المركز المصرى للدراسات الإقتصادية
ECES
The Egyptian Center for Economic Studies

ON THE ECONOMIC FEASIBILITY OF NUCLEAR POWER GENERATION IN EGYPT

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Working Paper No. 143

January 2009

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Abstract

Egypt is currently planning to introduce nuclear energy for national electricity generation. In this context, this paper provides an economic feasibility assessment of the use of nuclear power to generate electricity in Egypt and identifies the critical factors behind the choice of appropriate nuclear technology. The methodology applied is pure economic analysis of demand and supply elements of Egypt's electricity sector using elasticity, break-even analysis, sustainability criteria, and factor decomposition. It is derived that nuclear technology is economically feasible to generate a progressive share of future electricity supply to meet increasing electricity demand in Egypt. From an economic perspective, nuclear energy is required to generate 4 percent of countrywide electricity supply by 2017 progressing to 15 percent by 2050. The recommended choice of nuclear plant technology is Light Water Reactor (LWR) or evolutionary LWR. However, such feasibility is conditional on critical factors including capital cost per nuclear plant, nuclear operation costs, price of enriched uranium, nuclear conversion efficiency, nuclear plant lifetime, and nuclear plant capacity.

ملخص

تتخذ مصر الآن أولى الخطوات في التحضير لاستخدام تكنولوجيا الطاقة النووية لتوليد الكهرباء، ويعتمد اختيار نوع التكنولوجيا النووية على العوامل التي تؤدي إلى استدامة التوازن بين العرض والطلب على مستقبل الطاقة في مصر. ويتطلب ذلك دراسة جدوى الاستخدام النووي لتوفير احتياجات الطاقة المستقبلية بالإضافة إلى دراسة العوامل المؤثرة في اختيار نوع التكنولوجيا النووية المناسبة لقطاع الكهرباء في مصر. وتعتمد المنهجية المتبعة في هذا البحث على تحليل اقتصادي لتوقعات العرض والطلب على الطاقة الكهربائية في مصر بناء على قياس المرونة وتحليل العناصر الرئيسية التي تؤثر على استخدامات الطاقة الكهربائية. وفي ضوء هذا التحليل، يخلص البحث إلى أن هناك جدوى من استخدام التكنولوجيا النووية في توليد الطاقة بنسبة تدريجية من العرض المستقبلي وذلك لتلبية الزيادة المتوقعة في الطلب على الطاقة الكهربائية في مصر. كما يخلص إلى أن الطاقة النووية لها جدوى اقتصادية على أساس توليد ٤% من إجمالي الطاقة الكهربائية المتوقعة في عام ٢٠١٧، و١٠% في عام ٢٠٢٥ و١٢% في عام ٢٠٣٠ و١٥% في عام ٢٠٥٠. ويكون الاختيار المقترح لتكنولوجيا المفاعل النووي المستخدمة هو استعمال تكنولوجيا مفاعل الماء الخفيف ذي دورة الوقود المفتوحة LWR أو evolutionary LWR غير أن هذه الجدوى مرهونة بعدة محددات أساسية تتعلق بالتخطيط والتنفيذ والمدة الزمنية للتشغيل.

1. INTRODUCTION

This paper assesses the economic feasibility of nuclear power generation in Egypt. It is motivated by the assumption that Egypt's traditional energy resources of oil and natural gas are not sustainable in the future compared to forces of population growth, a growing base of industrial production, expected rate of GDP growth, and subsequently, aggregate electricity demand. Recent studies have foreseen a countrywide energy shortage as early as 2020.[1,2] This necessitates a study of: (1) the economic *feasibility* of the use of nuclear technology to meet the future energy needs of the Egyptian economy, (2) the *critical factors* behind the choice of *appropriate technology* to face future energy demand, minimize technological risk, and make available cost-effective nuclear solutions, and (3) 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 provide energy for the generation of electricity.[3] According to an International Atomic Energy Agency (IAEA) study (IAEA 2007), nuclear power generation provides 7 percent of the world's total energy supply (thermal equivalence) and 15.7 percent of the world's electricity supply. This by itself is a testimony to the high efficiency of nuclear technology compared to conventional means. The United States produces 20 percent of the world nuclear supply (the largest quantity in absolute terms) whereas France produces the highest share of nuclear supply (80 percent) relative to total domestic electrical energy demand.[4]

Egypt is currently at an early planning stage to utilize nuclear energy technology for electricity generation. This is guided by a sustainability criterion regarding Egypt's energy demand and supply balance. According to a study by the World Nuclear Association (WNA), in 2005 Egypt produced 92 billion kWh/yr from 18 GWe of nuclear plant, giving per capita electricity consumption of 1350 kWh/yr. Egypt now holds approximately 23 GWe of electricity supply in 2008.[5] Electricity distribution by source is roughly 88 percent from gas and 12 percent from hydropower (mostly from the Aswan High Dam). Currently, a limited amount of oil is used in electricity generation after the Egyptian government announced that

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[1] IAEA (2007).

[2] Selim (2007).

[3] EIA (2007).

[4] Kristiansen (2007).

[5] IDSC (2008).

all thermal power plants must run on gas instead of oil.[6] Overall, the expected per-capita electricity demand growth is estimated to be 4-5 percent per annum until 2025.[7] This corresponds to a supply capacity or stock increases of 8 to 9 percent annually.[8]

Egypt has its own history when it comes to nuclear power. In 1964, a 150 MWe nuclear plant[9] with 20,000 m^3/day desalination was proposed, and in 1974 a 600 MWe plant was planned. Egypt's Nuclear Power Plants Authority (NPPA) was established in 1976, and in 1981 the *Dabaa* site on the Mediterranean coast was selected for a nuclear power plant. This plan fell through following the Chernobyl accident in 1986. Consequently, an agreement on peaceful uses of atomic energy was reached with the International Atomic Energy Agency (IAEA) based on nuclear cooperation and non-weapon proliferation.[10] By 2006, a nuclear cooperation agreement was reached with China,[11] and in early 2008 serious talks were conducted with Russia concerning technical cooperation in the area of nuclear power usage. In addition, the United States, United Kingdom and France have expressed 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 in 1998. Both are experimental pilot programs and rely on outdated technologies. So far, Egypt does not have a single operating nuclear generator for commercial energy purposes. There is also a technical feasibility study for a nuclear cogeneration plant at *Dabaa* conducted in October 2006. The Egyptian minister of energy and electricity announced that a minimum capacity of 1,000 MWe commercial reactor may be built there by 2017. The multi-billion dollar project will be implemented with the assistance of foreign technology, and it has been announced that such a mega project is of national importance due to energy security, civil liability and international obligations with respect to nonproliferation.[12]

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[6] American Chamber of Commerce (2005).

[7] WNA (2007).

[8] MIT (2003).

[9] 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)

[10] IAEA (2007).

[11] WNA (2007).

[12] NPPA (Nuclear Power Plants Authority), personal correspondence.

2. METHODOLOGY

This paper conducts an economic feasibility assessment of the use of nuclear power in Egypt. The study follows the economics and technology guidelines relevant to Egypt based on the following reference documents:

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

The first reference document provides comprehensive technological selection criteria of the 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, whereas the third reference is a highly specialized economics of technology document for the efficient use of nuclear energy in developing countries. These references have been used extensively by the US Department of Energy and the IAEA especially for emerging nuclear energy countries. The MIT study has been cited as one of the most important technological assessment document for countries pursuing the nuclear option (IAEA 2007).

The flow of the analysis in this paper is as follows:

1. Demand estimation and factor decomposition based on regression analysis. Per capita electricity consumption is forecasted based on time series data (1980-2007) by the use of elasticity (sensitivity) elements. The forecast is run to the year 2050.
2. The flow and stock of electricity supply is estimated on the assumption of demand and supply equilibrium. This is based on decomposed factor elements including price, income, output and productivity for the electricity sector in Egypt.
3. The stock of electricity supply based on conventional thermal sources is estimated and an energy gap outlook is used to economically estimate the potential use of nuclear energy as governed by critical feasibility parameters.

(4) Timeline of implementation for nuclear power plants is estimated based on discounting, opportunity costs and break-even analysis.

The above methodology is based on pure economic feasibility grounds and hence should be taken as the *minimum required level* of nuclear energy technology for the country's future.

3. EGYPT'S ELECTRICITY SECTOR: ANALYSIS AND FORECAST[13]

Egypt's installed generating capacity stood at 17.06 gegawatts (GW) in 2004, and has reached 18.01 GW in 2005, 23 GWe in 2008, with plans to add 4.5 GW of generating capacity by 2010. Overall, natural gas fuels more than 85 percent of Egypt's electricity production with the remainder coming from the Aswan High Dam.

Table 1 below 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.[14]

Electricity demand (per capita consumption) shows a 4.16 percent incremental growth rate (100 percent per capita demand impact) distributed as follows:[15]

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

Generally, 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 is shared by all those living in a household rather than

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[13] The forecast in this section is based on projections related to the country's population growth rate, GDP growth rate, industrial production growth, income growth rate and productivity increases. The main approach is based on historical data (1980-2007) and "business as usual" scenario, which provides a conservative scenario leading to minimum levels of electricity generation for Egypt's future.

[14] The historical data of 1980-2007 is based on actual supply-demand balance, whereas subsequent forecasts are based on the conservative scenario outlined in the previous footnote.

[15] Factor decomposition uses the following equation for growth in *TC* (per capita electricity consumption) decomposed by the following contributing factors: population (*H*), GDP production (*P*), income (*I*), and productivity (*R*): $\left[\frac{\Delta TC}{TC}\right] = \alpha\left(\frac{\Delta H}{H}\right) + \beta\left(\frac{\Delta P}{P}\right) + \gamma\left(\frac{\Delta I}{I}\right) + \eta\left(\frac{\Delta R}{R}\right)$.

consumed individually. Hence, the contribution of 0.80 percent per person would have multiple impacts if the number of people per household is factored in.

The impact of production on electricity demand is a little over one-third, which can be a direct consequence of the energy intensity of production. However, a rise in personal income also has over one-third contribution. Finally, productivity increases contribute a small 0.3 percent with a 7.2 percent impact rate showing the lack of innovation in electricity usage across most sectors of the economy.

In addition, elasticity measures for electricity consumption with respect to price, income (real GDP per capita) and GDP output yield elasticity values of 0.37 (inelastic), 1.23 (elastic), and 0.93 (neutral), respectively. Therefore, total electricity demand is deemed a necessity 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.

Egypt's total electricity supply (generation) has shown a 5.6 percent annual increase during 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, 18 GWe in 2005 and reached 23 GWe in 2008. The average increase in total installed capacity was less than 1 GWe per year for the past three decades.

Given the sensitivity results of the decomposition in Table 1, the baseline target demand and corresponding *minimum* supply levels for Egypt's electricity sector are shown in Figure 1. It is forecasted that baseline per capita demand for electricity will reach 1500 KWh by 2010, 2000 KWh by 2018, and 3500 KWh by 2030, whereas the economic forecast for *minimum* electricity supply as total installed capacity is 26 GWe by 2018, 35 GWe by 2030, 40 GWe by 2040 and 45 GWe by 2050.[16] This forecast is the *minimum* economically desirable supply based on baseline expected demand growth outlined in Table 1 below.

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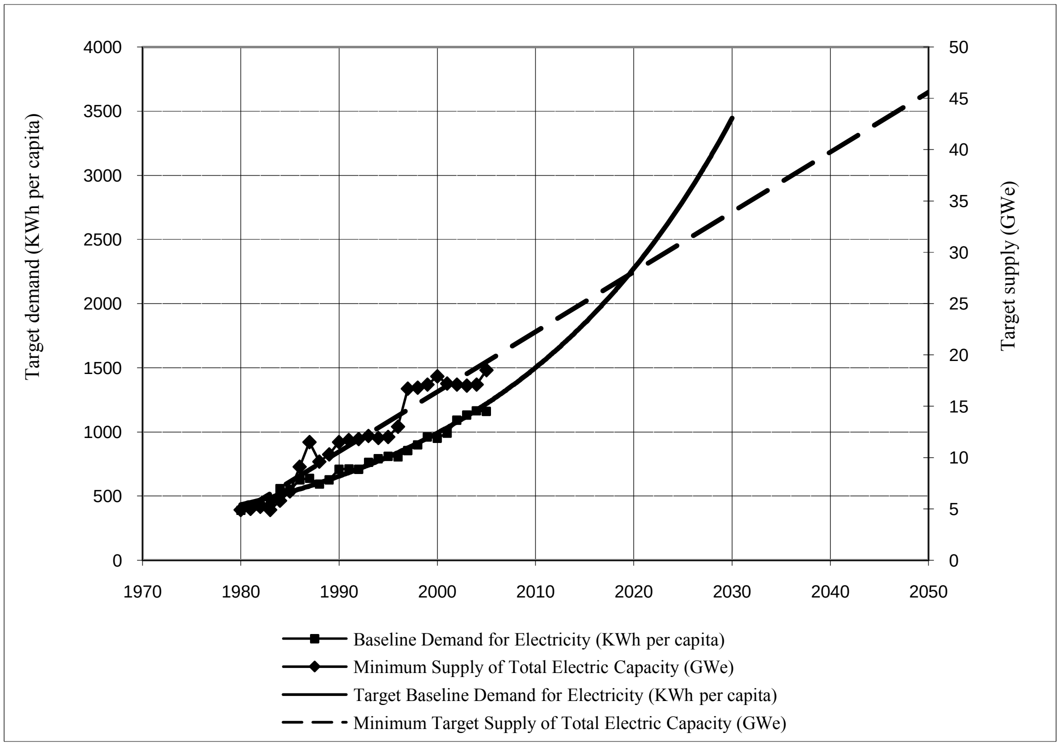
[16] These forecasts are based on the conservative assumptions outlined earlier and hence provide a "bare minimum" estimate. This economic analysis is a precondition for developing critical "break-even" feasibility criteria in the next two sections. It has also been mentioned to the author through personal correspondence with the NPPA that the minister of electricity spoke about possible supply in excess of 52 GWe by 2027. The ministry's forecast falls within the feasible economic criteria derived in this paper.

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

	Sensitivity of Electricity Sector in Egypt to Different Economic Variables	**Comment**
Per capita electricity consumption	1350 kWh per capita per year (2007) Long-run minimum target of 4000 kWh per capita (2050)	3,500 kWh per capita required by 2030
Total electricity consumption	4.16 percent incremental growth rate (100% per capita demand 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 (productivity)
Electrical installation capacity (supply)	18 GWe (2005) installed (non-nuclear) 23 GWe (2008) installed (non-nuclear) 4 GWe (2030) minimum required by nuclear energy 6 GWe (2050) minimum required by nuclear energy 1,000 MWe per plant minimum nuclear supply capacity 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 (at 95 percent 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).

Figure 1. Baseline Demand and Minimum Supply Balance for Egypt's Electricity Sector



Source: Author's calculations.[17]

4. EGYPT'S NUCLEAR ENERGY POTENTIAL

Egypt will need its first nuclear power plant by 2015 or 2017 at the latest, with additional nuclear plants by the years 2020, 2025, 2030, 2040 and 2050—a total of six nuclear plants. Nuclear plants should be capable of generating 4 GWe of electricity generation by 2030 and 7 GWe by 2050, ultimately reaching 15 percent of total electricity supply. Each nuclear plant should have a minimum capacity of 1000 MWe per plant using *LWR (Light Water Reactor) nuclear reactor type technology.*[18] The initial capital cost of the first nuclear power plant is estimated at $2.5 billion in 2008 US dollar prices. The corresponding 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.

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[17] Please refer to footnotes 13 and 14 for assumptions based on the conservative scenario.

[18] Based on required nuclear energy supply in Table 1. This is in conformance to the recommended nuclear technology for Egypt found in MIT (2003) and IAEE (2007). Evolutionary LWRs may become feasible in the future including Generation III/III^{+} nuclear power plants, such as ABWR, AP1000, EPR, HWRs, GCRs and FBRs. The latter is based on feedback from Egypt's Nuclear Power Plants Authority (NPPA), written correspondence.

The estimated choice of nuclear energy is summarized in Table 2 below. The selection of nuclear technology is assumed to follow the guidelines mentioned above, which also conform to the most consistent results on this topic as applied to Egypt (MIT 2003; WNA 2005; IAEA 2007). Figure 2 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 LWR nuclear plants* (GWe of nuclear power).

Egypt's nuclear capacity requirements dictate a rising (i.e., *progressive*) share of nuclear energy contribution to total electricity supply with a target contribution share of 4 percent in 2015, 12 percent in 2030 and 15 percent 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 across six nuclear power plants of LWR nuclear cycle capability.

The progressive intensity and timeline of nuclear energy for Egypt conforms to the experience of other developing countries such as Mexico, Argentina, Brazil, Bulgaria, Pakistan and Romania[19] (WNA 2005; IAEA 2007; IAEE 2007).

It is noteworthy here that there exists other more advanced fuel cycles than the open-cycle LWR reactor. Yet, open LWR nuclear fuel cycles are seen as the most desirable on an economic basis and as such the most demanded by other developing countries, the most cost-effective, the least costly initially (MIT 2003; WNA 2005; IAEA 2007), and fall within the feasible economic range (derived in Section 5 below). Future developments in the energy field may lower the initial cost of thermal and fast reactors with reprocessing in a "closed" fuel cycle that includes Plutonium Recycle Mixed Oxide, or PUREX/MOX, and in such case, such technologies would become feasible in the case of Egypt (refer to Section 5 below). Additionally, evolutionary LWRs may become economically feasible in the future. Nuclear reactors with closed fuel cycles like PUREX could generate double the energy intensity

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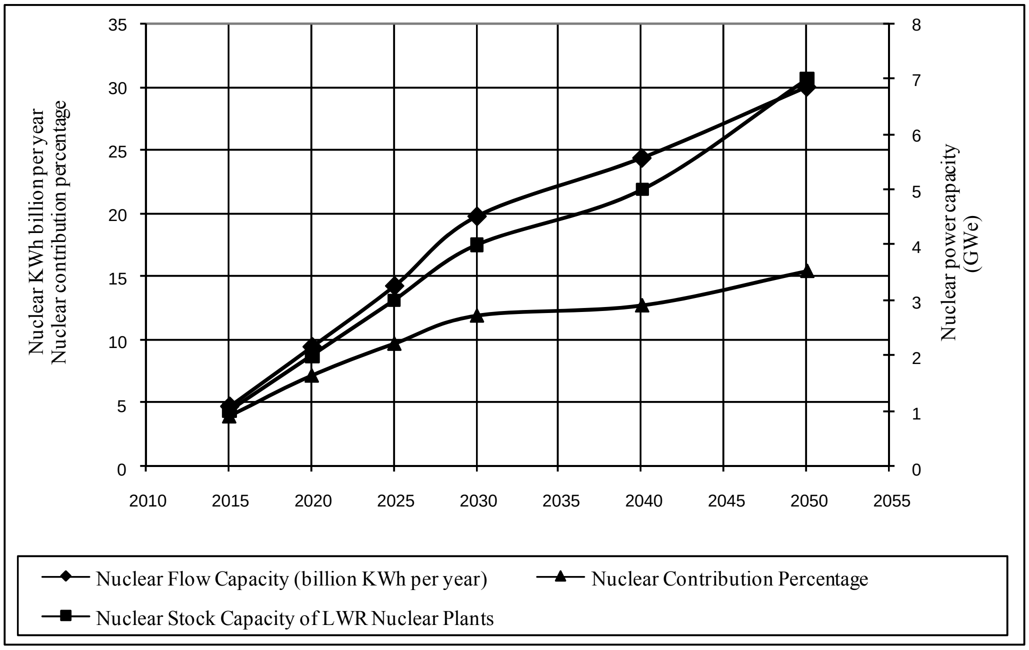
[19] Progressive installation of nuclear plants for developing countries and their dates vary. Examples of waiting periods between different installations include Mexico (1989, 1994), Brazil (1987, 1991), Bulgaria (1987, 1991) and Romania (1996, 2007). Similar progressive timelines have been applied in Pakistan, India and Argentina (WNA 2005; IAEA 2007; IAEE 2007). The exception to this is South Africa (1983, 1984), which has installed graphite nuclear technology built by the UK under the apartheid regime. An alternative *sliding* approach to nuclear plant installation has been implemented by advanced economies such as Sweden, Canada, France, UK, Japan, Russia, Germany and the US.

output of an LWR open fuel cycle and does not require decommissioning at its terminal life, but is four times as expensive in capital cost and requires a high maintenance team with specialized training. Thus, it involves higher operating costs and "exponentially higher risk" of negligence or mismanagement (MIT 2003). Other alternatives include LWR advanced designs, high temperature gas reactor (HTGR), and liquid-metal-fast-reactor (LMFR), which could generate higher energy output intensity, but are considered experimental in nature due to their exceedingly high technology skills, and because there exist very few real life commercial nuclear plants on the ground in the case of developing countries. These advanced technologies can generate more electricity output per plant, but such technologies are not economically feasible for a developing country like Egypt, generally because of risk and labor issues in addition to high capital cost in excess of the feasible limit.[20] Nevertheless, it should be noted that the LWR nuclear cycle has a long-term disadvantage compared to advanced nuclear technologies in its decommissioning cost requirement[21] at its terminal life of 40 years. More advanced nuclear cycles do not include this requirement.

Figure 2. Egypt's Nuclear Capacity Requirements (2010-2050)



Source: Author's calculations.

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[20] See Section 5 of this paper for the maximum feasible capital cost.

[21] LWR nuclear plants have an added terminal life "decommissioning cost requirement" where both low-level waste disposal fees and the amount of labor required to perform specific tasks comprise the two largest portions of estimated decommissioning costs. Consequently, a 1000 MWe LWR nuclear plant would require an additional $350 million at its terminal life of 40 years.

Table 2. Nuclear Energy Forecast for Egypt (2010-2050)

Year	Forecasted Electricity Consumption (kWh per capita)	Estimated Nuclear Energy Usage	Minimum Potential for Nuclear Production (kWh billion)	Number of Nuclear Plants	Estimated Future Capital Cost of Nuclear Power (Undiscounted)	Discounted 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	0 GWe (0%)	-	None	-	-	-	-
2011	1562	0 GWe (0%)	-	None	-	-	-	-
2012	1627	0 GWe (0%)	-	None	-	-	-	-
2013	1695	0 GWe (0%)	-	None	-	-	-	-
2014	1766	0 GWe (0%)	-	None	-	-	-	-
2015	1839	1 GWe (4.0%)	4.8	1	$2 billion	$1.16 billion	$125.5	$18.8
2016	1916	1 GWe (3.9%)	4.8	1	-	-	$117.3	$18.1
2017	1995	1 GWe (3.8%)	4.8	1	-	-	$109.7	$17.4
2018	2078	1 GWe (3.7%)	4.8	1	-	-	$102.5	$16.7
2019	2165	1 GWe (3.6%)	4.8	1	-	-	$95.8	$16.0
2020	2255	2 GWe (7.2%)	9.5	2	$2.7 billion	$2.05 billion	$177.2	$30.5
2021	2349	2 GWe (7.0%)	9.5	2	-	-	$165.6	$29.4
2022	2446	2 GWe (6.9%)	9.5	2	-	-	$154.7	$28.2
2023	2548	2 GWe (6.8%)	9.5	2	-	-	$144.6	$27.2
2024	2654	2 GWe (6.6%)	9.5	2	-	-	$135.2	$26.1
2025	2764	3 GWe (9.7%)	14.3	3	$3.8 billion	$3.25 billion	$190.1	$36.7
2026	2879	3 GWe (9.6%)	14.3	3	-	-	$177.7	$35.2
2027	2999	3 GWe (9.4%)	14.3	3	-	-	$166.1	$33.9
2028	3124	3 GWe (9.2%)	14.3	3	-	-	$155.2	$32.6
2029	3254	3 GWe (9.1%)	14.3	3	-	-	$145.1	$31.3
2030	3389	4 GWe (11.9%)	19.8	4	$5.3 billion	$4.45 billion	$187.7	$41.7
2040	5094	5 GWe (12.7%)	24.4	5	$10.5 billion	$5.65 billion	$117.6	$34.7
2050	7657	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 given in Table 1 and Figure 1. Assumptions include 7 percent opportunity cost of capital, 90 percent operating capacity, 40 year lifetime per nuclear plant, LWR nuclear technology reactor types for all nuclear plants, a 3 percent yearly price increase for uranium, 1000 MWe per nuclear plant generation, 0.515 cents per KWe uranium requirement with 3-5 percent uranium enrichment requirement based on 0.711 percent 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. (MIT 2003; WNA 2005; IAEA 2007).

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

The above analysis assumes that nuclear energy is economically more 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 assessment (break-even analysis) for the potential use of LWR nuclear technology in Egypt as compared to conventional thermal plants. Consequently, the above derived *nuclear supply requirements* is conditional on an economic feasibility assessment as a benchmark of comparison between nuclear and conventional thermal plants for electricity supply. This analysis can be estimated using the following parameters:[22]

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);
C_T = Operating unit cost of thermal generation (5.6 cents per KWh);
η_x = Relative efficiency (thermal plant efficiency is 72 percent of nuclear plant efficiency);
r = Discount rate (opportunity cost of capital) with a bare minimum rate of 5 percent;
t = Lifetime of power plant (40 years for both);
DC_t = Decommissioning cost at terminal life for nuclear power only ($350 per KWe).

Hence, the break-even formula for nuclear energy is given by:[23]

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

The two energy supply options (nuclear *vs.* thermal) can be compared by the net discounted value of nuclear costs as related to their equivalent thermal costs by Equation 1 above. If the net benefits from the two options are assumed to be similar over time per unit of energy supply, then the relative cost dimension (including opportunity costs and efficiency factors) would provide the extent of nuclear feasibility compared to thermal power. The

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[22] The break-even analysis is based on author calculations derived from Kristiansen (2007), WNA (2005), De Neufville (1990) and White (1982).

[23] This is based on the present value feasibility criterion with annuity of cost-benefit differentials between nuclear and thermal power plants, and also includes the added LWR nuclear decommissioning cost requirement at the terminal life. Comparative efficiency is also factored in using η_x. Capital costs are K_N (nuclear) and K_T (thermal). Environmental costs are omitted but do not affect the general conclusions since nuclear technology is more environmentally friendly but also carries the risk of nuclear leakage.

rationale is that even though nuclear power is initially more costly, and terminally more costly, yet its higher efficiency coupled with lower operating costs per unit of energy supply can overcome these higher costs.[24]

Based on the present value feasibility criterion, the only unknown in Equation 1 is the yearly target supply of electricity generation (X). Hence, there exists a minimum break-even level of energy supply by which nuclear power is economically feasible. Given this rationale, the break-even energy supply for nuclear feasibility X_{BE} is determined as:

$$X_{BE} = 4.4 \text{ billion} \tag{2}$$

(KWh per 1000 MWe nuclear plant capacity).

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

Table 2 shows that Egypt's nuclear potential has an average of 4.86 billion KWh per plant with a lower to upper bound range of 4.75-4.95 billion KWh of nuclear energy supply per plant. Therefore, nuclear energy is economically feasible for Egypt's future energy plans since future energy demand exceeds the minimum feasible energy supply output by nuclear technology.[25]

The feasibility of nuclear energy generation in Egypt has several limits to its implementation. Table 3 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 percent;
(3) unit nuclear operating cost of 6.03 cents per KWh;
(4) price of uranium of 0.74 cents per KWe.[26]

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[24] The above break-even analysis does not include environmental costs. Nuclear technology is generally deemed more environmentally friendly and carbon-free although it involves the continuous risk of nuclear leakage.

[25] Technically, the NPPA has provided the author with the corresponding "capacity factor" for X_{BE} as 51.6 percent, given that a capacity factor of 75 percent is typical for a base-load generation unit. Hence, in addition to economic feasibility, the derived critical value is technically feasible. Actual implementation would yield a capacity factor in excess of the critical value.

[26] Includes cost of enrichment.

Table 3. Nuclear Sensitivity Analysis for the Case of Egypt

Critical Feasibility Parameter	Parameter Description	Critical Value	Conditions
Maximum feasible capital cost	Nuclear capital cost per 1000 MWe	\$2.682 billion (2008 US \$)[27]	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 (including enrichment)	0.74 cents per KWe	U-235 content of 0.711% with enrichment of 3 to 5%
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 LWR technology stock capacity	905 MWe	Normal LWR capacity is 1000 MWe

Source: Author's calculations**.**

In addition to maximum critical values for nuclear feasibility, there also exist the following *minimum critical values for nuclear feasibility* as described in Table 3:

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

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

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[27] EPC cost: overnight capital cost (engineering, procurement and construction).

6. DISCUSSION OF RESULTS

Egypt's nuclear energy potential is economically feasible. Nuclear energy is desirable for future demand-supply energy sustainability and is critical for the country's future power supply in the electricity sector. Per capita demand consumption is estimated to grow exponentially by 4.17 percent per year and its equivalent power supply in stock capacity is estimated at 8.08 percent annually.[28] The electricity demand factors are: (1) population, (2) output, (3) income, and (4) productivity, representing 19 percent, 36 percent, 38 percent and 7 percent impacts, respectively. This implies that output (production levels) and income (expenditure levels) are the dominant economic factors in electricity demand and future electricity supply.

Based on feasible nuclear supply requirements as provided in Tables 1 and 2, Egypt's nuclear capacity requirements dictate a rising (i.e., progressive) share of nuclear energy contribution. As dictated by economic feasibility, target nuclear contribution shares of total electricity supply are 4 percent by 2015, 12 percent by 2030 and 15 percent by 2050. The *progressive share* of nuclear technology to total power supply could be seen as an economic asset whereby learning effects can be factored in and labor training on nuclear safety and operational technologies can be accounted for. The first nuclear power plant is economically desirable by 2015 or 2017 at the latest. Six nuclear plants are economically feasible as forecasted to the year 2050. The long-term target should be to generate 15 percent of total countrywide electricity supply by nuclear technology. Such a long-term target is to start initially with a 4 percent contribution share in 2015-2017 and should reach 15 percent by 2050 along the following time schedule of feasibility:

(1) 4 percent nuclear contribution share by 2015-2017 (first nuclear plant);
(2) 7 percent nuclear contribution share by 2020 (second nuclear plant);
(3) 10 percent nuclear contribution share by 2025 (third nuclear plant);
(4) 12 percent nuclear contribution share by 2030 (fourth nuclear plant);
(5) 13 percent nuclear contribution share by 2040 (fifth nuclear plant);
(6) 15 percent (long-term target) nuclear contribution share by 2050 (sixth nuclear plant).

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[28] Per capita electricity annual consumption growth of 4.17 percent is indexed by historical population growth (2.4 percent) and GDP elasticity (1.23) for an energy supply growth (stock growth rate) of 8.08 percent annually.

The above timeline of nuclear plant installation is not without bounded constraints. It has been derived, based on the break-even feasibility analysis in Section 5, that *each nuclear power plant* has critical feasibility parameters related to planning, implementation and lifetime operation. These critical feasibility parameters are as follows:[29]

(1) Maximum feasible initial capital cost for a single nuclear power plant is $2.682 billion (2008 US$) per 1000 MWe of nuclear electricity supply;

(2) Maximum unit cost of nuclear operations is 6.03 cents per KWh (nuclear operating cost);[30]

(3) Maximum price of uranium for nuclear feasibility is 0.74 cents per KWe (in 2008 US$ prices);[31]

(4) Minimum nuclear power plant lifetime is 33 years;[32]

(5) Minimum absolute nuclear operating efficiency is 28 percent;[33]

(6) Minimum nuclear plant capacity is 90 percent (nuclear operational capacity);

(7) Minimum scale for nuclear feasibility is 4.4 billion KWh per year for LWR 1000 MWe nuclear capacity plant;[34]

(8) Maximum opportunity cost of capital (interest rate) for nuclear feasibility is 13.2 percent annually;

(9) Minimum power output is 905 MWe per nuclear plant;[35]

(10) Minimum nuclear contribution share to countrywide electricity supply is 4 percent (with a long-term target of 15 percent).

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[29] All economic figures are in 2008 US dollars unless otherwise specified.

[30] International estimates are at 4.2 cents per KWh for nuclear operational expenses (IAEE 2007; EIA 2007; Kristiansen 2007).

[31] Includes cost of enrichment. The price of uranium is based on the international uranium market. The average price of enriched uranium for the past two years has been in the range of 0.515 cents per KWe but with 3 percent price volatility (Kristiansen 2007). The cost of enrichment itself is a portion of this price and has been estimated to be between 37 to 40 percent of the price (Kristiansen 2007; MIT 2003). During the past two years, the cost of enrichment stood at 0.19 cents per KWe (Kristiansen 2007).

[32] Normal nuclear power plant lifetime with LWR nuclear technology is 40 years (WNA 2005; EIA 2007; IAEE 2007).

[33] Normal nuclear operating efficiency for LWR nuclear cycles is 33 percent (WNA 2005; EIA 2007; IAEE 2007).

[34] The expected range for Egypt is 4.75-4.95 billion KWh per year (see Table 3).

[35] The common (average) nuclear output for LWR nuclear power plants is 1000 MWe per plant. This may change in the future especially when evolutionary LWRs become more widely operational.

The above feasibility conditions are highly critical in planning, operation and implementation of Egypt's nuclear power plants program and should complement the timeline schedule of nuclear plant installation previously outlined.

7. CONCLUSION

This paper assesses the economic feasibility of nuclear power generation in Egypt. The paper's demand and supply analysis and forecast for Egypt's electricity sector take a conservative approach. The paper finds out that nuclear technology is economically feasible and is forecasted to generate a *progressive share* of electricity in Egypt. Based on LWR (light water reactor) nuclear technology, six nuclear plants are required by 2050, with a time schedule of shared power generation with respect to total countrywide electricity supply equivalent to 4 percent in 2017, 10 percent in 2025, 12 percent in 2030 and 15 percent by 2050. The study shows that minimum feasible energy supply output by nuclear technology is 4.4 billion KWh annually per nuclear LWR 1000 MWe capacity. In addition, several *critical factors dictate nuclear feasibility* for Egypt. These include:[36] initial capital cost per nuclear plant (maximum feasible capital cost of $2.682 billion in 2008 US$ per 1000 MWe nuclear capacity); discount rate (maximum rate of 13.2 percent); unit nuclear operating cost (maximum operating cost of 6.03 cents per KWh); price of enriched uranium (maximum price to purchase at 0.74 cents per KWe including cost of enrichment);[37] nuclear plant lifetime (minimum plant lifetime of 33 years); nuclear operating efficiency (minimum nuclear efficiency of 28 percent); and nuclear capacity per plant (minimum capacity of 905 MWe per nuclear plant). In short, Egypt's potential for nuclear energy is both feasible and necessary from an economic point of view. However, such feasibility is not universal, but conditional on multiple critical factors that act as bounded constraints on nuclear feasibility concerning planning, implementation and lifetime operation. All the above conclusions are from an economic feasibility point of view. Beyond economics, further study is needed.

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[36] All economic figures are in 2008 US$ prices unless otherwise indicated.

[37] Estimated cost of enrichment is 0.19 cents per KWe nuclear output.

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