Economic Evaluation of Long-term Operation of NPPs in Korea

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1. Introduction

It is inevitable for Korean government to establish the energy policy which can support the energy security and independence since Korea depends on approximately 97% of energy resources from abroad. We selected nuclear power plant to overcome the problem. Since Kori unit 1 began operating as a first nuclear power plant, nuclear power generation has been played a big role in providing about 30% of total electricity supply in Korea. Many researchers and economists have already assessed about safety and economic aspects of the nuclear power generation. This paper will deal with the economic benefits for the contribution of nuclear power generation especially long-term operation of NPPs to the Korean society.

2. Nuclear Power Status in Korea

According to the 7th basic plan for long-term electricity supply and demand (2015~2029) announced on July 2015, Korean government significantly focuses on the stable power supply after suffering from the huge rolling blackout all over the Korea on September 2011. The plan seeks for not only securing new construction of nuclear power plants but also reducing the greenhouse gas emission as the most pursuing agenda

On the basis of the second energy basic plan, Korean government plans to secure the nuclear power capacity up to 29% of total amount by 2035. Approximately 43GW of nuclear power plant should be equipped by 2035 based on the plan as shown in Table I and Fig. 1. [1][2]

Table I: Nuclear power capacity

Year	Nuclear power capacity(MW)	Total installed capacity(MW)	Percent	Operating NPPs (EA)
2014	20,716	88,155	23.5%	23
2020	26,729	119,809	22.3%	27
2025	32,329	129,292	25.0%	31
2029	38,329	136,097	28.2%	35
2035	42,705	147,259	29.0%	39

Table II shows the status of nuclear power plants in Korea. Twenty four NPPs are currently under operation after Shin Wolsong unit 2 plant operates. The aggregate will be thirty six NPPs by adding twelve NPPs more by 2029. The emerging issue is LTO problem that we should consider the existing plant to be shut down as an alternative way to increase the capacity. The target NPPs for LTO to be considered by 2028 are ten except for Kori unit 1 to be shut down and Wolsong unit 1 to be operated by 2022 as specified in Table II. [1][2]

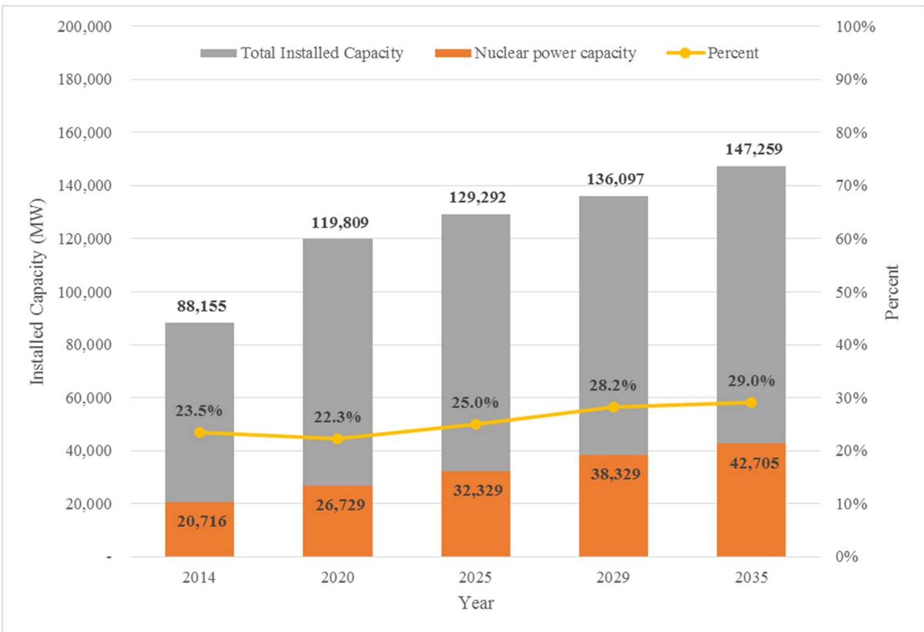

Fig. 1. Nuclear power capacity

Table II: The status of nuclear power plants in Korea.

No.	Plant	Type	Capacity (MW)	Operation (Year)	Design life (Years)	Expiration (Year)	Remarks
1	Kori #1	PWR	587	1978	30	Extended by 2017	Shut down in 2017
2	Wolsong #1	PHWR	679	1983	30	Extended by 2022	Target NPPs for analysis
3	Kori #2	PWR	650	1983	40	2022	
4	Kori #3	PWR	950	1985	40	2024	
5	Kori #4	PWR	950	1986	40	2025	
6	Hanbit #1	PWR	950	1986	40	2025	
7	Hanbit #2	PWR	950	1987	40	2026	
8	Hanul #1	PWR	950	1988	40	2027	
9	Hanul #2	PWR	950	1989	40	2028	
10	Hanbit #3	PWR	1,000	1995	40	2034	
11	Hanbit #4	PWR	1,000	1996	40	2035	
12	Wolsong #2	PHWR	700	1997	30	2026	
13	Wolsong #3	PHWR	700	1998	30	2027	
14	Hanul #3	PWR	1,000	1998	40	2037	
15	Wolsong #4	PHWR	700	1999	30	2028	
16	Hanul #4	PWR	1,000	1999	40	2038	
17	Hanbit #5	PWR	1,000	2002	40	2041	
18	Hanbit #6	PWR	1,000	2002	40	2041	
19	Hanul #5	PWR	1,000	2004	40	2043	
20	Hanul #6	PWR	1,000	2005	40	2044	
21	Shin Kori #1	PWR	1,000	2011	40	2050	
22	Shin Kori #2	PWR	1,000	2012	40	2051	
23	Shin Wolsong #1	PWR	1,000	2012	40	2051	
24	Shin Wolsong #2	PWR	1,000	2015	40	2054	
25	Shin Kori #3	PWR	1,400	2016	60	2075	APR1400 model
26	Shin Kori #4	PWR	1,400	2017	60	2076	
27	Shin Hanul #1	PWR	1,400	2017	60	2076	
28	Shin Hanul #2	PWR	1,400	2018	60	2077	
29	Shin Kori #5	PWR	1,400	2021	60	2080	
30	Shin Kori #6	PWR	1,400	2022	60	2081	
31	Shin Hanul #3	PWR	1,400	2022	60	2081	
32	Shin Hanul #4	PWR	1,400	2023	60	2082	
33	Cheonji #1	PWR	1,500	2026	60	2085	
34	Cheonji #2	PWR	1,500	2027	60	2086	
35	Cheonji #3	PWR	1,500	2028	60	2087	
36	Cheonji #4	PWR	1,500	2029	60	2088	

3. Methods

3.1. Scenarios

Since Kori unit 1 commercially operated, Korean nuclear power industry has been developed dramatically. The plants modeled OPR1000 are under operation and APR1400 model plants are under construction in Korea and UAE. Furthermore APR$^+$ developed with 100% of Korean technologies and sized 1,560MW capacity will be deployed in the future. We will discuss about economic analysis of LTO cases for old plants of less than and equal to 1,000MW capacity only.

We will leave out Kori unit 1 as a target NPP for the analysis since it will be shut down in 2017. As for the Wolsong unit 1, the plant temporarily shut down on June 2012 and started to operate on July 2015 after achieving the renewal license. Hence we will omit the saved capacity from 2013 to 2014. Twenty three target NPPs including Wolsong unit 1 as specified in Table II will be assumed for our economic analysis in this paper.

We assume four scenarios for LTO. First, each plant will be shut down without LTO. Second, the lifetime of each plant will be extended for 10years. Third, the lifetime of each plants will be extended for 20years. Finally, the lifetime of each plants will be extended for 30years.

Additionally secured capacities after each LTO duration can be obtained from difference between the accumulated capacity and no extension. Based on that results, we can figure out the increased electricity sales of utility, equivalent NPPs compared to APR1400 capacity, and cost savings as well.

3.2. Terminology

3.2.1. LCOE

The levelized cost of electricity, LCOE is a one of the indicators which can be used to compare the economics of different generation type. The LCOE equation specified in this section was referred from NEA/OECD report. [3] The working group of NEA/OECD used the equation, $LCOE_{EO}$ which is the levelized cost for extended operation, to assess the economics of long-term operation of nuclear power plants for each country.

LCOE and $LCOE_{EO}$ are important characteristics to be used for analyzing the economics in this paper. The details on their calculation are given below;

- Calculation of $LCOE_{EO}$

The general formula for LCOE used for all sources of electricity is written below (1).

$$LCOE = \frac{\sum_{t=-t_C}^{Lifetime} \frac{(Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)}{(1+r)^t}}{\sum_{t=1}^{Lifetime} \left(\frac{Electricity_t}{(1+r)^t}\right)} \quad (1)$$

The subscript "t" denotes the year in which the electricity production takes place or the expenses are made:

t_C: Construction duration
$Electricity_t$: The amount of electricity produced in year "t"
r: Annual discount rate, constant
$Investment_t$: Investment cost in year "t"
$O\&M_t$: Operations and maintenance cost in year "t"
$Fuel_t$: Fuel cost in year "t"
$Carbon_t$: Carbon cost in year "t"
$Decommissioning_t$: Decommissioning cost in year "t"

- Calculation of $LCOE_{EO}$ after refurbishment and lifetime extension

The formula for $LCOE_{EO}$ corresponding to the period of extended operation is written below (2).

$$LCOE_{EO} = \frac{\sum_{t=-t_R}^{t_{EO}} \frac{(Refurbishment_t + O\&M_t^{EO} + Fuel_t^{EO} + Decommissioning_t^{EO})}{(1+r)^t}}{\sum_{t=1}^{t_{EO}} \left(\frac{Electricity_t^{EO}}{(1+r)^t}\right)} \quad (2)$$

Where:
t_R: Refurbishment duration
t_{EO}: Duration of extended operation
$Electricity_t^{EO}$: The amount of electricity produced in year "t", after refurbishment
r: Annual discount rate, constant
$Refurbishment_t$: Refurbishment cost in year "t"
$O\&M_t^{EO}$: Operations and maintenance cost after refurbishment, in year "t"
$Fuel_t^{EO}$: Fuel cost after refurbishment, in year "t"
$Decommissioning_t^{EO}$: Decommissioning cost associated with refurbishment in year "t"

We applied LCOE values to the calculation of cost savings which is estimated in Reference [4] as described in Table III. They considered a new construction of APR1400 power plant and three cases of LTO duration; 10years, 20years and 30years.

Table III: Estimated $LCOE_{EO}$

Discount rate	Capacity factor	For 10 years LTO			For 20 years LTO			For 30 years LTO			APR1400 Construction
		Kori #1	Wolsong #1	1,000 MW	Kori #1	Wolsong #1	1,000 MW	Kori #1	Wolsong #1	1,000 MW	
3%	60%	60.97	80.75	46.89	52.15	70.15	41.24	56.82	67.20	45.17	52.44
	70%	52.80	69.64	40.72	45.24	60.56	35.87	49.24	58.03	39.24	45.48
	80%	46.67	61.31	36.08	40.06	53.36	31.84	43.56	51.15	34.79	40.25
	90%	41.90	54.83	32.48	36.03	47.76	28.71	39.14	45.79	31.33	36.19
6%	60%	63.08	83.89	48.51	54.99	74.18	43.41	63.27	72.28	50.12	63.33
	70%	54.61	72.33	42.10	47.67	64.01	37.73	54.77	62.38	43.48	54.81
	80%	48.25	63.67	37.30	42.18	56.38	33.47	48.40	54.95	38.50	48.41
	90%	43.31	56.92	33.56	37.92	50.45	30.16	43.44	49.18	34.63	43.44
1+0%	60%	66.13	88.43	50.84	59.29	80.28	46.70	73.25	80.13	57.76	80.12
	70%	57.22	76.22	44.10	51.36	69.24	40.55	63.32	69.11	50.03	69.20
	80%	50.54	67.07	39.05	45.41	60.96	35.94	55.88	60.84	44.23	61.01
	90%	45.34	59.95	35.11	40.78	54.52	32.35	50.09	54.41	39.72	54.64

Unit: Won / kWh

Due to the gap of fixed cost and variable cost resulted from difference type between Kori unit 1 (PWR) and Wolsong unit 1 (PHWR), they calculated the individual LCOE by reflecting those costs. Nuclear power plants in Korea have mostly about 1,000MW capacity. They estimated the LCOE for 1,000MW power plant applying capacity compensation coefficient based on the Kori unit 1.

Table IV shows the application of $LCOE_{EO}$ for each power plant to calculate the cost savings.

Table IV: Applied $LCOE_{EO}$ by plant type

$LCOE_{EO}$	Applied NPPs	No. of NPPs
Kori #1	Kori #2	1
Wolsong #1	Wolsong #1~4	4
1,000MW	Kori #3 & 4, Hanbit #1~6, Hanul #1~6, Shin Kori #1~2, Shin Wolsong #1~2	18
Total sum		23

3.2.2. Electricity price

Korea Power Exchange, KPX decides the electricity price in their power pool. The base load generation including nuclear power are calculated based on Base Load Marginal Price, BLMP instead of System Marginal Price, SMP for general generation. The settlement unit payment for Korea Hydro & Nuclear Power Corporation, KHNP as a utility can be calculated by dividing trade price by generated capacity. The payment in 2014 obtained from KPX is 54.70 Won/kWh. Also the purchase price for Korea Electric Power Corporation. KEPCO can be calculated by dividing the total amount of trading price by purchased capacity. The purchase price of KEPCO in 2014 is 54.96 Won/kWh. In this paper, we will apply the settlement unit payment to calculate electricity sales for utility point of view. [5] [6]

3.2.3. Discount rate

Discount rate is the rate used in discounted cash flow analysis to determine the present value of future cash flows. The discount rate considers the time value of money and the risk or uncertainty of the anticipated future cash flows which might be less than expected. The discount rate is expressed as annual rate, and about 6~7% has been applied to the domestic project. We applied 3%, 6%, and 10% of discount rate in this paper.

3.2.4. Capacity factor

It defines the ratio of actual output of power plant over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time. Capacity factors vary greatly depending on the type of fuel that is used and the design of the plant. The capacity factors we applied in this paper are 60%, 70%, 80%, and 90%.

3.3. Mathematical descriptions

3.3.1. Saved capacity

Each future amount of capacity to be gotten from the LTO will be discounted by discounted rate and be applied by capacity factor.

$$\text{Saved capacity(MW)} = \left(\sum_{t=1}^{t_{EO}} \frac{Capacity_t^{EO}}{(1+r)^t}\right) \times \text{Capacity factor} \quad (3)$$

The subscript "t" denotes the year in which the electricity production takes place or the expenses are made:

t^{EO} : Duration of extended operation
r : discount rate, constant (3%, 6%, and 10%)
$Capacity_t^{EO}$: The amount of capacity in year "t", after extended operation
Capacity factor: 60%, 70%, 80%, and 90%

[Assumptions]
- The extended operation continues without suspension right after expiration.
- All power plants have the same discount rate and capacity factor for whole life time.

3.3.2. Electricity sales

Using the saved capacity obtained from the Equation. (3), we can calculate the electricity sales by applying capacity factor and electricity price. The discounted capacity has the same meaning to the discounted electricity sales for whole LTO duration.

$$\text{Electricity sales} = \text{Saved capacity(MW)} \times 24(hours) \times 365(days) \times Capacity\ factor(\%) \times Electricity\ price(Won/kWh) \quad (4)$$

Where,
Saved capacity: Every year's total sum of saved capacity discounted by discount rate (3%, 6%, and 10%)
Capacity factor: 60%, 70%, 80%, and 90%
Electricity price: 54.70 Won/kWh

[Assumption]
- The commercial operation dates of starting and finishing year are from January 1 to December 31.

3.3.3. Equivalent NPPs

In this part, we can figure out the conversion additionally secured capacity from LTO into the equivalent APR1400 NPPs using the Equation. (5).

$$\text{Equivalent NPPs} = \frac{\textit{Saved capacity of individual NPPs (MW)} \times \textit{Extended lifetime}}{\textit{Unit capacity of APR1400 model NPP (MW)} \times (\textit{Design life} + \textit{Extended lifetime})} \quad (5)$$

Where,
Saved capacity: Total sum of saved capacity for all existing NPPs
Unit capacity: Unit capacity of NPP to be compared (APR1400, 1400MW)
Extended life time: 10years, 20years, and 30years

[Assumptions]

- Discount rate and capacity factor are the same for whole duration of LTO. For the aggregate capacity and APR1400 model capacity, we didn't apply the discount rate and capacity factor because both numerator and denominator will be applied.
- Uprated powers attributed by LTO and new construction are the same amount.
- APR1400 capacity calculates for design life and extended lifetime with the same condition of existing NPP.

3.3.4. Cost savings

We can acquire the cost savings in choosing the LTO of existing power plants compared to the new construction of APR1400 power plants.

$$\text{Cost savings} = (\text{LCOE} - LCOE_{EO}) \times \textit{Saved capacity}_o\ (MW) \quad (6)$$

Where,
LCOE: Levelized cost of electricity reflected by construction cost for new APR1400 NPP
$LCOE^{EO}$: Levelized cost of electricity reflected by refurbishment cost for LTO of NPP
Saved capacity_o: Total sum of saved capacity of all existing NPPs without applying discount rate and capacity factor.

[Assumption]
The saved capacity and capacity factor weren't applied since levelized cost of electricity was estimated based on those variables already.

4. Results

4.1. Saved capacity

The different size of area between extended duration and design lifetime which is the same value as height of line indicates capacity savings for individual LTO as shown in Fig. 2. The following Table V shows saved capacities calculated with reflection of various discount rates and capacity factors for each case of LTO. We can save about 42 GW of capacity where 6% of discount rate and 90% of 80% of capacity factor by extending only 10 years which is similar capacity to the government's plan to obtain by 2035. Considering that the average of capacity factor is about 85% now, the more capacity might be secured.

4.2. Electricity sales

Table V and Fig. 3 show the electricity sales. The highest amount of electricity sales was where discount rate was 3% and capacity factor was 90%. On the contrary, the lowest point was where discount rate was 10% and capacity factor was 60%. The average capacity factor of KHNP power plant in 2015 is about 85%. Hence the more capacity factor close to 90% we can make, the more sales amounts we can get.

Table V: Saved capacity and Electricity sales

Discount rate	Capacity factor	Saved Capacity (MW)			Electricity Sales (Million USD)		
		for 10 years	for 20 years	for 30 years	for 10 years	for 20 years	for 30 years
3%	60%	59,735	104,798	138,329	24,890	43,666	57,638
3%	70%	69,690	122,264	161,384	29,038	50,944	67,244
3%	80%	79,646	139,731	184,439	33,186	58,222	76,851
3%	90%	89,602	157,197	207,494	37,334	65,499	86,457
6%	60%	31,686	49,848	59,989	13,203	20,770	24,996
6%	70%	36,967	58,156	69,987	15,403	24,232	29,162
6%	80%	42,248	66,463	79,985	17,603	27,693	33,328
6%	90%	47,529	74,771	89,984	19,804	31,155	37,494
10%	60%	15,655	22,020	24,475	6,523	9,175	10,198
10%	70%	18,264	25,691	28,554	7,610	10,705	11,898
10%	80%	20,873	29,361	32,633	8,697	12,234	13,597
10%	90%	23,482	33,031	36,712	9,784	13,763	15,297

Exchange rate: 1,150 KRW/USD (As of July 2015)
KPX settlement unit payment: 54.70 KRW/kWh (As of December 2014)

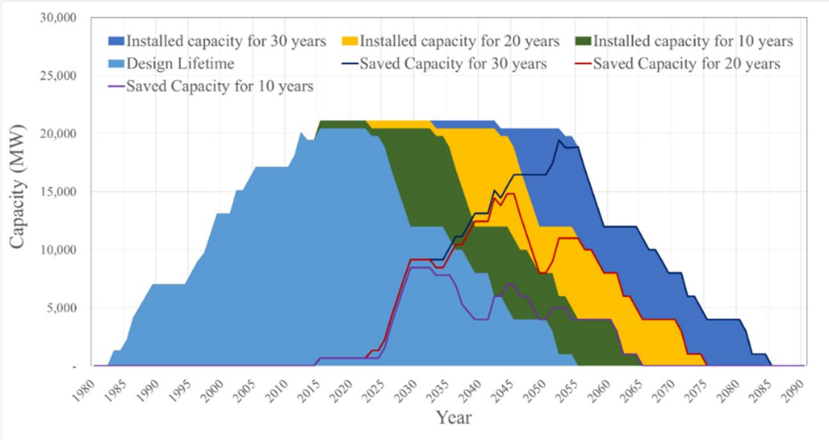

Fig. 2. Accumulated capacity savings

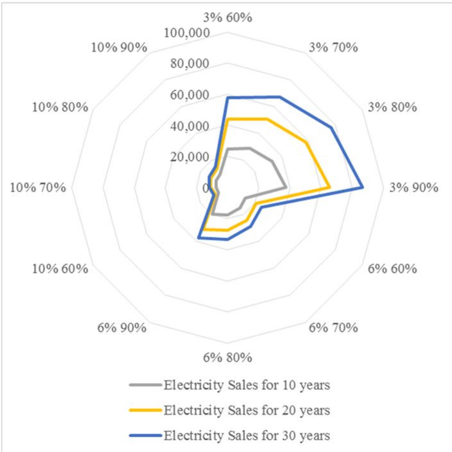

Fig. 3. Electricity sales

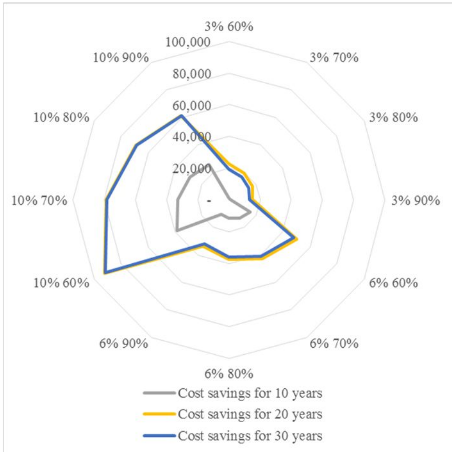

Fig. 5. Cost savings compared to APR1400 NPP

4.3. Equivalent NPPs

From Table VI and Fig. 4, we found that we would save three APR1400 new construction by extending life time for 10years. In the same way, we would save about five NPPs from 20years LTO and more than six NPPs from 30years LTO. The difference between 10years and 20years was about two NPPs. The difference between 20years and 30years was about 1.5 NPPs which is lower than the amount from 10years and 20years. The guessed reason is that the costs to be invested for replacement of aging equipment and components are different for each LTO case. The investment costs for the refurbishment cannot be optimized by utility because the regulatory body doesn't any confirmed duration of LTO to them.

Table VI: Equivalent NPPs of APR1400

Item	10 years LTO	20 years LTO	30 years LTO
APR1400 capacity (MW)	70,000	84,000	98,000
Saved capacity (MW)	209,932	421,222	632,512
Equivalent No. of NPPs (EA)	3.00	5.01	6.45

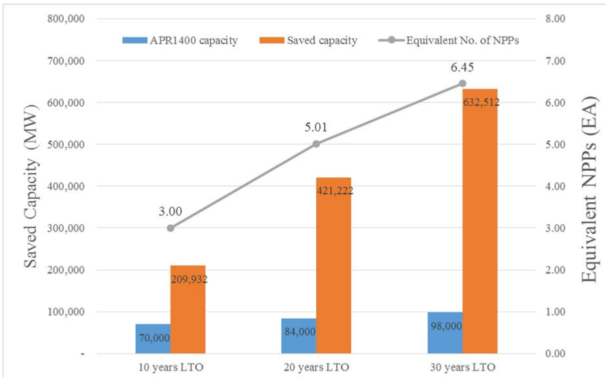

Fig. 4. Equivalent NPPs of APR1400

4.4. Cost savings

The cost savings of LTO compared to new construction of APP1400 NPP was specified in Table VII and Fig. 5. From the results, the highest cost savings came out where discount rate is 10% capacity factor is 60%. The other way we found the lowest value where 3% of discount rate and 90% of capacity factor. Above all, we can get not only cost savings but also the reduced construction of new APR1400 power plants as shown in section 4.3.

Table VII: Cost savings compared to APR1400 NPP

Discount rate	Capacity factor	Generation costs for extended operation (ⓐ)			Generation costs for New APR 1400 (ⓑ)			Cost savings (ⓐ-ⓑ)		
		10 years	20 years	30 years	10 years	20 years	30 years	10 years	20 years	30 years
3%	60%	83,333	146,070	233,821	84,401	168,802	253,203	1,068	22,732	19,382
3%	70%	72,258	126,845	202,886	73,199	146,398	219,597	941	19,553	16,711
3%	80%	63,935	112,417	179,674	64,782	129,563	194,345	846	17,146	14,671
3%	90%	57,473	101,206	161,618	58,247	116,494	174,741	774	15,288	13,123
6%	60%	86,287	153,909	258,027	101,928	203,857	305,785	15,642	49,948	47,757
6%	70%	74,778	133,562	223,620	88,216	176,431	264,647	13,438	42,869	41,027
6%	80%	66,158	118,301	197,812	77,915	155,830	233,745	11,757	37,529	35,932
6%	90%	59,442	106,442	177,758	69,916	139,832	209,747	10,474	33,389	31,990
10%	60%	90,540	165,789	295,398	128,951	257,903	386,854	38,411	92,114	91,457
10%	70%	78,427	143,746	255,658	111,376	222,752	334,128	32,949	79,006	78,470
10%	80%	69,351	127,220	225,841	98,194	196,389	294,583	28,844	69,169	68,742
10%	90%	62,274	114,354	202,655	87,942	175,884	263,826	25,668	61,530	61,171

Unit: Billion USD
Exchange rate: 1,150 KRW/USD (As of July 2015)

5. Conclusion

In this paper, the economic analysis of the LTO for the existing power plant less than and equal to 1,000MW compared to no extension was investigated. The selected durations of LTO are 10 years, 20 years, and 30 years beyond design life. The result from the analysis is that LTO of NPPs is more beneficial than observance of its design life. In the aspects of utility's electricity sales increase and reducing the new construction of APR1400 NPPs with cost savings, LTO is one of the best option in order to provide electric energy with Korean society.

6. Acknowledgement

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