Nuclear Engineering and Design 277 (2014) 234–247

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Dynamic analysis of once-through and closed fuel cycle economics using Monte Carlo simulation

Sungyeol Choi, Hyo Jik Lee, Won Il Ko*

Korea Atomic Energy Research Institute, 989-111, Daedeok-daero, Yuseong-gu, Daejeon 305-353, Republic of Korea

HIGHLIGHTS

- Dynamic behavior of system costs, both reactor and fuel cycle costs, is analyzed.
- Relative economics of once-through and closed fuel cycles is explored.
- Probabilistic approaches are adopted for levelized electricity generation costs.
- Main cost drivers for cost gaps between once-through and closed cycles are identified.

ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form 3 June 2014
Accepted 22 June 2014

ABSTRACT

Although no consensus about the best approach to manage spent fuels has been achieved, economics is one of the major criteria for assessing and selecting acceptable management options. This study compares the reactor and fuel cycle costs of the closed system associated with sodium-cooled fast reactors and pyroprocessing versus the once-through system. We specifically investigated the fuel cycle transition cases of the Republic of Korea from 2013 to 2100. The results revealed that the closed system (34.00 mills/kWh as a mean value) could be more expensive than the once-through system (32.75 mills/kWh). In contrast, the once-through fuel cycle costs (8.31 mills/kWh), excluding reactor costs, were projected to be greater than the closed fuel cycle costs (7.77 mills/kWh) because of the increased costs of interim storage estimated by the Korean government and the limited contribution of backend fuel cycle components to the discounted costs. The capital cost of sodium-cooled fast reactor is the largest component contributing to the cost gap between the two systems. Among fuel cycle components, pyroprocessing has the largest uncertainty contribution to the cost gap. We also calculated the breakeven unit costs of SFR capital cost and PWR spent fuel pyroprocessing cost.

1. Introduction

Without exceptions, nuclear power countries are facing or will eventually encounter difficult management issues of spent nuclear fuel. Economics is one of the significant criteria for spent fuel management because generating low-priced electricity while reducing environmental impact is critical for energy security and market competitiveness.

1.1. Background

No countries have yet developed proven and market-ready technologies for solving spent fuel problems. Some countries are exploring different fuel cycle options, and these options are typically categorized as two approaches. One is to dispose of spent fuels directly in final geological repositories, while the other is to reuse them by recovering and recycling plutonium, uranium, or other actinide elements and only disposing of remaining wastes. Despite decades-long discussions, no consensus about the best approach to manage spent fuels has been reached at any level of scholarly, professional, or policy debate. The decision-making of future nuclear energy systems in a national energy strategy is a complex process involving many different criteria as well as competing decision-making actors.

Until now, a number of economic assessments have been conducted for current and future nuclear energy systems (Aubert et al., 2006; Bunn et al., 2003; Kazimi et al., 2011; Ko et al., 2001; Ko and Gao, 2012; Machiels, 2009; OECD/NEA, 1994; Shropshire et al., 2009). The relative economics of a closed system versus a once-through system is always controversial and still

* Corresponding author. Tel.: +82 42 868 2040; fax: +82 42 868 8679.
E-mail addresses: csy@kaeri.re.kr (S. Choi), hyojik@kaeri.re.kr (H.J. Lee), nwiko@kaeri.re.kr (W.I. Ko).

http://dx.doi.org/10.1016/j.nucengdes.2014.06.027
0029-5493/

unfolding. According to the Harvard report in 2003, "there is general agreement in recent studies that with today's low uranium and enrichment prices, reprocessing and recycling [a closed system] is more expensive than direct disposal of spent fuel [a once-through system]. The only argument is over the magnitude of the difference and how long it is likely to persist (Bunn et al., 2003)."

As one of the spent fuel management options, the Republic of Korea is developing a closed system associated with sodium-cooled fast reactors (SFRs) and pyroprocessing (Hahn et al., 2009; Lee et al., 2011). Pyroprocessing treats spent fuels to recover extremely long-lived radioactive actinides from a waste stream, and leaves behind short-lived or stable fission products to final disposal. Recovered actinides are burned in fast neutron spectrum SFRs and highly heat-generating isotopes are stored in decay storage, reducing the long-term environmental burden. It is significant to demonstrate whether this future nuclear energy system brings positive impacts on nuclear waste management, but we simultaneously have to investigate how much this approach will cost throughout the overall system evolution process, in comparison with a once-through system. Because this system is under development, there are large uncertainties in technical and economic perspectives. These large uncertainties can be considered using a probabilistic approach.

We first collected different unit cost data from various sources, compared them to explain what makes these different cost estimates, and selected reference cost data. Based on the once-through and closed systems, cost breakdown structures were calculated for the total system costs consisting of reactor and fuel cycle costs. We then estimated the levelized costs of electricity generation as probabilistic distributions by using a Monte Carlo simulation rather than single values. This study also identified the major components producing the cost gap between the two systems and calculated the breakeven unit costs of SFR and PWR spent fuel pyroprocessing.

1.2. Definition

Because this paper simultaneously considers both reactor and fuel cycle costs, the terminologies are required to be clearly defined to avoid confusion between the two costs:

- When we refer to the overall reactor and fuel cycle systems, we express them as *a once-through system* and *a closed system*, and thus *the total system costs* mean the overall electricity generation costs including reactor costs and associated fuel cycle costs.
- When we refer to fuel cycle systems excluding only reactor systems, we express them as *the once-through fuel cycle* and *the closed fuel cycle*, and thus *the fuel cycle costs* mean the electricity generation costs without reactor-related costs.

2. Nuclear energy system transition scenarios

Based on the 5th Basic Plan on Electricity Demand and Supply in 2010 (Ministry of Knowledge Economy, 2010) and the 1st National Energy Basic Plan in 2008 (Office of the Prime Minister, 2008), we developed a reference growth scenario of nuclear electricity demand until 2100 (Choi and Ko, 2014). In the reference scenario, the contribution of nuclear power in the electricity supply will increase from the current 35–59% by 2030 (Office of the Prime Minister, 2008), and remain unchanged. The 4 different phases are considered until 2100 to obtain the reference growth projection of nuclear electricity demand (Choi and Ko, 2014):

- Phase 1 (2013–2024): 10 Pressurized Water Reactors (PWRs) construction, 14,200 MWe, according to the 5th Basic Plan on Electricity Demand and Supply (Ministry of Knowledge Economy, 2010).
- Phase 2 (2025–2030): new 7 PWRs construction with 1500 MWe to meet an annual growth of 0.89% in total electricity demand and eventually supply 59% of national electricity demand by nuclear power in 2030 (Office of the Prime Minister, 2008).
- Phase 3 (2031–2050): an increase of total electricity demand at an annual rate of 0.89% while nuclear power keeps supplying 59% of electricity demand.
- Phase 4 (2051–2100): a growth rate of total electricity demand gradually decreases down to 0 in 2100 while keeping the share of nuclear power as 59%.

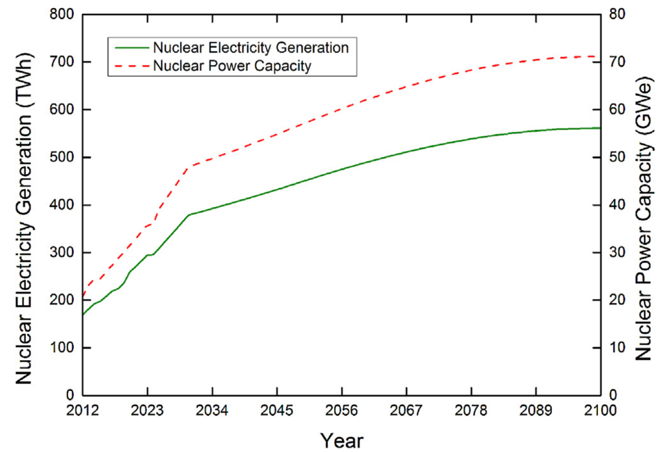

Fig. 1. Estimation of nuclear electricity demand and installed nuclear power capacity until 2100 based on the 5th basic plan on electricity demand and supply released in 2010 and the 1st national energy basic plan released in 2008 (actual data: 2012, estimated data: 2013–2100).

As shown in Fig. 1, nuclear electricity demand rapidly grows between 2012 and 2030 (Phase 1) up to about 380 TWh. After that, the slope of nuclear electricity demand and nuclear power capacity suddenly decreases because the share of nuclear power remains at a constant from Phase 2. In 2100, the annual nuclear electricity demand reaches about 570 TWh while installed nuclear power capacity is over 70 GWe.

Two fuel cycle transition scenarios are compared: the once-through system associated with PWRs and Pressurized Heavy Water Reactors (PHWRs), i.e., Fig. 2(a), and the closed system involved with PWRs, PHWRs, and SFRs, i.e., Fig. 2(b). In both scenarios, there are no new PHWR constructions, and all current 4 units will be closed before 2050. Table 1 shows the design specifications and characteristics of nuclear reactors considered in this study.

In the once-through system, all spent fuel from PWRs and PHWRs are directly disposed of in the geological repository after being stored in the interim storage for decades. PWR spent fuels

Table 1
Design specifications and characteristics of nuclear reactors used in the once-through system (PWR, PHWR) and the closed system (PWR, PHWR, SFR).

	PWR	PHWR	SFR (CR[a] 0.57)	Unit
Power	1000	713	600	MWe
Thermal efficiency	34	33	39	%
Capacity factor	90	90	85	%
Fuel types	UO_2	UO_2	U-TRU-Zr metal	
Discharge burn-up	55,000	7500	128,000	MWD/tHM
Uranium enrichment	4.5	0.711	–	wt%
Lifetime	60	50[b]	60	years

[a] CR: conversion ratio.
[b] 20 years life-extension considered for conservative dealing with spent fuel management issues. PHWRs produced more spent fuels than PWRs.