On the Economic Feasibility of Nuclear Power Generation in Egypt

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By

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Abstract

Egypt is now at an early planning stage to undertake nuclear energy technology for electricity generation. Egypt's choice of nuclear technology should be guided by a sustainability criterion regarding Egypt's energy demand and supply balance. This necessitates a study of the feasibility of the use of nuclear technology towards sustainability of future energy needs for the Egyptian economy and the critical factors behind the appropriate choice of nuclear technology for Egypt's energy future. The approach undertaken in this research is forecasting demand and supply analysis for Egypt's electricity sector until the year 2050 using elasticity and factor decomposition by population growth, household income level, and GDP production. It is seen that Egypt's traditional energy sources of oil and natural gas are not expected to sustain future electricity demand. Nuclear technology is seen as feasible to generate a progressive share of forecasted electricity supply. It is derived that nuclear energy is required to generate an equivalent 4% (1 GWe) of total country wide electricity supply by 2015, 10% (3 GWe) by 2025, 12% (4 GWe) by 2030, and 15% (7 GWe) by 2050. In addition, the optimal choice of nuclear plant technology is S-LWR (*open-cycle Slow Light Water Reactor*) nuclear type technology with 1,000 MWe electricity supply per nuclear plant. Timeline of nuclear power installation is also derived. The first nuclear power plant is required by the year 2015, the second by 2020, with four nuclear plants required by 2030, and 6 nuclear plants by 2050. In general, it is concluded that Egypt's potential for nuclear energy is both feasible and necessary from an economic point of view. However, such feasibility is not universal, but is conditional on multiple critical factors which act as bounded constraints on nuclear feasibility concerning planning, implementation, and lifetime operation. The derived minimum feasible energy supply output by nuclear technology is 4.4 billion KWh annually per nuclear S-LWR 1000 MWe plant. In addition, other critical factors which dictate feasibility include capital cost per nuclear plant (upper bound of $2.682 billion in 2008 US$), unit nuclear operating cost (upper bound of 6.03 cents per KWh), price of uranium (upper bound of 0.74 cents per KWe), nuclear conversion efficiency (lower bound of 28%), nuclear plant lifetime (lower bound of 33 years), and nuclear plant capacity (lower bound of 905 MWe per nuclear power plant).

1. INTRODUCTION

The topic of this paper is on economic and technological aspects of the potential use of nuclear energy for Egypt. In general, it is seen that Egypt's traditional energy sources of oil and natural gas are not expected to be sustainable in the future compared to the forces of population growth, a growing base of industrial production, expected rate of GDP growth, and subsequently, aggregate electricity demand. Specifically, recent studies have shown a country-wide energy shortage as early as the year 2020 [1,2]. This necessitates a study of: (1) the *feasibility* of the use of nuclear technology towards sustainability of future energy needs for the Egyptian economy, (2) the *critical factors* behind the choice of *appropriate technology* to meet future energy demand, minimize technological risk, and make available cost-effective nuclear solutions, and (3) a comprehensive assessment for the required intensity of *nuclear reactor technology* for Egypt's energy security.

Nuclear power is defined as the controlled use of nuclear chain reactions to free energy for the generation of electricity[3]. Based on an International Atomic Energy Agency (IAEA) study in 2007, nuclear power generation provides 7 per cent of the world's total energy supply (thermal equivalence) and 15.7% of the world's electricity supply. This by itself is a testament to the high efficiency produced by nuclear technology compared to conventional means. The United States produces the most nuclear energy in quantity terms (20% of world nuclear supply) whereas France produces the highest relative share of nuclear supply per total domestic electrical energy demand (80%)[4].

Egypt is now at an early planning stage to undertake nuclear energy technology for electricity generation. This is to be guided by a sustainability criterion regarding Egypt's energy demand and supply balance. In a recent study by the World Nuclear Association, it is reported that Egypt produces 92 billion kWh/yr from 18 GWe of plant, giving per capita electricity consumption of

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[1] *International Atomic Energy Agency (IAEA)*, Country Fact sheet: Egypt, 2007.

[2] Selim, Tarek, "On Efficient Utilization of Egypt's Natural Resources: Oil and Gas", *Egyptian Center for Economic Studies,* Working Paper 117, January 2007.

[3] Energy Information Administration (EIA), U.S. Department of Energy, *Nuclear Energy Basics*, 2007.

[4] Kristiansen, Tarjei, "Nuclear Power Generation", *International Association for Energy Economics (IAEE) Newsletter*, Third Quarter 2007.

1350 kWh/yr. Electricity distribution by source is roughly 84% from gas and 16% from hydro[6]. The latter is predominantly from the Aswan High Dam. A negligible amount of oil is currently used in electricity generation after the Egyptian government announced that all thermal power plants must run on gas instead of oil[5]. Overall, expected electricity demand growth is expected to be between 4 to 5 per cent per annum until 2025[6].

Egypt has its own history when it comes to nuclear power. In 1964 a 150 MWe nuclear plant[7] with 20,000 m^3/day desalination was proposed and in 1974 a 600 MWe plant was initially planned. The government's Nuclear Power Plants Authority (NPPA) was then established in 1976, and in 1983 the *Dabaa* site on the Mediterranean coast was selected for a nuclear power plant. This plan was aborted following the Chernobyl accident in 1987. More recently, the NPPA carried out a feasibility study for a nuclear cogeneration plant for electricity and desalination in 2003. Consequently, a new agreement on peaceful uses of atomic energy was signed at the end of 2004 with the International Atomic Energy Authority (IAEE) as a legal document. By 2006, a nuclear cooperation agreement was reached with China[8], and in early 2008 there are serious talks with Russia concerning technical cooperation for nuclear power use. In addition, the United States, United Kingdom, and France have shown keen interest in cooperating with Egypt regarding its potential use of nuclear energy.

Egypt already has a 1961-vintage 2 MW Russian research reactor and a 22 MW Argentinean research reactor at *Inshas* in the Nile delta which started up in 1997. Both are experimental pilot programs and carry outdated technologies. Specifically, until today, Egypt does not have a single operating nuclear generator for commercial energy purposes. However, a very recent agreement with Russia has been established in March 2008 for building a 970 MWe nuclear power plant at a cost of $1.5 billion. This has been a direct consequence of a technical feasibility study for a nuclear cogeneration plant at *Dabaa* conducted in October 2006. Specifically, the Egyptian

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[5] Egypt's Petroleum Sector, *The American Chamber of Commerce*, Business Studies Division, December 2005.

[6] Emerging Nuclear Energy Countries, *World Nuclear Association*, Egypt: Country Briefings, September 2007.

[7] kWh Kilo-Watt Hour of Electricity (in 1,000 Watt-Hours of Electric Work)
GWe Gega-Watt of Electricity (in billions of Watts of Electric current)
MWe Mega-Watt of Electricity (in millions of Watts of Electric current)

[8] Emerging Nuclear Energy Countries, *World Nuclear Association*, Egypt: Country Briefings, September 2007.

Minister for Energy and Electricity announced that a 1,000 MWe commercial reactor would be built there by 2015. The $1.5 to $2 billion project was said to be open to shared foreign participation. However, it is important to note that 1,000 MWe is insufficient to meet Egypt's expected energy gap in the long-term future. Most studies point to a need for 4,000 MWe of electricity by nuclear technology as necessary supply by the year 2030 (MIT, 2003).

2. METHODOLOGY

The methodology undertaken in this paper is a techno-economic assessment for the use of nuclear power generation for Egypt. The study will generally follow economics and technology guidelines appropriate to Egypt based on the following reference documents:

(1) Massachusetts Institute of Technology (MIT), Nuclear Energy Experts Committee, Program on Science, Technology, and Public Policy, *The Future of Nuclear Power*, 2003.
(2) World Nuclear Association, *The New Economics of Nuclear Energy*, December 2005.
(3) International Association for Energy Economics (IAEE), *Nuclear Power Generation*, September 2007.

The first reference provides comprehensive technological selection criteria for appropriate nuclear technology using a cost-effective risk-minimizing nuclear solution. The second reference uses an economic feasibility framework in cost-benefit analysis for the potential use of nuclear energy, while the third reference is a highly specialized economics of technology document for the efficient use of nuclear energy for developing countries. These references have been used extensively by the U.S. Department of Energy and the International Atomic Energy Agency (IAEA) especially for emerging nuclear energy countries. Specifically, the MIT study has been cited as one of the most important technological assessment documents for countries pursuing the nuclear option (IAEA, 2007).

As a general outcome, this research paper will include policy directives that are recommended for Egypt's potential use of nuclear energy. The choice of nuclear technology, timeline of implementation, energy security concerns, nuclear reactor cycle assessment, and number and distribution of nuclear power plants are the major policy issues of relevance. Policy directives regarding Egypt's overall energy sustainability will be addressed, including target shares of nuclear energy supply, and associated nuclear technology sensitivities to economic policy factors. Specific technological factors, such as nuclear reactor cycle efficiency, risk minimization, and plant proliferation and nuclear plant cost-effectiveness will be analyzed. All of these issues carry direct policy recommendations to decision makers and are important dimensions to Egypt's future nuclear outlook.

3. EGYPT'S ELECTRICITY SECTOR: ANALYSIS AND FORECAST

Egypt's installed generating capacity stood at 17.06 gigawatts (GW) as of 2004, and has reached 18.01 GW in 2007, with plans to add 4.5 GW of additional generating capacity by 2010 and 8.38 GW by mid-2012. Overall, natural gas fuels 85 percent of Egypt's electricity production with the remainder coming from the Aswan High Dam.

Table 1 shows an analysis of the electricity sector in Egypt based on a supply-demand balance. Historical values were used from 1980 to 2007 in order to calculate elasticity estimates and decomposition of various economic factors. In particular, decomposition of total electricity consumption (*TC*) into contributions due to household population (*H*), GDP real production index (*P*), income (*I*), and productivity (*R*), the following decomposition relationship was used:

$$\left(\frac{\Delta TC}{TC}\right) = \alpha\left(\frac{\Delta H}{H}\right) + \beta\left(\frac{\Delta P}{P}\right) + \gamma\left(\frac{\Delta I}{I}\right) + \eta\left(\frac{\Delta R}{R}\right) \qquad (1)$$

The rationale for (1) is that changes in electricity consumption are explained by contributed changes in population (α), GDP production (β), income level (γ), and productivity (η).

Total electricity demand (consumption) has shown a 4.16 per cent incremental growth rate (100% impact) caused by the following four factors:

(1) population growth (*H*) contributes 0.80 per cent (19.2% impact rate)
(2) GDP real production index (*P*) contributes 1.49 per cent (35.8% impact rate)
(3) income (*I*) contributes 1.57 per cent (37.7% impact rate)
(4) productivity increases (*R*) contribute 0.3 per cent (7.2% impact rate)

In general, it may seem that the impact of population growth is not substantial. A possible reason is that most electricity demand by households is shared rather than per capita based. For example, an air conditioner or TV or heater or radio is shared by all people living in a household rather than consumed individually. Hence, the contribution of 0.80 per cent per person would have a higher impact if number of people per household is factored in. Consequently, the household impact rate would be 2.72 per cent given that the average number of people per household in Egypt is 3.4.

The impact of production on electricity demand is a little over one-third which can be a direct consequence of the capital intensity used in production. On the other hand, a rise in personal income also has over one-third contribution. Finally, productivity increases contribute a small 0.3 per cent with a 7.2% impact rate showing the lack of innovation in electricity usage across all sectors of the economy.

In addition, elasticity measures for electricity consumption with respect to price, income, and GDP output, yield elasticity values of 0.37 (inelastic), 1.23 (elastic), and 0.93 (neutral) respectively. Therefore, total electricity demand is seen as necessary in terms of consumer expenditure with respect to prices, yet a luxury in terms of consumer expenditure with respect to income level. The economy's output is uniformly proportional to total electricity demand.

Based on the above analysis, Figure 1 shows impact diagrams for Egypt's electricity consumption with respect to population, income, and GDP production. Figure 2 shows the trend of Egypt's electricity consumption over time and is used in the estimation of contribution shares for population, income, GDP production, and productivity, as derived in (1) above.

Figure 1: Impact Diagrams for Egypt's Electricity Consumption

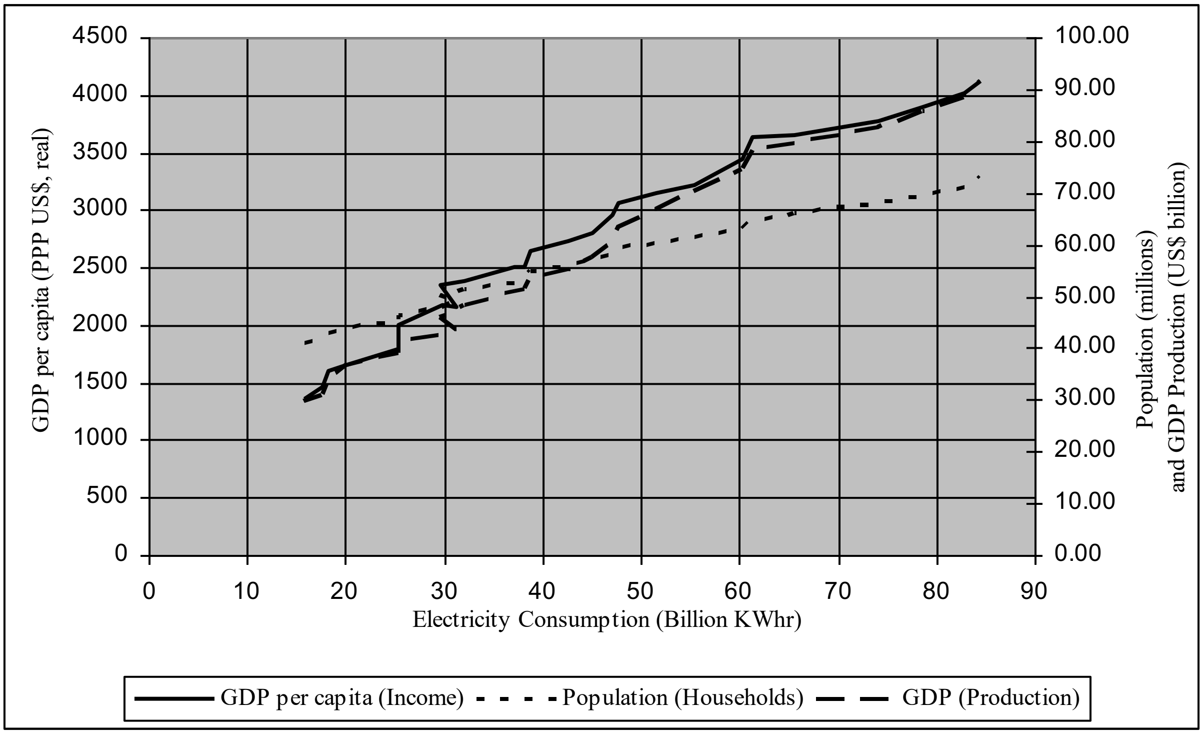


Figure 2: Trend of Egypt's Electricity Consumption and Contribution Shares

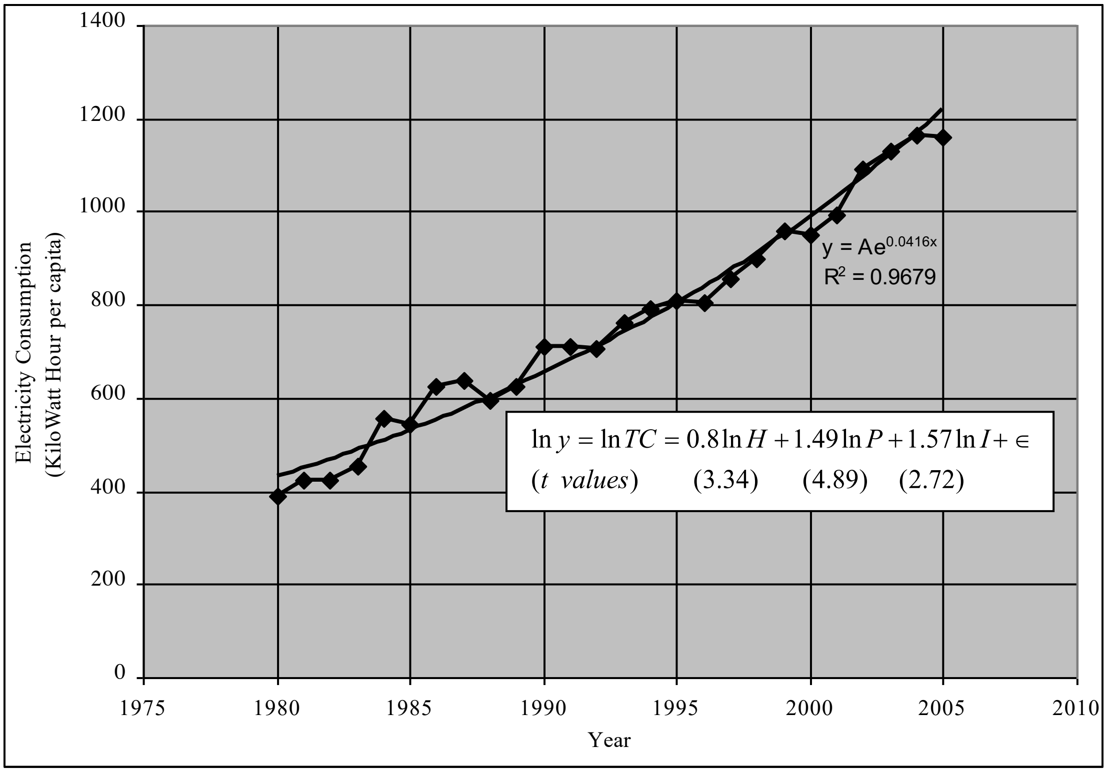


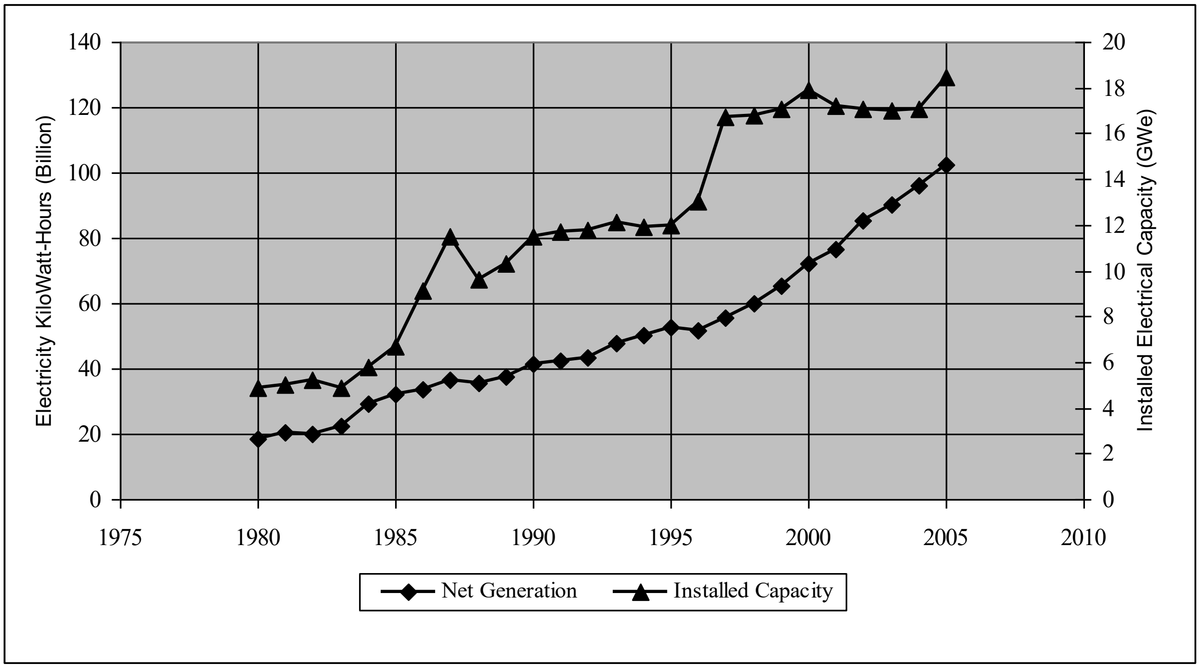
Table (1): Analysis of the Electricity Sector in Egypt (1980-2007)

	Sensitivity of Electricity Sector in Egypt to various Economic Variables	**Comment**
Per capita Electricity Consumption	1350 kWh per capita per year (2007) Target value of 3500 kWh per capita (2030)	4,000 kWh per capita required by 2050
Total Electricity Consumption	4.16 per cent incremental growth rate (100% impact)	1980-2007
Contribution of Population Growth	0.80 (19.2% impact rate)	Decomposition by regression
Contribution of GDP Production Index	1.49 (35.8% impact rate)	Decomposition by regression
Contribution of per capita GDP Growth Rate	1.57 (37.7% impact rate)	Decomposition by regression
Contribution due to Growth in Productivity	0.3 (7.2% residual impact)	Residual
Electrical Installation Capacity (Supply)	18 GWe (2007) currently installed (none nuclear) 4 GWe (2030) required by nuclear energy 6 GWe (2050) required by nuclear energy 1,000 MWe per plant average supply requirement 4 nuclear plants required by 2030 and 6 nuclear plants required by 2050	20% target value of additional installed capacity, with a bare minimum constraint of 10% for total installed capacity
Price elasticity (Sensitivity of Electricity Demand to Price increase)	0.37 (with a decomposition of 85% thermal electric generation and 15% to hydroelectric generation)	Inelastic (Relatively Insensitive)
Income elasticity (Sensitivity of Electricity Demand to Income increase)	1.23 (historical average, 1980-2007)	Elastic (Highly Sensitive)
GDP Elasticity (Sensitivity of Electricity Demand to GDP)	0.93 (historical average, 1980-2007)	Neutral

Note: Author's calculations. The significance of the decomposition of Total Electricity Consumption by regression is tested with a critical t statistic (95% confidence level) of 2.07. Results imply significance based on t values of 3.34, 4.89, and 2.72 for population, GDP production, and per capital GDP growth rates, respectively. The contribution of productivity is derived using the criteria of "Solow residual" (Mankiw 1992).

On the other hand, Egypt's total electricity supply (generation) has shown a 5.6 per cent annual increase for the period 1980-2005. Total supply as a stock variable (total installed capacity) was 5 GWe in 1980, 10 GWe in 1990, 17 GWe in 2000, and reached 18 GWe in 2007. The average increase in total installed capacity was 0.6 GWe per year for the past three decades. Figure 3 shows Egypt's supply trend of electricity generation and total installed capacity.

Figure 3: Egypt's Electricity Generation and Total Installed Capacity



Using the decomposition analysis results (from Table 1), combined with the demand and supply trends in Figures 1 to 3, a forecast time path for electricity "equilibrium" is derived, where demand equals supply, given by:

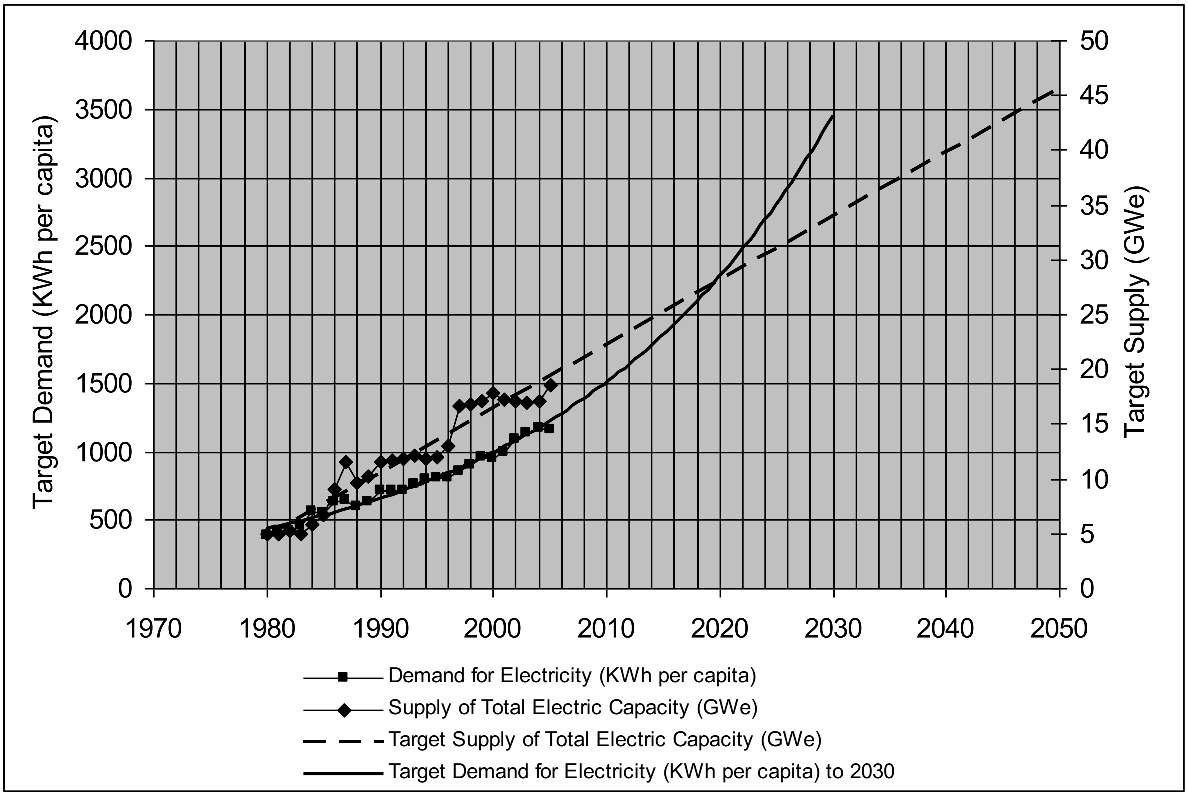
$$TC_t = TC_{t-1} + \Delta TC^e = TC_{t-1}\left\{1 + 0.8\left(\frac{\Delta H}{H}\right) + 1.49\left(\frac{\Delta P}{P}\right) + 1.57\left(\frac{\Delta I}{I}\right) + 0.3\left(\frac{\Delta R}{R}\right)\right\} = \frac{I_t}{C_f} \qquad (2)$$

Equation (2) above is used to forecast the equilibrium values of demand (*TC*), using the sensitivity factors derived from Equation (1) above and given in Table 1, and to equate each demand target per year to a corresponding target level of electricity supply (I_t). However, since total installed capacity is a stock variable, a *technological conversion factor* must be used for electricity generation. This conversion factor, denoted by C_f in (2), is derived to be:

$$C_f = 0.015085\,(\pm\ 2.8\%) \tag{3}$$

The technological conversion factor in (3) is critical in the choice of nuclear intensity and nuclear fuel cycle components (MIT, 2003). More specifically, the main assumption is that total installed capacity shall include a nuclear technology component carrying 20% target value of additional installed capacity with a bare minimum constraint of 10% for total installed capacity. This also constrains the forecast results to a specific type of nuclear technology with certain technological characteristics which shall be analyzed further in the next section of this paper.

Figure 4: Target Demand and Target Supply Balance for Egypt's Electricity Sector



Given the implicit technological choice of nuclear energy from (2) and (3), and the sensitivity results of decomposition found in Table (1), the target demand and supply levels for Egypt's electricity sector are shown in Figure 4 above.

It is forecasted that per capita demand for electricity will reach 1500 KWh by 2010, 2000 KWh by 2018, and 3500 KWh by 2030. On the other hand, the forecast for electricity supply as total installed capacity is 22 GWe by 2010, 26 GWe by 2018, and 35 GWe by 2030. An extended supply forecast yields 40 GWe by 2040 and 45 GWe by 2050.

4. EGYPT'S NUCLEAR ENERGY POTENTIAL

Egypt is in need of a nuclear power plant by 2015 with additional nuclear plants by the years 2020, 2025, 2030, 2040, and 2050 for a total of 6 nuclear plants generating a total of 4 GWe of electricity generation by 2030 equivalent to 12% of total country wide electricity supply, and 7 GWe by 2050 reaching 15% of total electricity supply. Each nuclear plant must carry a minimum capacity of 1000 MWe per plant using an *open cycle S-LWR (Slow Light Water Reactor) nuclear type technology*. The initial capital cost for the first nuclear power plant is estimated at $2 billion whereas the average capital cost per nuclear plant (2010-2050) is estimated at $1.2 billion in 2008 dollars. Target nuclear supply is 4.8 billion KWh in 2015, 9.5 billion KWh in 2020, 14.3 billion KWh in 2025, 19.8 billion KWh in 2030, 24.4 billion KWh in 2040, and 30.0 billion KWh in 2050.

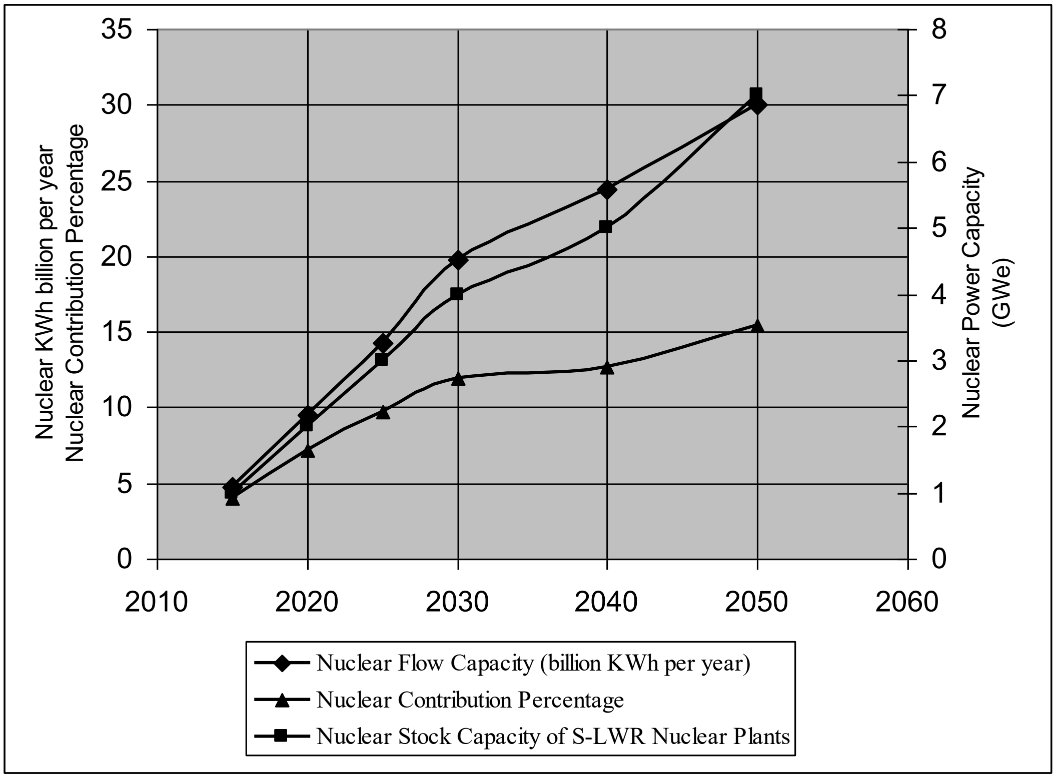
The estimated choice of nuclear energy is summarized in Table (2) below. The selection of nuclear technology and its associated technological conversion factor is assumed to follow the guidelines mentioned above and which also conform to the most consistent results on this topic as applied to Egypt (MIT, 2003, WNA, 2005, Selim 2007, and IAEA, 2007). Figure 5 shows Egypt's required nuclear capacity (2010-2050). Three inter-related nuclear supply requirements are illustrated: (1) *Nuclear Flow Capacity* (billion KWh per year), (2) *Nuclear Contribution Percentage* (defined as the ratio of nuclear supply by total electrical demand forecast), and (3) *Nuclear Stock Capacity of S-LWR Nuclear Plants* (GWe of nuclear power).

Table (2): Nuclear Energy Potential for Egypt (2010-2050)

Year	*Forecasted Electricity Consumption (kWh per capita)*	*Required Electricity Supply (GWe)*	*Estimated Nuclear Energy Usage*	*Target Nuclear Production (kWh billion)*	*Number of Nuclear Plants*	*Estimated Future Capital Cost of Nuclear Power*	*Cumulative Capital Cost of Nuclear Power (2008 US$)*	*Estimated Operating Cost of Nuclear Power (2008 US$ millions)*	*Estimated Uranium Fuel Cost Requirement (2008 US$ millions)*
2010	1500	22.0	0 GWe (0%)	-	None	-	-	-	-
2011	1562	22.6	0 GWe (0%)	-	None	-	-	-	-
2012	1627	23.2	0 GWe (0%)	-	None	-	-	-	-
2013	1695	23.8	0 GWe (0%)	-	None	-	-	-	-
2014	1766	24.3	0 GWe (0%)	-	None	-	-	-	-
2015	1839	24.9	1 GWe (4.0%)	4.8	1	$2 billion	$1.16 billion	$125.5	$18.8
2016	1916	25.5	1 GWe (3.9%)	4.8	1	-	-	$117.3	$18.1
2017	1995	26.1	1 GWe (3.8%)	4.8	1	-	-	$109.7	$17.4
2018	2078	26.7	1 GWe (3.7%)	4.8	1	-	-	$102.5	$16.7
2019	2165	27.3	1 GWe (3.6%)	4.8	1	-	-	$95.8	$16.0
2020	2255	27.8	2 GWe (7.2%)	9.5	2	$2.7 billion	$2.05 billion	$177.2	$30.5
2021	2349	28.4	2 GWe (7.0%)	9.5	2	-	-	$165.6	$29.4
2022	2446	29.0	2 GWe (6.9%)	9.5	2	-	-	$154.7	$28.2
2023	2548	29.6	2 GWe (6.8%)	9.5	2	-	-	$144.6	$27.2
2024	2654	30.2	2 GWe (6.6%)	9.5	2	-	-	$135.2	$26.1
2025	2764	30.8	3 GWe (9.7%)	14.3	3	$3.8 billion	$3.25 billion	$190.1	$36.7
2026	2879	31.3	3 GWe (9.6%)	14.3	3	-	-	$177.7	$35.2
2027	2999	31.9	3 GWe (9.4%)	14.3	3	-	-	$166.1	$33.9
2028	3124	32.5	3 GWe (9.2%)	14.3	3	-	-	$155.2	$32.6
2029	3254	33.1	3 GWe (9.1%)	14.3	3	-	-	$145.1	$31.3
2030	3389	33.7	4 GWe (11.9%)	19.8	4	$5.3 billion	$4.45 billion	$187.7	$41.7
2040	5094	39.5	5 GWe (12.7%)	24.4	5	$10.5 billion	$5.65 billion	$117.6	$34.7
2050	7657	45.4	7 GWe (15.4%)	30.0	6	$25.7 billion	$7.16 billion	$73.5	$28.8

Note: Author's calculations based on forecast results from Equations (1) and (2) and given in Table (1). Additional assumptions derived from MIT (2003), WNA(2005), and IAEA (2007). Assumptions include 7% opportunity cost of capital, 90% operating capacity, 40-year lifetime per nuclear plant, open cycle LWR nuclear technology reactor types for all nuclear plants, a 3% yearly price increase for uranium, 1000 MWe per nuclear plant generation, 0.515 cents per KWe uranium requirement with 3-5% uranium enrichment requirement based on 0.711% U-235 content. Estimated nuclear operating expenses are assumed to start at 4.2c/kWe compared to 5.6c/KWe for conventional thermal power plants.

Figure 5: Egypt's Nuclear Capacity Requirements (2010-2050)



Egypt's nuclear capacity requirements dictate a rising share of nuclear energy contribution to total electricity supply with a target contribution share of 4% in 2015, 12% in 2030, and 15% in 2050. The long-term target is to achieve 30 billion KWh per year of electricity generation by nuclear energy with a nuclear plant stock installation capacity of 7 GWe, distributed through 6 nuclear power plants of S-LWR nuclear cycle capability. This scenario is seen to be the most cost-effective nuclear solution for Egypt's energy future.

It should be mentioned here that there exist other more advanced nuclear plant technologies than the S-LWR nuclear cycle. Yet, the S-LWR nuclear cycle is seen as the most desirable because it is the most demanded by other developing countries, the most cost-effective, and the least costly initially (MIT 2003, WNA 2005, and IAEA 2007). Other nuclear technology cycles include the closed PUREX nuclear cycle which can generate double the energy intensity output of an S-LWR nuclear cycle and does not require decommissioning at its terminal life, but is four times as expensive in capital cost and requires a well-trained high maintenance team. Thus, it involves higher operating costs and a higher risk of negligence or mismanagement (MIT 2003). Another alternative is fast-cycle nuclear reaction plants, such as CANDU and HTGR, which also generate higher energy output intensity, but are considered experimental in nature due to their exceedingly high technology skills requirements in labor, and because there exist very few real life commercial nuclear plants on the ground for the case of developing countries (they mostly operate in Japan and Canada).

Overall, higher technology nuclear cycles (beyond the chosen S-LWR nuclear technology) can generate more electricity output per plant, but such technologies may not be suitable for a developing country like Egypt generally because of risk and labor issues. Nevertheless, the S-LWR nuclear cycle has a long-term disadvantage relative to higher nuclear technologies in its decommissioning cost requirement at its terminal life of 40 years. More advanced nuclear cycles do not have this requirement.

5. BREAK-EVEN FEASIBILITY ANALYSIS FOR EGYPT'S NUCLEAR ENERGY POTENTIAL

The above analysis assumes that nuclear energy is economically feasible at all energy capacity levels compared to thermal power plants. This may not be necessarily true for all energy output levels or cost of capital variations. This demands an economic feasibility for the potential use of S-LWR nuclear technology for Egypt as compared to thermal plants. Since it is seen that the S-LWR type of nuclear cycle is the most suitable for a developing country like Egypt, given risk and management issues, it is now important to test for the break-even level of nuclear energy that would be cost-effective as compared to its thermal plant equivalent.

Consequently, the *feasibility of nuclear supply requirements* in the previous section requires an economic break-even analysis as a benchmark of comparison between nuclear S-LWR power plants and their equivalent conventional thermal plants. The break-even analysis for nuclear power generation compared to conventional thermal power can be summarized by the following formula:

$$\left(K_N - K_T\right) + X\left[\frac{C_N - C_T}{100}\right]\left(\frac{1}{\eta_x}\right)\left[\frac{(1+r)^t - 1}{r(1+r)^t}\right] + \frac{DC_t}{(1+r)^t} = 0 \tag{4}$$

where:

K_N = Capital cost of nuclear power plant ($2000 per KWe)
K_T = Capital cost of thermal power plant ($500 per KWe)
X = Target electricity power flow per year (KWh per year)
C_N = Operating unit cost of nuclear generation (4.2 cents per KWh per year)
C_T = Operating unit cost of thermal generation (5.6 cents per KWh per year)
η_x = Relative efficiency (thermal plant efficiency is 72% of nuclear plant efficiency)
r = Discount rate (opportunity cost of capital) with a bare minimum rate of 5%
t = Lifetime of power plant (40 years for both)
DC_t = Decommissioning cost at terminal life for nuclear power only ($350 per KWe)

The two energy supply options (nuclear vs. thermal) can be compared by usage of Equation (4) which incorporates the net discounted value of nuclear costs as compared to thermal conventional costs. If the net benefits from the two options are assumed to be similar over time per unit of energy supply, then Equation (4) would provide the extent of nuclear feasibility compared to thermal power. The rationale is that even though nuclear power is initially more costly, and also terminally more costly, yet its higher efficiency coupled with lower operating costs per unit of energy supply can overcome these higher costs. Hence, there exists a minimum break-even level of energy supply by which nuclear power is economically feasible. Given this rationale, Equation (4) takes account of the relative initial capital cost, unit operating costs, decommissioning cost of the nuclear option, discount rate as the opportunity cost of capital, and the relative technical efficiency of the two options. The only unknown in (4) is the yearly target supply of electricity generation (X).

Solving for X in (4) to get the break-even energy supply for nuclear feasibility X_{BE}:

X_{BE} = 4.4 billion KWh per 1000 MWe nuclear plant capacity.

Hence, the *minimum feasible energy supply output by nuclear technology* is 4.4 billion KWh per S-LWR 1000MWe plant.

From Table (2), it is seen that Egypt's nuclear potential has an average of 4.86 billion KWh per plant with a lower bound-upper bound range of 4.75-4.95 billion KWh of nuclear energy supply per plant. Therefore, it is generally concluded that nuclear energy is economically feasible for Egypt's future energy plans.

Table (3): Sensitivity of Nuclear Energy Feasibility to Various Parameters

Description of Critical Parameter	*Nuclear Energy Parameter Description*	*Critical Value*	*Conditions*
Maximum Feasible Capital Cost	Nuclear Capital Cost of 1000 MWe plant	$2.682 billion (2008 US $)	Generate output of 4.86 billion KWh per year Discount rate more than 3%
Maximum Discount Rate for Nuclear Feasibility	Discount Rate (opportunity cost of capital)	13.2%	1000 MWe nuclear plant
Maximum Unit Cost of Operating Nuclear Power	Unit Cost of Nuclear Power	6.03 cents per KWh	90% nuclear plant capacity
Maximum Price of Uranium for Nuclear Feasibility	Price of Uranium	0.74 cents per KWe	U-235 content of 0.711%
Maximum Relative Efficiency of Thermal to Nuclear	Relative Efficiency	161%	Normal relative efficiency is 72%
Minimum Nuclear Operating Efficiency	Absolute Nuclear Operating Efficiency	28%	Normal efficiency is 33%
Minimum Electricity Output for Nuclear Feasibility	Nuclear Output	4.4 billion KWh per year	Expected range of 4.75-4.95 billion KWh per year for Egypt (2010-2050)
Minimum Nuclear Plant Lifetime	Nuclear Lifetime	33 years per nuclear plant	Normal lifetime is 40 years
Minimum Nuclear Stock Capacity per Plant	Nuclear S-LWR Technology Stock Capacity	905 MWe	Normal S-LWR capacity is 1000MWe

Source: Author's calculations.

The feasibility of nuclear energy for Egypt has several limits to its implementation. Table (3) above shows the critical values by which nuclear energy is generally feasible. In particular, Egypt's nuclear feasibility has both upper bound (maximum) and lower bound (minimum) critical values for various parameters. Critical parameters for nuclear feasibility include the following *maximum critical values for nuclear feasibility*:

(1) capital cost of $2.682 billion (2008 US$)
(2) discount rate of 13.2%
(3) unit nuclear operating cost of 6.03 cents per KWh
(4) price of uranium of 0.74 cents per KWe

In addition to maximum critical values for nuclear feasibility, there also exist *minimum critical values for nuclear feasibility* as described in Table (3) and these are:

(1) output of 4.4 billion KWh per year
(2) nuclear plant lifetime of 33 years
(3) nuclear operating efficiency of 28%
(4) 905 MWe nuclear capacity per plant

Accordingly, although nuclear energy supply is generally feasible for Egypt's future, yet such feasibility contains both upper bound and lower bound critical values for various economic parameters. Hence, Egypt's nuclear feasibility is not universal, but rather conditional on, multiple critical parameter values of certain economic parameters. Such a constraint on nuclear feasibility must be taken seriously in the implementation phase of nuclear operation in Egypt.

6. CONCLUSION

The topic of this paper is Egypt's potential for nuclear energy. This has been tackled by demand and supply analysis for Egypt's electricity sector until the year 2050. It is seen that Egypt's traditional energy sources of oil and natural gas are not expected to sustain future electricity demand. Total electricity demand (consumption) is forecasted to have 4.16 per cent incremental growth rate such that per capita electricity demand is forecasted to reach 3389 KWh in 2030 and 7657 KWh in 2050, compared to 1350 KWh in 2007. On the other hand, the forecast for electricity supply to meet aggregate demand as total installed capacity is 22 GWe by 2010, 35 GWe by 2030, and 45 GWe by 2050, compared to the current supply of 18 GWe in 2007.

Nuclear technology is seen as feasible to generate a share of forecasted electricity in Egypt. Nuclear energy is required to generate 1 GWe (2015), 2 GWe (2020), 3 GWe (2025), 4 GWe (2030), and 7 GWe (2050). Using 1,000 MWe per plant average nuclear supply requirement based on S-LWR (slow open-cycle light water reactor) nuclear type technology, the first nuclear power plant is required by the year 2015, the second by 2020, with four required nuclear plants by 2030 and 6 nuclear plants by 2050. In essence, nuclear energy in Egypt would meet a shared generation of total country wide electricity supply equivalent to 10% in 2025, 12% in 2030, and 15% in 2050. Target nuclear supply for Egypt is 4.8 billion KWh in 2015, 9.5 billion KWh in 2020, 14.3 billion KWh in 2025, 19.8 billion KWh in 2030, and 30.0 billion KWh in 2050.

However, it is also seen that feasibility of nuclear energy for Egypt is not without limits. It is derived that the *minimum feasible energy supply output by nuclear technology* is 4.4 billion KWh annually per nuclear S-LWR 1000MWe plant. In addition, several critical factors dictate the range of nuclear feasibility. These are capital cost per nuclear plant (upper bound estimate of $2.682 billion in 2008 US$), discount rate (upper bound of 13.2%), unit nuclear operating cost (upper bound of 6.03 cents per KWh), price of uranium (upper bound of 0.74 cents per KWe), nuclear plant lifetime (lower bound of 33 years), nuclear operating efficiency (lower bound of 28%), and nuclear capacity per plant (lower bound of 905 MWe per nuclear plant).

In summary, Egypt’s potential for nuclear energy is both feasible and necessary from an economic point of view for the sustainable long run development of the country. However, such feasibility is not universal, but is seen to be conditional on multiple critical factors which act as bounded constraints on nuclear feasibility concerning planning, implementation, and lifetime operation.

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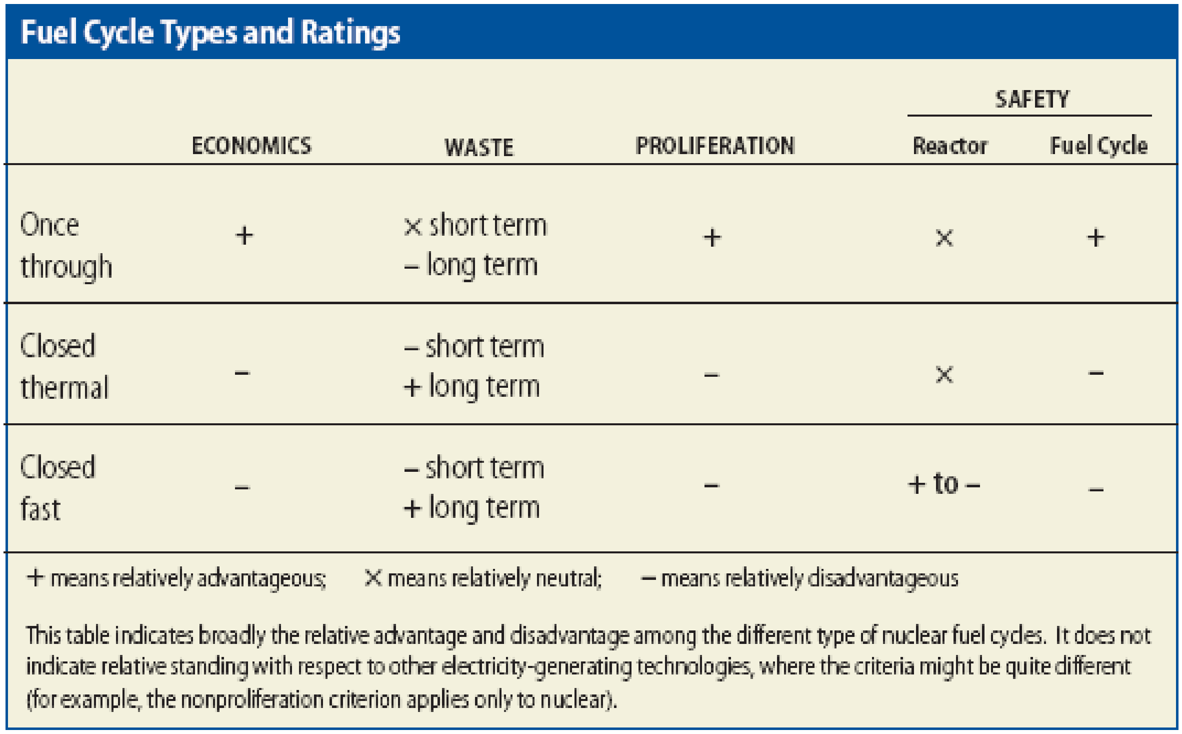
TECHNOLOGICAL POTENTIAL FOR NUCLEAR ENERGY

a. Critical Factors
b. Appropriate Technology
c. Nuclear Reactor Generation
d. Nuclear Plants and Distribution
e. Energy Security
f. Risk Assessment



Fuel Cycle Types and Ratings

				SAFETY	
	ECONOMICS	WASTE	PROLIFERATION	Reactor	Fuel Cycle
Once through	+	× short term – long term	+	×	+
Closed thermal	–	– short term + long term	–	×	–
Closed fast	–	– short term + long term	–	+ to –	–

+ means relatively advantageous; × means relatively neutral; – means relatively disadvantageous

This table indicates broadly the relative advantage and disadvantage among the different type of nuclear fuel cycles. It does not indicate relative standing with respect to other electricity-generating technologies, where the criteria might be quite different (for example, the nonproliferation criterion applies only to nuclear).

NUCLEAR CYCLE TYPES

Fuel Uranium: 0.711% U-235 isotope (fission reactor) and remainder U-238 (non-fission), inclusive of 3-5% uranium enrichment requirement for nuclear reaction cycle.

Open-cycle (slow reactor) nuclear fuel cycle options: Light Water Cooled Reactor (LWR), includes two similar technologies BWR (Boiling Water Reactor) and PWR (Pressurized Water Reactor).

Closed-cycle (fast reactor) nuclear fuel cycle: PUREX (Plutonium/Uranium mix), high technology, more expensive 4x in 40-yr lifetime of cycle, BUT higher efficiency (75% compared to 33% for LWR).

Mixed nuclear reactors: CANDU (Canadian Deuterium-uranium nuclear reactor), Heleum high temperature gas nuclear reactor (HTGR)

MIT Study on the Future of Nuclear Power (Open versus Closed Fuel Cycles, MOX Option)

Figure 4.1 Open Fuel Cycle: Once-Through Fuel — Projected to 2050

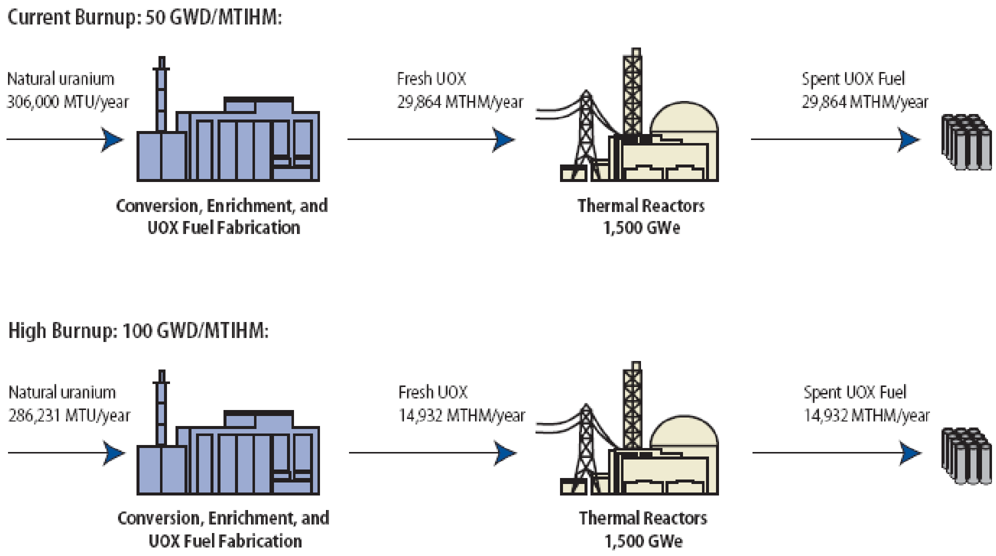
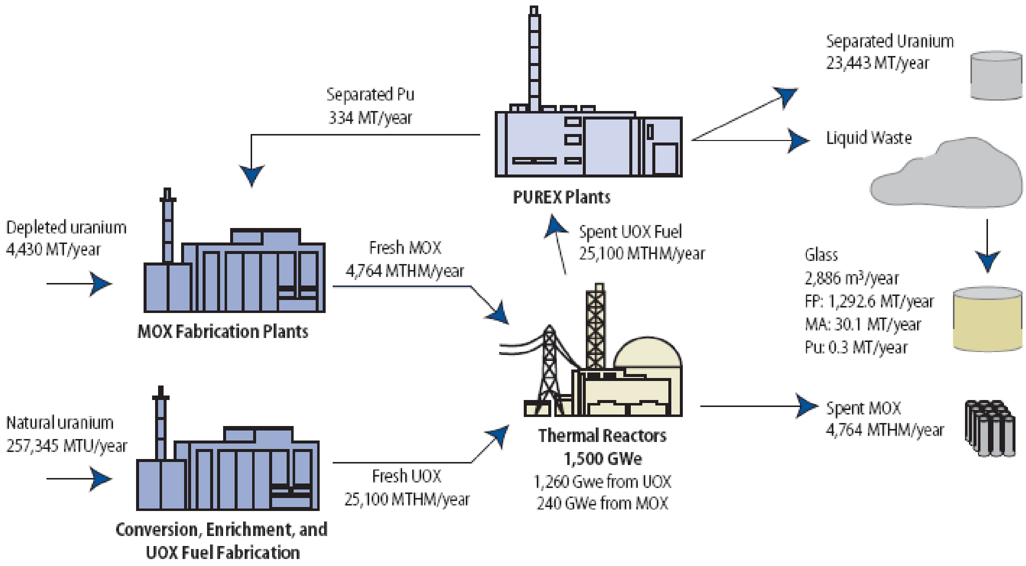
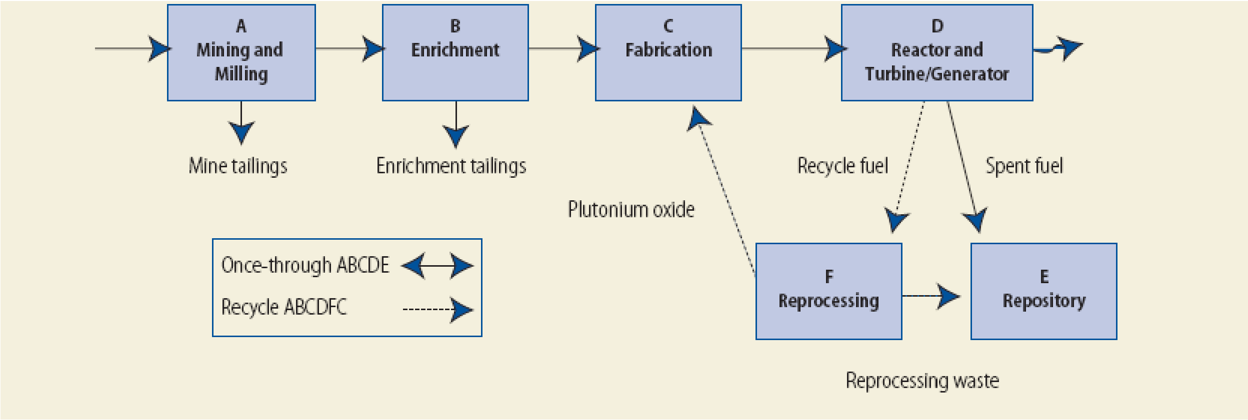
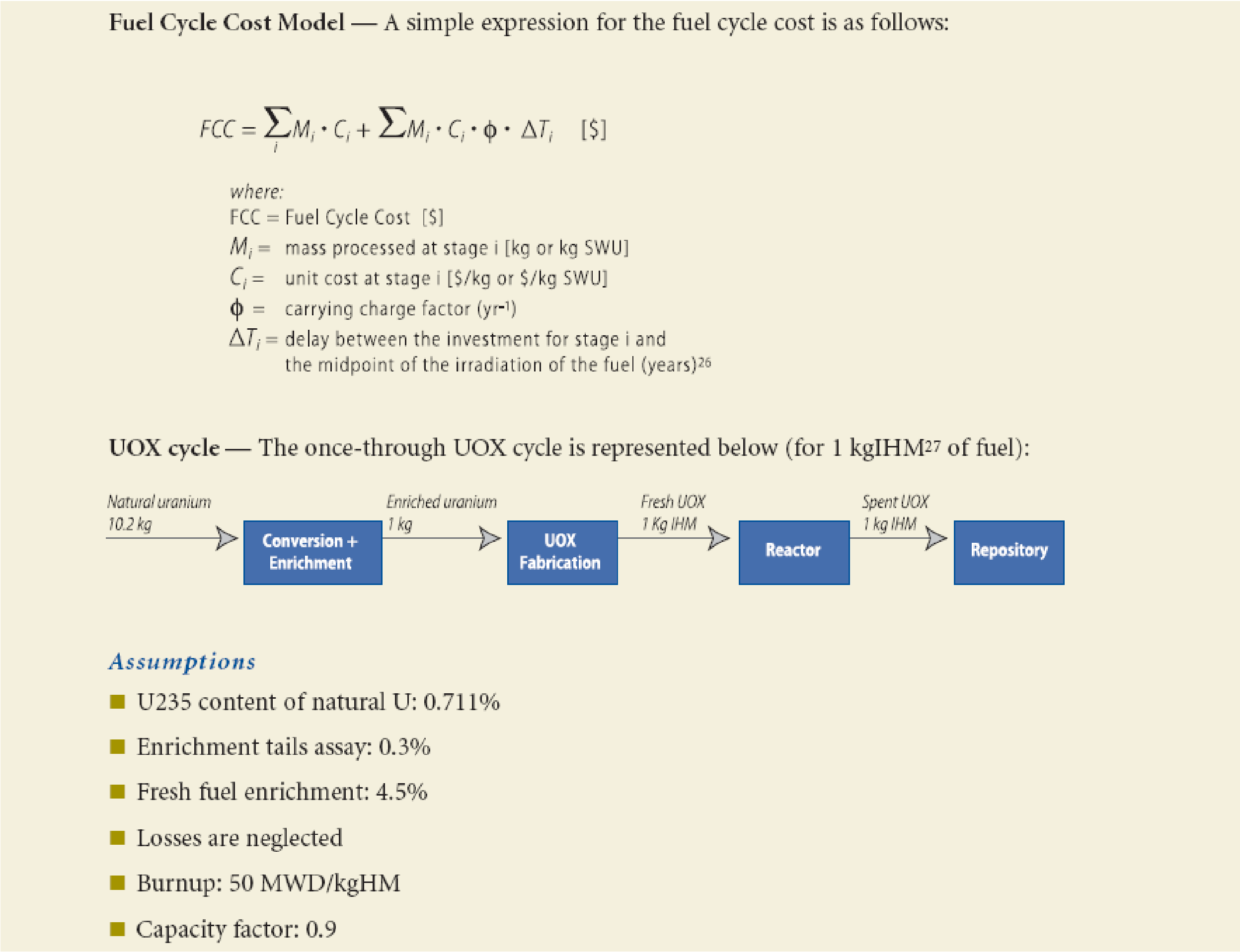


Figure 4.2 Closed Fuel Cycle: Plutonium Recycle (MOX option - one recycle) — Projected to 2050







Fuel Cycle Cost Model — A simple expression for the fuel cycle cost is as follows:

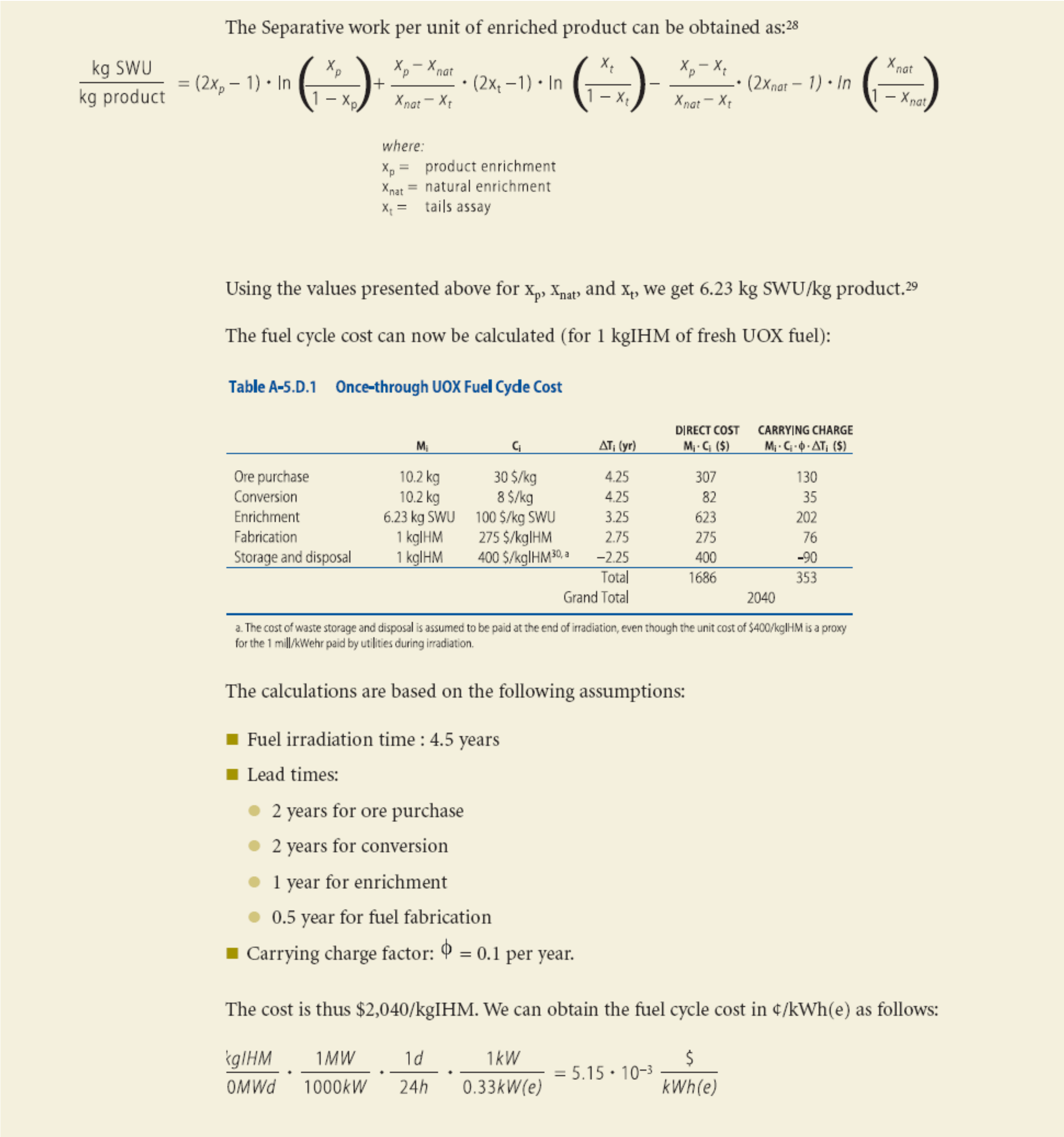
$$FCC = \sum_i M_i \cdot C_i + \sum M_i \cdot C_i \cdot \phi \cdot \Delta T_i \quad [\$]$$

where:
FCC = Fuel Cycle Cost [$]
M_i = mass processed at stage i [kg or kg SWU]
C_i = unit cost at stage i [$/kg or $/kg SWU]
ϕ = carrying charge factor (yr^{-1})
ΔT_i = delay between the investment for stage i and the midpoint of the irradiation of the fuel (years)[26]

UOX cycle — The once-through UOX cycle is represented below (for 1 kgIHM[27] of fuel):

Assumptions

- U235 content of natural U: 0.711%
- Enrichment tails assay: 0.3%
- Fresh fuel enrichment: 4.5%
- Losses are neglected
- Burnup: 50 MWD/kgHM
- Capacity factor: 0.9



The Separative work per unit of enriched product can be obtained as:[28]

$$\frac{\text{kg SWU}}{\text{kg product}} = (2x_p - 1) \cdot \ln\left(\frac{x_p}{1 - x_p}\right) + \frac{x_p - x_{nat}}{x_{nat} - x_t} \cdot (2x_t - 1) \cdot \ln\left(\frac{x_t}{1 - x_t}\right) - \frac{x_p - x_t}{x_{nat} - x_t} \cdot (2x_{nat} - 1) \cdot \ln\left(\frac{x_{nat}}{1 - x_{nat}}\right)$$

where:

x_p = product enrichment

x_{nat} = natural enrichment

x_t = tails assay

Using the values presented above for x_p, x_{nat}, and x_t, we get 6.23 kg SWU/kg product.[29]

The fuel cycle cost can now be calculated (for 1 kgIHM of fresh UOX fuel):

Table A-5.D.1 Once-through UOX Fuel Cycle Cost

	M_i	C_i	ΔT_i (yr)	DIRECT COST $M_i \cdot C_i$ (\$)	CARRYING CHARGE $M_i \cdot C_i \cdot \phi \cdot \Delta T_i$ (\$)
Ore purchase	10.2 kg	30 \$/kg	4.25	307	130
Conversion	10.2 kg	8 \$/kg	4.25	82	35
Enrichment	6.23 kg SWU	100 \$/kg SWU	3.25	623	202
Fabrication	1 kgIHM	275 \$/kgIHM	2.75	275	76
Storage and disposal	1 kgIHM	400 \$/kgIHM[30, a]	−2.25	400	-90
			Total	1686	353
			Grand Total	2040	

a. The cost of waste storage and disposal is assumed to be paid at the end of irradiation, even though the unit cost of \$400/kgIHM is a proxy for the 1 mill/kWehr paid by utilities during irradiation.

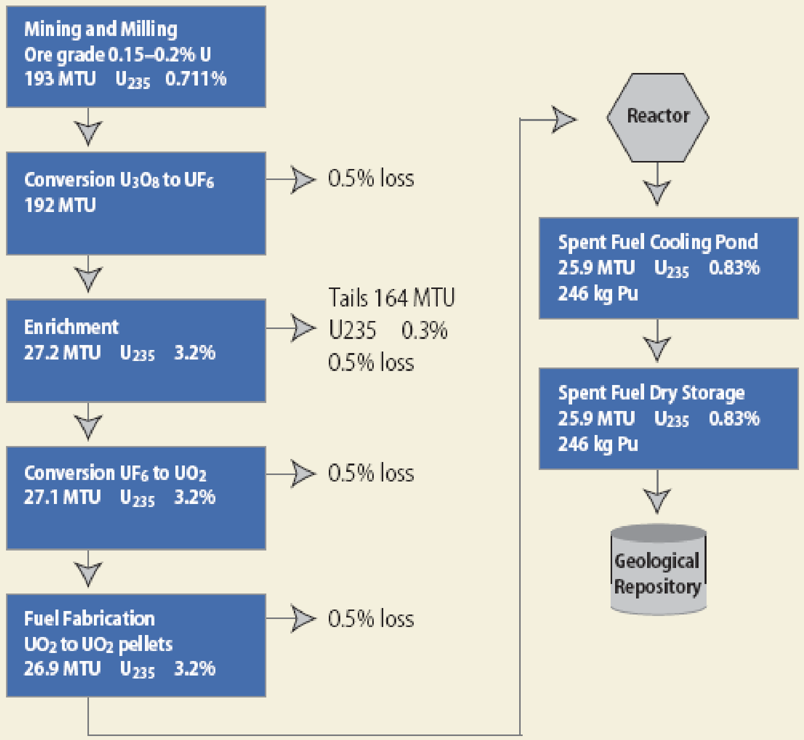
The calculations are based on the following assumptions:

- Fuel irradiation time : 4.5 years
- Lead times:
  - 2 years for ore purchase
  - 2 years for conversion
  - 1 year for enrichment
  - 0.5 year for fuel fabrication
- Carrying charge factor: ϕ = 0.1 per year.

The cost is thus \$2,040/kgIHM. We can obtain the fuel cycle cost in ¢/kWh(e) as follows:

$$\frac{kgIHM}{0MWd} \cdot \frac{1MW}{1000kW} \cdot \frac{1d}{24h} \cdot \frac{1kW}{0.33kW(e)} = 5.15 \cdot 10^{-3} \frac{\$}{kWh(e)}$$

Figure A-4.1 Once-through Fuel Cycle



Source: Adapted from Appendix C, Norman Rasmussen MIT & Allen Croff ORNL, Nuclear Wastes, National Research Council, p.135 (1996).

EGYPT ELECTRICITY GRID MAP