ISSN 2229-5518

Assessment of Economic Feasibility of Nuclear Option for Newcomer Countries Using INPRO Methodology

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Abstract—The increase of greenhouse gases in the atmosphere, the depletion of gas and oil resources and the volatility of their prices, and high prices of renewable sources of energy, and the economic advantages of nuclear power plants have all stimulated the world-wide interest for nuclear energy. The IAEA launched the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and developed the INPRO Methodology to provide guidelines and to assess the characteristics of a future innovative nuclear energy system in areas such as safety, economics, waste management, and proliferation resistance. INPRO initiated in 2001 and has the main objective of helping to ensure that nuclear energy will be available to contribute in a sustainable manner to the energy needs of the 21st century. This paper presents the results of the economic assessment of the nuclear option for newcomer countries using the assessment methodology developed under the INPRO, co-ordinated by the International Atomic Energy Agency (IAEA). The economic analysis involved studying the sensitivity of two main economic indicators, namely, the Levelized Unit Electricity Cost (LUEC) and the Total Capital Investment Cost (TCIC). Several dimensions of economic feasibility have been studied and some suggestions have been made for sustainable growth in the power and energy sector.

Index Terms— INPRO Methodology; Nuclear Power; Nuclear Newcomer;Economic Feasibility; Levelized Unit Electricity Cost; Internal Rate of Retur; Return of Investment .

1 Introduction

THE world will need greatly increased energy supply in the next 20 years, especially cleanly-generated electricity. Electricity demand almost doubled from 1990 to 2011, and is projected to grow 81% from 2011 to 2035[1]. Increased electricity demand is most dramatic in Asia, projected to average 4.0% per year respectively to 2035. Currently some two billion people have no access to electricity, and it is a high priority to address this lack. With the United Nations predicting world population growth from 7.3 billion in 2015 to 8.7 billion by 2035, demand for energy must increase substantially over that period. Both population growth and increasing standards of living for many people in developing countries will cause strong growth in energy demand, as outlined above. Over 70% of the increased energy demand is from developing countries, led by China and India – China overtook the USA as top CO_2emitter in 2007. Superimposed on this, the UN Population Division projects an ongoing trend of urbanization, from 52% in 2011 to 62% in 2035 and reaching 70% worldwide by 2050, enabling world population to stabilize at about 9 billion with better food supply, clean water, sanitation, health, education and communication facilities.

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Coal is not limited globally, but large amounts need to be moved from where it is plentiful to where it is needed, mainly for power generation. This has both economic and carbon emission implications (apart from actually burning it). Natural gas is abundant and increasingly traded over long distances, with supplies in several countries increasing due to technology enabling access to gas in shale beds. Oil is more limited, in 2012 global production increased to almost 76 million barrels per day (27 billion barrels/yr), and known reserves increased 8% to 1600 billion barrels. In the World Energy Outlook 2013 New Policies scenario, coal demand increases 0.7% per year from 2011 to 2035, gas increases 1.6% pa, and oil increases 1.1% pa to 2020 then 0.4% pa. For electricity, coal use increases 35% to 2035 thus reducing its share of generation from 41% to 33%, gas increases 72% so that its share remains at 22%, nuclear increases 66% pa to hold its 12% share, and renewables other than hydro increase nearly five-fold.

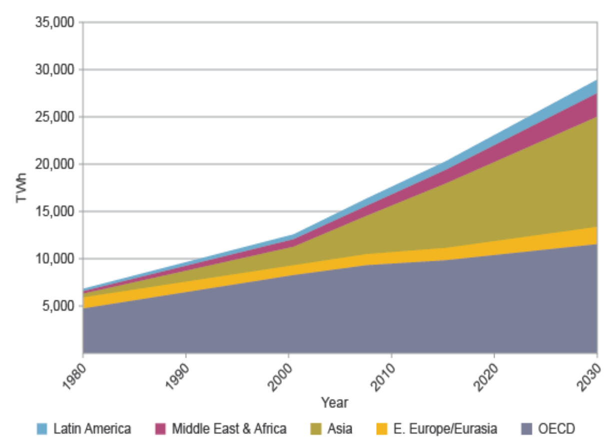

Fig. 1. World Energy Consumption by Region [2]

2 Nuclear Power In The World Today

Nuclear technology uses the energy released by splitting the atoms of certain elements. It was first developed in the 1940s, and during the Second World War to 1945 research initially focused on producing bombs by splitting the atoms of particular isotopes of either uranium or plutonium.

In the 1950s attention turned to the peaceful purposes of nuclear fission, notably for power generation. Today, the world produces as much electricity from nuclear energy as it did from all sources combined in the early years of nuclear power. Civil nuclear power can now boast over 16,000 reactor years of experience and supplies almost 11.5% of global electricity needs, from reactors in 31 countries. In fact, through regional grids, many more than those countries depend on nuclear-generated power.

Today, only eight countries are known to have a nuclear weapons capability. By contrast, 56 operate about 240 civil research reactors, over one third of these in developing countries. Now 31 countries host over 435 commercial nuclear power reactors with a total installed capacity of over 375,000 MWe [2]. This is more than three times the total generating capacity of France or Germany from all sources. About 70 further nuclear power reactors are under construction, equivalent to 20% of existing capacity, while over 160 are firmly planned, equivalent to half of present capacity.

Sixteen countries depend on nuclear power for at least a quarter of their electricity. France gets around three-quarters of its power from nuclear energy, while Belgium, Czech Republic, Finland, Hungary, Slovakia, Sweden, Switzerland, Slovenia and Ukraine get one-third or more. South Korea and Bulgaria normally get more than 30% of their power from nuclear energy, while in the USA, UK, Spain, Romania and Russia almost one-fifth is from nuclear. Japan is used to relying on nuclear power for more than one-quarter of its electricity and is expected to return to that level. Among countries which do not host nuclear power plants, Italy and Denmark get almost 10% of their power from nuclear.

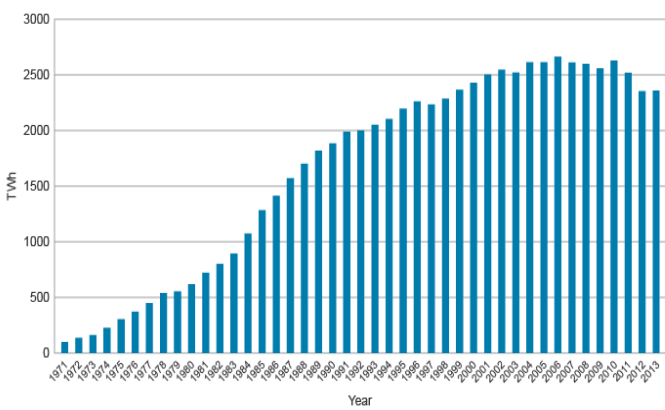

Fig. 2. Electricity Production from Nuclear Sources

In electricity demand, the need for low-cost continuous, reliable supply can be distinguished from peak demand occurring over few hours daily and able to command higher prices. Supply needs to match demand instantly and reliably over time. There are number of characteristics of nuclear power which make it particularly valuable apart from its actual generation cost per unit – MWh or kWh. Fuel is a low proportion of power cost, giving power price stability, its fuel is on site (not depending on continuous delivery), it is dispatch able on demand, it has fairly quick ramp-up, it contributes to clean air and low-CO_2 objectives, it gives good voltage support for grid stability. These attributes are mostly not monetized in merchant markets, but have great value which is increasingly recognized where dependence on intermittent sources has grown.

Due to several benefits over other options many of the developing and middle-east countries are considering to incorporate the nuclear option in their energy mix. Over the last three years, the United Arab Emirates and Belarus became the first countries in around two decades to start constructing their first reactors. Bangladesh [3], Jordan, Turkey and Poland are making good progress on the path to nuclear power and they are most likely to have their first reactors under construction in the next five years. The decision to go for the nuclear option is a critical one for a newcomer and it requires to ensure several levels of confidence including financial sustainability in the long run.

3 INPRO Methodology

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was established in the year 2000 to bring together technology holders and users so that they can jointly consider the international and national actions required for ensuring sustainability of nuclear energy through innovations in technology and/or institutional arrangements. This methodology identifies a set of basic principles, user requirements and criteria in a hierarchical manner as the basis for the assessment of an innovative nuclear system. INPRO takes a holistic approach to assess innovative nuclear systems in seven areas which are economics, infrastructure, waste management, proliferation resistance, physical protection, environment and safety. In order to apply INPRO Economic Assessment in an energy system the planning study or energy scenario, which sets out the anticipated growth of energy demand as a function of time and which identifies the available energy supply options and the role of a nuclear energy system (NES) in meeting the energy demand projection, is required. INPRO basic principle in the area of economics is that energy and related products and services from nuclear energy systems shall be affordable and available. The cost of energy supplied by nuclear energy systems, taking all relevant costs and credits into account, C_N, must be competitive with that of alternative energy sources, C_A, that are available for a given application in the same time frame and geographical region or jurisdiction [4-6]. The total investment required to design, construct and commission nuclear energy systems, including interest during construction, should be such that the necessary investment funds can be raised. The risk of investment in nuclear energy systems should be acceptable to investors. As for any large scale project, there are many risks that can impinge on an NPP project. Innovative nuclear energy systems should also be compatible with meeting the requirements of different markets.

4 Economics of Nuclear Power Generation

The economics of new nuclear power plants is a controversial subject, since there are diverging views on this topic, and multi-billion dollar investments ride on the choice of an energy source. Nuclear power plants typically have high capital costs for building the plant, but low fuel costs and low external costs, namely carbon tax [6]. Assessing the relative costs of new generating plants utilizing different technologies is a complex matter and the results depend crucially on location. Coal is, and will probably remain, economically attractive in countries such as China, the USA and Australia with abundant and accessible domestic coal resources as long as carbon emissions are cost-free. Gas is also competitive for base-load power in many places, particularly using combined-cycle plants, though rising gas prices have removed much of the advantage. Nuclear power plants are expensive to build but relatively cheap to run. In many places, nuclear energy is competitive with fossil fuels as a means of electricity generation. Waste disposal and decommissioning costs are included in the operating costs. If the social, health and environmental costs of fossil fuels are also taken into account, the economics of nuclear power are outstanding.

TABLE I. COMPARISON AMONG DIFFERENT ENERGY GENERATION TECHNOLOGIES

Technology	Unit Size	Lead Time	Capital Cost	Operating Cost	Fuel
CCGT	Medium	Short	Low	Low	High
Coal	Large	Long	High	Low	Medium
Nuclear	Huge	Long	High	Low	Low
Hydro	Huge	Long	Very High	Very Low	Nil
Wind	Small	Short	High	Medium	Nil

Nuclear power and gas are currently the two most competitive electricity generation options upon the introduction of carbon pricing in liberalized electricity markets. However, nuclear power does not necessarily become the most profitable as carbon prices rise. The competitiveness of nuclear energy depends on significant but not overly high carbon prices. Even though the profitability of nuclear power increases in this scenario, its competitiveness against gas decreases. This is because the profitability of gas actually improves disproportionately with high and very high carbon prices (assuming that no carbon capture and storage is introduced). The competitiveness of nuclear energy against gas also declines rapidly with falling gas prices, which almost unilaterally determine the profitability of gas. A qualitative comparison among different generation technologies has been made in Table I.

To build and operate a power system a specific cash flow for building, fuelling, operating and maintenance, dismantling the plant, including waste management and refurbishment need to be considered. Levelized lifetime costs are defined as the costs per unit of electricity generated, which are the ratio of total lifetime expenses versus total expected output, expressed in terms of present value equivalent. Levelized lifetime costs are thus equivalent to the average price that would have to be paid by consumers to repay exactly for capital, operation and maintenance (O&M), and fuel, with a proper discount rate. The summation of all these three costs, termed LUAC, LUOM and LUFC, respectively, gives the levelized unit energy cost (LUEC):

$$LUEC = LUAC + LUOM + LUFC \quad (1)$$

In INPRO, two financial figures of merit have been chosen to evaluate investments: the internal rate of return (IRR) and the return on investment rate (ROI). IRR is the rate of discount for which the present value of a project's expected cash inflow equals the present value of the project's cost. ROI is the return on investment earned or allowed to be earned by a utility enterprise calculated as a percentage of its fair value or rate base. In the end, the acceptance limit is that the values of these indicators be attractive compared with investments in competing energy technologies.

5 RESULTS

In this section, several important economic parameters are calculated and these parameters are then used as input for an assessment of the economics of nuclear option according to the INPRO methodology in the context of planned nuclear energy system of any newcomer country. Input data for a calculation of the main economic parameters are shown in Table 2 for three selected types of power plants that are available as future energy sources: two reactors of the type AES-2006 (VVER-1200) and, as alternative energy sources, four coal fired plants of capacity 600MW each and six gas fired plants with capacity 400 MW each [7,8].

TABLE II. INPUT DATA FOR ECONOMIC CALCULATION

No.	Parameters	Unit	Power Plant Fuel Types		
			Nuclear	Coal	Gas
1	Net electric power output	kW(e)	2 X 1200	4X600	6X400
2	Construction Time	years	6	4	3
3	Plant lifetime	years	60	30	30
4	Average load factor	-	0.9	0.8	0.8
5	Decommissioning cost	mills/kW	1	-	-
6	Overnight cost	$/kW(e)	5200	1500	1000
7	Capital investment schedule				
	First Year	%	2	15	30
	Second Year	%	14.6	30	50
	Third Year	%	22	30	20
	Fourth Year	%	24.4	25	-
	Fifth Year	%	21.7	-	-
	Sixth Year	%	15.3	-	-

All three power plant types have approximately the same power output. The main sources of these input data are for fossil fuel power plants and international market values collected from different sources along with data used for previous similar cases. LUEC, defined as the costs per unit of electricity generated, which is the ratio of total lifetime expenses and the total expected output, expressed in terms of present value equivalent [9]. LUEC (C) is equivalent to the average price that would have to be paid by consumers to repay the investor (utility) exactly the expenditures for capital (CI_t), O&M ($O\&M_t$) and fuel (F_t), with a proper discount rate (r) for the time period of t_0 to t.

Over the plant lifetime (P_t) with a fixed load-factor (Lf_t) LUEC can be calculated using Eq. 1 and Eq. 2.

$$\sum_{t=t_{STSRT}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^{t-t_0}} = \sum_{t=t_{STSRT}}^{t_{END}} C\, \frac{P_t \,.\, 8760 \,.\, Lf_t}{(1+r)^{t-t_0}} \quad (2)$$

$$C = \frac{\sum_{t=t_{STSRT}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^{t-t_0}}}{\sum_{t=t_{STSRT}}^{t_{END}} \frac{P_t \,.\, 8760 \,.\, Lf_t}{(1+r)^{t-t_0}}} \quad (3)$$

The levelized net income (*NI*) is also called net present value (*NPV*) If the electricity price is constant in terms of 'real money a constant reference price per unit of electricity sold to the customer, which is called PUES [10] and can be obtained from Eq. 3 and Eq. 4.

$$NI(t_0, r, R_t) = \sum_{t=t_{STSRT}}^{t_{END}} \frac{P_t .8760.Lf_t}{(1+r)^{t-t_0}} . R_t - \sum_{t=t_{STSRT}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^{t-t_0}} \quad (4)$$

$$NI(t_0, r) = (PUES - LUEC) \sum_{t=t_{STSRT}}^{t_{END}} \frac{P_t .8760.Lf_t}{(1+r)^{t-t_0}} \quad (5)$$

Calculations have been carried out using the input data in Table II and a tool of the NESA support package called NEST (NESA Economic Support Tool), which has been provided by IAEA. As proposed in the INPRO Manual for Economics in Volume 2 of the report IAEA-TECDOC-1575 Rev.1 and its update, for the three types of plant to be compared, the following economic parameters were calculated as shown in Table III. Levelized unit electricity costs, internal rate of return, return of investment, total investment volume and investment limit.The results has been found consistent with earlier results found in the analysis for Bangladesh in 2014 [11].

TABLE III. RESULTS OF ECONOMIC PARAMETER CALCULATION

Indicators	unit	Abbre-viation	Value
Levelized unit electricity cost - NPP AES - Coal Power Plant - Natural Gas Power Plant	Cent / kW.h	C_N C_{A1} C_{A2}	9.76 9.13 8.77
Internal Rate of Return - NPP AES - Coal Power Plant - Natural Gas Power Plant	- - -	IRR_N IRR_{A1} IRR_{A2}	0.103 0.151 0.225
Return of Investment - NPP AES - Coal Power Plant - Natural Gas Power Plant	- - -	ROI_N ROI_{A1} ROI_{A2}	0.119 0.113 0.128

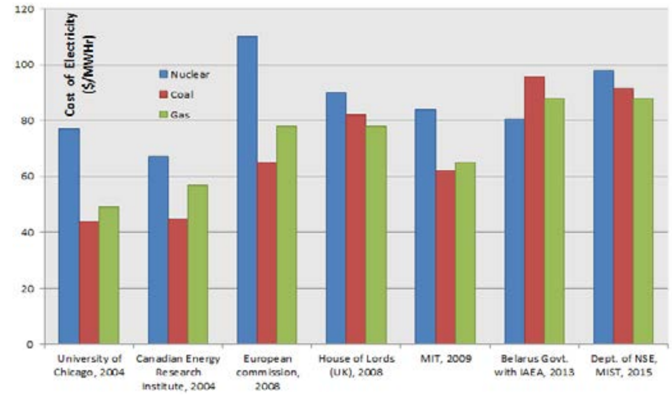

Fig. 3. Levelized cost of electricity (LUEC) from different studies

The levelized unit electricity cost LUEC consists of three factors, the capital costs, the operation and maintenance costs (O&M), and the fuel costs. LUEC is equivalent to the price of electricity that would have to be paid by consumers to repay exactly all costs for capital, O&M and for fuel supply with a proper discount rate and without considering profits. A comparison of levelized cost of electricity obtained from different studies during the last ten years along with this study is shown in Fig. 3.

6 CONCLUSION

The key outcomes of this analysis are:

- The levelized unit electricity cost from nuclear source is in comparable range with coal or gas.
- The IRR from nuclear is the lowest due to huge investment cost and relatively longer period of time required for return of investment.
- Excellent ROI expected if the plant could be operated in maximum plant factor up to expected life time.

Although the decision makers would like to know the LUEC for the next generation nuclear systems in the early stages of their development, there is a high level of uncertainty in the cost estimates and the sensitivity analyses must be performed over a sufficiently broad range of cost parameter values. The two main components of the LUEC, with relatively large uncertainties are the capital costs and the fuel costs. Capital costs are the largest contributor to the LUEC, yet the cost estimates are based on limited design information available at the concept development stage, and therefore, larger rates of contingencies must be considered. The capital costs are highly sensitive to the location where the reactor is built. For some countries, where a new reactor has not been built in the last two decades, a reference reactor may not exist for the current construction environment. The financing cost is directly related to the operating environment, and has a major influence on both the LUEC and the TCIC.

In order to get a complete picture, assessment study in all other aspects is mandatory. It is necessary to perform those studies in near future so that a newcomer country can adopt the ideal mechanism to materialize its dream of becoming a successful user of nuclear energy for electricity generation in a sustainable manner.

ACKNOWLEDGMENT

The authors wish to thank MIST for the support.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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