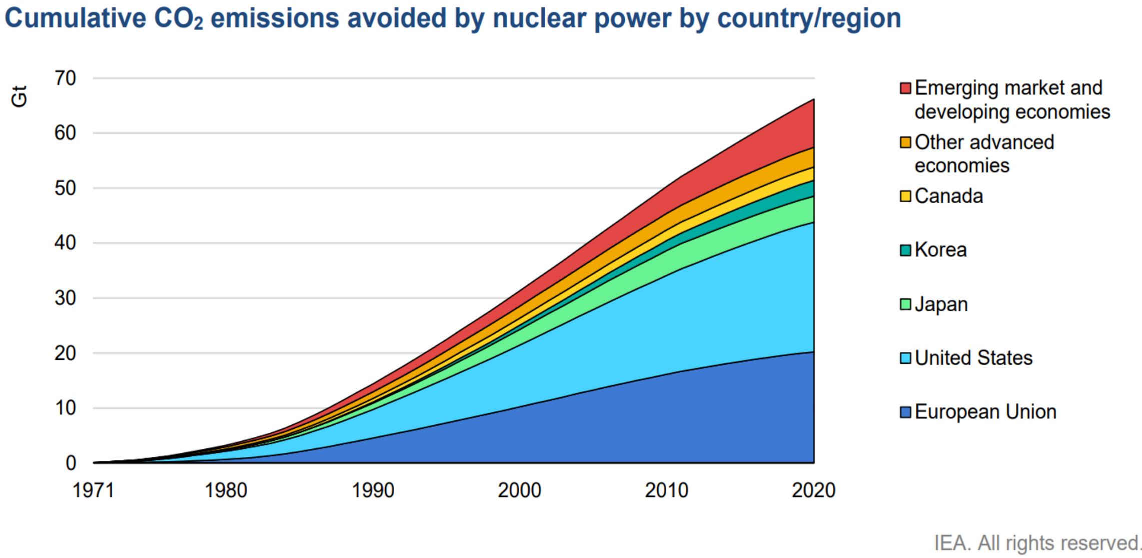
TWO clear Drivers for NE expansion (including deployment of SMRs)

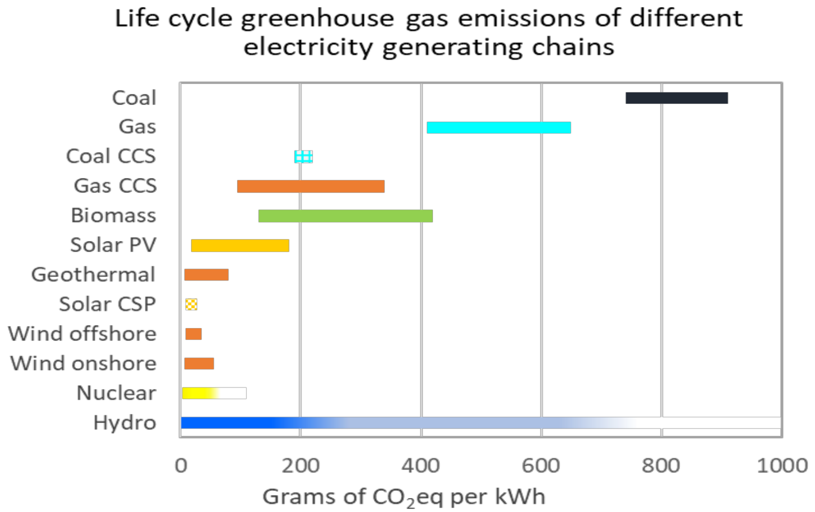
Climate change:

- mitigation needs reliable 24/7 low-carbon electricity supply - VRE needs a reliable partner:
- NE is vital to all Sustainable Development Goals, not just SDG 7, with excellent emission credentials
- Low carbon energy services will increasingly be based on electricity with consequent demand growth to electrify as much as feasible for all sectors & decarbonize electricity

Energy Security:

- Back on the global agenda, following Ukraine war
  - Technology diversity, with nuclear included, is a key element of any low-risk energy transition pathway
  - NE is more than electricity generation: Heating, process heat, hydrogen, water desalination…..
- However, climate benefits of nuclear energy are not visible in the marketplace – Internalization of externalities -





Curtesy H. H. Rogner WFS Webinar 02 Feb. 2023

Challenges, and prospects for a robust nuclear expansion (renaissance)

revised

- **Economic competitiveness of NP has been challenged, mainly** in OECD, **from:**
  - alternative power technologies, mainly RE with rapidly falling prices, helped by favorable environment of incentives/subsidy policies, & low Gas & Coal prices, specially in OECD
  - High upfront investments
  - Excessive cost overruns for GenIII+ delays due loss of engineering knowledge, + FOAK, regulation, etc..
  - Almost impossible for private business to consider new NPP projects w/o strong govt. support, (OECD)
  - No compensation for nuclear 24/7 capacity availability; No recognition of nuclear climate environmental benefits
- **3 S concerns persist**
  - Safety: minimize the risk of release of radioactivity from operations, accidents of NFC
  - Security; protect & secure radioactive material & NFC
  - Safeguards, (non-proliferation): diverting technology and material to military purpose

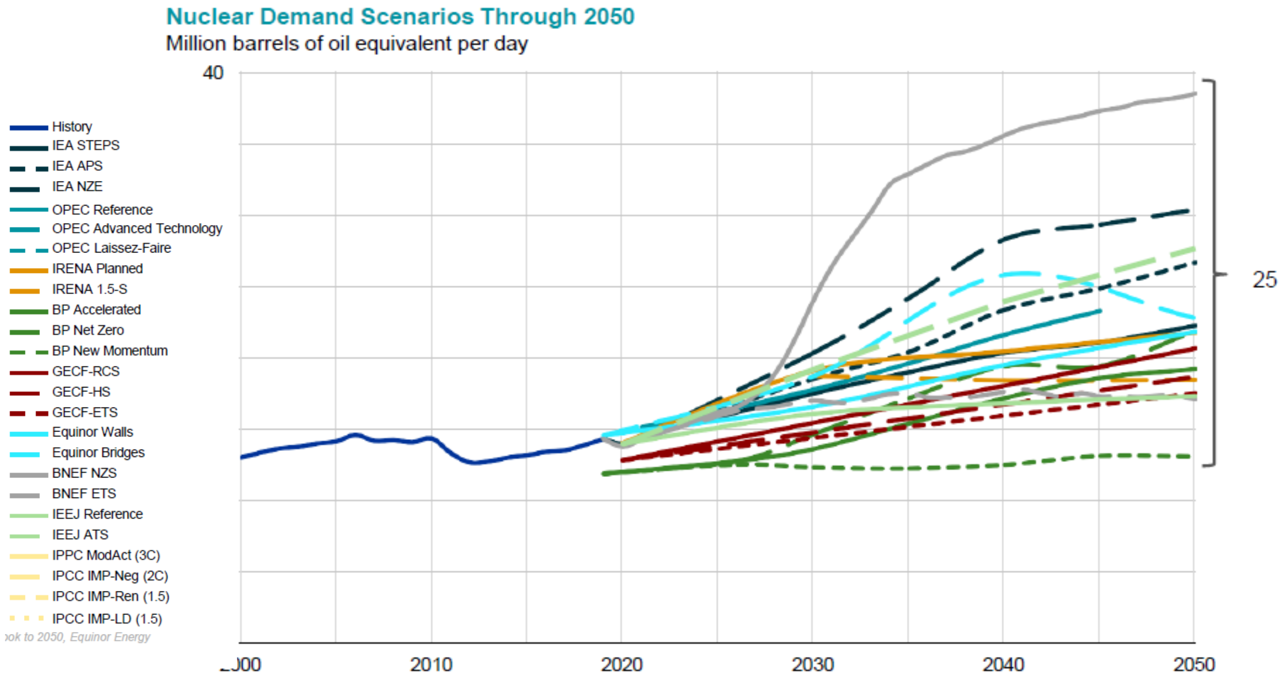
- A rebound of NPP construction in large numbers globally has yet to take off – but:
- Precursors visible , strengthened in the aftermath of Russia's war in Ukraine:
  - Mounting pressures to accelerate the energy system transformation towards NZE by 2050
  - Unrelenting growth of energy demand, especially in developing countries, adds to the challenge
  - License extensions are increasing, an initial step consistent with a renaissance
  - Numerous RD&D activities, outside traditional nuclear vendors has emerged – mostly for SMRs
  - Changes of national policies, combined with accelerated regulatory & technical development
- Prospects are better than ever since Fukushima noticeable increase in % public favoring nuclear

Outlook for Nuclear Power to 2050: Wide divergence but rising projections in recent years

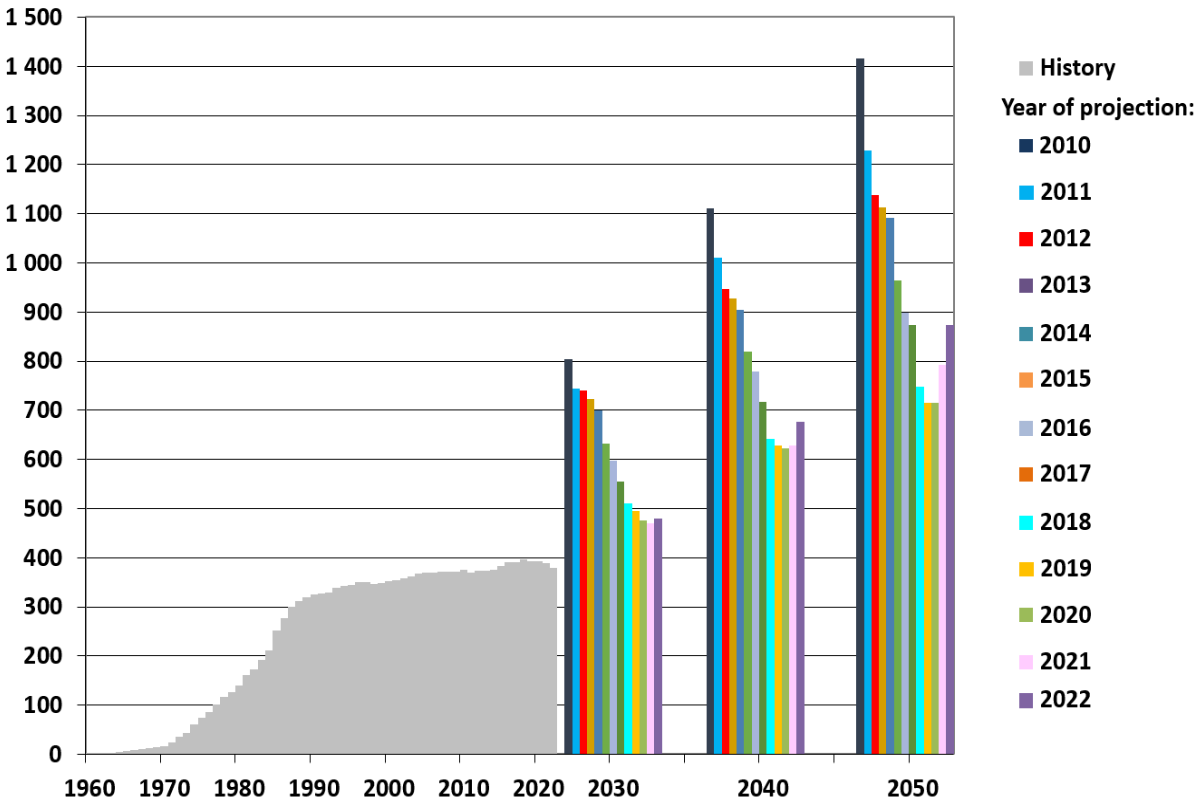
Outlook for Nuclear Energy till 2050: all show increase

- The projected growth in NE shows **wide divergence in outlook for role with upbeat y/y**

- More than Half of All Scenarios Show Nuclear Demand Increasing By >50% in 2050 Compared to 2021 Levels;
- Recent IAEA projections show higher share by 2050



IAEA – Global nuclear capacity outlook (HIGH) Annual projections 2010 to 2022 (GWe)



“SMRs – a game changer for nuclear power?”

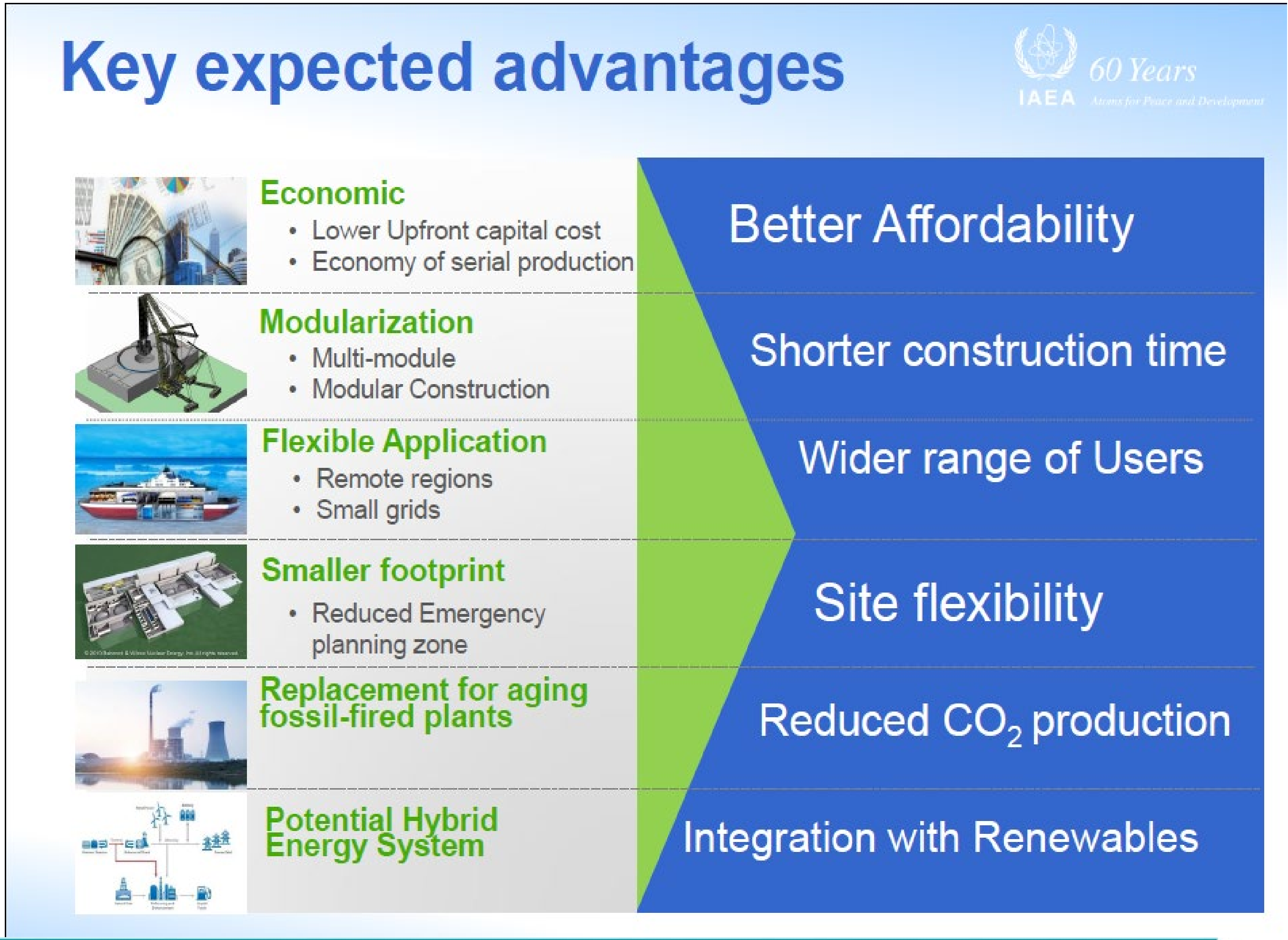
[Will small modular reactors (SMRs), thanks to their enhanced safety, lower cost, smaller size and reduced project risks, improve social acceptance and attract private investment?]

Introduction

What are SMRs?

- Usually understood as advanced reactors with an electricity generating capacity of a few MWe to 300 MWe per module
- The emphasis is on being "small" and "modular" – either all or good part assembled at factory and shipped to site
  - SMRs are significantly smaller than the typical large LWRs now in operation around the world
- Modular implies that a typical nuclear-energy site could either
  - host several individual SMR "modules" , or
  - single modules supplying electricity and other energy services to energy intensive industries, to locations with small grid or serving isolated grids and remote locations

Why rising interest & support for SMRs?



Source: Subki, IAEA 2019

SMR potential: advantages, concerns & challenges vs large reactors:

SMRs have the potential to make a nuclear renaissance happen, together with LRs; taking nuclear energy to the next level

Technology aspects

- Factory fabrication of all or good portion of instead of construction, modularization & multiples unit production
- Design simplicity
- Enhanced, often passive, safety aspects & reliability, including increasing feasibility of SNF take back
- Long refuelling cycles
- Integrability with intermittency and suitability for providing non-electric energy services
- Replacement of retired fossil plants
- Suitable for smaller electricity grids
- *High prospects for technology learning*

Non-Technology aspects

- Lower upfront capital cost exposure
- Easier financing
- Lower exposure to future demand uncertainty
- Site flexibility
- Reduced emergency planning zone………

Technology aspects

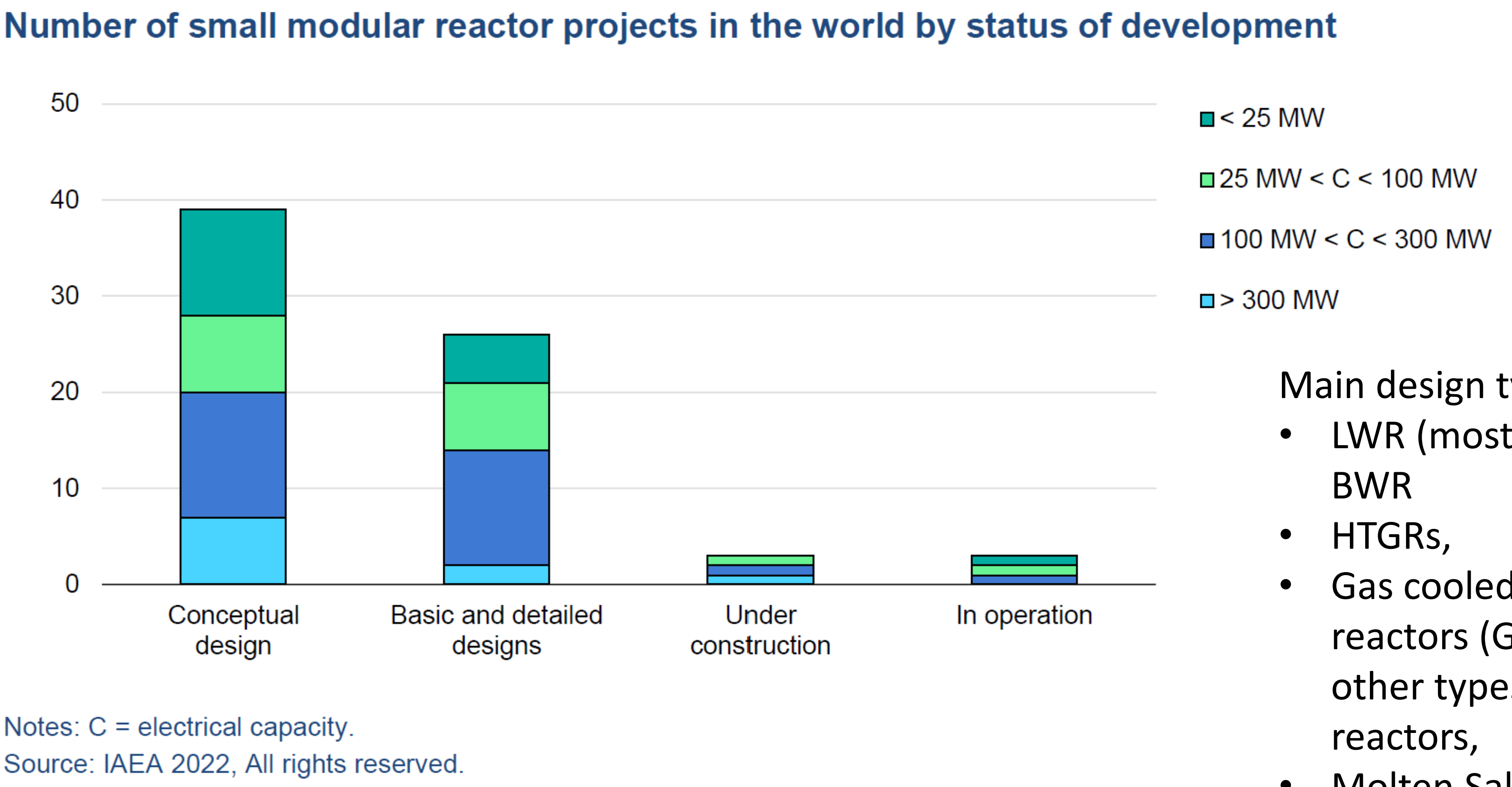
- Licensability (FOAK designs)
- Non-LWR technologies
- Operability and maintainability
- Staffing for multi-module plant
- Supply chain for multi-modules
- Advanced RD&D needs
- Construction of FOAK units

Non-Technology aspects

- **Economic competitiveness (FOAK)**
- Financial institutions
- Large number of designs
- Plant cost estimates
- Regulatory infrastructure
- Availability of designs for newcomers
- Physical security unique to SMRs
- NSF handling unique to SMRs
- Institutional issues,
- LT govt. support & public acceptance

Number of small modular reactor projects in the world

Currently there are > 80 SMR designs under development for advanced applications and different phase of development, IAEA

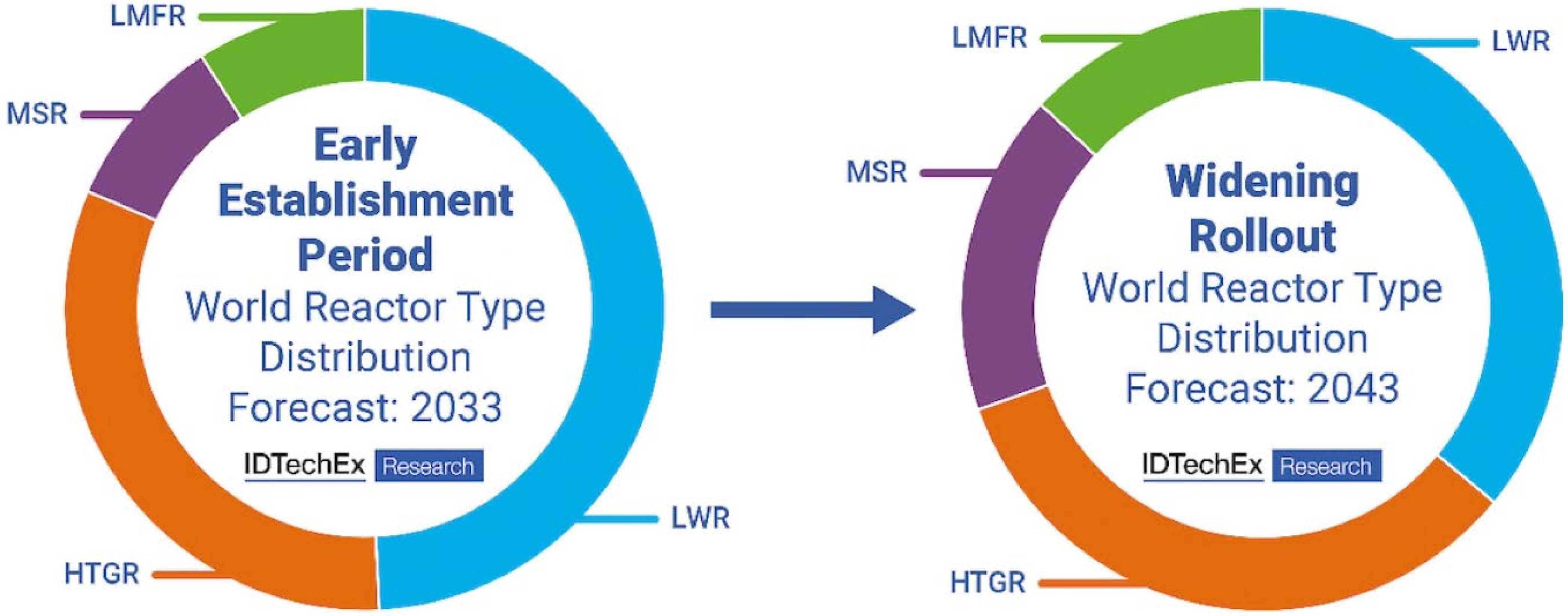


Main design types:

- LWR (mostly PWR but also BWR
- HTGRs,
- Gas cooled modular fast reactors (GCFRs), and other types of fast reactors,
- Molten Salt reactors (MSR)

Source: IEA, June 2022

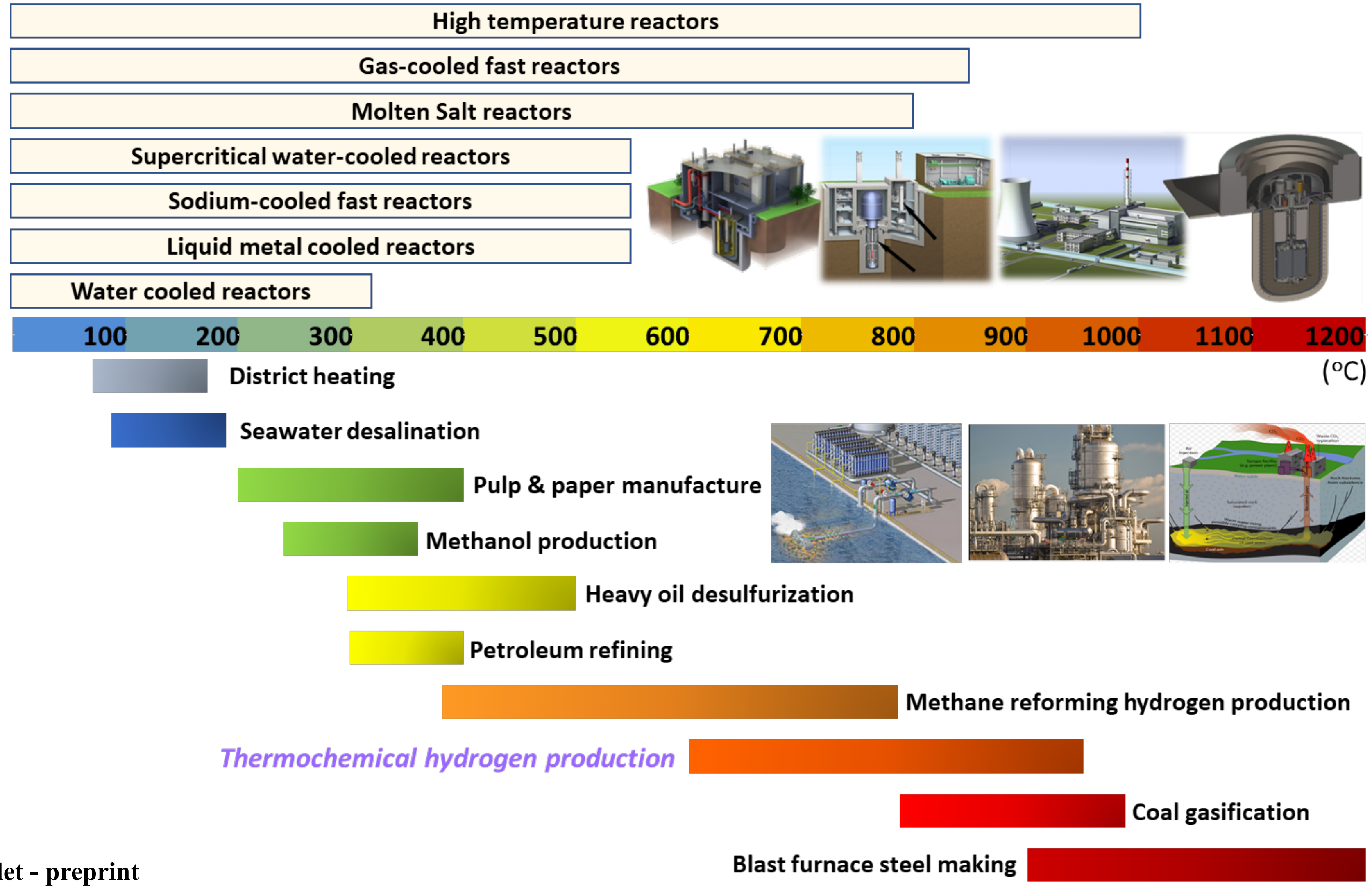
Nuclear Power and Secure Energy Transitions: From today's challenges to tomorrow's clean energy systems



The distribution of reactor technologies globally is expected to change as the SMR fleet becomes more established. Source: IDTechEx

SMRs for non-electric application

Reactor Type, Temperature and Application



Source: IAEA 2022 (SMR Booklet - preprint

Designs and Status of SMRs for Near-Term Deployment (IAEA 2022)

Design and Status of SMRs for Near Term Deployment

Design	Output MW(e)	Type	Designers	Country	Status
WATER COOLED SMALL MODULAR REACTORS					
CAREM	30	PWR	CNEA	Argentina	**Under construction**
ACP100	125	PWR	CNNC	China	**Under construction**
NUWARD	2 × 170	PWR	EDF, CEA, TA, Naval Group	France	Conceptual design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea	Standard design approval received
KLT-40S	2 × 35	PWR in floating NPP	JSC Afrikantov OKBM	Russian Federation	**In operation**
RITM-200N	2 × 53	PWR	JSC Afrikantov OKBM	Russian Federation	Detail design
UK SMR	443[a]	PWR	Rolls-Royce and Partners	United Kingdom	Conceptual design
NuScale	6 × 77	PWR	NuScale Power Inc.	United States of America	Received US NRC certification
BWRX-300	270–290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	United States of America and Japan, Canada	Pre-licensing
HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	**In operation**
GTHTR300	100–300	HTGR	JAEA	Japan	Pre-licensing
Xe-100	82.5	HTGR	X-Energy LLC	United States of America	Basic design
FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
EM²	265	GMFR	General Atomics	United States of America	Conceptual design
MOLTEN SALT SMALL MODULAR REACTORS					
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual design
KP-FHR	140	Pebble bed salt cooled Reactor	KAIROS Power, LLC.	United States of America	Conceptual design
MICROREACTORS					
U-Battery	4	HTGR	Urenco	United Kingdom	Conceptual design
MMR	5–10	HTGR	Ultra Safe Nuclear Corporation	United States of America, Canada	Conceptual design
Aurora	1.5	FR	OKLO, Inc.	United States of America	Conceptual design

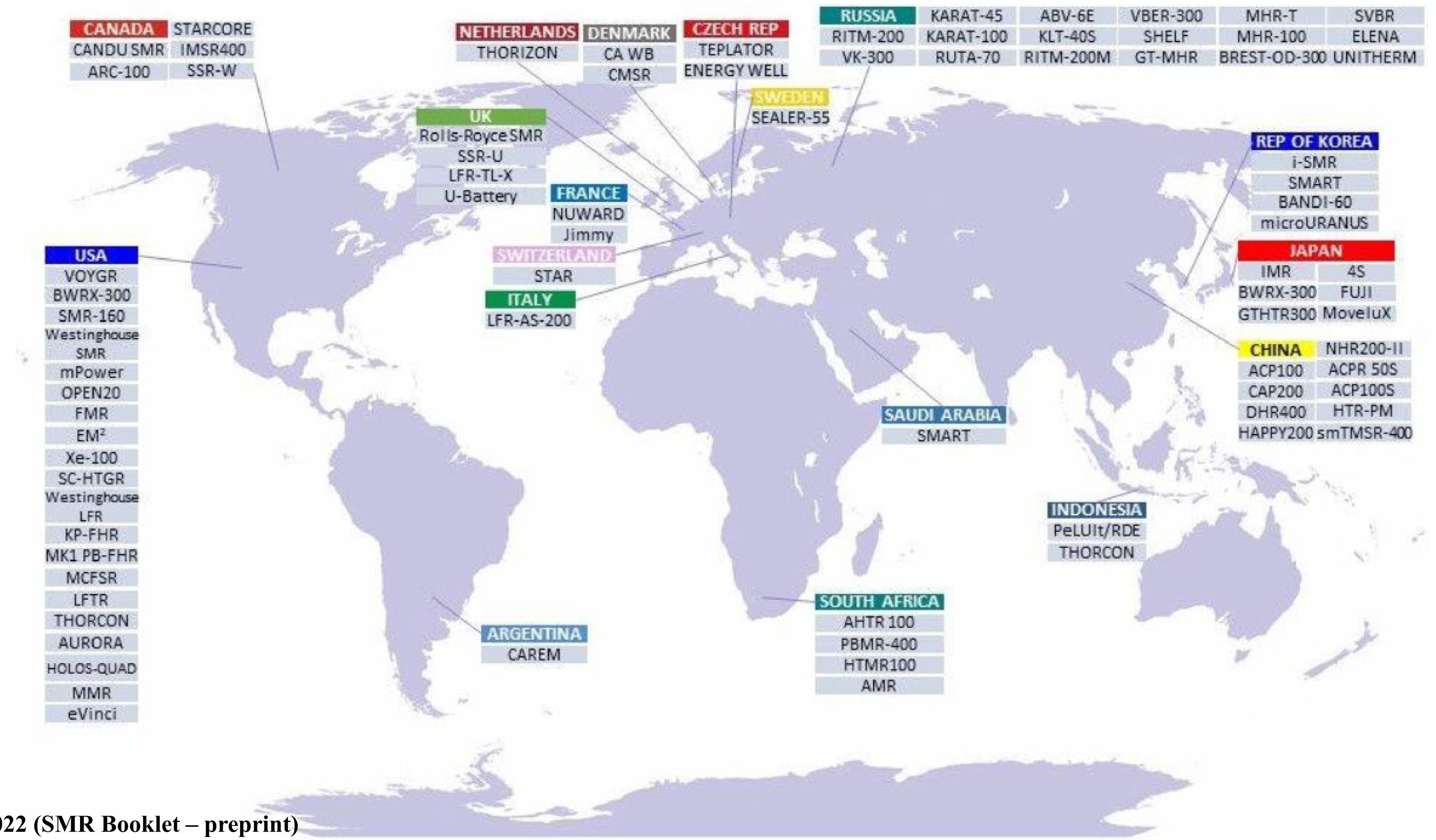
Note: CNEA — National Atomic Energy Commission (of Argentina); CNNC — China National Nuclear Corporation; EDF — Électricité de France; CEA — French Alternative Energies and Atomic Energy Commission; KAERI — Korea Atomic Energy Research Institute; K.A.CARE — King Abdullah City for Atomic and Renewable Energy, Saudi Arabia.

[a] Power rating above 300 MW but considered an SMR by the UK government.

- IAEA lists 18 SMR designs for near-term deployment
  - **There are at least 17 Member States without Nuclear Power interested or participating in SMRs development at various stages (IAEA)**
  - Two are deployed, Russia's Akademik Lomonosov floating power unit (FPU), The HTR-PM located in Shandong province in China
  - Two are being manufactured: The CAREM (Central Argentina de Elements Modulars) reactors; the ACP-100 or Linglon, in Chengjiang, China
  - Others in different stages: *basic design, design approval received, detailed design, received USNRC certification, pre-licensing, or still in conceptual design,*
- TYPEs: PWR (8), BWR (1), HTGR (5), FRs (2) Molten Salt (2), Micro (3)
- Who?: Argentina (1), Canada (2), China (2), France (1) Russia (2), R. of Korea (1) (with KSA), Japan (2), USA (7), UK (2)

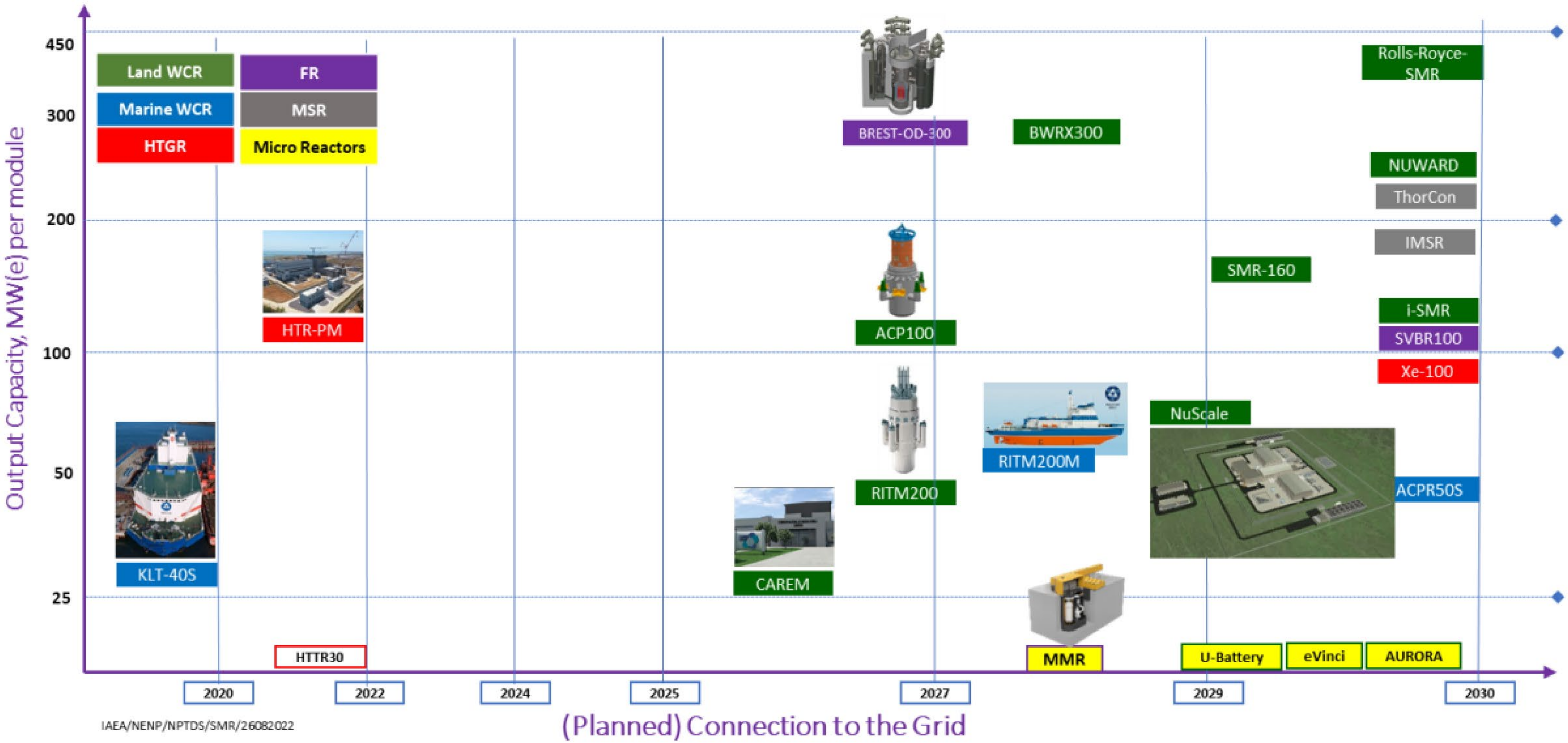
Source: IAEA 2022 (SMR Booklet - preprint

Summary of SMR designs and technologies across the world's regions



Source: IAEA 2022 (SMR Booklet – preprint)

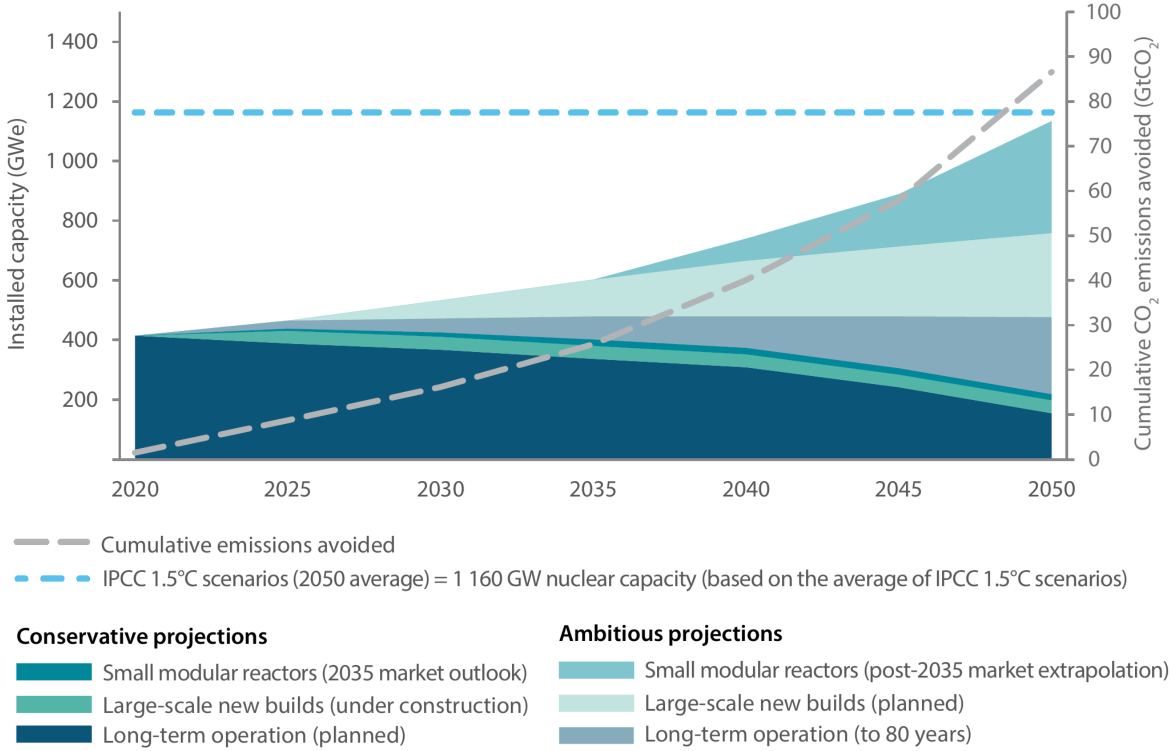
SMR deployment timeline by design — through 2030



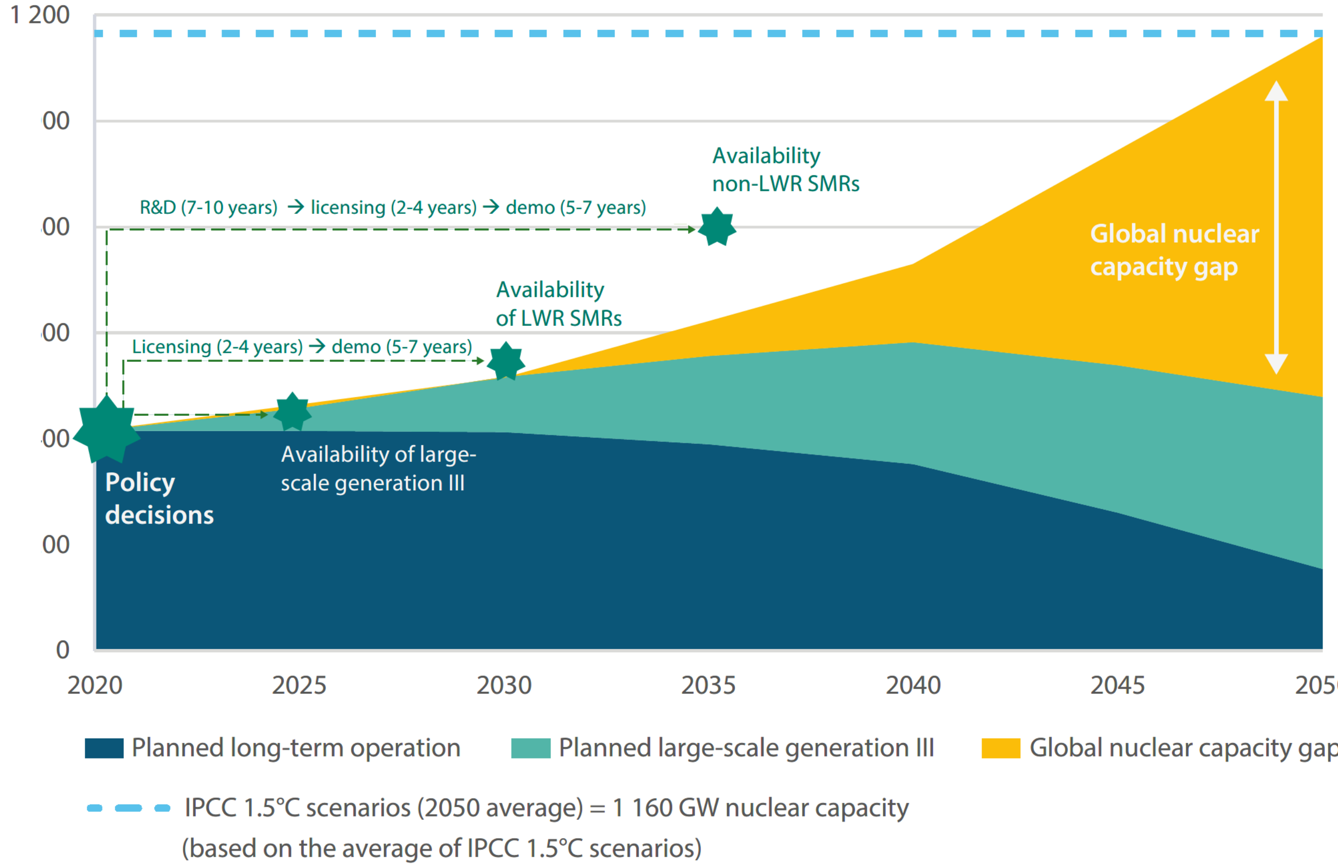
Source: IAEA 2022 (SMR Booklet – preprint)

Full Potential of nuclear contributions to NZE & Potential role of SMRs to fill the gap

Full potential of nuclear contributions to net zero



Global installed nuclear capacity gap (2020-2050)



Source: NEA (2022a).

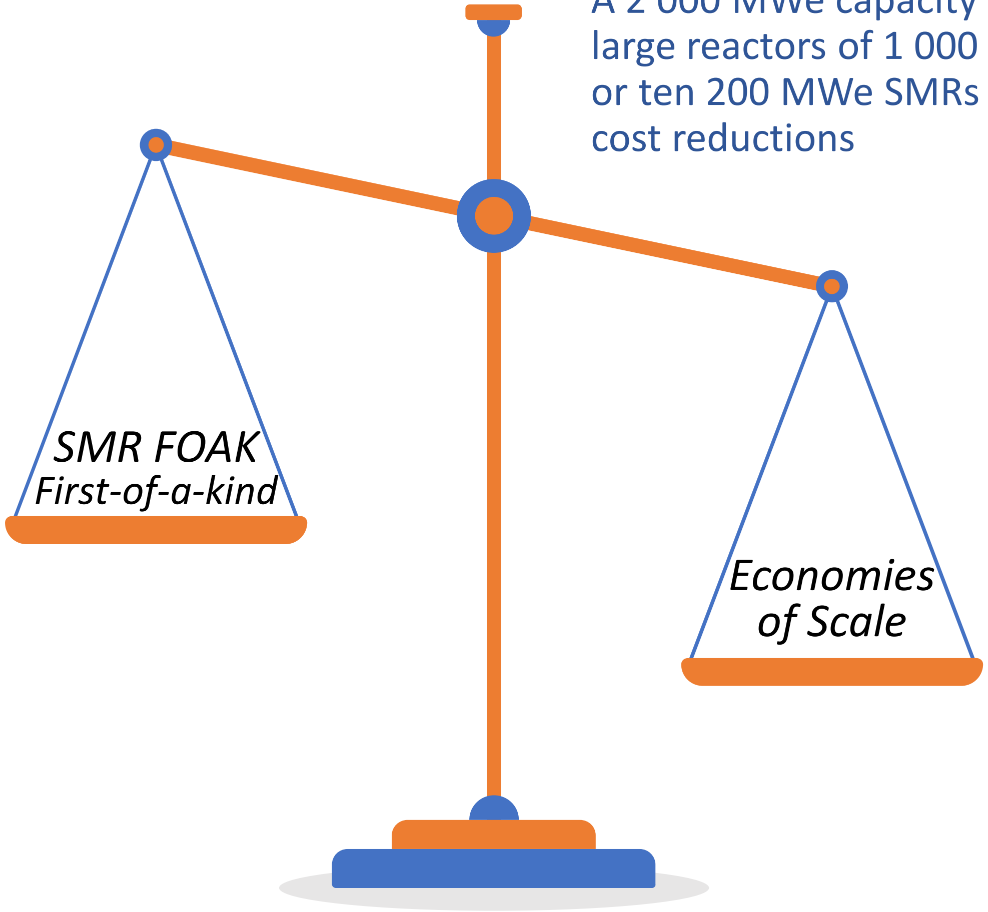
NEA: SMRs Dashboard report (2023)

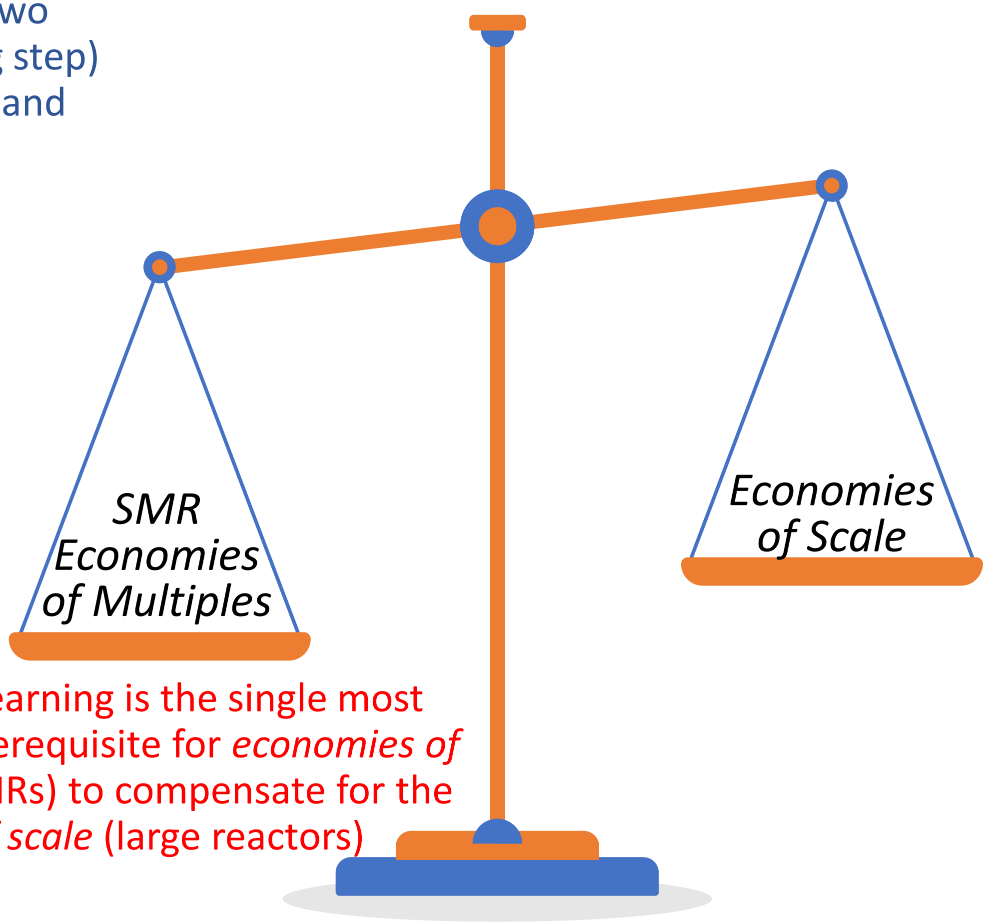
Is there an Economic Rationale for Small Modular Reactors (SMRs)?

Technology learning for balancing economics of economies of multiples and economies of scale

Measure of competitiveness [USD/MWh]

A 2 000 MWe capacity demand can be met by two large reactors of 1 000 MWe each (one learning step) or ten 200 MWe SMRs with nine learning steps and cost reductions

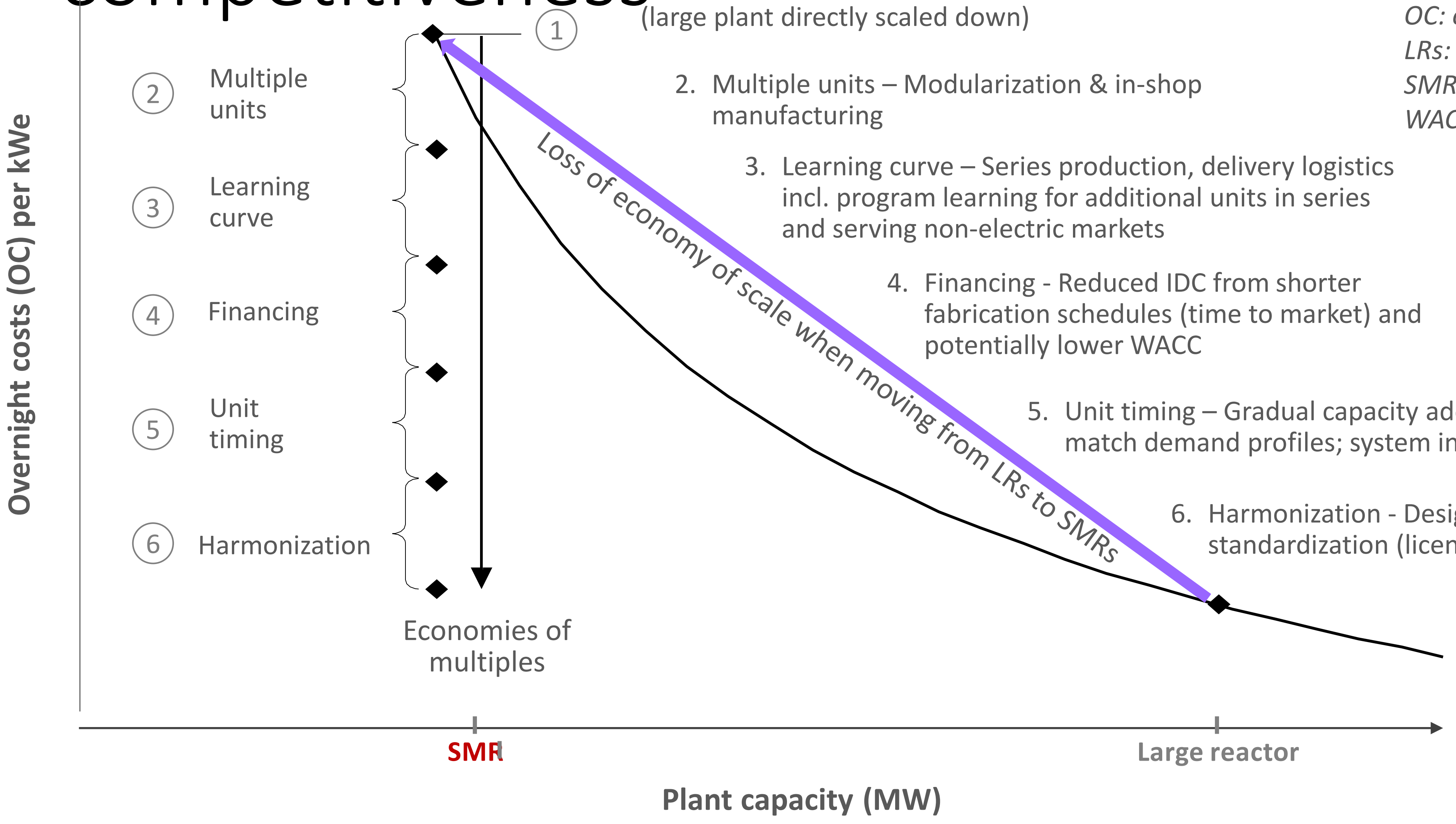




Technology learning is the single most important prerequisite for *economies of multiples* (SMRs) to compensate for the *economies of scale* (large reactors)

Courtesy: Holger Rogner

Measures leading to SMR economic competitiveness



1. Assumes single unit and same LR design concept (large plant directly scaled down)
2. Multiple units – Modularization & in-shop manufacturing
3. Learning curve – Series production, delivery logistics incl. program learning for additional units in series and serving non-electric markets
4. Financing - Reduced IDC from shorter fabrication schedules (time to market) and potentially lower WACC
5. Unit timing – Gradual capacity additions to match demand profiles; system integration
6. Harmonization - Design simplifications and standardization (licensing, codes, regulation)

IDC: interest during construction
OC: overnight costs
LRs: large reactors (1000 – 1700 MWe)
SMRs: small modular sized reactors
WACC: Weighted average cost of capital

Sources: Adapted from IAEA, 2014 and NEA, 2022

SMRs Safety: The new advanced SMRs are designed to be generally a lot more "safer" than today's fleet of large power reactors

SMRs: reduced likelihood of an accident

- large-LWR sequences involve large external events (or internal fires or floods) *and the accident sequence evolves over relatively short time frames*-- often designed away
- For many of the SMRs, the accident sequences of concern evolve over a much longer time period (hours or even days vs. minutes-to-hours)

SMRs: reduced consequences of an accident

- The smaller SMRs have much less radioactivity and much less thermal energy to manage.
- Many of the SMR designs have features that make it much more difficult for radioactivity to be released after a damaging accident
- For many SMRs, the radioactivity is largely contained within the fuel even during an accident

SMRs are also : easier to construct (factory fabrication), generally involve less complex technical regulations because the designs are simpler, much simpler to operate; designed with ease of maintenance as a design feature

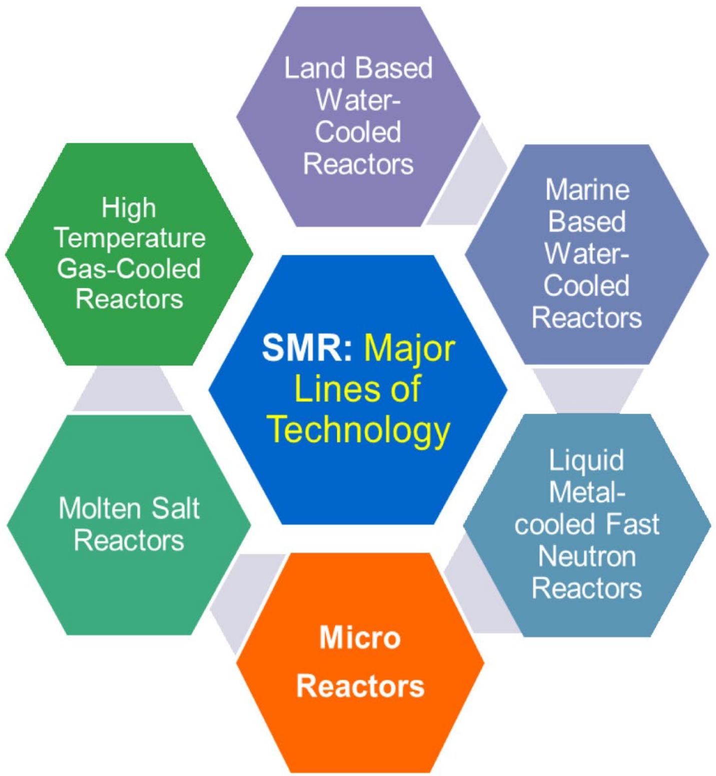
Source: Bob Budnitz, Energy PMP Webinar, 02 February 2023

Will SMRs simplify or complicate solutions to nuclear waste management (disposal)?

Credit: the following few slides are based on presentation by Charles McCombie to Energy PMP Webinar on SMRs, 2 February, 2023

Spent Fuel *(SF)* and Waste Management depend on Fuel cycle, which in turn depends on SMR Category, Fuel Type, enrichment level, etc.

SMR Categories



Fuel Types & enrichment level)

- **Oxide/ceramic fuels with cladding**
- **TRISO fuels**
- **Metallic fuels**
- **Liquid salt fuels**

LEU	< 5% enriched U-235)	
LEU+	[5%;10%] enriched U-235)	
HALEU	[10%;20%] enriched U-235)	
HEU	≥ 20% enriched U-235)	
Mixed U & Pu (oxide, metal, or salt)		
Thorium (oxide, metal, or salt)		

SF volumes & Costs of disposal

- **The *SF* Volumes are NOT the main issue! (despite some recent controversy on *SF* generation in SMRs**
- **More or less spent fuel to be disposed of makes little difference to policy –But NO need for SF disposal (take-back, or MNR) could be major change**
- **Back End Costs for LRs are only a minor part of life cycle costs (a few percent). Will also be minor for SMRs - will be relatively higher because of lower investment costs**

Graphics from IAEA and Orano presentations; Ottawa SMR Conference 2022 Source: Charles McCombie, Energy PMP Webinar on SMRs, 2 February, 2023

POTENTIAL STRATEGIC RWM IMPACTS OF WIDESPREAD SMR ADOPTION

- Significant adaptations will be required in **national nuclear programs** that integrate (advanced) SMRs into an existing large reactor fleet.
- Deployment of **isolated and off-grid SMRs** (e.g. for industrial applications) will present new RWM technical and regulatory challenges
- Suppliers or users of SMRs – especially those with novel fuel cycles – may be interested in building **multinational "user groups"**
- **New nuclear countries** are more likely to order an SMR if the supplier takes back the entire module or the SNF; suppliers of SMRs may exert pressure on their home countries to accept return of core modules or of SNF elements

- Pressure by vendors and customers may make **"take-back" of spent fuel** become more probable
- The **security issues** associated with numerous countries possessing one or a few SMRs may strengthen international support for implementation of a large and secure **multinational repository (MNR).**
- There may be renewed interest in the **commercial disposal service provider** approach – in a SMR producer country, a user country or even a non-nuclear country

NOTE: Existing nuclear countries with small programs could fully benefit from the "take back" option if the spent fuel from their existing plant(s) *could also be exported.*

Source: Charles McCombie, Energy PMP Webinar on SMRs, 2 February, 2023

Will SMRs - potentially a game changer for nuclear energy - ease or pose additional challenges to ensure security and non-proliferation concerns about nuclear energy for peaceful purposes?

the basic set-up to ensure Non-proliferation and nuclear Security

- **Peaceful nuclear activities must be implemented in line with related international agreements and treaties:**
  - The NPT, Safeguards, AP, Convention on the Physical Protection of Nuclear Materials, as amended, and the International Convention on the Suppression of Acts of Nuclear Terrorism, together with UNSC Resolution 1540 (2004).
- New nuclear technologies for nuclear energy or applications (e.g. medical, industry, ..) *must not add doubt* on achieving the objectives defined through the international legal framework.

The basic nuclear security and proliferation threats

SMRs must prove itself as meeting the expectations of secure and proliferation-safe applications of nuclear energy, thereby:

- **Not** be a source of nuclear material that could be attractive for terrorists or criminals for use in nuclear explosive devices
- **Not** present a risk for unacceptable radiological consequences, should there be an act of intentional damage to the unit or its processes.
- **Be recognized** as peaceful and compliant with all requirements of international safeguards.

Non-proliferation and international safeguards Comparing reactor technologies

Reactor type	Facility type	Fresh fuel; physical form	Continuity of knowledge	Refuelling	Cost of Verification
LWRs	Item facility, LWR mostly	Fuel assemblies, LEU	Item continuity. Can be counted	1-2 years	Reference
Molten salt	Bulk facility of some kind. Variable size of inventory	Salt, liquid LEU, Thorium	*Cannot be counted*	Online	More than reference
TRISO	Not as an LWR . Variablesize of inventory	Pebbles, micro-spheres, not identified LEU, Thorium	*Cannot be counted*	Online	More than reference
Fast spectrum reactor	Item facility. Can be very small	Fuel assemblies LEU, initially in some cases Pu/U	*Item continuity. Can be counted*	Periodically. Long operating periods possible.	Less than reference

- Source: Anita Nilsson, Energy PMP Webinar on SMRs, 2 February 2023

Concluding remarks

- Not all that shines is gold – many questions related to SMRs still await an answer
  - Too many designs with yet to be demonstrated performance characteristics compete for an unknown market
  - Can the nuclear community (industrial supply chain entities and regulators) correct the history failed delivery schedules and cost overruns - delivery on time and on budget is essential
    - Can the industry effectively & efficiently harvest substantial rates of technology learning - assuming the necessary market pull?
    - Is a timely establishment of SMR supply chains - from fuel manufacturing to spent fuel management - forthcoming?
  - Will nuclear regulation adjust in time to account for the specificities of new SMR designs and applications?
  - Financial uncertainty remains the major risk factor for private sector sponsorship of SMRs
- BUT there is changing socio-political acceptance
  - Recent geopolitical developments, heightened energy security awareness & growing concerns about insufficient action on climate mitigation appear to ease public opposition (the media are a key driver of change here)
  - Public climate policy increasingly embraces and supports NE in general and SMRs specifically as 'climate-benign' technologies (T20 India?)
  - The younger generation generally has less problems with embracing nuclear technology
- THEREFORE, the prospects for SMR economics and market potentials are highly favorable

Adapted by CM and ASE from: HH Rogner: Energy PMP Webinar on SMRs, 2 February, 2023

End

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