Progress in Nuclear Energy 105 (2018) 83–98

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

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

Victor Nian

Energy Studies Institute, National University of Singapore, Singapore

A R T I C L E I N F O

Keywords:
Nuclear industry trends
Nuclear energy policy
Technology diffusion
New user state
International cooperation
Advanced reactor development

A B S T R A C T

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-

E-mail address: nian@nus.edu.sg.

https://doi.org/10.1016/j.pnucene.2017.12.009
Received 8 May 2017; Received in revised form 16 November 2017; Accepted 25 December 2017
0149-1970/

Nomenclature

Abbreviations

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

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.

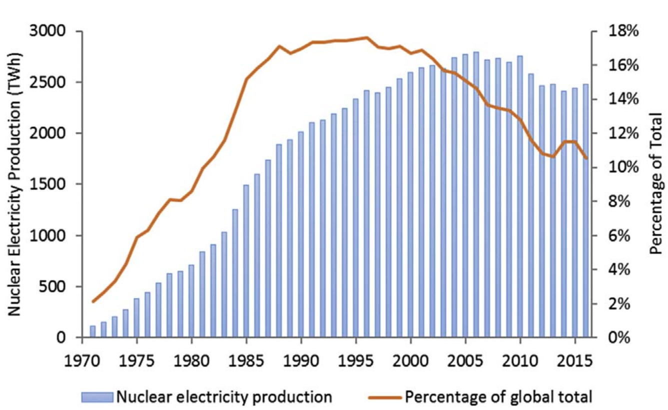

Fig. 1. Global electricity production from atomic energy.

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