STUDY ON ECONOMIC ASSESSMENT OF NUCLEAR ENERGY SYSTEM USING NEST TOOL

Thi Huong Vo, Thi Thanh Thuy Nguyen, Tran Chung Le, Nhu Viet Ha Pham
Institute for Nuclear Science and Technology, Vietnam Atomic Energy Institute
179 Hoang Quoc Viet str., Cau Giay Dist., Hanoi, Viet Nam;
Email: vohuong1705@gmail.com

Abstract: This paper performed research on the use of Nuclear Economics Support Tool (NEST) to gain a basic understanding on the algorithm, necessary input parameters, and output parameters of this tool. Then, the application of NEST version 4 for a case study to calculate the economic parameters for a 1000MW(e) PWR nuclear reactor operating with a once-through fuel cycle 1 was also carried out. The purpose is to initially build the capacity in the economic assessment of the nuclear energy system. The calculated parameters including levelized unit energy cost (LUEC), internal rate of return (IRR), Return on Investment (ROI), Net present value (NPV), and total investment were compared with those in IAEA No.NG-T-4.4. The comparative results showed that the calculated results are in good agreement with IAEA results. The sensitivity evaluations were also performed to identify the most sensitive parameters that influent the LUEC. The sensitivity analysis results showed that the LUEC is highly dependent on the discount rate, the construction cost, the reactor lifetime, and the capital investment schedule. However, LUEC is almost insensitive to the cost of natural uranium. The analysis also shows that the discount rate and construction cost should be kept to a minimum and the reactor lifetime should be increased to a maximum to minimize the value of LUEC, then enhance the competitiveness of NES. In addition, the distribution of capital investment during the construction period should be carefully considered because it influences the electricity cost considerably.

Keywords: NEST, Version 4, LEUC, IRR, NPV, ROI, Sensitivity

I. INTRODUCTION

At the global climate change conference COP26 in Glasgow, Viet Nam has committed to phase out coal fuel energy production by the 2040s and then reach net-zero emission target by 2050. These commitments lead to the possibility that Viet Nam may reconsider nuclear power again because of the fact that it can play a crucial role in future energy transition in Viet Nam. Therefore, although the Ninh Thuan nuclear power plant projects have been postponed since November 2016, building capacity for Viet Nam to analyze and evaluate nuclear power deployment scenarios, to support decision making and to systematically assess the sustainability of nuclear energy systems (NES) become very important and necessary.

Economic is one of the INPRO methodology area of NES sustainability assessment. The Nuclear Energy System Assessment (NESA) Economic Support Tool (NEST) was developed to enable an assessor using the INPRO methodology in the area of economic to easily determine numerical economic parameter such as total capital investment cost (TCIC), levelized unit energy cost (LUEC), and other financial figures of merit including internal rate of return (IRR), return of investment (ROI) and net present value (NPV).

Several simple calculations using NEST are given in IAEA No-T-4.4. [1]. NEST has also been used to calculate economic parameters for economic evaluation of several reactors in Bangladesh and Belarus, Thailand [2-4]. Many other countries also have applied this tool in assessing the sustainability of their existing or planted NES such as Argentina, China, India, Indonesia, Romania, Russia and Ukraine [5].

NEST consists of a set of Excel spread-sheets that calculate parameters for different type of reactors, fuel cycles and for alternative systems. NEST comprises the four modules which are based on the different analytical models and can be used in parallel to estimate impact from specific methodological assumptions. The detailed description of the NEST modules is provided in Ref.1 [1] and can be briefly summarized as follows:

- Version 1 was developed within INPRO in 2004-2008 [6] and covers a nuclear power plant operating in once-through fuel cycle and alternative non-nuclear power plant.
- Version 2 is based on Harvard University study [7]
- Version 3 is based on a cash-flow model published by Massachusetts Institute of Technology (MIT) [8]
- Version 4 is an extension of module version 1 (involving some ideas of the version 2) designed for break-even closed fuel cycle system calculations and reactors operating with conversion rate other than one (breeders or burners).

In this study, a research on the use of NEST was performed to gain a basic understanding on the algorithm, necessary input parameters, and output parameters of this tool. Then, the application of NEST version 4 for a case study to calculate the economic parameters for a 1000MW(e) PWR nuclear reactor operating with a once-through fuel cycle 1 was also carried out. The purpose is to initially build the capacity in the economic assessment of nuclear energy system. The calculated parameters including Levelized Unit Energy Cost (LUEC), Internal Rate of Return (IRR), Return on Investment (ROI), Net Present Value (NPV) and total investment were compared with those in IAEA No.NG-T-4.4. A sensitivity evaluations were also performed to identify the most sensitive parameters that influent the LUEC.

II. METHODOLOGY

The general input and output parameters for NEST are presented in Fig.1. NEST converts basic technical and economic inputs of the proposed NES into standard functions used in economics such as LUEC, NPV, IRR, ROI, and total investment. Technical parameters include net electric output, net thermal efficiency, average load factor, construction time and plant life and so on. The economic parameters include discount rate, capacity cost, operating cost, fuel cost and so on

- **Capital cost** with details of overnight capital cost (direct construction cost include the cost of the plant component and materials and the labour required for installation), capital investment schedule, interest during construction, back-fitting cost (major refurbishment cost not included in the annual O&M costs) and decommissioning cost.
- **Operating cost** with details of fixed and variable operation and maintenance cost, including waste management cost, taxes and so on.
- **Fuel cost** with details of entire fuel cycle costs – natural uranium cost, conversion cost, enrichment cost, fuel fabrication cost and back end costs such as spent fuel storage, reprocessing, disposal and so on. For fuel cost calculations, additional information is needed, such as enrichment level of first core and reloads, core power density, losses of nuclear materials at each fuel cycle step.

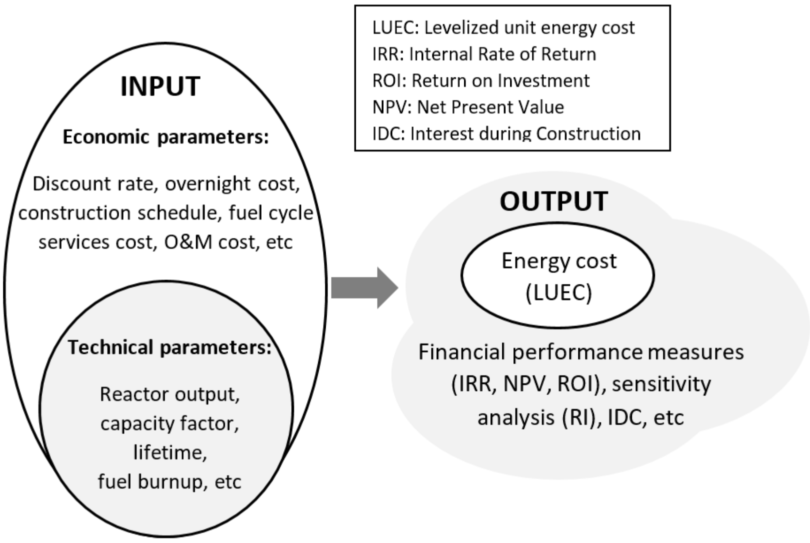

Fig.1. Input and output parameters of NEST

The main outputs of NEST are LUEC, NPV, IRR, ROI. Nuclear technologies can be compared with alternative energy sources using these indicators. LUEC is defined as the costs per unit of electricity generated. The smaller value of LUEC, the higher competitiveness of nuclear energy. Specific equations for LUEC calculation in NEST may vary depending on the system and options. However, the general approach is the same as the equation (1). All other equations for IRR, ROI, NPV and total investment calculation are presented in Ref.1. [1]

$$LUEC\left(\frac{\$}{MWh}\right) = \frac{\sum_{t=t_{STATT}}^{t_{END}} \frac{CI_t+O\&M_t+F_t}{(1+r)^t}}{P_{net}*L_f*8760*\sum_{t=t_{STATT}}^{t_{END}} \frac{1}{(1+r)^t}} \quad (1)$$

With: CI_t is the capital investment expenditures at year t (including overnight cost, interest during construction, backfitting and decommissioning); O&Mt is the operation and maintenance expenditures at year t; F_t is the fuel expenditures at year t (including first core); L_f is the load factor; P_{net} is the reactor capacity (net); r is the real discount rate; t_{START} is the beginning of project (start of the first construction period); t_{END} is the end of the project (including decommissioning)

In this study, NEST version 4 was used to calculate the economic parameters for a 1000MW(e) PWR nuclear reactor operating with a once-through fuel cycle. LUEC and NPV are calculated as equations in **Table 1 [9]**. The calculation equations of IRR, ROI, and total investment are given in Ref.1&9 [1,9]. The necessary input data for NEST is presented in Table 2 [1].

Table 1. Equations used in NEST tool to calculate LUEC

$LUEC = LUAC + LUOM + LUFC$	(2)	LUAC LUOM LUFC	Levelized unit life cycle amortization cost Levelized unit life cycle O&M cost Levelized unit life cycle cost
$LUAC = 10^3.\frac{ONT + IDC}{Lh} + LUAC_D + LUAC_{BF}$	(3)	ONT IDC $LUAC_D$ $LUAC_{BF}$	Total overnight cost per unit of installed capacity Interest accumulated during construction period Levelized cost of decommissioning Levelized backfitting cost
$Lh = 8760.Lf.\left(\frac{1-\left(\frac{1}{1+r}\right)^{t_{LIFE}+1}}{1-\left(\frac{1}{1+r}\right)} - 1\right)$	(4)	Lh Lf t_{LIFE} r	Intermediate parameter calculated in NEST Average load factor, 100% Lifetime of the plant Real discount rate
$ONT = OCC + CC + CO$	(5)	OCC CC CO	Overnight construction cost Contingency cost Owners cost
$IDC = ONT.\sum_{t=t_{START}}^{0}\left(\frac{\omega_t}{(1+r)^t} - 1\right)$ $\omega_t = \frac{ONT_t}{ONT}; ONT = \sum_{t=t_{START}}^{0} ONT_t$	(6)	IDC t_{START} ω_t	Interest accumulated during construction Start of the first construction period Normalized capital investment schedule (share per year) during construction
$LUAC_D = 10^3.\frac{\frac{OD_D}{(1+r_d)^{t_{END}}}}{Lh}$	(7)	t_{END} OD_D r_d	End of the project Overnight cost of decommissioning which are paid at year t_{END} Discount rate of decommissioning
$LUAC_{BF} = 10^3.\frac{\sum_{i=1}^{nbf}\frac{OBF_i}{(1+rbf)^{tbf_i}}}{Lh}$	(8)	nbf: OBF_i rbf	Number of backfittings Single overnight backfitting expenditure at year tbf_i Discount rate of backfitting cost
$LUOM = 10^3.\frac{(O\&M)_{FIX}}{8760.Lf} + (O\&M)_{VAR}$	(9)	$O\&M_{FIX}$ $O\&M_{VAR}$	Fixed operation & maintenance cost Variable operation& maintenance cost

$NPV = (PUES - LUEC).\frac{Lh}{10^3}$	(10)	NPV	Net Present Value	
		PUES	Price of unit electricity sold	
		10^3	Dimensions adjustment coefficient	

Table 2. Cost characteristic assumed for the PWR under consideration

Parameters		Value	Parameters	Value
Net electric power, MWe		1000	Nuclear fuel backend cost, $/kg HM	1000
Overnight cost, $/kWe		5000	Spent nuclear fuel average burnup, MWd/kg HM	50
Contingency cost, $/kWe		0	Nuclear thermal efficiency of the plant, %/100	0.33
Owners cost, $/kWe		0	Reactor first core average power density, kW/kg HM	28.89
Decommisioning cost, $		500.10^6	Natural U purchase cost, $/kg	70
Backfitting cost, mills/kW.h		0	U conversion cost, $/kg	10
Average load factor, %/100		0.9	U enrichment cost, $/SWU	150
Lifetime, a		60	Nuclear fuel fabrication cost, $/kg	300
Construction time, a		5	Time from U purchasing to fuel loading, a	1.5
Normalized capital investments schedule (share per annum, %/100)	0	0	Time from U conversion to fuel loading, a	1
	-1	0.2	Time from U enrichment to fuel loading, a	0.75
	-2	0.2	Time from fuel fabrication to loading, a	0.5
	-3	0.2	Losses at U purchasing, %/100	0
	-4	0.2	Losses at U conversion, %/100	0.005
	-5	0.2	Losses at U enrichment, %/100	0
	-6	0	Losses at fuel fabrication, %/100	0.01
Tax rate, %/100		0	First core lowest U-235 concentration, %/100	0.02
Price per unit of electricity sold, mills/kW.h		80	First core medium U-235 concentration, %/100	0.03
Fixed O&M cost, $/kWe		100	Refueling fuel U-235 concentration, %/100	0.045
Variable O&M cost, mills/kW.h		0	Natural U-235 concentration, %/100	0.0071
			Enrichment tails U-235 concentration, %/100	0.0025

Since there are large uncertainties in some of the inputs. NEST allows for sensitivity and uncertainty analyses for establishing the competitiveness of the proposed NES. The input values for various parameters can be chosen within technically feasible and economically viable ranges in regard to the selected metric. In this study, two sensitivity studies were performed.

- The first case is a NEST in-built sensitivity analysis to 5 important parameters: discount rate, overnight construction cost, cost of natural uranium, construction period, and reactor lifetime. It is assumed that the discount rate is constant during reactor lifetime. This analysis is automatically integrated into the NEST tool to identify the most sensitive parameters that affect the LUEC. It is performed by calculating the LUEC for every variation of 5 input parameters. It is noted that only a single parameter is considered at a time. Variated parameters are to be multiplied by relative variations (relative index) as shown in Table 4. For example, the original discount rate, r=0.07 will be multiplied by 0.1, and the new discount rate r = 0.07 will yields a new LUEC value. Conversion of LUECs into relative values is done by dividing with the original LUEC value. Relative variation 1 corresponds to the initial LUEC with unperturbed data.

- The second case is the sensitivity analysis to capital investment schedule to investigate the effect of this parameter on LUEC. The change in the input data of investment distribution during the construction is given in Table 5.

III. RESULT

The comparison of calculated values of LUEC, NPV, IRR, ROI, and total investment between the case study and IAEA is shown in **Table 3.** The value of LUEC components and the cost of each stage of the fuel cycle are shown in Fig.2 & Fig.3, respectively**.** The sensitivity analysis result to 5 important parameters including discount rate, overnight construction cost, cost of natural U, construction period, and the reactor time is presented in **Fig.4.** Relative values of 5 uncertainty parameters and corresponding relative values of LUEC are shown in **Table 4**. The sensitivity analysis results to the capital investment schedule are shown in **Table 5.**

Table 3. The comparison of economic parameters between case study and IAEA

Parameter	Unit	IAEA Value	Case study value	The difference between 2 cases
LUEC	mills/kWh	72.9	76.843	5.41%
NPV	$/kW e	839	349.45	58.35%
IRR	%/100	0.079	0.073	7.59%
ROI	%/100	0.091	0.092	1.1%
Total investment	Billions of dollars	6.15	6.15	0%

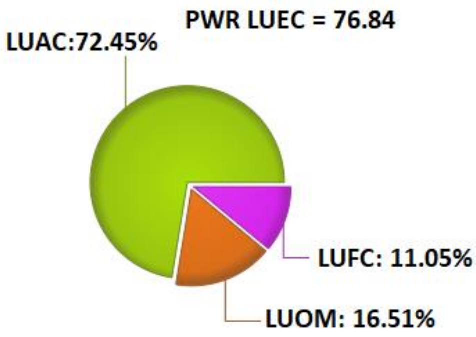

Fig.2. The component value of LUEC

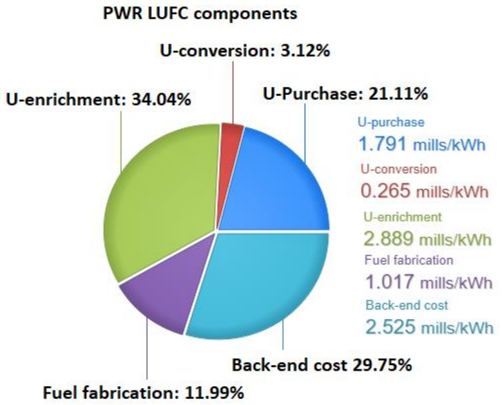

Fig.3. The cost of each stage of fuel cycle

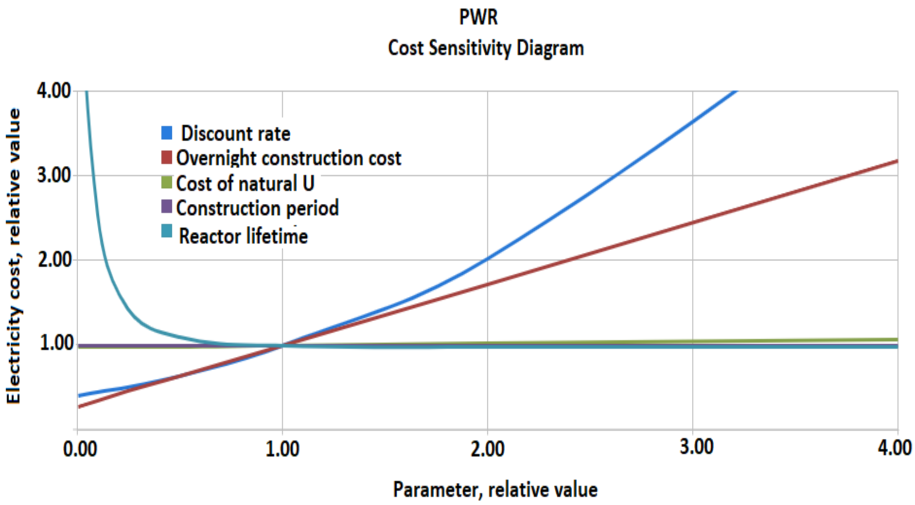

Fig.4. Sensitivity analysis to 5 important parameters in-built in NEST

Table 4. Relative value of 5 uncertainty parameters and relative values of LUEC

Index	Discount rate	Overnight construction cost	Cost of natural U	Construction period	Reactor lifetime
0	0.4081	0.2773	0.9767	1	6.3807
0.1	0.443	0.3489	0.979	1	2.5473
0.25	0.5064	0.4574	0.9825	1	1.4306
0.5	0.6399	0.6383	0.9883	1	1.1045
1	1	1	1	1	1
2	2.0271	1.7235	1.0233	1	0.9865
4	5.4471	3.1704	1.0699	1	0.9863

Table 5. Sensitivity analysis to investment distribution

	Investment distribution, (w_t), %							LUEC, mills/kWh
t, year	-6	-5	-4	-3	-2	-1	0	
case study	0	0.2	0.2	0.2	0.2	0.2	0	**76.84**
Case 1	0	0	0	0.2	0.4	0.4	0	**72.34**
Case 2	0	0.4	0.4	0.2	0	0	0	**81.35**
Case 3	0	0	0	0	0	1	0	**69.59**
Case 4	0	0	0	0	1	0	0	72.97
Case 5	0	0	0	1	0	0	0	**76.59**
Case 6	0	0	1	0	0	0	0	80.46
Case 7	0	1	0	0	0	0	0	84.61
Case 8	1	0	0	0	0	0	0	**89.04**

IV. **DISCUSSION**

Table 3 shows that the calculated values of LUEC, IRR, ROI, and total investment are acceptable and in good agreement with IAEA values. The difference between these two cases for those parameters is 5.41%, 7.59%, 1,1%, and 0%, respectively. The difference of NPV value between case study and IAEA case is about 58.35%. NPV is calculated by equation (10) and (4) ($NPV = (PUES - LUEC).\frac{Lh}{10^3} = (80 - 76.84).\frac{110684.90}{10^3} = 349.76$). It shown that NPV is strongly dependent on LUEC by big multiplier ($Lh/10^3 = 110.68$). It means that even if the difference of LUEC is small, it will still lead to a large difference of NPV. In this calculation, the difference of LUEC (5.41%) is acceptable. Therefore, the calculated value of NPV still can be acceptable.

The value of LUEC (the costs per unit of electricity generated) is about 76.84 mills/kWh. Fig. 2 indicates that the levelized unit life cycle amortization cost (LUAC), levelized unit life cycle O&M cost (LUOM), and levelized unit life cycle fuel cost (LUFC) account for 72.45%; 16.51% and 11.05%, respectively. It means that the competitiveness of nuclear energy is substantially influenced by the investments needed for developing the plant.

Fig.3 indicates that for a life fuel cycle cost, the front-end cost (70.25%) is higher than back-end cost (29.75%). The highest expenditures in the front end are due to Uranium enrichment (34.04%) and Uranium purchase (21.11%). The back-end cost includes all the expenditures for spent fuel and nuclear waste management, interim storage, reprocessing of spent fuel, and final disposal of nuclear waste is about 29.75% of life fuel cycle cost (LUFC).

Fig.4 and Table 4 show that the discount rate, construction cost, and reactor lifetime are the most sensitive parameters affecting the LUEC. The dependence of LUEC on construction cost, discount rate, and reactor lifetime is presented by equations in Table 1. The value of LUEC tends to increase if the discount rate and construction cost increase. In contrast, the value of LUEC tends to increase if the reactor lifetime decreases. It means that the project managers should concentrate on keeping the discount rate and construction cost to a minimum and increase the reactor lifetime to a maximum to minimize the value of LUEC, then enhance the competitiveness of NES. In addition, LUEC is almost insensitive to the cost of natural uranium, because the cost of natural uranium only accounts for a very small percentage of LUEC as shown in Fig 2&3.

Table 5 indicates that the LUEC is also affected by the capital investment schedule during the construction. It can be explained by equations (2), (3), and (6) in Table 1. The value of LUEC tends to increase if the investment distribution is high in the early years of the construction period. And LUEC tends to decrease if the investment distribution is high in the late years of the construction process. This information could be useful for project managers in using capital investment during the construction period. The NES economic assessors using NEST tool should be carefully considered this parameter in their analysis.

V. CONCLUSIONS

A study on the use of NEST and the application of NEST version 4 for a case study to calculate the economic parameters for a 1000MW(e) PWR nuclear reactor operating with a once-through fuel cycle were performed in this work. Several important economic parameters such as LUEC, IRR, ROI, NPV, and total investment are calculated. The results are acceptable and in good agreement with IAEA results. The sensitivity analysis to several important parameters including discount rate, overnight construction cost, cost of natural uranium, construction period, reactor lifetime and capital investment schedule was also performed. The results indicate that LUEC is highly dependent on the discount rate, the construction cost, reactor lifetime, and the capital investment schedule. However, LUEC is almost insensitive to the cost of natural uranium. It means that the project managers should concentrate on keeping the discount rate and construction cost to a minimum and increase the reactor lifetime to a maximum to minimize the value of LUEC, then enhance the competitiveness of NES. In addition, the distribution of capital investment during the construction period should be carefully considered because it influences the electricity cost considerably.

ACKNOWLEDGEMENT

This work is supported by VINATOM under grant number of DTCS: CS/23/04-04.

REFERENCE

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics, IAEA Nuclear Energy Series No. NG-T-4.4, IAEA, Vienna (2014).

[2] Jubair Sieed, Shaheed Hosain, Khorshed Ahmad Kabir, 2015, Application of INPRO Methodology to Assess Economic Feasibility of Propossed Rooppur Nuclear Power Plant, *International Conference on Materials, Electronic & Information Engineering (ICMEIE), 2015, Faculty of Engineering, University of Rajshahi, Bangladesh*

[3] IAEA (2013), INPRO Assessment of the Planned Nuclear Energy System of Belarus, IAEA-TECHDOC-1716

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Multi-criteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final report of the INPRO Collaborative Project KIND, IAEA Nuclear Energy Series No. NG-T-3.20, IAEA, Vienna (2019).

[5] https://www.iaea.org/newscenter/news/iaea-updates-tool-for-economic-assessment-of-electricity-generation-technologies

[6] International Atomic Energy Agency, 2008. Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems. INPRO Manual – Economics. Volume 2 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). IAEA-TECDOC-1575 Rev. 1, IAEA, Vienna

[7] Bunn, M., et al., 2003. The economics of reprocessing vs. direct disposal of spent nuclear fuel. Final report, No. DE-FG26-99FT4028, Harvard University, Cambridge MA, USA

[8] Ansolabehere, S. et al., 2003. The Future of Nuclear Power – An Interdisciplinary MIT Study. Massachusetts Institute of Technology, MA, USA

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, NEST Algorithm step 4 rev 1.0 (2017).