Environmental Impacts and Benefits of Regional Power Grid Interconnections for the Republic of Korea: Potential Impacts on Nuclear Power Generation and Nuclear Waste Production

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1. Introduction

Since the first commercial operation of a nuclear power plant (NPP) in the Republic of Korea (ROK) in 1978, the ROK has placed fourteen units of pressurized water reactors (PWRs) and four units of CANDU (Canadian Deuterium Uranium) reactors in operation. These units have a total electricity generation capacity of 15.7 GWe, and supplied about 38.9% of the total electricity generated in the nation as of the end of 2002. Two more PWRs units are under construction, with eight additional PWRs to be deployed by the year 2015. Recently, however, "anti-nuke" movements by local residents and anti-nuclear non-governmental groups have been strengthening in the ROK. As a result, it will arguably be difficult for the ROK government to construct all of the eight additional planned PWRs by the year 2015.

Electrical grid interconnections between adjoining countries in Northeast Asia could provide several benefits to the host countries, including environmental and economic benefits. If the

ROK could import electricity generated in the Russian Far East (RFE) via a ROK-Democratic Peoples' Republic of Korea (DPRK)-RFE power grid interconnection, it could replace the deployment of two or of the planned NPP units, and as such could provide environmental and economic benefits to ROK by reducing the generation of nuclear wastes such as spent nuclear fuel and Low and Intermediate Level Waste (LILW), as well as decommissioned reactors. This study evaluates these potential benefits.

2. Total Electricity, Nuclear Capacity and Nuclear Waste Generation

2.1. Projection of Total Electricity Generation and Nuclear Capacity

The magnitude of future spent fuel generation from PWRs and CANDU reactors in the ROK will depend on installed nuclear capacity, which in turn will depend on the total electricity generation required in the ROK and on the share of nuclear power used to supply that generation over the period of time being studied. In August 2002, the South Korean government published estimated projections of total electricity generation and installed nuclear capacity through 2015 [1]. Table 1 shows total electricity generation, electricity generation by nuclear power, total generating capacity and installed nuclear capacity in ROK projected for the years 1995 through 2015 [1, 2]. The projected installed nuclear capacity in the ROK through the year 2015 is provided in Table 2 and in Figure 1 [1].

Table 1: Electricity generation and generating capacity in ROK (1995-2015)

Year	Electricity generation (TWh)		Generating capacity (GWe)	
	Total	Nuclear	Total	Nuclear
1995	184.7	67.0 (36.3%)	32.2	8.6 (26.8%)
2000	266.4	109.0 (40.9%)	48.5	13.7 (28.3%)
2005	345.2	134.1 (38.8%)	61.8	17.7 (28.6%)
2010	395.8	166.7 (42.1%)	79.0	23.1 (29.3%)
2015	436.9	201.3 (46.1%)	77.0	26.6 (34.6%)

Note: Values before the year 2003 of Table 1 are historical data.

2.2. Projection of Spent Fuel Generation

By the end of 2002, 5,788 metric tons of initial heavy metal (tHM) of spent reactor fuel had been discharged from PWRs and CANDU reactors, and stored in AR (at-reactor) spent fuel storage facilities at NPP sites in South Korea: 2,810 tHM of spent PWR fuels and 2,978 tHM of spent CANDU fuel are in storage [3]. Currently, there are four NPPs sites in South Korea: the Kori, Yonggwang and Ulchin sites host PWR units, and the Wolsong site has CANDU reactors. Figure 2 shows the locations of the NPP sites. Table 3 shows details of the inventory of spent fuel in the ROK [3, 4].

Based on the projections of installed nuclear capacity as shown in Table 2, spent fuel discharges from PWRs and CANDU reactors in the ROK are estimated through the year 2080 in which the last pool of New Nuclear 2 is planned to be decommissioned. The historical inventories of spent fuel, as given in Table 3, are combined with these projections to provide estimates of cumulative inventory of spent fuel. These estimates assume a once-through nuclear fuel cycle, with no fuel reprocessing.

Average discharged burnup levels for ROK's commercial spent fuel through 2007 are around 44,000 MWd/tHM, 52,000 MWd/tHM, 52,000 MWd/tHM for spent PWR fuel discharged from the NPPs at Kori, Yonggwang, and Ulchin, respectively, and 7,200 MWd/tHM for spent CANDU fuel from the Wolsong reactors. After 2008, however, ROK's spent PWR fuel would be produced at a burnup rate of around 55,000 MWd/tHM [5].

The lifetime of all reactors is assumed to be 40 years--although the design lifetime of APWR units is nominally 60 years--except for the first CANDU reactor installed in the ROK, which the operating lifetime is assumed to be 30 years. The average thermal efficiency levels used to calculate the ROK's commercial spent nuclear fuel are assumed to be 34% and 33% for PWRs and CANDU reactors, respectively. Constant capacity factors of 88% are assumed for both PWRs and CANDU reactors.

Table 2: The ROK's Nuclear Power Supply Plan through the Year 2015

First Operation Year	Unit	Type	Capacity (MWe)	Site
1978	Kori 1	PWR	587	Kori
1983	Kori 2	PWR	650	Kori
1983	Wolsong 1 [a]	CANDU	679	Wolsong
1985	Kori 3	PWR	950	Kori
1986	Kori 4	PWR	950	Kori
1986	Yonggwang 1	PWR	950	Yonggwang
1987	Yonggwang 2	PWR	950	Yonggwang

1988	Ulchin 1	PWR	950	Ulchin
1989	Ulchin 2	PWR	950	Ulchin
1995	Yonggwang 3	PWR	1,000	Yonggwang
1996	Yonggwang 4	PWR	1,000	Yonggwang
1997	Wolsong 2	CANDU	700	Wolsong
1998	Ulchin 3	PWR	1,000	Ulchin
1998	Wolsong 3	CANDU	700	Wolsong
1999	Ulchin 4	PWR	1,000	Ulchin
1999	Wolsong 4	CANDU	700	Wolsong
2002	Yonggwang 5	PWR	1,000	Yonggwang
2002	Yonggwang 6	PWR	1,000	Yonggwang
2004	Ulchin 5	PWR	1,000	Ulchin
2005	Ulchin 6	PWR	1,000	Ulchin
2008	Shinkori 1	PWR	1,000	Shinkori [b]
2009	Shinkori 2	PWR	1,000	Shinkori
2009	Shinwolsong 1	PWR	1,000	Shinwolsong [c]
2010	Shinkori 3	APWR	1,400	Shinkori
2010	Shinwolsong 2	PWR	1,000	Shinwolsong
2011	Shinkori 4	APWR	1,400	Shinkori
2014	New Nuclear 1	APWR	1,400	Shinwolsong (?) [d]
2015	New Nuclear 2	APWR	1,400	Shinwolsong (?)

[a] Wolsong 1 will be shut down in 2013.
[b] Shinkori is assumed to be the same site of Kori since it is adjacent to Kori.
[c] Shinwolsong is assumed to be the same site of Wolsong since it is adjacent to Wolsong.
[d] New Nuclear 1 & 2 might be constructed at Shinwolsong.

Table 3: Inventory of Nuclear Spent Fuel in the ROK at End of 2002

Kori site (PWR, tHM)	Yonggwang site (PWR, tHM)	Ulchin site (PWR, tHM)	Wolsong site (CANDU, tHM)
1,288	866	656	2,978

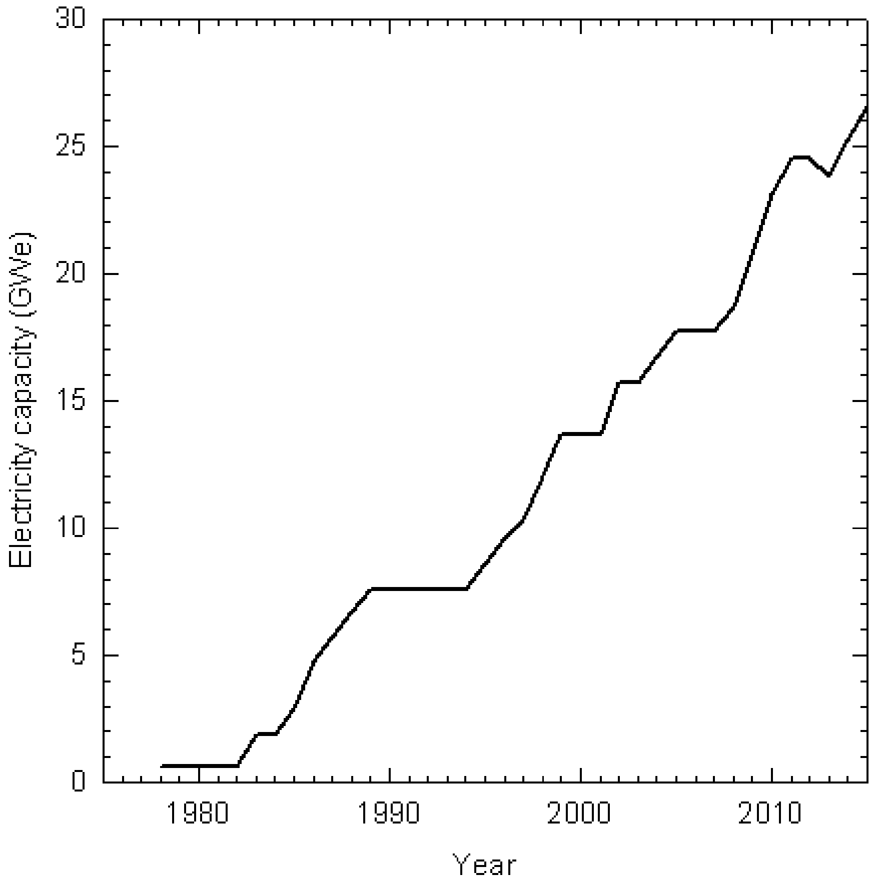

Figure 1: Installed nuclear capacity in ROK through the year 2015

Figure 2: NPP sites in the ROK

Estimates of the annual amount of spent fuel discharges are calculated as follows [6].

$$SF_t = \frac{NC_t * 365 * CF_t}{TE_t * BU_t} ,$$

where:

SF_t = annual amount of spent nuclear fuel discharged in year t (tHM),

NC_t = net nuclear capacity in year t (MWe),

CF_t = capacity factor in year t,

TE_t = thermal to electrical efficiency in year t, and

BU_t = average discharge burnup in year t (MWd/tHM).

Table 4 and Figure 3 show the projections of spent fuel generation in terms of cumulative inventory. These results include spent fuel discharged from decommissioned reactors. Approximately 19,293 tHM of PWR spent fuel is discharged, while approximately 13,943 tHM of CANDU spent fuel is discharged, overall, in the ROK.

Table 4: Cumulative Nuclear Spent Fuel Generation in the ROK

Year	Kori site (PWR, tHM)	Yonggwang site (PWR, tHM)	Ulchin site (PWR, tHM)	Wolsong site (PWR, tHM)	Wolsong site (CANDU, tHM)
By 2010	1,896	1,735	1,495	52	6,094
By 2020	3,274	2,748	2,509	708	9,212
By 2030	4,448	3,747	3,573	1,532	12,051
By 2040	5,272	4,393	4,322	2,357	14,323
By 2050	6,158	4,575	4,590	3,277	14,323
By 2060	6,639	4,575	4,590	3,758	14,323
By 2070	7,199	4,575	4,590	4,239	14,323
By 2080	7,302	4,575	4,590	4,613	14,323

2.3. Additional Spent Fuel Storage Capacity

All spent fuel discharged from PWRs and CANDU reactors in the ROK has been stored in AR spent fuel storage pools, or, for some CANDU spent fuel, at a dry storage facility at the reactor site. Table 5 shows the status of AR spent fuel storage capacities at the four NPP sites in the ROK. The pool capacity of each planned PWR after 2005 is assumed to be the same capacity as that of Ulchin 5 and 6 [7].

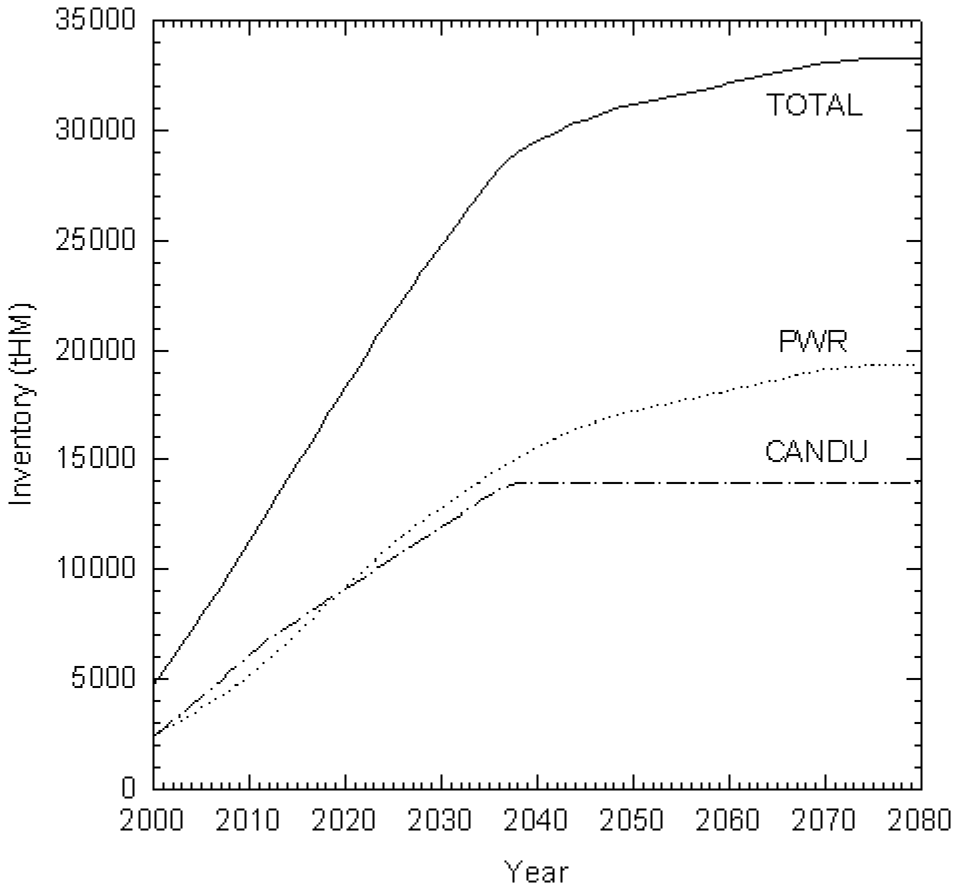

Figure 3: Cumulative inventory of spent fuel generation in ROK

Table 5: Status of AR spent nuclear fuel storage capacity in ROK

Unit	Management pool capacity (tHM) [a]	Increase of capacity by re-racking for PWR spent fuel (tHM) [b]
Kori 1	163.6	0.0
Kori 2	313.0	0.0
Wolsong 1	817.0	6080.7 [c]
Kori 3	248.4	638.4
Kori 4	248.4	592.8
Yonggwang 1	248.4	592.8
Yonggwang 2	248.4	171.2
Ulchin 1	132.8	270.7
Ulchin 2	132.8	169.9
Yonggwang 3	208.9	162.6
Yonggwang 4	208.9	162.6
Wolsong 2	801.0	0.0
Ulchin 3	208.9	162.6
Wolsong 3	801.0	0.0
Ulchin 4	208.9	162.6
Wolsong 4	801.0	0.0
Yonggwang 5	218.1	166.8
Yonggwang 6	218.1	166.8
Ulchin 5	218.1	187.6
Ulchin 6	218.1	187.6
Shinkori 1	218.1	187.6
Shinkori 2	218.1	187.6
Shinwolsong 1	218.1	187.6
Shinkori 3	188.9	187.6
Shinwolsong 2	218.1	187.6
Shinkori 4	188.9	187.6
New Nuclear 1	188.9	187.6
New Nuclear 2	188.9	187.6

[a] These values assume that one full core of storage capacity is reserved for emergencies.
[b] These values contains capacities increased and to be increased in a near future.
[c] Dry storage capacity of 2,250.0 tHM is in operation at end of 2003 and dry storage capacity of 6,080.7 tHM would be in operation by 2008 in Wolsong site.

Additional spent fuel storage requirements are also estimated for a case in which it is assumed that spent fuel transfer between NPPs at the same site is allowed. A reactor whose pool is full may ship its discharged fuel assemblies to another reactor pool that has more capacity. For spent fuel to be discharged from decommissioned reactors, five years are assumed for the movement of all spent fuel from pools to additional storage facility after plant shutdown.

Table 6 shows the years in which the Kori, Yonggwang, Ulchin and Wolsong sites are expected to saturate their spent fuel storage capacities and the cumulative additional storage capacities.

Table 6: Cumulative additional storage capacity required in ROK

	Kori (PWR)	Yonggwang (PWR)	Ulchin (PWR)	Wolsong (PWR)	Wolsong (CANDU)
Saturated years	2022	2020	2017	2030	2017
By 2020 (tHM)	0	0	248	0	710
By 2030 (tHM)	2,042	974	1,313	0	3,894
By 2040 (tHM)	3,708	3,252	2,768	792	7,073
By 2050 (tHM)	4,594	4,575	4,590	1,713	14,323
By 2060 (tHM)	5,886	4,575	4,590	3,005	14,323
By 2070 (tHM)	6,446	4,575	4,590	3,486	14,323
By 2080 (tHM)	7,302	4,575	4,590	4,613	14,323

2.4. Low and Intermediate Level Radioactive Waste (LILW)

The amount of LILW stored at four NPP sites at end of 2002 is 64,940 drums, based on a standard 200-liter drum [8]. To reduce the volume of LILW discharged from NPPs, volume reduction equipment such as concentrate waste drying systems (CWDS), spent resin drying systems (SRDS) and super compactors have been used in the ROK. As of the end of 2002, an average of 141 drums of LILW are generated from a NPP per year in the ROK. Table 7 shows the cumulative volume of LILW discharged from NPPs in the ROK through 2080.

Table 7: Cumulative LILW Generation in the ROK (Unit: drums) [a]

	Kori (PWR)	Yonggwang (PWR)	Ulchin (PWR)	Wolsong (PWR)	Wolsong (CANDU)
By 2010	43,070	17,370	18,375	423	9,108
By 2020	53,927	25,830	26,835	5,076	13,620
By 2030	61,118	33,021	34,590	10,716	17,850
By 2040	66,758	37,110	39,525	16,356	20,811
By 2050	71,693	37,392	40,512	21,573	20,811
By 2060	74,513	37,392	40,512	24,393	20,811
By 2070	77,192	37,392	40,512	27,213	20,811
By 2080	77,192	37,392	40,512	28,200	20,811

[a] These values do not include LILW discharged from decommissioned reactors.

3. Benefits of Regional Power Grid Interconnections for Nuclear Waste Production

3.1. ROK-DPRK-RFE Interconnection

As one of the hypothetical interconnection route between the ROK and the DPRK, the "Shin Gapyong (ROK) – Wonsan (DPRK) – Sinpo (DPRK)" route could be considered for the potential utilization of electricity generated from Korean Peninsula Energy Development Organization (KEDO) NPPs at Sinpo in the future [9]. To create a ROK-DPRK-RFE interconnection, a grid interconnection between Sinpo and Vladivostok could be added to the above ROK-DPRK interconnection.

3.2. Environmental Benefits with Regard to Nuclear Waste Production

This study assumes that the ROK imports electricity generated from 2 GWe of capacity in the RFE that is equivalent to the output of two 1 GWe NPPs. These imports are assumed to displace the ROK deployment of two NPPs yet to be built, that is, the Shinkori 1 and 2 reactors. Current plans call for the commissioning of the Shinkori reactors in 2008 and 2009, respectively. Table 8 shows cumulative spent fuel and LILW generation at the Kori site with and without deployment of Shinkori 1 and 2. The case of no deployment of Shinkori 1 and 2 shows a reduction of cumulative spent PWR fuel by approximately 7.2%, compared to the reference case, and reduction of cumulative LILW by approximately 5.5%. The case of no deployment of Shinkori 1 and 2 also does not produce nuclear waste generated from the decommissioning of the two reactors. The year in which pool-saturation occurs at the Kori site, however, is brought forward to 2021 because there is no further increase of pool capacity, since Shinkori 1 and 2 are not built.

Table 8: Cumulative Nuclear Spent Fuel and LILW Generation at the Kori Site

	Spent fuel (tHM)		LILW (drums)	
	Reference case	W/o Shinkori 1 and 2 case	Reference case	W/o Shinkori 1 and 2 case
By 2010	1,896	1,810	43,070	42,365
By 2020	3,274	2,845	53,927	50,402
By 2030	4,448	3,675	61,118	54,773
By 2040	5,272	4,156	66,758	57,593
By 2050	6,158	4,637	71,693	60,413
By 2060	6,639	5,118	74,513	63,233
By 2070	7,199	5,678	77,192	65,912
By 2080	7,302	5,781	77,192	65,912

3.3. <u>Economic Benefits of Interconnection Related to Nuclear Waste Production</u>

Cost savings related to the storage and disposition of nuclear waste are anticipated for the case in which there is no deployment of Shinkori 1 and 2, compared to the reference case. The unit cost assumptions for storage and disposition of spent PWR fuel used in this study are $140/kgHM and $700/kgHM respectively [4, 10]. This study assumes $1,600-3,200/m^3 as a disposal cost for LILW [11]. For the decommissioning cost of a PWR, approximately 320 million dollars is assumed [12].

Based on the above cost assumptions, the cost savings relating to nuclear waste generation for the case of no deployment of Shinkori 1 and 2 are approximately 1.95-1.99 billion dollars (total undiscounted costs), compared to the reference case. These avoided costs include 1,277 million dollars for storage and disposition of spent PWR fuel, approximately 36-72 million dollars for disposition of LILW, and approximately 640 million dollars for decommissioning of two PWRs. Considering, for example, that the construction cost of the two KEDO PWRs, each with a capacity of 1 GWe, is about 4.6 billion dollars of, total cost savings of the case of no deployment two PWRs (each with a capacity of 1 GWe) therefore would be about 6.6 billion dollars.

4. Conclusions

The ROK-DPRK-RFE power grid interconnection could provide significant environmental and economic benefits to the ROK by allowing a considerable reduction in the amount of generation of nuclear waste—such as spent nuclear fuel, Low and Intermediate Level Waste (LILW), and waste from decommissioned reactors—as well as by avoiding the deployment of two PWR units.

5. REFERENCES

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