

Technology perspectives from 1950 to 2100 and policy implications for the global nuclear power industry



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ABSTRACT

There have been two completed phases of developments in nuclear reactor technologies. The first phase is the demonstration of exploratory Generation I reactors. The second phase is the rapid scale-up of Generation II reactors in North America and Western Europe followed by East Asia. We are in the third phase, which is the construction of evolutionary Generation III/III⁺ reactors. Driven by the need for safer and more affordable nuclear reactors post-Fukushima, the nuclear industry has, in parallel, entered the fourth phase, which is the development of innovative Generation IV reactors. Through a comprehensive review of the historical reactor technology developments in major nuclear states, namely, USA, Russia, France, Japan, South Korea, and China, this study presents a projection on the future potentials of advanced reactor technologies, with particular focus on pressurized water reactors, high temperature reactors, and fast reactors, by 2100. The projected potentials provide alternative scenarios to develop insights that complement the established technology roadmaps. Findings suggest that there is no clear winner among these technologies, but fast reactors could demonstrate a new and important decision factor for emerging markets. Findings also suggest small modular reactors, especially those belonging to Generation IV, as a transitional technology for developing domestic market and indigenous technology competence for emerging nuclear states. With reference to the East Asian experience in developing nuclear competence, participation with international cooperation in the research and development of Generation IV and nuclear fusion reactor systems could demonstrate strategic entry points for countries with a long-term plan to derive indigenous nuclear reactor technologies.

1. Introduction

Atomic energy has been repeatedly emphasised by the International Energy Agency (IEA, 2014, 2015a) and the Intergovernmental Panel on Climate Change (IPCC, 2014) as an important source of low carbon energy from which the cost of electricity generation is on parity with that from fossil energy (IEA, 2015c). When in normal operation, nuclear power plants produce nearly negligible airborne pollutants (Brook et al., 2014) and far less radiation as compared to coal fired power plants (Gabbard, 1993). However, a combination of cost escalation, completion time overrun, severe accidents, law suits, and negative public perception has severely hindered the rapid development of atomic energy (Escobar-Rangel and Lévêque, 2015; Golay et al., 1977; Grubler, 2010; Koomey and Hultman, 2007; Lovering et al., 2016; Phung, 1985; Rust and Rothwell, 1995). This is reflected in Fig. 1, drawn based on statistics published by the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (OECD NEA, 2013), The United States Energy Information Administration (EIA, 2013), IEA (2015b), and Enerdata (2016).

With reference to the Power Reactor Information System (PRIS) of the International Atomic Energy Agency (IAEA, 2017b) on major nuclear states, namely, Canada, China, France, Germany, India, Japan, Russia (including then Soviet Union states), South Korea, UK, and USA; the roadmaps published by the OECD NEA and IEA (2015); and the Generation IV International Forum (GIF, 2014), the world has gone through two phases of developments in nuclear reactor technologies (Fig. 2). The first phase is characterized by the development of exploratory Generation I reactors. The second phase is characterized by the rapid scale-up of commercially proven Generation II reactors in the North American and Western European markets followed by a shift towards East Asian markets through technology transfer and strategic partnerships. Light water reactor (LWR) technologies from Westinghouse, Combustion Engineering (C-E), General Electric (GE), and OKB Gidropress have made important contributions in the globalization of atomic energy.

Driven by the need for safer and more reliable atomic energy to address national energy objectives (Nian and Chou, 2014), the third and four phases of developments came almost in parallel post-

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Nomenclature

Abbreviations

ABWR	Advanced boiling water reactor	JAEA	Japan Atomic Energy Agency
ACR	Advanced CANDU reactor	KEPCO	Korea Electric Power Corporation
AECL	Atomic Energy Canada Limited	KHNP	Korea Hydro & Nuclear Power
APWR	Advanced pressurized water reactor	KSNP	Korean Standard Nuclear Plant
ASEAN	Association of South East Asian Nations	KSTAR	Korean Superconducting Tokamak Advanced Reactor
ASTRID	Advanced sodium technological reactor for industrial demonstration	LFR	Liquid-metal-cooled fast reactor
BAU	Business-as-usual	LWR	Light water reactor
BWR	Boiling water reactor	MECSST	Ministry of Education, Culture, Sports, Science and Technology
CEA	French Alternative Energies and Atomic Energy Commission	MHI	Mitsubishi Heavy Industry
CGNPC	China General Nuclear Power Corporation	MOTIE	Ministry of Trade, Industry and Energy (South Korea)
CNNC	China National Nuclear Corporation	MSR	Molten salt reactor
COL	Combined Construction and Operating license	MWe	Megawatt electric
C-E	Combustion Engineering (USA)	MWth	Megawatt thermal
EDF	Électricité de France	NEA	Nuclear Energy Agency
EIA	Energy Information Administration (USA)	NPIC	Nuclear Power Institute of China
ESBWR	Economic simplified boiling water reactor	NRC	Nuclear Regulatory Commission (USA)
FBR	Fast breeder reactor	NSSS	Nuclear steam supply system
FCD	First concrete-pour date	PHWR	Pressurized heavy water reactor
FNR	Fast neutron reactor	PWR	Pressurized water reactor
FOAK	First-of-a-kind	R&D	Research and development
GE	General Electric	SFR	Sodium-cooled fast reactor
GCR	Gas-cooled reactor	SNERDI	Shanghai Nuclear Engineering Research & Design Institute (China)
GFR	Gas-cooled fast reactor	SNPTC	State Nuclear Power Technology Corporation (China)
GIF	Generation IV International Forum	TMI	Three Mile Island
HTR	High temperature reactor	UAE	United Arab Emirates
HWR	Heavy water reactor	VVER	Water-water energetic reactor
IAEA	International Atomic Energy Agency	WH	Westinghouse
IEA	International Energy Agency	WNA	World Nuclear Association
IEEJ	Institute for Energy Economics Japan	WNN	World Nuclear News
INET	Institute of Nuclear Energy Technology (China)		
IPCC	Intergovernmental Panel on Climate Change		
IPHWR	Indian pressurized heavy water reactor		
iPWR	Integral pressurized water reactor		
ITER	International Thermonuclear Experimental Reactor		

Symbols

K	Maximum value of the S-curve
t	Time
t_0	Midpoint of the S-curve
α	Cost of first unit production
ε	Learning rate
τ	Steepness of the S-curve

Fukushima. The third phase is characterized by the development of radically improved Generation III and evolutionary Generation III⁺ reactor systems (see Table 1 for a summary) and the fourth phase is characterized by the development of innovative Generation IV reactor systems. According to the GIF (2014) and the IAEA (2016a), some of the Generation IV reactor systems and small modular reactors (SMRs) could become commercially deployable around 2030. In particular, fast-

neutron reactors (FNRs) or fast reactors and high temperature reactors (HTRs) are among the promising options under demonstration in Russia and China.

With reference to Goldberg and Rosner (2011), Generation III reactors are essentially Generation II reactors with state-of-the-art design improvements, including fuel technology, thermal efficiency, modularized construction, passive safety systems, standardized design, and longer operational lifespans of possibly 60 years and beyond. Generation III⁺ reactors are evolutionary developments of Generation III reactors with significant improvements in safety. Generation IV reactors are conceived to have all of the features of Generation III⁺ reactors with the ability to achieve economical hydrogen production, thermal energy off-taking, and water desalination when operating at high temperature, and actinide management when operating with fast neutron spectra.

If there were a fifth phase, it would be characterized by the development of nuclear fusion reactors. Although a prototype fusion reactor may still be decades away, significant efforts are undertaken in the International Thermonuclear Experimental Reactor (ITER) project and in countries like Russia and China (Nian, 2017a). According to Yamada et al. (2016), the nuclear fusion energy community in Japan has announced plans for the development of DEMO (acronym for DEMOnstration Power Plant) by 2030 for commercialization by mid-21st

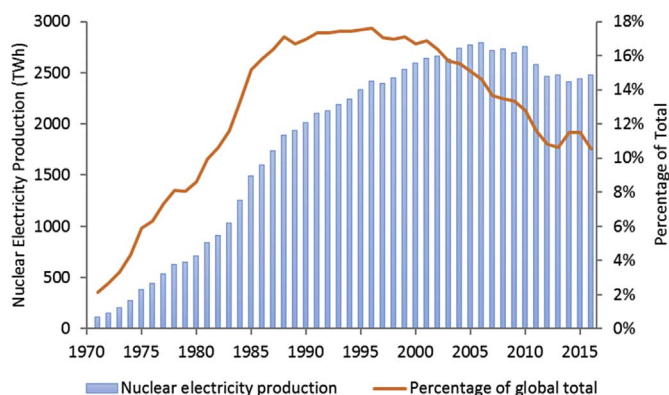


Fig. 1. Global electricity production from atomic energy.

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