2009 International Nuclear Atlantic Conference - INAC 2009
Rio de Janeiro,RJ, Brazil, September27 to October 2, 2009
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 978-85-99141-03-8

ECONOMIC ASSESSMENT OF THE IRIS REACTOR FOR DEPLOYMENT IN BRAZIL USING INPRO METHODOLOGY

Orlando João Agostinho Gonçalves Filho

Instituto de Engenharia Nuclear (IEN / CNEN – RJ)
Rua Hélio de Almeida 75
21941-906 Rio de Janeiro, RJ
orlando@ien.gov.br

ABSTRACT

This paper presents the main results of the evaluation of the economic competitiveness of the International Reactor Innovative and Secure (IRIS) for deployment in Brazil using the assessment methodology developed under the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), co-ordinated by the International Atomic Energy Agency (IAEA). INPRO was 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. Among its missions are the development of a methodology to assess innovative nuclear energy systems (INS) on a global, regional and national basis, and to facilitate the co-operation among IAEA Member States for planning the development and deployment of INS. Brazil joined INPRO since its beginning and in 2005 submitted a proposal for the screening assessment of two small-sized integral-type PWR reactors as alternative components of an INS completed with a conventional open nuclear fuel cycle based on enriched uranium. This paper outlines the rationale and the main results of the economic assessment of the IRIS-based INS completed in August 2008. The study concluded that IRIS reference design satisfies most of INPRO criteria in the area of economics.

1. INTRODUCTION

The National Plan of Energy 2030 (PNE 2030) [1], elaborated by the Energetic Research Company (EPE) of the Ministry of Mines and Energy (MME), predicts an expansion of about 5,300 MWe in Brazil’s nuclear-electricity installed-capacity in the next twenty-five years. A first step toward achieving this goal was the approval by the National Council for Energy Planning (CNPE) in June 2007 of the restart of the construction of the 1,350 MWe Angra 3 unit, a conventional KWU/Siemens PWR design twin to Angra 2 unit, which is now expected to enter into operation in 2013. From then on, four units of about 1,000 MWe each shall be deployed at an average time interval of five years. Advanced (evolutionary and innovative) nuclear power plants designs and associated fuel cycles are now being considered for future deployment, including but limited to pressurised water reactor technology and improved once-through nuclear fuel cycle with no reprocessing.

In 2001, the International Atomic Energy Agency (IAEA) launched the International Project on Innovative Nuclear Reactors and Fuel cycles (INPRO) with the 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. INPRO offers a methodology [2] for the holistic assessment of innovative nuclear energy systems (INS) composed of nuclear power plants and associated nuclear fuel cycles on a global, regional and national basis. INPRO also serves as a forum to bring together technology holders and technology users to consider jointly the research and development actions necessary to bring the desired innovations into reality. Brazil joined

INPRO since its initial stages and participated in the project Phase-1B by performing the screening assessment of two small-sized innovative nuclear reactors – the International Reactor Innovative and Secure (IRIS) [3-8] and the Fixed Bed Nuclear Reactor (FBNR) [9-10] – for possible deployment in Brazil using INPRO methodology. These reactors were assessed as alternative components of an INS completed by an indigenous once-through fuel-cycle with enriched uranium oxide and no reprocessing requirements. For IRIS, the scope of the assessment was limited to the methodology areas of economics and safety.

This paper presents the main results of the evaluation using INPRO methodology of the economic competitiveness of IRIS to contribute to the expansion of the nuclear-electricity installed-capacity in Brazil between 2005 and 2030, as predicted in the PNE 2030 reference scenario. As an alternative to fulfil this scenario, a plant arrangement of 3 independent IRIS single units of 335 MWe each, equivalent to a total capacity of 1005 MWe, is assessed here.

2. SUMMARY DESCRIPTION OF IRIS REACTOR

IRIS [3-8] is a modular, small power (335 MWe per module), pressurised water reactor that utilises an integral reactor coolant system layout and a conventional refuelling scheme. While firmly based on the proven light water reactor (LWR) technology, the IRIS design has introduced many engineering and project innovations that define its unique characteristics, as claimed by its designers, such as for example: a safety-by-design™ approach, which aims at eliminating by design the possibility for an accident to occur, rather than dealing with its consequences; enhanced and easier to implement security, based on its design characteristics; enhanced proliferation resistance through extended refuelling cycle, while retaining use of current demonstrated fuel, facilitating international safeguards; and, economic gains, through simplicity, modularity, and economy of serialisation instead of economy of scale.

3. OUTLINE OF INPRO METHODOLOGY

The INPRO methodology [2] has been developed for screening an innovative nuclear system (INS), for comparing different INS to find a preferred one consistent with the sustainable development of a given State, and for identifying the research, development and demonstration needed to improve the performance of existing components of an INS and/or to develop new components. An INS encompasses all nuclear facilities of the front and back end of a nuclear fuel cycle, i.e., mining/milling, conversion, enrichment, fuel fabrication, reactor, reprocessing and materials management (including transportation, storage and waste management), together with all related infrastructure measures. INPRO takes a holistic approach to assess innovative nuclear systems in seven areas, namely, economics, safety, waste management, environment, proliferation resistance, physical protection and infrastructure.

For each area, the INPRO methodology identifies a set of basic principles (BPs), user requirements (URs) and criteria (CRs) in a hierarchical manner as the basis for the assessment of an INS. The highest level in the INPRO hierarchy is a BP, which is a statement of a general goal that is to be achieved in an INS. The second level is a UR that sets out the measures to be taken (mostly by the designers/developers but also by owners/operators and government institutions) to meet the general goal of the corresponding BP. On the third level of hierarchy, to verify whether the user requirements have been properly met, the assessor of the INS uses a criterion.

3.1. INPRO'S methodology for economic assessment [2, Volume 2]

For calculating the economic costs of different electricity generation options and assessing their relative competitiveness in a comprehensive harmonised framework, INPRO adopted the Levelized Lifetime Cost (LLC) method, also called Levelized Unit Energy Cost (LUEC) method.

Overview of Levelized Lifetime Cost method

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, and fuel with a proper discount rate. The summation of all these three costs gives the Levelized Unit Energy Cost (LUEC).

In INPRO, two financial figure of merit have been chosen to evaluate investments: the internal rate of return (IRR) and the return on investment rate (ROI). The acceptance limit is that the values of these indicators be attractive compared with investments in competing energy technologies. Besides that, the risk of the investment in innovative nuclear energy systems should be acceptable to investors taking into account the risk of investments in other energy/electricity generating projects. INPRO set out four criteria for evaluating the risk of investment in INS: maturity of the project, construction time, financial robustness, and political environment.

Finally, an INPRO economic assessment requires the evaluation of the flexibility of the INS components to be compatible with meeting the requirements of different markets. Although this UR has been incorporated in the methodology, it has not been developed further in the current version of the INPRO manual [2] and was not considered in this study.

4. INS CHOSEN AND ENERGY OPTIONS

The INS considered in this study is comprised of the IRIS reactor completed by the indigenous once-through fuel cycle with enriched uranium oxide and no reprocessing requirements, and by the country existing nuclear power infrastructure and institutional measures (agreements, treaties, national and international legal framework and conventions). As an alternative to fulfil the role predicted for the nuclear energy in the PNE 2030 reference scenario, a plant arrangement of three independent IRIS reactor single units of 335 MWe each, equivalent to a total installed capacity of 1005 MWe, to start full operation in 2020, is assessed here. This plant arrangement is based on the assumption that the three units would be constructed in series in a "slide-along" manner. Thus, the units would be started up in sequence as construction, pre-operation testing, fuel load and start-up testing are all completed for a unit. The units will be spaced sufficiently apart so that the first completed unit could be operated while construction of the subsequent one is still in progress. As an alternative to the deployment of the IRIS three single-units site arrangement, a large unit, similar to Angra 3 reactor, was considered in this study in order to exploit the recent feasibility studies performed by Eletronuclear for approval of the completion of Angra 3 construction.

With regard to the nuclear fuel cycle, the system proposed considers that all the different elements of the once-through (OT) fuel cycle will be bought from the internal market. However, since some stages of the fuel cycle (namely, conversion and enrichment) are not fully commercially available in the country at the time of preparing this report, a different approach was followed for the nuclear options assessed. For IRIS, the fuel cycle costs were determined from the international market, whereas for the Angra 3 reactor type the fuel costs for operating the twin Angra 2 unit were used. These latter costs are a combination of the costs of the fuel cycle services (milling, mining, reconversion and fabrication) already provided by the Brazilian Nuclear Industries (INB) and those services (conversion and enrichment) contracted in the international market. For better comparison with the reference date for the reactor system costs, most of the fuel cycle costs are in US$ of December 2004.

5. TECHNICAL ASSUMPTIONS

5.1. Nuclear Fuel Cycle

Nuclear fuel cycle data used for the economic assessment of IRIS is compiled in Table 1. The time periods used at each fuel cycle stage were found in the open literature and are typical ones. Prices for the uranium purchase, conversion and enrichment services are based on long-term contracts in the international market [13], while fuel fabrication price was taken from a NEA/OECD study [14]. Fuel back end costs for interim storage and disposal of low and intermediate radioactive wastes were based on a recent study conducted by the Belfer Centre at University of Harvard [15]. Most of these prices are in US$ of Dec. 2004, unless otherwise indicated.

Table 1. Nuclear fuel cycle data (price for US$ December 2004 or other specified date)

Stage	Time (years)	Base value	References
Uranium purchase	1.5	25 $/kgU	[13]
Conversion	1	11.5 $/kgU	[13]
Enrichment (*)	0.75	107 $/SWU	[13]
Fabrication	0.5	250 $/kgU (2002 $)	[14]
Back end interim storage and disposal of low level waste (LLW) and Intermediate level waste (ILW)	At time of discharge	400 $/kgU (2003 $)	[15]

Facilities specifications of the nuclear fuel cycle relevant for the economic assessment of IRIS are given in Table 2.

Table 2. Nuclear fuel cycle data facilities specifications

Stage	Items	References
Uranium purchase	0 % losses	[16]
Conversion	0.5 % losses	[16]
Enrichment	0 % losses; tail assay 0.25 %; feed assay 0.711 %	[16]
Fuel Fabrication	1.0 % losses	[16]

All fuel cycle costs for the economic assessment of Angra 3 reactor type are reported in Table 4 and are derived from the corresponding values for the twin Angra 2 unit.

5.2. Reactor specification

The main technical data of the IRIS reactor are taken from Refs. [3,4] and economic data from Refs. [5-7] (Table 3). For the Angra 3 reactor type option, most of the technical data comes from the Final Safety Analysis Report of Angra 2 since again both Angra 2 and Angra 3 reactors are twin units [11]. Economic data of Angra 3 reactor type comes mainly from the economic-financial feasibility study performed in 2004 for the actual Angra 3 unit by Eletronuclear, the plant's owner and operator [12] (Table 4).

Table 3. IRIS reactor specification - 3 Single modules (price for US$ year 2003(*))

Reactor type	IRIS reactor		
Item	Data		Reference
	Single Unit	3 Modules	
Thermal Output	1,000 MWth	3,000 MWth	[3]
Net Electrical Output	335 MWe	1005 MWe	[3]
Load Factor	96 %	96%	[3]
Life of Plant	60 years	60 years	[3]
Average Fuel burn up	53,000 MWth d/tonU	53,000 MWth d/tonU	[4]
Fuel enrichment	4.95% U235	4.95% U235	[4]
Initial fuel enrichment (range)	2.1 - 4.95% U235	2.1 - 4.95% U235	[4]
Fuel inventory	48.5 tonU	145.5 tonU	[3]
Average full power density	20.62 kWth/kgU	20.62 kWth/kgU	This Table
Construction time (1)	3 years	9 years	[3]
Overnight Cost (2)	836 $/kWe	766 $/kWe	[5]
Contingency Cost	149 $/kWe	134 $/kWe	[5]
Owner Costs (3)	---	---	---
Interest During Construction - IDC (4)	617 $/kWe	564 $/kWe	[5]
Annual Fixed O&M Costs	23 M$ (69 $/kWe)	69 M$ (69 $/kWe)	[6] (This table)
Annual Variable O&M Costs (5)	6.00 mills/KWh	6.00 mills/KWh	[6]
Decommissioning Costs	200 $/kWe	200 $/kWe	[7]

(1) Deployment with a three-year period between successive modules.
(2) Considering “learning” benefits in construction and operation.
(3) Not specified in the references. Assumed included in the overnight costs.
(4) Discount rate: 10% per year. Construction time used for IDC calculation (inferred): 9yr.
(5) Representative costs based on an earlier IRIS design.
(*) Cost reference date: 2003 (inferred).

Table 4. Angra 3 reactor type specification (price for US$ year 2004 [12])

Reactor type	Angra 3 reactor type	
Item	Data	Reference
Thermal Output	3,765 MWth	[11]
Net Electrical Output	1,229 MWe	[11]
Load Factor	90 %	[12]
Life of Plant	40 years	[12]
Average Fuel Burn up	44,000 MWth d/tonU	[11]
Fuel Enrichment	3.9% U235	[11]
Initial Fuel Enrichment	1.9/2.5/3.2% U235	[11]
Fuel Inventory	104 tonU	[11]
Full Power Density	36.21 kWth/kgU	This table
Construction Time	5.5 years	[12]
Overnight Cost (1)	2,265 M$ (1,843 $/kWe)	[12] (This table)
Contingency Cost	110 M$ (89 $/kWe)	[12] (This table)
Owner Costs	584 M$ (475 $/kWe)	[12] (This table)
Interest During Construction-IDC (2)	462 M$ (376 $/kWe)	[12] (This table)
Total Annual O&M Costs (3)	82 M$ (66.5 $/kWe)	[12] (This table)
Initial Fuel Cost	144.5 M$	[12]
Annual Fuel Costs	74 M$	[12]
Decommissioning Costs	Included in the O&M costs (3)	[12]

(1) Includes the cost (750M US$) of the major imported equipment already bought and stored at the plant future site. This cost is not considered in Ref. [12], which focuses mainly on the economic-financial evaluation for completion of the Angra 3 construction.
(2) Determined using a discount rate of 3.61% per year, which accounts for national and international funding, corporate taxes and a construction time of 5.5 years. It does not include the interest paid for the major imported equipment already purchased and stored at the plant future site.
(3) It accounts for fixed and variable O&M costs plus liability insurance based on the operational costs for the twin Angra 2 nuclear power plant (NPP). Includes also annual provisions for establishing a decommissioning fund in 30 years and incorporates the annual costs for waste management and for disposal of low and medium radioactive wastes to be collected over the plant lifetime.

6. DISCOUNT AND FINANCIAL RATES

In accordance with INPRO methodology for the economic area, all costs elements used in calculation were expressed in constant monetary term.

The discount rate (***r***) for the financial cost calculations was taken as 10% per year. The annual average selling price per unit of electricity sold (PUES) was assumed 30 percent higher than the cheapest alternative levelized unit energy cost (LUEC) for news plants, that is, PUES = 1.3 * min {$LUEC_{IRIS}$; $LUEC_{ANGRA\ 3\ TYPE}$}. The limit for the internal rate of return (IRR) was taken as 12% per year, 2% higher than the discount rate, due to the relatively high-risk perception in the country for long-term projects of electricity generation. The limit for the return on investment rate (ROI) in its turn was assumed 2% higher than the internal rate of return (IRR), that is, 14% per year.

7. EVALUATION OF INPRO ECONOMIC CRITERIA

7.1. Economic Basic Principle BP: *Energy and related products and services from Innovative Nuclear Energy Systems shall be affordable and available.*

To ensure that nuclear energy and related services are affordable, the price to the consumer must be competitive with low cost/priced alternatives. To be available INSs need to compete successfully for investment for its development and deployment. There are 5 URs associated with this BP.

7.1.1. User Requirement UR1: *The cost of energy from innovative 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 geographic region***.**

Indicator IN1.1: *Single Levelized real discounted Unit net generated Electricity plant's life total Costs* ($LUEC_N$) *for the complete INS, using a discount rate that reflects the economic decision making investment environment.*

Indicator IN1.2: *Single Levelized real discounted Unit net generated Electricity plant's life total Costs* ($LUEC_A$) *for the strongest competitor power generation investment option A, using the same discount rate as applied in the* C_N *calculation.*

Acceptance limit AL1: $C_N / C_A < k \quad (LUEC_N / LUEC_A < k)$

Assessment against Indicators IN1.1 and IN1.2

Using the data in Tables 1, 2 and 3 and the formulas of Annex A of the INPRO Manual on Economics [2, vol.2], the LUEC for IRIS was calculated as 38.36 mills/KWh. Similarly using the data in Table 4 and the same formulas, the LUEC for Angra 3 reactor type was calculated as 59.37 mills/KWh. For this case, the fuel costs for the first core and the annual fuel cycle cost required for the calculation of levelized unit energy fuel cycle cost were already available. With the above values of LUEC for IRIS (= $C_N = LUEC_N$) and for Angra 3 reactor type (= C_A = $LUEC_A$), and assuming the factor k equal to 1, it can be seen that the acceptance criterion AL1 is clearly fulfilled for the INS based on the IRIS reactor.

7.1.2. User Requirement UR2: *The total investment required to design, to construct, and to commission innovative nuclear energy systems, including interest during construction, should be such that the necessary investment funds can be raised.*

Indicator IN2.1: *Financial figures of merit: Internal Return Rate (IRR) and Rate of Investment (ROI).*

Evaluation parameter EP2.1.1*: The internal Return Rate (IRR) produced by selling the net electricity generated by the INS at the defined real reference Price for Unit of Electricity Sold (PUES), excluding costs not defined in price setting mechanisms and including costs for confident lifecycle operation, decommissioning and waste treatment;*

Evaluation parameter EP2.1.2: *The Rate of Investment (ROI) calculated for the average lifecycle total plant invested capital and lifecycle average operating net income produced from the sale of electricity.*

Acceptance limits: ***AL2.1.1:*** $IRR_N > IRR_{LIMIT}$, *and* ***AL2.1.2:*** $ROI_N > ROI_{LIMIT}$,

where IRR_{LIMIT} *and* ROI_{LIMIT} *are the minimum acceptable levels required by the investor for competing technologies of comparable sizes.*

Assessment against indicator IN2.1

To calculate the IRR and ROI indicators it is necessary first to define the PUES (item 6). From the item 7.1.1, the cheapest LUEC for the addition of new nuclear power plants is 38.36 mills/KWh what, with the addition of 30%, gives a PUES value of 49.87 mills/KWh. The values of the IRR for both reactors were computed repeating the calculation of the LUEC for different discount rates until the corresponding LUEC was equal to the PUES above. This computational procedure led to IRR_{IRIS} = 14.07 % per year and $IRR_{ANGRA\text{-}3\ TYPE}$ = 8.03 % per year. With the *IRR* minimum limit of 12 % per year (item 6), the acceptance criterion AL2.1.1 is fulfilled for the IRIS reactor. For the Angra 3 reactor type, it would actually be necessary to reduce the annual discount rate to 8.03 % per year in order to sell the electricity produced at the reference price of 49.87 mills/KWh.

In the model used the PUES is assumed constant during the plant life. Thus, the average net operating incomes could be calculated as the difference between PUES value and the O&M and fuel costs of Tables 3 and 4. The invested capital is the overnight cost multiplied by the net electrical power. The ROI value is calculated dividing the average net operating incomes by the total capital investment (overnight costs, contingency costs and owner's costs). Using the data in Tables 3, 4 and the PUES value of 49.87 mills/KWh, the return of investment for each reactor are calculated as ROI_{IRIS} = 25.59 % per year and $ROI_{ANGRA\ 3\ TYPE}$ = 10.61 % per year. With *ROI* minimum limit of 14% per year (item 6), the acceptance criterion AL2.1.1 is also fulfilled for the IRIS reactor. For Angra 3 reactor type, selling the electricity at the defined PUES would reduce the return of the invested capital to only 10% per year, approximately, what, in turn, would increase the payback period considerably compared with the IRIS option.

Indicator IN2.2: *Total investment: the highest single plant total investment up to commissioning the reactor within the complete INS, that is, the sum of the overnight total cost and the interest during construction multiplied by the net electrical power.*

Acceptance limit AL2.2: $Investment_N < Investment_{LIMIT}$,

where $Investment_{LIMIT}$ *is the maximum level of capital that could be raised in the market climate.*

Assessment against indicator IN2.2

Considering the projected growth of the gross domestic product (GDP) in the next decades, the investments already made and the financial funds being negotiated for completion of the construction of the Angra 3 unit up to 2013 (a lump sum of about $3 billion), an upper limit of $4 billion has been estimated to be feasible to raise in the national and international market. In the actual case of the Angra 3 construction, a substantial part of the required capital investment, about 40%, should come from foreigner investors.

The total investment up to commissioning the reactor within the complete INS is the sum of the overnight total cost and the interest during construction multiplied by the net electrical power. Considering the data at Tables 3 and 4, the required investments for both reactor alternatives are 1,471 M$ for IRIS (= $Investment_{IRIS}$) and 4,369 M$ for the Angra 3 type reactor ($Investment_{ANGRA\ 3\ TYPE}$). From these investment data, the AL2.2 is clearly fulfilled for the IRIS reactor. For an Angra 3 reactor type, the total investment at the discount rate of 10% per year is considerably greater than the amount being raised for the completion of construction of Angra 3 unit in 2013 at the discount rate of 3.61% per year [7]. As discussed previously, to sell the electricity produced at the reference PUES price of 49.87 mills/KWh, the discount rate in this evaluation would have to be reduced to 8.03% per year what in turn would reduce the total investment to $4.06 billion, barely above the proposed upper limit for total investment.

7.1.3. User Requirement UR3: The risk of investment in innovative nuclear energy systems should be acceptable to investors taking into account the risk of investment in other energy projects.

Indicator IN3.1: *Level of licensing application to regulatory body required to start the construction of a reference or specific plant or reactor.*

Acceptance limit AL3.1.1: *Plants of same basic design have been constructed and operated.*
Acceptance limit AL3.1.2: *Design is licensable in the country of origin.*

Assessment against Indicator IN3.1

Pre-certification of IRIS is proceeding in the Nuclear Regulatory Commission of the United States (USNRC). IRIS sponsors have a targeted certification completion date of 2010 with commercial deployment to follow. Thus, the acceptance limits AL.3.1.1 and AL3.1.2 shall be fulfilled before a final decision is taken for the deployment of an IRIS reactor in the country.

Indicator IN3.2: *Evidence is available to the investor that the project constructions and commissioning times used in the financial analyses are realistic and not optimistic.*

Acceptance limit AL3.2: *A convincing argument that the construction schedule is realistic and consistent with experience with previous NPP construction projects carried out by the supplier and includes adequate contingency.*

Assessment against Indicator IN3.2

A first-of-a-kind plant has not been constructed for IRIS yet, so there is no practical evidence from previous projects that the schedule used in the financial analysis is realistic. Nonetheless, the experience of the leading company in the IRIS consortium (Westinghouse) in the design, financial analysis and construction of several PWR reactors around the world can be considered as evidence that the schedule proposed for IRIS is quite realistic.

Indicator IN3.3: *Financial robustness index of INS, RI.*

Acceptance limit AL3.3: The RI should be ≥ 1 for all critical economic indicators.

Assessment against Indicator IN3.3

The discount rate and the construction time were considered the critical factors that could jeopardise the economic competitiveness of IRIS with regard to the alternative Angra 3 type of reactor. Two data sets (d_j) have then been selected to estimate the robustness index for deviation from the data used in the reference scenario:

(1) (d_1=r): *discount rate:* Recent study carried out by EPE/MME [1] suggests that three discount rates may be applied for future energy projects in the country: 8%, 10% and 12% per year. To bind the robustness index for variations in the reference discount rate of 10% per year, a lower and an upper limit of 7% and 13% per year, respectively, were used. These perturbed values of the discount rate are used for the recalculation of both C_N and C_A values.

(2) (d_2=T_c): *construction time:* The plant arrangement of three independent IRIS single reactor units of 335 MWe constructed in a "slide–along" manner, allows for the consideration of "learning" in the construction process what should lead to a reduction in the overall construction time and, consequently, in the interests to be charged during construction. (learning benefits in construction are derived mainly from maintaining the core team throughout the construction). On the other hand, there is always the possibility of some unexpected financial, technical or even non-technical problems in nuclear reactor projects, especially innovative ones, which may cause considerably delays in construction time. Thus, to bind the robustness index a lower limit of 6 years and an upper limit and 12 years construction time were used. To calculate the IDC values at these different construction times the mean investment time formula (Eq. 19 of Annex A [2, Vol. 2] was used. The perturbed values of the construction time are used only for the recalculation of C_N since the construction time for the alternative Angra 3 reactor type is considered realistic (Table 5).

Table 5. Robustness index elements for reference scenario and deviation data

Reactor	(d_1=r) (%/year)	(d_2=T_c) (%/year)	C_N *(mills/KWh)*	C_A *(mills/KWh)*	$RI = C_A/C_N$
Reference scenario					
IRIS	10	9	38.36	---	1.55
Angra 3 type	10	5.5	---	59.37	
Deviation data					
IRIS	7	9	31.43	---	1.44
Angra 3 type	7	5.5	---	45.35	
IRIS	13	9	46.60	----	1.63
Angra 3 type	13	5.5	---	76.16	
IRIS	10	6	35.47	---	1.67
Angra 3 type	10	5.5	---	59.37	
IRIS	10	12	39.77	---	1.49
Angra 3 type	10	5.5	---	59.37	

The lowest value of RI in Table 5 is taken as the RI index of the INS. With RI = 1.44, the AL3.3 is clearly fulfilled for the selected INS.

Indicator IN3.4: *Long term commitment to nuclear option.*

Acceptance limit AL3.4: *Commitment sufficient to enable a return of investment.*

Assessment against Indicator IN3.4

The country operates two nuclear power plants since 1981 and the National Council on Energetic Policy (CNPE) has recently approved the restart of the construction of a third large PWR nuclear power plant, which is now scheduled to start operation in 2013. These facts indicate that exist some political support for nuclear power in the country and that this support is likely to be sustained in the next few decades at least. The AL3.4 is thus fulfilled.

6. CONCLUSIONS

Table 6. Indicators, comparison with acceptance limits and judgement on potential of INS based on the International Reactor Innovative and Secure - IRIS

Indicator	Indicator value	Acceptance limit	Units	Judgement on potential of INS
IN1.1 - $LUEC_{IRIS}$	38.36	< 59.37	mills/ KWh	Compliant
IN2.1-EP2.1.1- IRR_{IRIS}	14.07	≥ 12	% / year	Compliant
IN2.1-EP2.1.2 - ROI_{IRIS}	25.59	≥ 14	% / year	Compliant
IN2.2 - $Investment_{IRIS}$	1,471	≤ 4,000	M$	Compliant
IN3.1 -$Licensing_{IRIS}$	A similar plant has not been operated	Similar plant licensed and operated in country of origin	None	Potential
IN3.2 - Construction $Schedule_{IRIS}$	A first-of-a-kind plant has not been built	Construction schedule times used in financial analyses have been met in previous construction projects for plants of the same basic design and include contingency	None	Potential
IN3.3 - RI_{IRIS}	1.44	> 1	None	Compliant
IN3.4 -Long term commitment to nuclear option	Political support has been modestly addressed	Commitment sufficient to enable a return of investment	None	Compliant

From Table 6 it can be seen that the economic basic principle is not entirely fulfilled yet. Two indicators (IN3.1 and IN3.2) shall only comply with the corresponding acceptance limits at the beginning of the next decade when the certification process at the USNRC shall be completed and a first-of-a-kind IRIS plant shall start commercial operation.

REFERENCES

1. Energetic Research Company (EPE)/Ministry of Mines and Energy (MME), *National Plan of Energy 2030 – Thermonuclear Generation*, Rio de Janeiro (2006).
2. International Atomic Energy Agency, *Guidance for the Application of the Assessment Methodology for Innovative Nuclear Energy Systems – INPRO Manual: Overview of the Methodology*, IAEA-TECDOC-1575 Ver. 1, Vienna (2008).
3. International Atomic Energy Agency*, Status of Innovative Small and Medium Sized Reactor Designs 2005 – Reactors with Conventional Refuelling Schemes,* IAEA-TECDOC-1485, Vienna (2006).
4. M. D. Carelli, *IRIS – International Reactor Innovative and Secure*, Final Technical Progress Report, Pittsburgh (November 2003).
5. K. Miller, *The IRIS Project – Economics: Mature and Developing Markets*, IRIS Team Meeting (October 26, 2005).
6. D. T. Ingersoll et al, "Nuclear Desalination Options for the International Reactor Innovative and Secure (IRIS) Design", *5th International Conference on Nuclear option in Countries with Small and Medium Electricity Grids*, Dubrovnik, Croatia, (May 16-20 2004).
7. International Atomic Energy Agency, Reference Technology Database (RTDB), IAEA, Vienna (2002).
8. IRIS official web site – IRIS Home Page : http://hulk.cesnef.polimi.it/
9. International Atomic Energy Agency, *Status of Small Reactor Designs without On-site Refuelling*, IAEA-TECDOC-1536, Vienna (2007).
10. FBNR official web site, http://www.rcgg.ufrgs.br/fbnr.htm
11. Eletronuclear, *Angra 2 Final Safety Analysis Report – rev. 9* (January 2005).
12. R. B. De Andrade, "ANGRA-3: Economical-Financial Evaluation of the Enterprise", *XI Brazilian Energy Congress*, Rio de Janeiro, Brazil (August 16-18 2006).
13. Trade Tech's Uranium Information Web Site, http://www.uranium.info
14. Nuclear Energy Agency (NEA) / Organisation for Economic Co-operation and Development (OECD), *Trends in Nuclear Fuel Cycle Paris*, France (2002).
15. M. Bunn, S. Fetter, J. Holdren, and B. Van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel, Managing the Atom Project*, Belfer Centre for Science & International Affairs, Harvard University (2003).
16. Nuclear Energy Agency (NEA)/Organisation for Economic Co-operation and Development (OECD), *The Economics of the Nuclear Fuel Cycle*, France (1994).