ANNEX V.

NATIONAL ROMANIAN SCENARIOS WITH RELIANCE ON DOMESTIC AND IMPORTED U /FUEL SUPPLY, BY CONSIDERING REGIONAL COLLABORATION IN NUCLEAR FUEL CYCLE AND INCLUDING ECONOMIC ANALYSIS

V-1. INTRODUCTION

The analyses included in the Romanian study have been performed by the team of experts from the Technologies for Nuclear Energy State Owned Company, Institute for Nuclear Research Pitesti, (RATEN-ICN Pitesti).

The Romanian study was included as Scenario A.3 (Scenarios Family A: LWR mono U/Pu recycling) under Task 1 ″Evaluation of Synergistic Collaborative Scenarios of Fuel Cycle Infrastructure Development″ of the IAEA's INPRO SYNERGIES Collaborative Project.

The SYNERGIES project main objective is to identify and evaluate mutually beneficial collaborative architectures and the driving forces and impediments for achieving globally sustainable Nuclear Energy Systems, being focused on the synergies related to the nuclear fuel cycle and specifically the regional and/or global collaborative approaches providing Member States the opportunity to keep options open to the future while bringing solutions to short/medium-term challenges, [V-1].

V-2. OBJECTIVE AND PROBLEM FORMULATION

The main objective of the Romanian study was to analyze the development of nuclear capacity and increasing of its share in the national energy mix in order to assure the sustainability, by considering regional collaborative architectures both in the front-end and back-end of the nuclear fuel cycle.

Romanian Nuclear Programme started in 1950. Two research reactors were commissioned, VVR-S in 1957 (decommissioning started in 1997) and TRIGA 14MW in 1979. Romania's current policy is for a Once-Through Nuclear Fuel Cycle based on indigenous facilities, without enrichment or reprocessing. The front-end activities are carried on in the U ore mines, Feldioara UO_2 Powder Plant, Nuclear Fuel Plant from Pitesti and Heavy Water Plant. The nuclear generation is assured by the Cernavoda Nuclear Power Plant with two PWHR reactors, CANDU 6 type (700 MW(e) each), in operation (Unit1 since December 1996 and, respectively, Unit 2 since 2007). The management of Spent Nuclear Fuel at Cernavoda is assured by the intermediate wet storage in SNF Bay (at least for 6 years), intermediate dry storage, MACSTORE type (for 30 years; first module became operational in 2003) and intermediate storage for solid Radioactive Waste (1400 mc total capacity). Final disposal of the low and intermediate level waste (LILW) from Cernavoda NPP (currently in stage of site authorization) is based on a Near-Surface Repository with multiple barriers (Saligny site, inside the NPP exclusion zone, disposal area ≈ 25 hectares (ha), general site layout ≈ 66 ha). Research is carried on the geological environment for spent nuclear fuel (SNF) and high level waste (HLW) Deep geological repository (very preliminary stage). The National Repository for LILW at Baita operates since 1985.

The electricity generated by Cernavoda NPP represents about 20% from the national

electricity production. According to the medium-term National Strategy for the Nuclear Energy Field Development and the National Nuclear Plan, ″in 2025-2050 Romanian NPPs must contribute with about 40% to the total national electricity production in cost competitive conditions and assuring nuclear safety at the international standard requirements″, see [V-2].

The development of the Energy Sector is based on the actual short-term ″Romanian Energy Strategy for 2007-2020″, whose main objective is ″…to satisfy the energy needs on short, intermediate and long term, with costs as low as possible, adequate to a modern market economy and a civilized life standard, in conditions of quality, supply security and with respect of the sustainable development principles″. The strategic objectives refer to: Security of energy; Sustainable development; Competitiveness. After a couple of updating attempts, the National Energy Strategy for 2014-2035 (draft) is in process of institutional assessment. Romanian Government considers nuclear power as a stable component of the energy-mix taking into consideration security of supply, reliability, economic efficiency, and GHG low emissions. Nuclear energy development is envisaged by: completion of the construction by 2020 and start the operation of another two PHWR reactors, CANDU 6 type (720 MW(e)) – Units 3 & 4 of the Cernavoda NPP, and prospects for construction of a new NPP (Gen III+ or Gen IV; reactor technology to be further selected) after 2030, see [V-3].

The case study analyses were performed for three distinct nuclear energy system (NES) development scenarios, as follows: a) Basic case: four PHWR, CANDU type (existing CANDU U1&U2 reactors, 700 MW(e) each, in operation, and new CANDU U3 &U4 reactors, 720 MW(e) each, with projected in-service after 2020) ; b) Pessimistic case : two PHWR, CANDU type (existing CANDU U1&U2, in operation); c) Optimistic case : four PHWR, CANDU type (as in Basic case) and another NPP, advanced PWR (1000 MW(e)) or advanced PHWR (Enhanced CANDU, 720 MW(e)), the projected in-service being after 2035.

For sensitivity analyses, three variation factors were considered, namely: a) annual electricity demand (according to [V-13, V-14, IAEA's experts mission in Romania ″Nuclear Energy System Assessment in Romania using INPRO methodology″ national project, April 2014]); b) annual discount rate (5%, 8% and 10%, respectively; 8% discount rate was considered the most appropriate for Romania's conditions and its economic and financial environment); c) CANDU Unit1&Unit2 time life (35 years with the possibility of extension to 40 years of operation).

The key questions to be answered were:

- What is the potential of nuclear energy to participate with an important share in the national energy mix, according to the strategic documents in force, in conditions of cost competitiveness, safety and security of supply, with assurance of the projected national electricity demand?
- What is the impact of considered scenarios on the national energy mix portfolio of capacities and electricity production?
- What is the impact of considered scenarios on the domestic resources of Uranium?
- What is economic projection of considered scenarios in terms of investments needed for new nuclear capacities addition?
- What are the implications of each considered scenario on the level of fresh fuel requirements for nuclear capacities?
- Which are the amounts of spent fuel annually discharged from the reactors and transferred to interim wet storage for cooling?
- What is the cumulative SNF volume in interim dry storage?
- What is the impact of various discount rates on the annual evolution of interest parameters, till reaching of the considered time horizon for modelling?

- What is the impact of CANDU Unit1 & Unit2 extended lifetime on the presence and operation timing of nuclear capacities in the national energy mix, Uranium resources consumption, U and fresh fuel requirements, SNF volume in interim dry storages?

Beside the assessment of possible scenarios including collaboration both in front-end and back-end of the nuclear fuel cycle based on ″win-win″ approach and the current existing and near-term projected technologies and infrastructure, in the present study an economic analysis using the suggested Task 1 key indicators (see Chapter 2 of the report) was performed. The economic analysis on the competitiveness of nuclear energy against alternative electricity sources was considered useful in order to provide a substantial technical support for the decision making regarding a comprehensive and responsible national nuclear energy strategy on medium term envisaging the transition to long–term globally sustainable NES. The long-range objective addressed by the present study is the global vision of the national collaboration options for energy sustainability in regional and global context.

V-3. ASSUMPTIONS, METHODS, CODES AND INPUT DATA USED

V-3.1. General assumptions

Romania's national energy mix was modelled taking into account available data and public information on the technologies participating to the national electricity generation (resources, capacities, activities, economic parameters – costs, efficiency, load factors, etc), according to the existing legal framework. To cover the lack of data, international agreed data studies in the domain have been used.

Romania has a balanced portfolio of generation capacity comprising hydro, nuclear, coal and gas-fired power plants, with renewables (other than hydropower) representing a small but rapidly growing subsector of the generation market.

The modelling period started from 2010, the time horizon for the proposed study being 2050. The national energy mix has been modelled including the corresponding specific producers of electricity, namely: classical power plants (PP) based on fossil fuels (coal-fired PP, gas-fired PP and combined cycle PP, respectively, producing electricity and heat), renewable energy PP (including hydro, wind farms and solar photovoltaic stations) and nuclear energy production.

The modelling of national energy mix considered both using of the existing domestic natural resources and import of resources, if necessary, at international market prices. Abundant domestic resources exist for coal-fired and hydro PP, and also the appropriate corresponding mining capability to cover the modelled period in present study; the import of coal was still allowed, if needed. The share of natural gas in the power generation sector is relatively low because a significant part of natural gas consumption is sourced from imports.

The renewable energy sources contribution to the national energy mix have been considered according to the strategic documents in force [V-4, V-5 and V-6] (in the context of EU integration, Romanian Government drafted the National Development Plan 2007-2013).

Electricity consumption patterns in Romania have showed considerable fluctuations in the last two decades before 2010, see Fig. V-1. Consumption decreased significantly from 1989 to 2000, when situation stabilized and the consumption started to rise reaching the peak in 2008. In 2010, electricity demand was fully met by domestic electricity production in Romania. Furthermore, Romania became a net exporter of electricity (2.91 TWh in 2010), see [V-7, V-8].

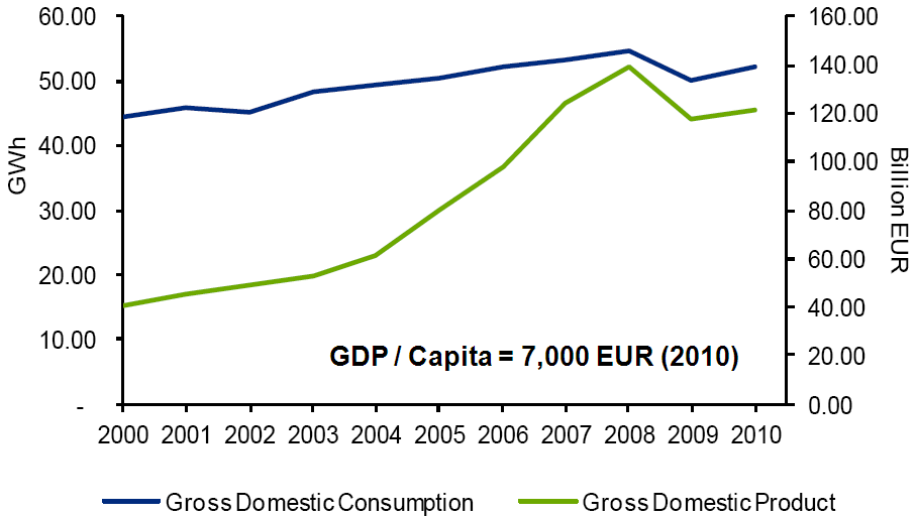

FIG. V-1. Romanian electricity consumption and GDP development, 2000-2010 [V-7, V-8].

Tables V-1 and V-2 present electricity generation structure for the period 2011-2013 [V-8] and the installed capacities structure at the level of the year 2011 [V-9, V-10], respectively. Fig.V-2 illustrates the evolution of the electricity delivered in the national energy system, by primary sources, in the period 2011-2013 [V-8].

TABLE V-1. ELECTRICITY GENERATION STRUCTURE FOR 2011-2013 [V-8]

Generation energy source	2011		2012		2013	
	TWh	%	TWh	%	TWh	%
Solid	24.16	40	22.51	39.7	16.18	29
Gas	7.07	11.7	7.26	12.8	8.20	14.7
Liquid	0.60	1	0.51	0.9	0.11	0.2
Nuclear	11.72	19.4	11.51	20.3	11.49	20.6
Hydro	15.70	26	12.93	22.8	15.84	28.4
Wind	1.15	1.9	1.98	3.5	3.96	7.1
Total	60.39	100	56.71	100	55.78	100

TABLE V-2. INSTALLED CAPACITIES STRUCTURE IN 2011 [V-9, V-10]

Generation type	Capacity, MW(e)	Share, %
Combustible fuel PP	11.616	56.67
Nuclear PP	1.411	6.88
Hydro PP	6.483	31.63
Wind farms	988	4.82
Total	20.498	100.00

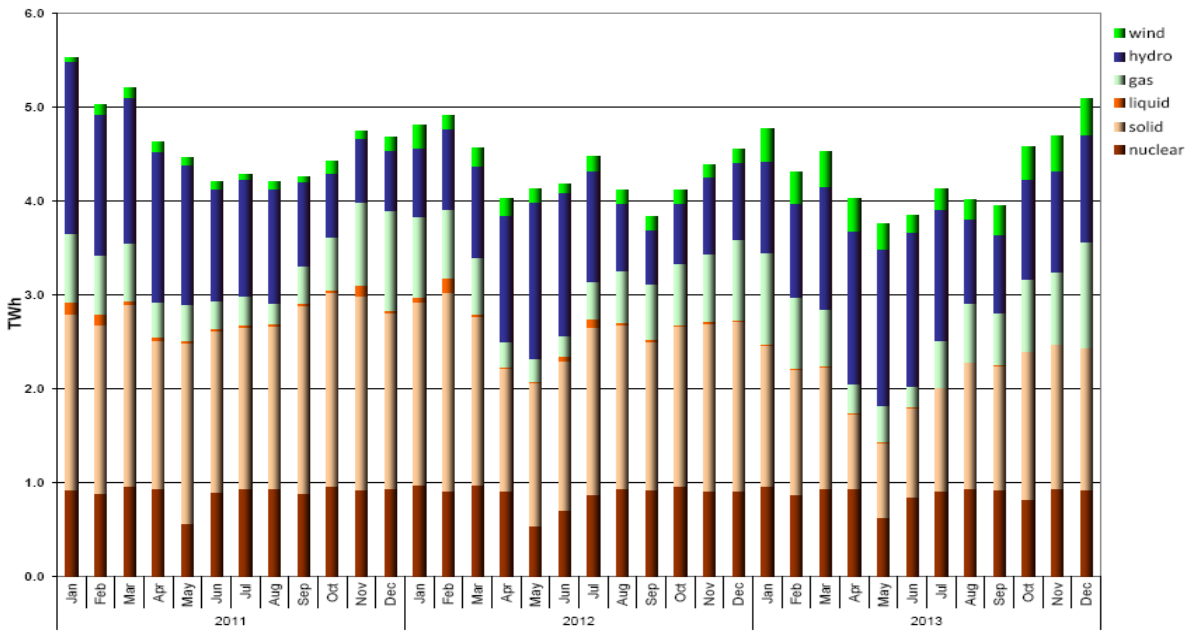

FIG. V-2. Electricity delivered by primary sources in Romania, 2011-2013 [V-8.]

The Romanian electricity generation sector is facing major challenges as a significant percentage of the generation assets are already past their useful technical life, with 30% being about 40 years old. The situation of Romanian generation capacities by their age distribution is illustrated in Fig. V-3. About 55% (generating power units with a total capacity of 11 GW(e)) from the total installed capacity will be closed down by 2035, taking into account that ~ 28% (5.5 GW(e)) of the total installed capacity must be replaced by 2020, and ~ 55% (11 GW(e)) by 2035, respectively [V-7, V-11 and V-12].

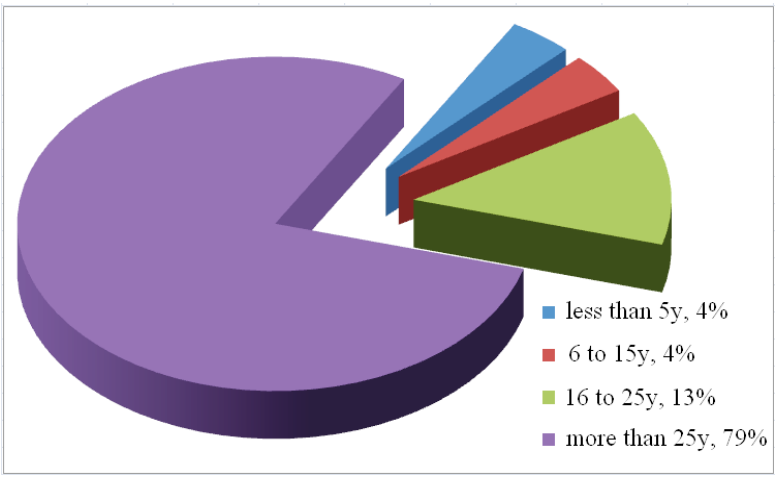

FIG. V-3. Age distribution of electricity generation capacities in Romania [V-7, V-11 and V-12].

For the electricity demand evolution, the Romanian Energy Strategy 2011-2035 scenarios (see Table V-3) have been taken into account, [V-13, V-14]. The scenarios were elaborated based on the GDP evolution outlooks realized by the National Institute for Economic Studies (2010-2014) and National Commission for Prognoses (2010-2020-2030).

The reference scenario implies the macroeconomic parameters agreed by the Government correlated with the International Monetary Fund stand-by treaty. The other two

scenarios take into account less favorable conditions for the business medium, both at national and international level, see [V-13 and V-14].

TABLE V-3. SCENARIOS FOR ENERGY DEMAND IN ROMANIA [V-13, V-14]

Scenario	2011 - 2014	2015 - 2020	2021 - 2025	2026 - 2030	2031 - 2035	2036 - 2050
Reference Scenario ″Ref ″						
Annual growth rate, %	2.7	2.6	2.2	1.3	1.1	1.1
1st Pessimistic Scenario ″Pes1″						
Annual growth rate, %	1.3	1.6	1.5	1.3	1.0	1.0
2nd Pessimistic Scenario ″Pes2″						
Annual growth rate, %	1.3	1.1	1.0	1.0	1.0	1.0

In the present study, both pessimistic scenarios for energy demand evolution have been considered, last period growth rate being extended to reach the considered 2050 time horizon. The third energy demand evolution scenario considered in our study was established during IAEA's experts mission in Romania (″Nuclear Energy System Assessment in Romania using INPRO methodology″ national project, April 2014), following the Institute of Energetic Studies and Designs suggestions. The ″NESA″ scenario assumes annual growth rates of 1.1% for 2011-2020 and 1.5% for 2020-2050, respectively.

V-3.2. Non-nuclear generation – assumptions and input data

According to existing national resources (see Table V-4), the lignite is abundant and can have a significant contribution in national electricity production for the next 2-4 decades, [V-11, V-13]. Nevertheless, the renewable energy source potential must be also taken into consideration. The energy potential of renewable energy sources in Romania is high: hydro – 40 TWh/year, out of which 6 TWh/year is for small (less than 10 MW) hydro power plant (PP), wind – 23 TWh/year and solar – 1.2 TWh/year, respectively), but the usable potential is much smaller, on account of technological limitations, economic efficiency and environmental restrictions, see [V-4 – V-6, V-7, V-11 – V-14].

TABLE V-4. ROMANIAN DOMESTIC PRIMARY ENERGY RESOURCES [V-11, V-13]

		Resources category			
		Hard coal	Lignite	Natural gas	Oil
Existing resources, Mtons*	Reserves	755	1 490	185	74
	Exploitable chartered	105	445	-	-
	In new perimeters	-	1 045	-	-
Estimated annual production, Mtons*		2.5	3.0	10.5	4.5
Resources estimation, years	Reserves	229	47	15	14
	Exploitable chartered	-	15	-	-
	In new perimeters	-	30	-	-

* Resources amounts and production was expressed in millions of tons (Mtons), except for natural gas expressed in billions of cubic meters

Coal-fired power plants

In the model only coal-fired PP fuelled by lignite were considered, because of this

primary energy resource abundance comparatively with the hard-coal. The domestic reserves of lignite are plenty and the mining capabilities of Romania can cover the considered period. The lignite extraction price is 40 $/kW per year, with a constant annual growth rate of 0.5%. Coal-fired PPs are presented as a technology (Lign_PP, Lign_CHP) and the new coal-fired PPs are introduced as separate technology (Lign_PP_new) in the model, the characteristic parameters for these technologies being presented in the following.

TABLE V-5. COAL-FIRED PP CHARACTERISTIC PARAMETERS

Parameter	Lign_PP	Lign_CHP	Lign_PP_new
Plant factor, %	90	90	90
Availability, %	80	75	80
Construction time, [years	-	3	4
Lifetime, years	45	45	45
Capital construction costs, $/kW(e)	1500	1800	1600
O&M fixed costs, $/kW(e)/year	11	20	25
O&M variable costs, $/kW*year/year	3	2	5
Efficiency, %	33	32	39
New capacity addition	historic capacity 7.2 GW(e)	historic capacity 1.7 GW(e)	up to 0.4 GW(e)/year

Gas-fired power plants

A significant part of natural gas consumption is sourced from imports, so beside the domestic reserves we considered in the model the import of natural gas (unlimited, but depending on the international market prices). The domestic gas extraction price is 60 $/kW per year with 0.5% annual constant growth; the import gas price is 242 $/kW per year, with 0.5% annual constant growth. In the model have been considered gas-fired PPs and gas-fired PPs with CC (combined cycle), producing only electricity and both electricity and heat. Gas-fired PPs are presented in the model as a technology (Gas_PP, Gas_CC, Gas_CHP, Gas_CC_CHP), the characteristic parameters being presented in the following.

TABLE V-6. GAS-FIRED PP CHARACTERISTIC PARAMETERS

Parameter	Gas_PP	Gas_CC	Gas_CHP	Gas_CC_CHP
Plant factor, %	95	95	95	95
Availability, %	80	80	80	80
Construction time, years	3	3	4	4
Lifetime, years	40	40	40	40
Capital construction costs, $/kW(e)	1000	1050	1300	1400
O&M fixed costs, $/kW(e)/year	17	17	18	20
O&M variable costs, $/kW*year /year	2	2	2	2
Efficiency, %	37.5	55	37	54
New capacity addition	historical capacity 4 GW(e)	0.400 GW(e)/year	historical capacity 2.5 GW(e)	0.400 GW(e)/year

Hydro power plants

As it was mentioned before, the hydro energy potential is very high in Romania: 40 TWh per year, out of which 6 TWh are for small hydro PP on internal rivers (capacity under 10 MW). The bonds on this potential are due to technology limitations, economic efficiency and environmental restrictions. Hydro PPs are presented as a technology (Hydro_PP, Hydro1_PP) in the model, first one representing hydro PPs on internal rivers and the second one hydro PP on the Danube River, including the great dam from Iron-Gates. The characteristic parameters for these technologies are presented in the following.

TABLE V-7. HYDRO PP CHARACTERISTIC PARAMETERS

Parameter	Hydro_PP	Hydro1_PP
Plant factor, %	100	100
Availability, %	60 to 70	45 to 60
Construction time, years	3	5
Lifetime, years	100	100
Capital construction costs, $/kW(e)	500	4000
O&M fixed costs, $/kW(e)/year	15	15
O&M variable costs, $/kW*year /year	5	10
Efficiency, %	100	100
Storage capacity, GWh	99	3443
New capacity addition	historical capacity ~ 2.800 GW(e)	historical capacity ~ 3.800 GW(e) up to 0.150 GW(e)/year

Wind and solar power plants

The renewable energy sources (REN) in Romania have a high potential, with wind energy potential of 23 TWh per year and solar photovoltaic energy potential of 1.2 TWh per year, this potential being not fully used because of the technological limitations, economic efficiency and environmental restrictions. Wind farms and solar power stations are presented as a technology (Wind_farm, Sol_PV) in the model. The characteristic parameters for these technologies are presented in the following.

TABLE V-8. WIND FARM AND SOLAR PP CHARACTERISTIC PARAMETERS

Parameter	Wind_farm	Solar_PV
Plant factor, %	30	50
Availability, %	30	15
Construction time, years	2	2
Lifetime, years	25	20
Capital construction costs, $/kW(e)	1200	5000
O&M fixed costs, $/kW(e)/year	10	15
O&M variable costs, $/kW*year /year	2	5
Efficiency, %	100	100
New capacity addition	historical capacity 0.988 GW(e) up to 9.0 GW(e) total installed capacity	-

In the model, REN has been taken into account according to Romanian Energy Strategy 2007-2020, National Renewable Energy Action Plan, EU Directive 2001/77/EC (amended by 2006/108/EC) and Directive 2009/28/EC, respectively. The considered share of RES in the total electricity consumption was: 33% till 2014, 35% in 2015-2019, 38% in 2020-2050.

V-3.3. Nuclear generation and nuclear fuel cycle – assumptions and input data

The nuclear energy development in Romania has been modelled according to the national strategic documents in force [V-2 and V-3]; the three scenarios have been considered as follows:
a) Base case: four PHWR, CANDU type (the two existing operational CANDU reactors, 700 MW(e) each, and another two CANDU reactors, 720 MW(e) each, with projected in-service after 2020) located in the SE of Romania, at Cernavoda.
b) Pessimistic case: two PHWR, CANDU type (the two existing CANDU reactors from Cernavoda NPP, operating since December 1996 and 2007, respectively).
c) Optimistic case: four PHWR, CANDU type (as in the base case scenario) and another NPP, advanced PWR (1000 MW(e)) or advanced PHWR (Enhanced CANDU, 720 MW(e)), the projected in-service being after 2035.

Uranium resources and processing

There is no Uranium market in Romania. Uranium National Company (CNU) is the one and only supplier of UO_2 powder used as raw material for nuclear fuel fabrication. The active exploitation of U ore is Suceava Subsidiary, Crucea and Botusana mines, located in NE of Romania. Figure V-4 presents the domestic Uranium resources* situation by considering both OECD/NEA Red Books references and former officials' declarations in media news [V-17].

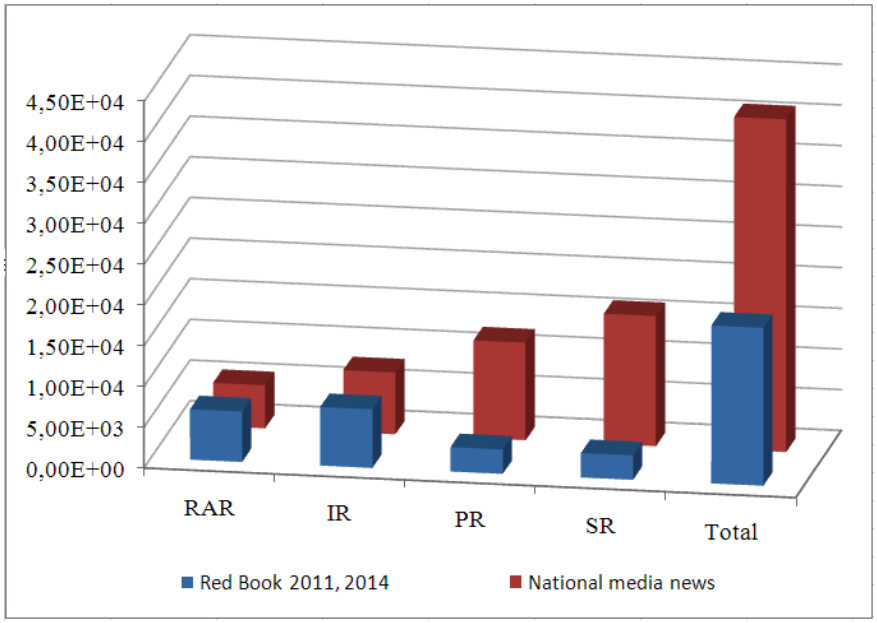

FIG. V-4. Situation of Romanian domestic uranium resources, tons [V-1 5÷ V-17]:
** RAR = Reasonably assured resources; IR = Inferred resources;*
PR = Prognosticated resources; SR = Speculative resources.

The uranium domestic reserves considered in the present study were according to OECD/NEA Red Books, [V-15 and V-16]. In the model, the considered uranium resources

price was as follows: 130$/kg U for 6700 tons of U – identified resources (RAR+IR); 260 $/kgU for 12700 tons of U – identified and undiscovered (PR+SR) resources.

The processing and refining of U technical concentrates are performed in Feldioara Subsidiary of CNU. UO_2 Powder Plant Feldioara (qualified by AECL Canada as CANDU UO_2 fuel supplier) has two modules: R Plant for U preparation (milling/ concentration) with 300 t U(U_3O_8) per year nominal capacity and E Plant for U refining /conversion with 300 t U(UO_2) per year nominal capacity, respectively [V-18 and V-19]. U conversion from ore to technical concentrates was defined as a technology in the model and considered price was 10 $/kgU.

Nuclear fuel

The nuclear fuel for existing CANDU reactors is fabricated by the Nuclear Fuel Plant Pitesti (qualified by AECL Canada as CANDU fuel supplier), with a production capacity of 110 tons of U per year, see [V-18 and V-19]. The U fuel fabrication was defined as a technology in the model and the considered price was 100 $/kg U.

The same path was used also for the fuel needed in CANDU Units 3&4 operation. It must be mentioned here that, according to the Romanian Energy Strategy 2007-2020 and updates, the Romanian Mining Industry Strategy [V-20] and the declaration of the Nuclear Fuel Plant manager in business media news [V-21], in order to sustain CANDU 3&4 operation, both UO_2 Powder Plant Feldioara and Nuclear Fuel Plant Pitesti must upgrade their facilities. New modules must be built in Feldioara for U ore milling/ processing (TG Plant) and U concentrates refining/conversion (YC Plant) to replace the existing R and E modules. Nuclear Fuel Plant Pitesti is able to upgrade the fabrication lines in order to increase the annual production from 10800 bundles/year (actual fuel production) to 20000 fuel bundles/year (assuring the fuel for all the 4 CANDU reactors), the estimated investment costs being 1-2 million euros for each 5000 bundles production upgrade, see [V-21 and V-22].

The nuclear fuel cycle (NFC) in Romania is once-through open fuel cycle, characteristic for CANDU reactors. In the model, for the considered time horizon (2050), we assumed that there are no changes in the option for NFC and also in national legislation regarding the decision to not support the activities for nuclear fuel enrichment and/or reprocessing.

The fresh fuel needed for advanced PWR or PHWR operation is assured by imports of already fabricated fuel assemblies. In the model, the fresh fuel import for advanced PWR or HWR was modelled as technology (LWR_fuel_imp, HWR_fuel_imp), the price being considered according to international databases and studies [V-23 ÷ V-28], namely: 275 $/kg HM for advanced PWR and 180$/kg HM for advanced HWR.

The SNF discharged from the reactors is cooled down first in the intermediate wet spent fuel bay inside the NPP (5 years for advanced PWR and 6 years for HWRs, respectively), than the cooling period continues with the intermediate dry storage (50 years for CANDU and advanced HWR reactors), the corresponding facilities being built on NPPs site. For the advanced PWR, spent fuel is considered that will be stored in a regional storage facility, with corresponding associated costs, as a service.

In the model, both wet and dry intermediate storages were modelled, as separate facilities for each defined type of reactor technology, as follows: CANDU12_cooling, CANDU12_storage, CANDU34_cooling, CANDU34_storage, PWR_cooling, PWR_storage, HWR_cooling and HWR_storage, respectively.

Intermediate wet storage costs are generally assumed to be a small part of the reactor capital and operations costs; typically, are not added as separate costs. The storage costs are based on commercial cost data associated with the reactor construction and operation. In the present study, waste storage costs (1.4 €/MWh) were included in variable costs of NPP; meantime decommissioning costs (0.6 €/MWh) were included in fixed costs of NPP.

However, for intermediate dry storage the investment, O&M and storage costs have been considered according to international references [V-23, V-26, V-29 and V-30].

In order to allow discharged spent fuel moving from the reactor core to the intermediate storage, two technologies have been considered, namely: fc_(reactor type) – take the spent fuel discharged from the reactor core and move it into the SNF bay (inside the NPP building) for cooling; tr_(reactor type) – take the spent fuel from the SNF bay and move it into the SNF intermediate dry storage installation (on the NPP site). Movement of the SNF is done by using the *consa* constraint, for the two before mentioned technologies being considered the *dummy level* as output (just for technical reasons in the program operation).

TABLE V-9. TECHNICAL AND ECONOMICAL PARAMETERS OF THE REACTORS

Parameter	CANDU U1&U2	CANDU U3&U4	Advanced PWR	Advanced HWR
Thermal capacity, GW(th)	2.121	2.182	3.030	2.182
Electric capacity, GW(e)	0.700	0.720	1.000	0.720
Plant factor, %	95	95	90	90
Availability, %	100	100	100	100
Efficiency, %	33	33	33	33
Average burn-up, MWday/tHM	7500	7500	45000	7500
Operation cycle length[1)], days	346.75	346.75	328.5	328.5
Fuel residence time[2)], days	346.75	346.75	1314	328.5
First load[3)], tHM	98.071	100.873	88.485	95.564
Annual reload[4)], tHM	98.071	100.873	22.121	95.564
Construction time, years	-	5	6	6
Lifetime, years	40	40	60	60
Investment costs, $/kW(e)	500	4500	3400	3000
O&M fixed costs, $/kW(e)/year	8	8	10	10
O&M variable costs, $/kW*year /year	55	55	50	55
Fresh fuel costs, $/kgU	100	100	275	180
Investment costs, $/kg HM SNF interim dry storage at reactor	250	250	-	250
O&M fixed costs, $/kgHM/year SNF interim dry storage at reactor	4.2	4.2	-	4.2
SNF dry storage – service, $/kgHM	-	-	300	-

[1)] 365 days x 95% = 346.75 days; 365days x 90% = 328.5 days
[2)] 346.75 days x 1 refuel. batch = 346.75 days; 328.5 days x 4 refuel. batches = 1314 days; 328.5 days x 1 refuel. batch = 328.5 days
[3)] 700 MW x 346.75 days/33%/7500 MWday/tHM = 98.071 tHM (as example of calculation)
[4)] 365 days x 98.071 tHM x 95%/346.75 days = 98.071 tHM (as example of calculation)

V-3.4. Codes and methods used

In order to perform the Romanian Energy system modelling, IAEA's MESSAGE code [V-33] has been used. MESSAGE software was designed for setting up models of energy systems and to perform the optimization of the modelled energy system. MESSAGE methodology is based on optimization of the objective function addressing specific set of constraints. The value of the objective function helps the users to choose the best solution according to the specified criteria.

The energy system modelling using MESSAGE includes specification of input data such as the parameters of electricity generation, technical and economical characteristics for alternative sources of energy considered in the energy system, user-defined constraints such as limits on produced resources, new investments, fuel availability and trade, environmental regulations and market penetration rates for new technologies, waste accumulation etc. MESSAGE allows modelling of all steps in the energy flows from supply to demand, which is generally referred to as energy chain, the steps being called levels.

In order to characterize a component of the energy system, two approaches can be used, as follows: modelling the energy system component as technology (production/operation of national existing facilities is given by specific technical and economical characteristics) or as *service* (the user can purchase it on domestic or international market; no need to specify detailed technical or economical characteristics of the component, just the costs of purchase).

The user describes a technology in MESSAGE by characteristics related to the technology activity (material balance of raw materials and end product, variable O&M costs) and capacity (operating life time, construction time, capital construction costs, fixed O&M costs, already existing capacities); bonds on activity and capacity can be also defined by the user.

The user describes a service in MESSAGE by given minimum input data, namely the material balance of raw materials and end product, and the service associated cost.

V-4. PRESENTATION AND ANALYSIS OF THE RESULTS

As it was mentioned in the previous section, three scenarios of electricity demand evolution have been taken into account for the considered time horizon. In the following, only the results obtained for the NESA electricity demand scenario will be presented, corresponding comments on the results for the other two considered scenarios being included.

For each electricity demand evolution scenario, various discount rate values (drate = 5%, 8% and 10%, respectively) were considered and separate runs were performed for each case. In the following, the results obtained for 8% annual discount rate will be firstly presented, this value being considered the most appropriate for Romania's conditions and its economic and financial environment.

The interest parameters (and their evolution during the modelling period for the considered time horizon) for our study were, as follows:

- Annual total electric generation growth, both in GW(e)*year and % share/year;
- Annual total installed capacity growth, both in GW(e) and % share;
- Annual nuclear electric generation growth, in GW(e)*year;
- Nuclear new installed capacities, in GW(e);
- Investments in new NPPs, in billion US$;
- Cumulative uranium consumption, in kt U;
- Annual uranium requirements, in kt U;
- Annual fuel requirements, in kt HM;
- Annual discharged SNFl (SNF in interim wet storages), in kt HM;

– SNF in interim dry storages, in kt HM.

The results obtained for the considered nuclear generation scenarios are presented and discussed in the following.

V-4.1. Nuclear generation basic scenario

Figures V-5–V-37 present the interest parameters evolution during the period of modelling for the nuclear generation Basic Scenario, in the conditions of NESA scenario for the electricity demand, considered discount rate values and CANDU1&2 different lifetimes.

The annual total electric energy generation and the nuclear electric energy production growth are presented in Figs V-5 – V-13. Figures V-14 – V-22 present the annual total installed capacity growth for the considered Romanian energy mix, new installed nuclear capacity and the corresponding investment evolution. Figures V-23 – V-28 present the annual U requirements and the corresponding cumulative U consumption, respectively. The fresh fuel requirements are illustrated in Figs V-29–V-31; Figures V-32 – V-34 and V-35 – V-37 present the amount of spent fuel annually discharged from the reactors core and the cumulative volume of spent fuel in interim dry storage, respectively.

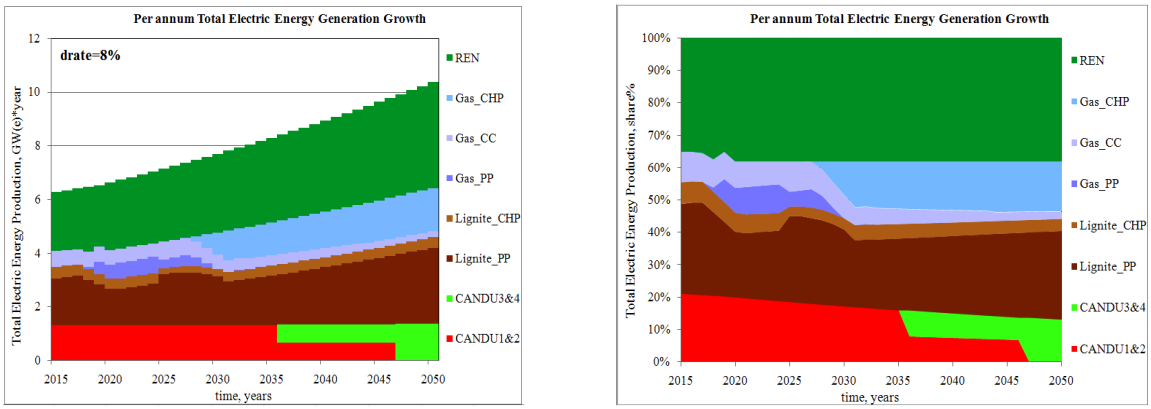

*FIG. V-5. Annual total electric energy generation growth, GW(e)*year, %share NESA - basic scenario, 8% discount rate, 40 years lifetime for CANDU 1&2.*

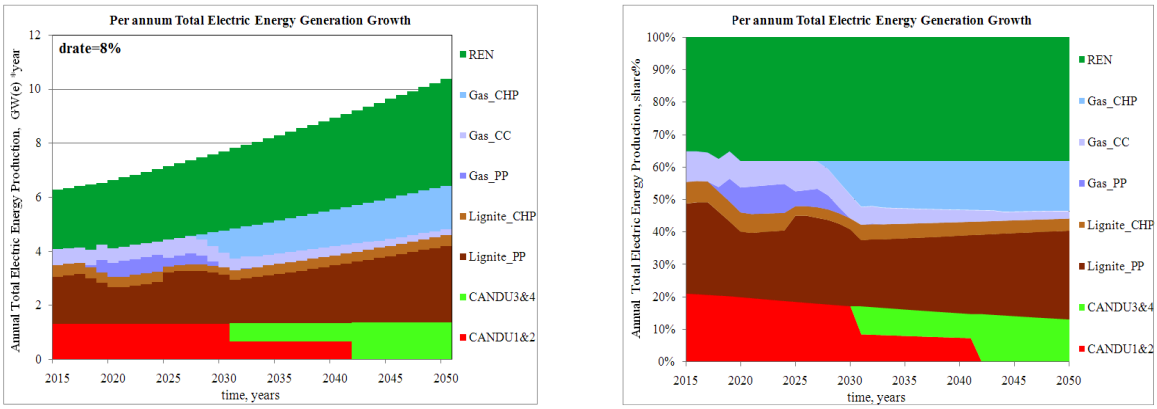

*FIG. V-6. Annual total electric energy generation growth, GW(e)*year, %share NESA - basic scenario, 8% discount rate, 35 years lifetime for CANDU 1&2.*

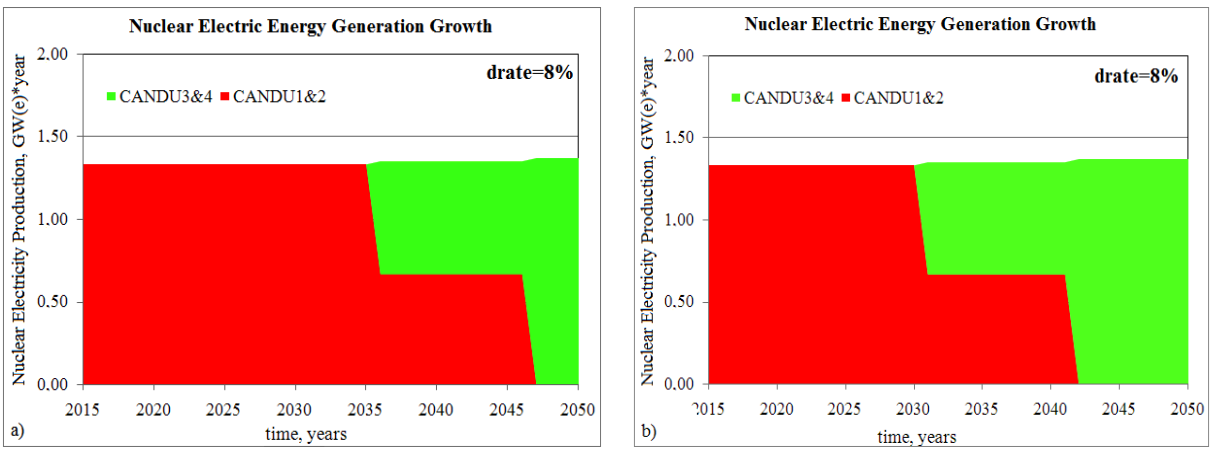

*FIG. V-7. Annual nuclear electricity production, GW(e)*year*
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

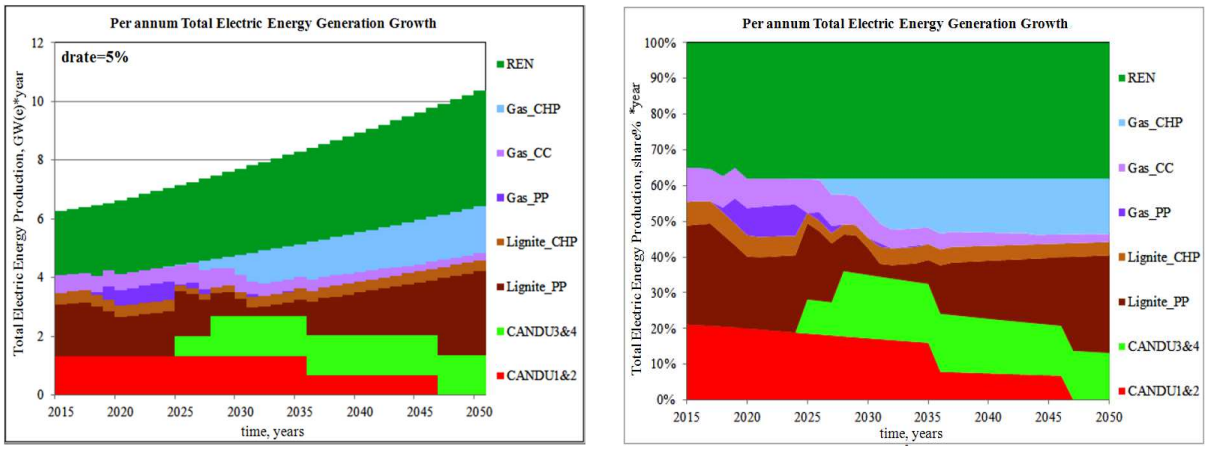

*FIG. V-8. Annual total electric energy generation growth, GW(e)*year, %share*
NESA - basic scenario, 5% discount rate, 40 years lifetime for CANDU 1&2.

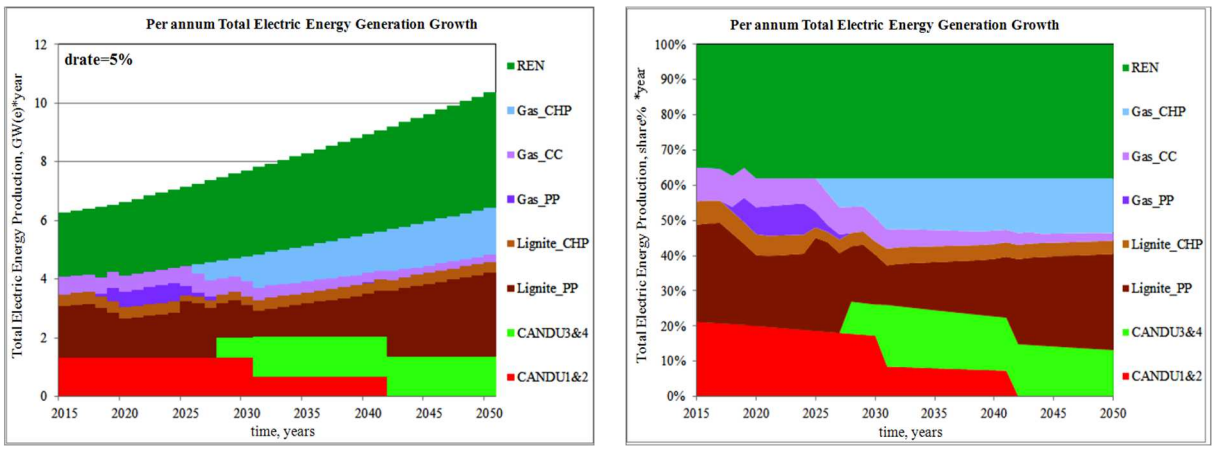

*FIG. V-9. Annual total electric energy generation growth, GW(e)*year, %share*
NESA - basic scenario, 5% discount rate, 35 years lifetime for CANDU 1&2.

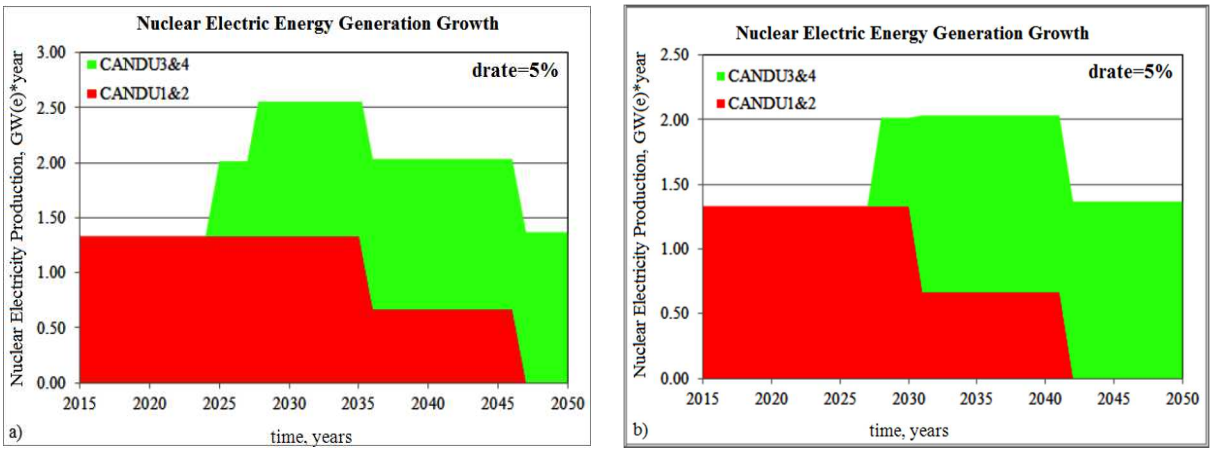

*FIG. V-10. Annual nuclear electricity production, GW(e)*year*
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

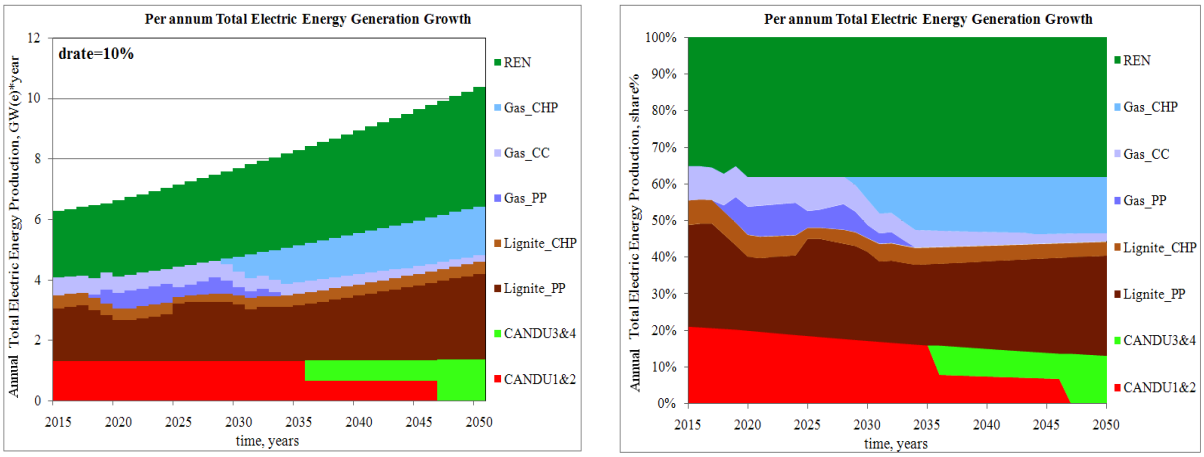

*FIG. V-11. Annual total electric energy generation growth, GW(e)*year, %share*
NESA - basic scenario, 10% discount rate, 40 years lifetime for CANDU 1&2.

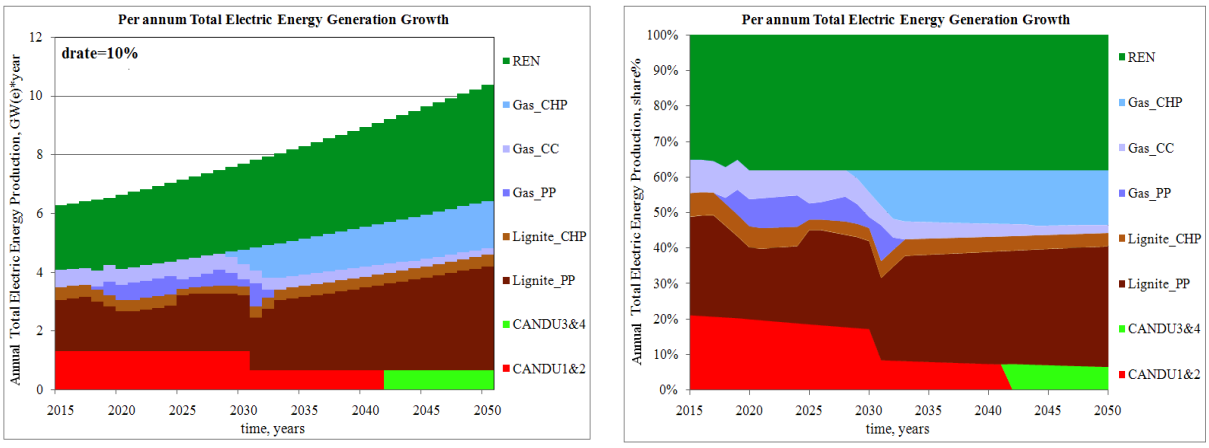

*FIG. V-12. Annual total electric energy generation growth, GW(e)*year, %share*
NESA - basic scenario, 10% discount rate, 35 years lifetime for CANDU 1&2.

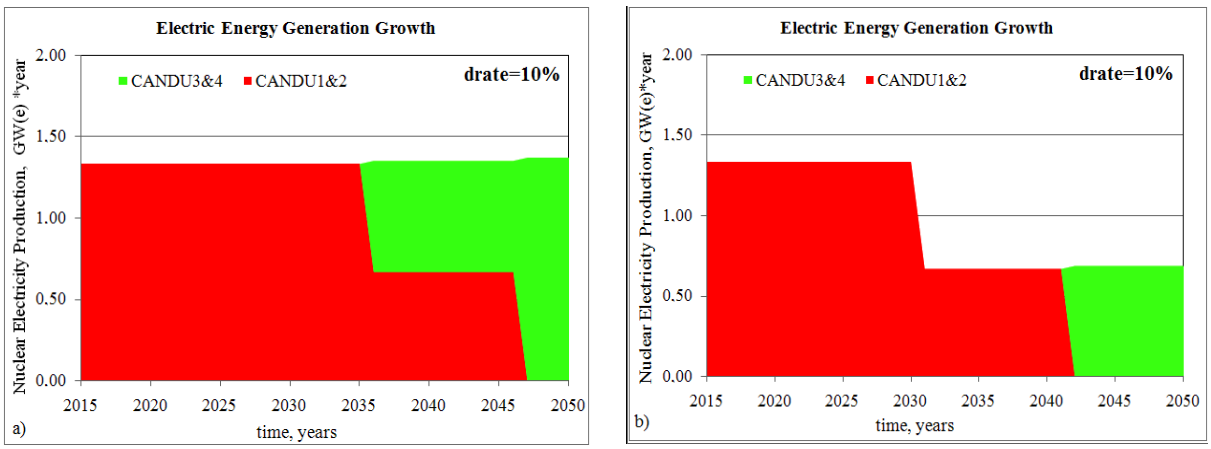

*FIG. V-13. Annual nuclear electricity production, GW(e)*year*
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

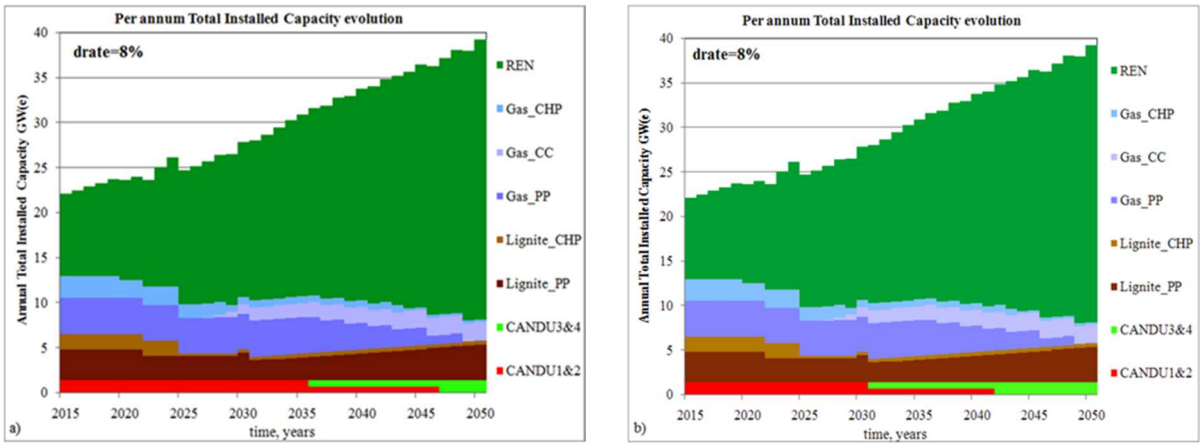

FIG. V-14 Annual total installed capacity growth, GW(e)
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

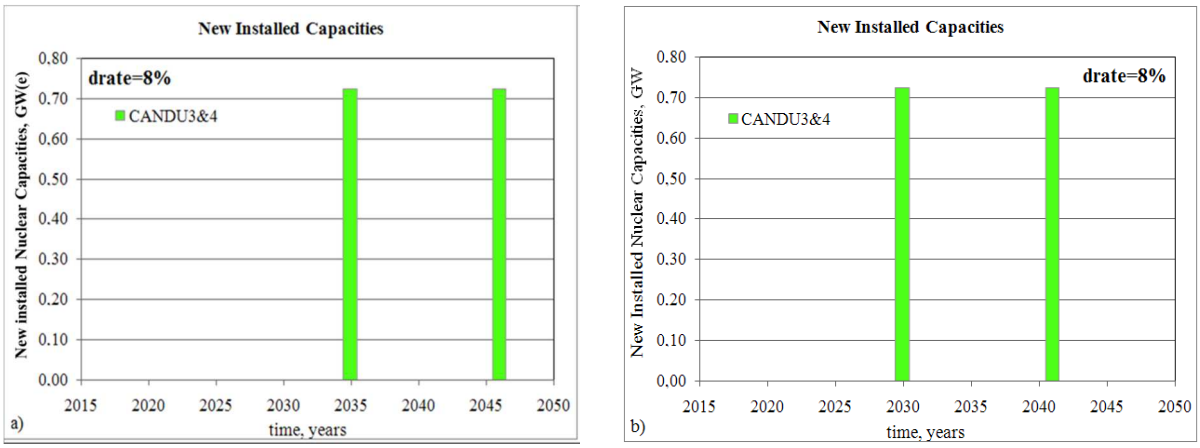

FIG. V-15. New installed nuclear capacities, GW(e)
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

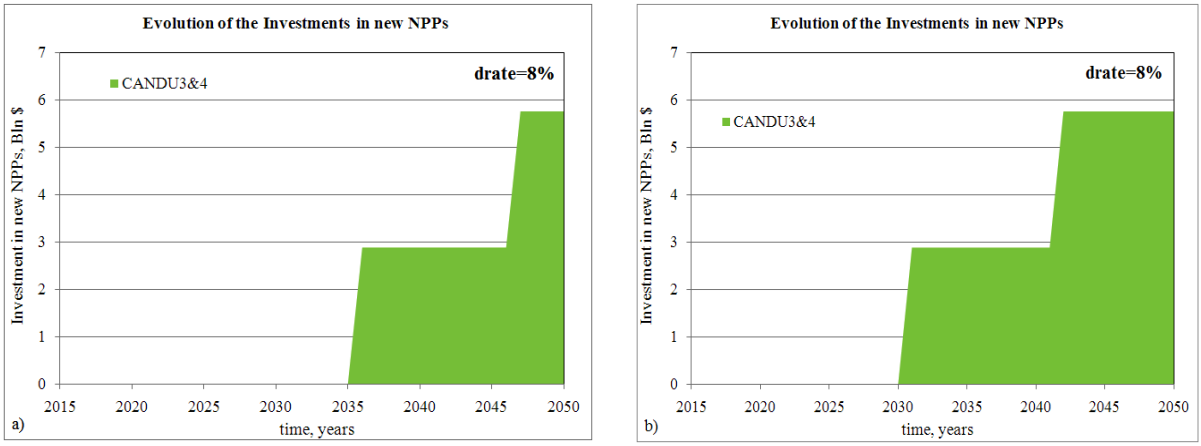

FIG. V-16. Investments in nuclear energy capacities, bln. $
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

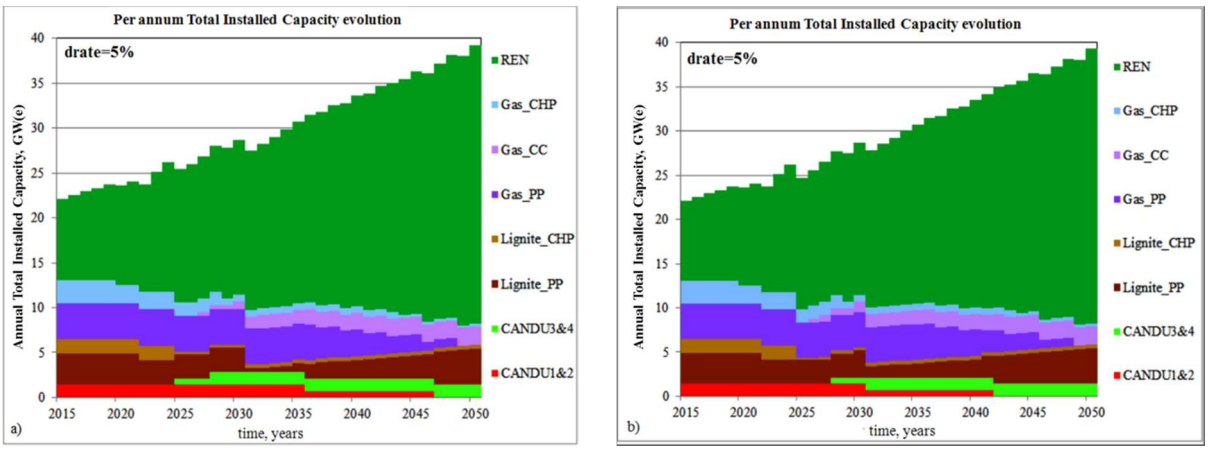

FIG. V-17. Annual total installed capacity growth, GW(e)
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

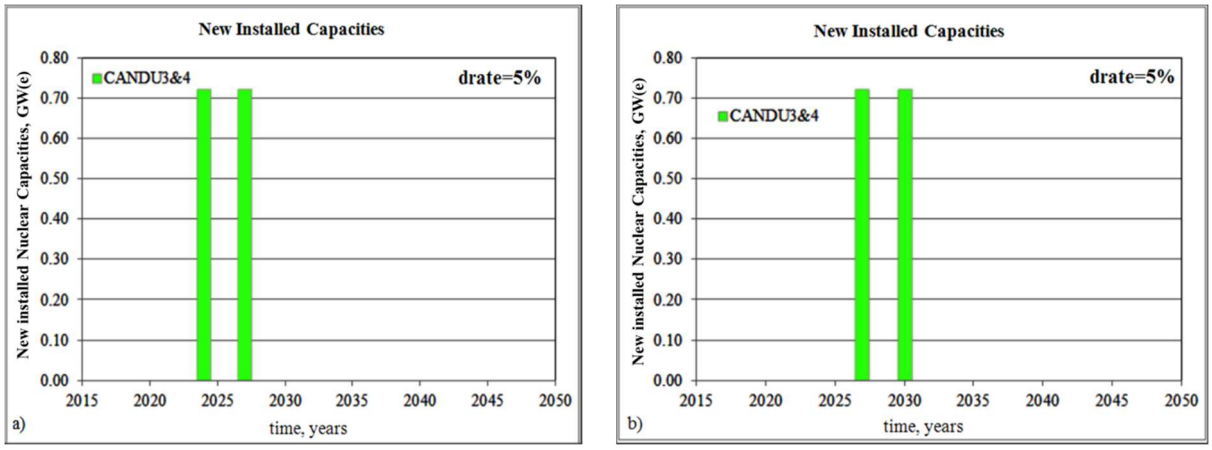

FIG. V-18. New installed nuclear capacities, GW(e)
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

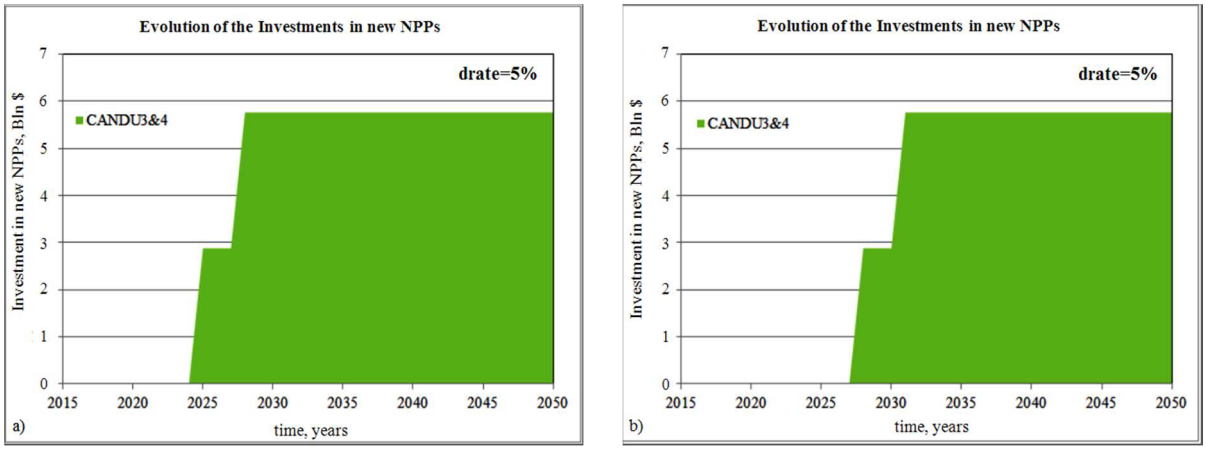

FIG. V-19. Investments in nuclear energy capacities, bln. $
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

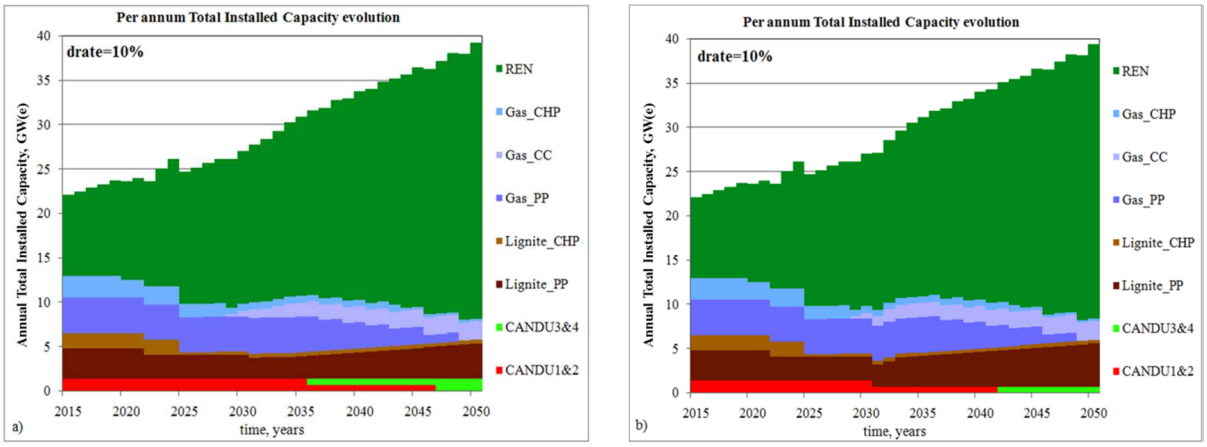

FIG. V-20. Annual total installed capacity growth, GW(e)
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

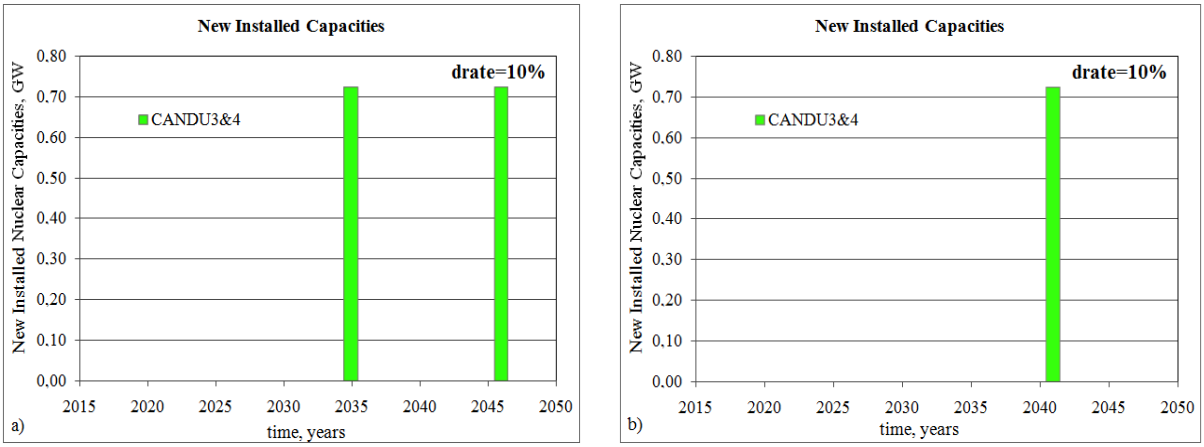

FIG. V-21. New installed nuclear capacities, GW(e)
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

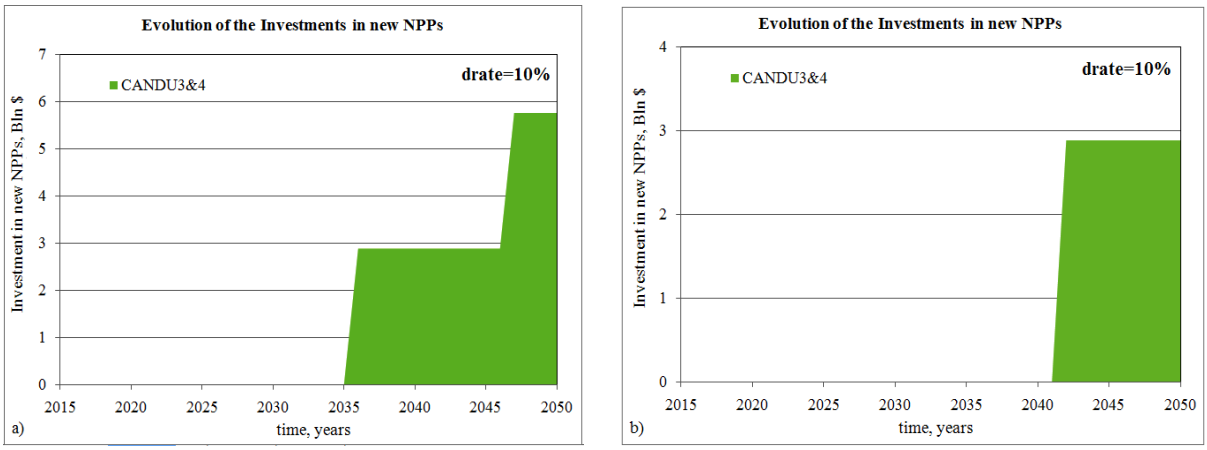

FIG. V-22. Investments in nuclear energy capacities, bln. $
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

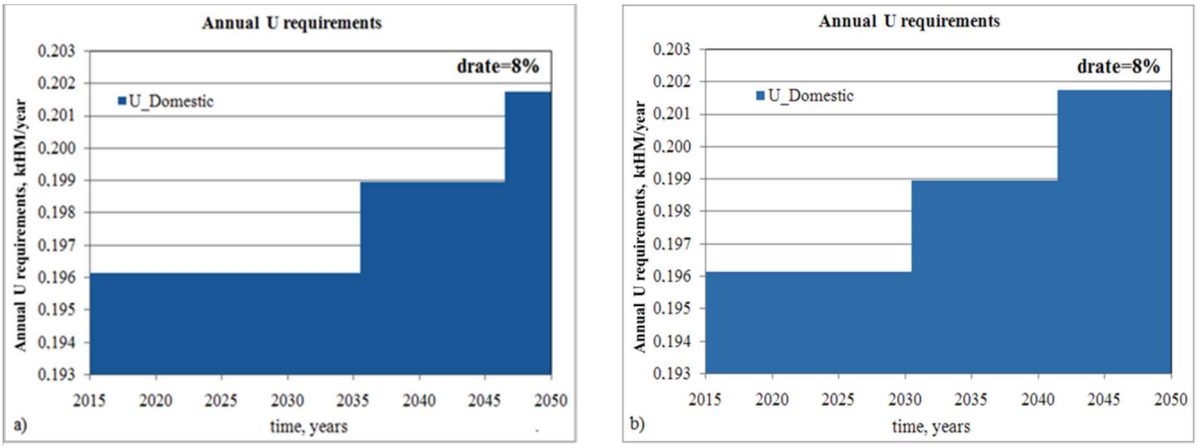

FIG. V-23. Annual U requirements, ktHM /year
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

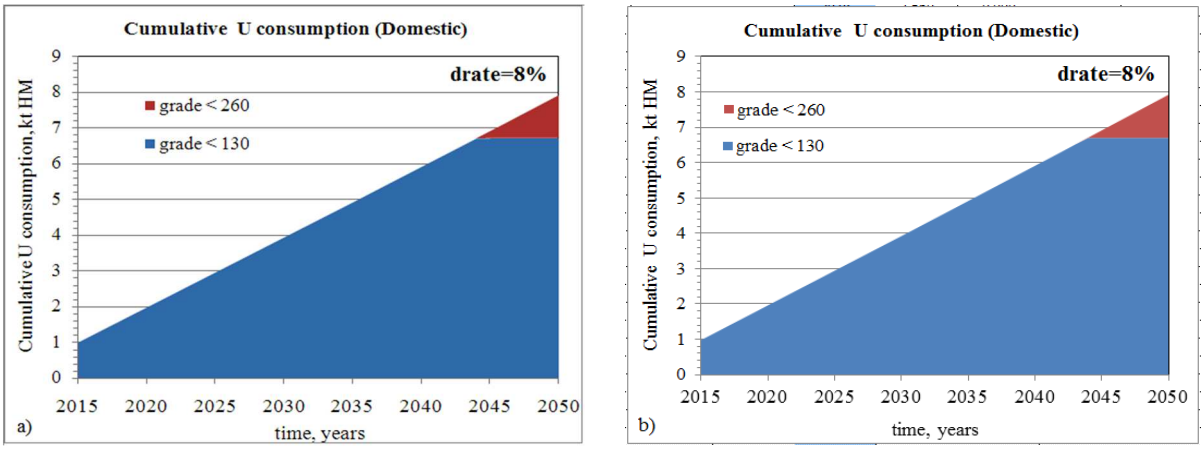

FIG. V-24. Cumulative U consumption, ktHM
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

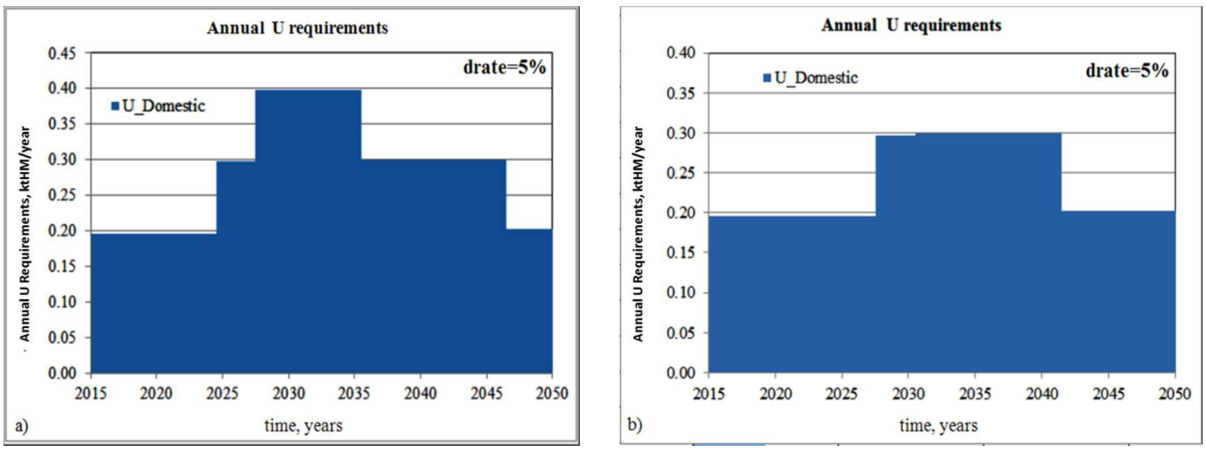

FIG. V-25. Annual U requirements, ktHM/year
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

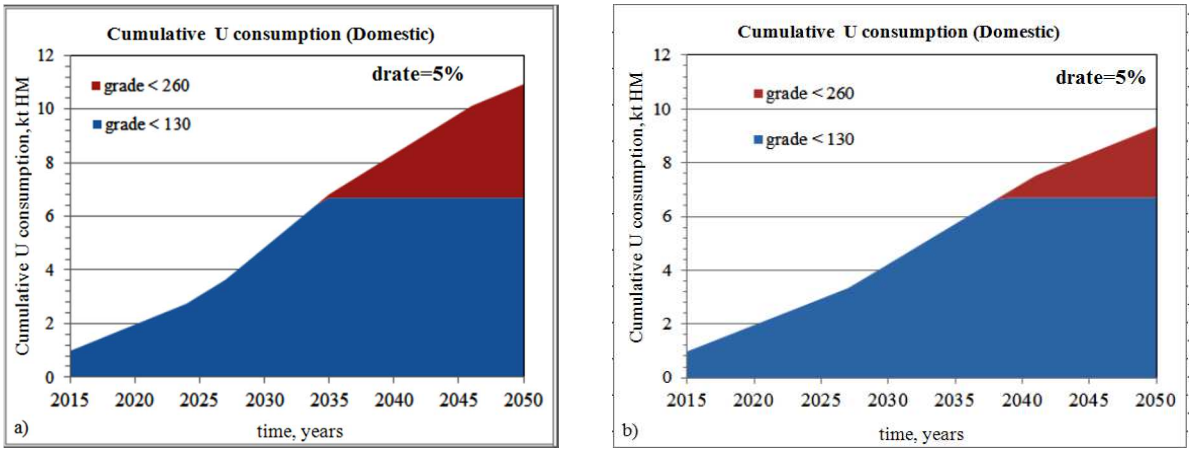

FIG. V-26 Cumulative U consumption, ktHM
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

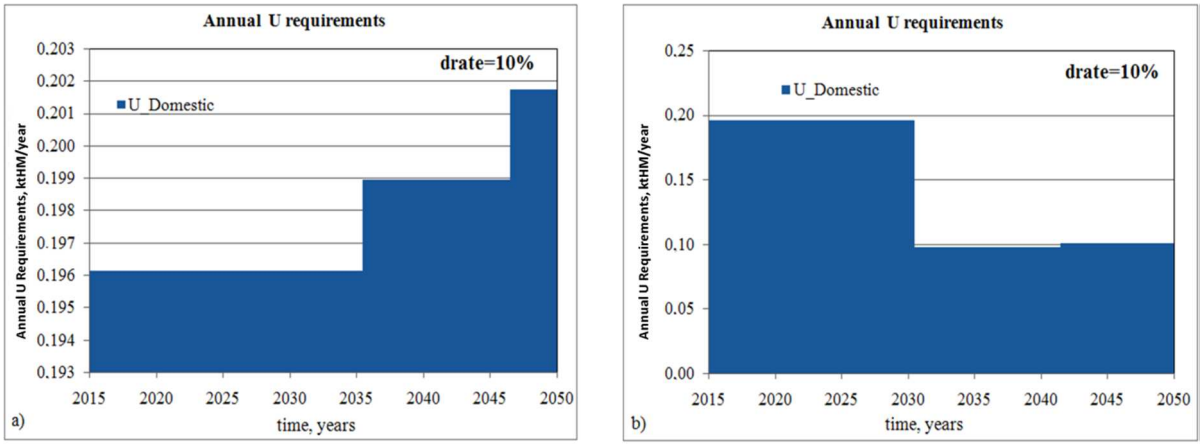

FIG. V-27. Annual U requirements, ktHM /year
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

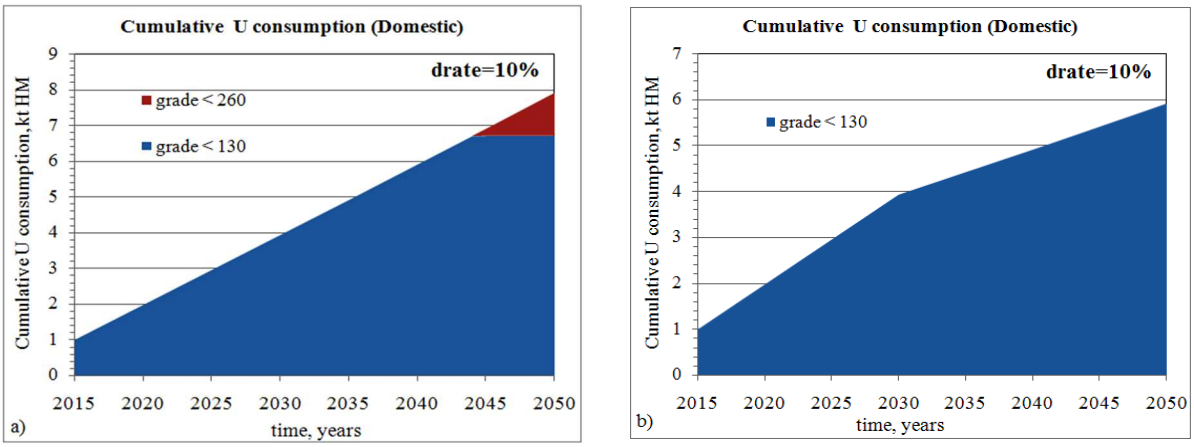

FIG. V-28. Cumulative U consumption, ktHM
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years

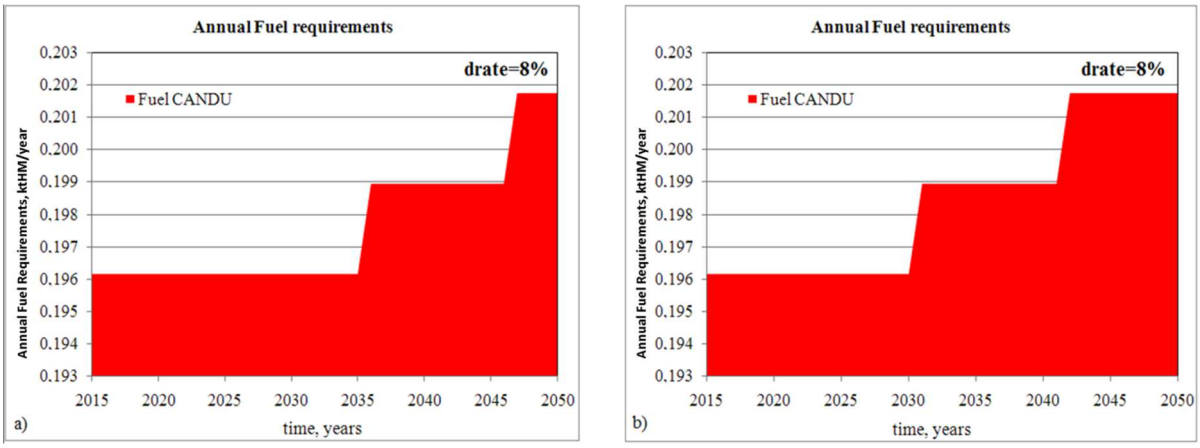

FIG. V-29. Fresh fuel annual requirements, ktHM /year
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

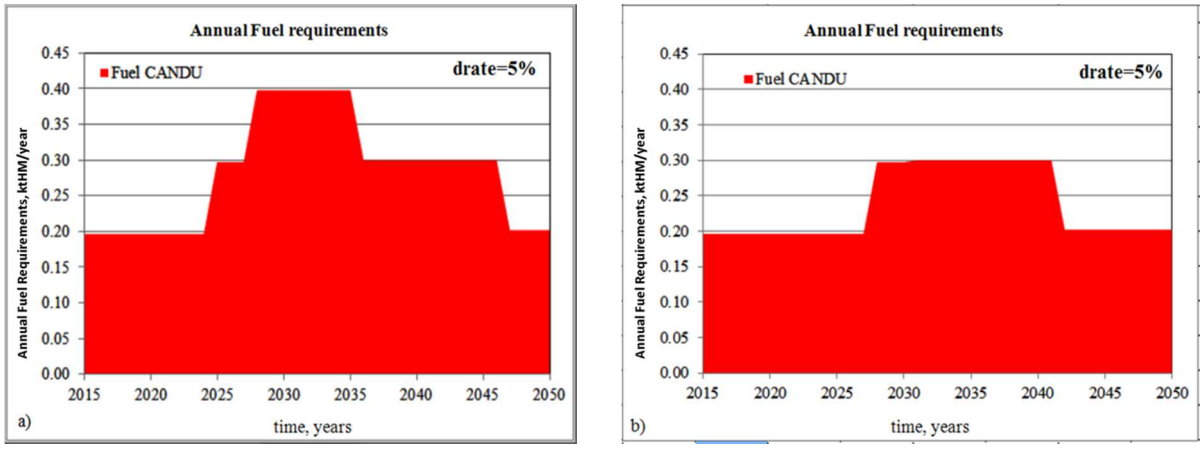

FIG. V-30. Fresh fuel annual requirements, ktHM /year
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

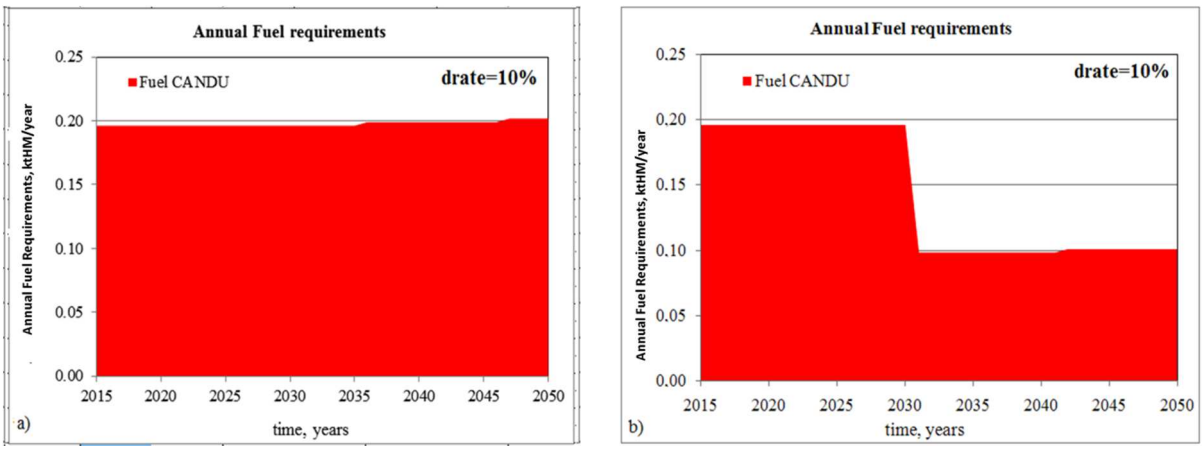

FIG. V-31. Fresh fuel annual requirements, ktHM /year
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

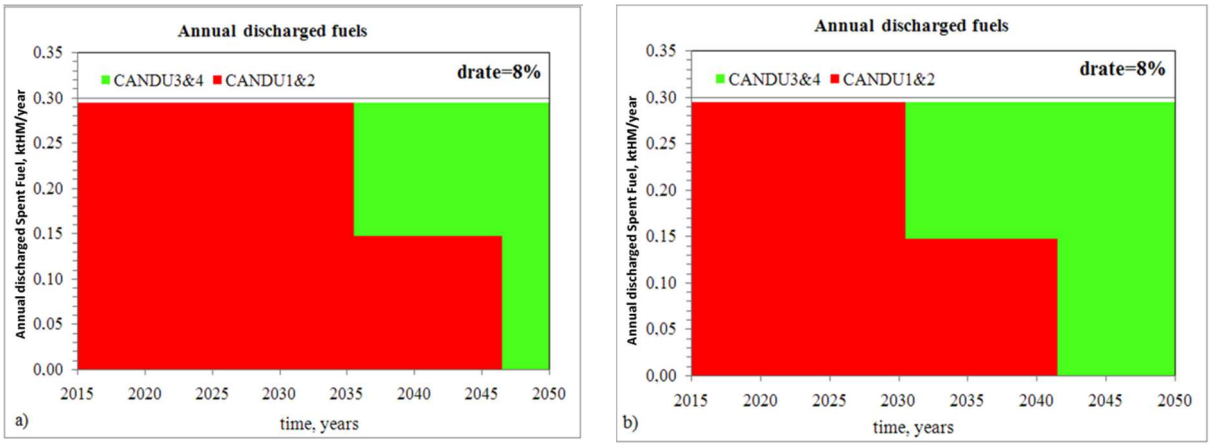

FIG. V-32. Spent fuel discharged from reactor core, ktHM/year
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

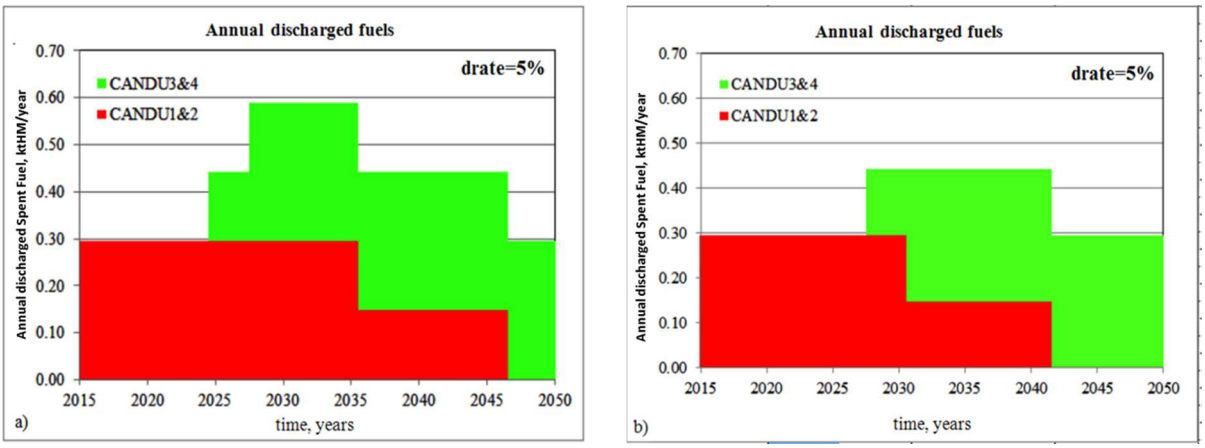

FIG. V-33. Spent fuel discharged from reactor core, ktHM/year
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

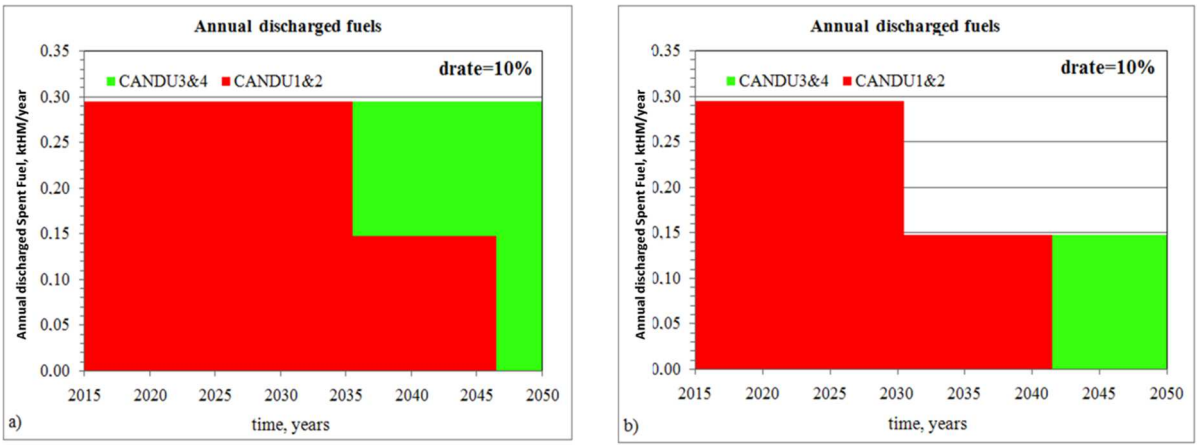

FIG. V-34. Spent fuel discharged from reactor core, ktHM/year
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

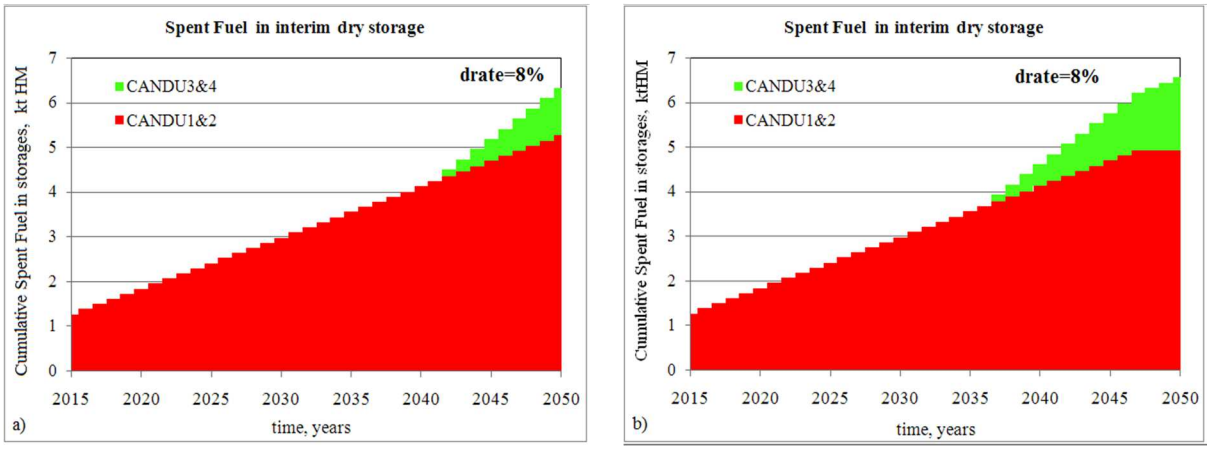

FIG. V-35. Cumulative spent fuel in storages, ktHM
NESA - basic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

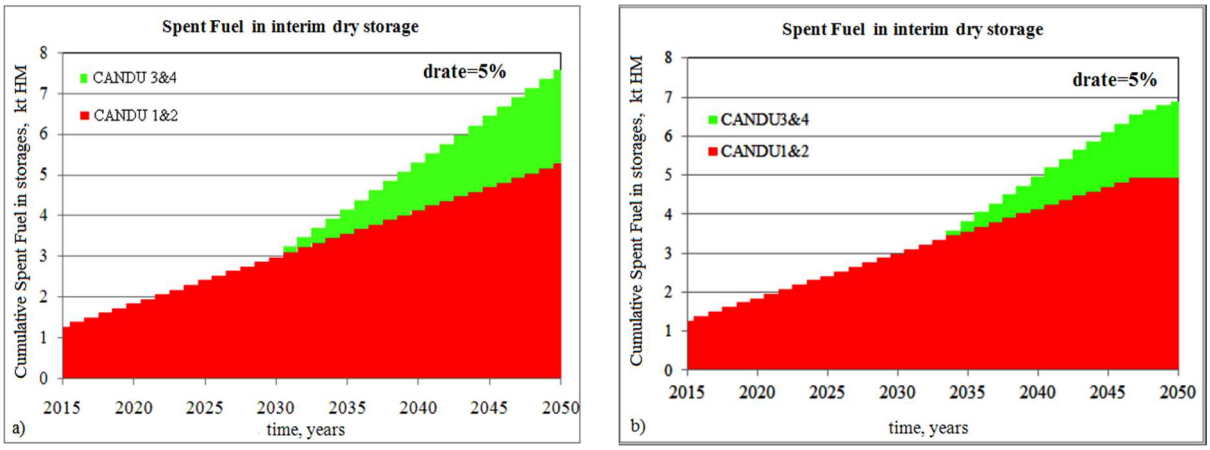

FIG. V-36. Cumulative spent fuel in storages, ktHM
NESA - basic scenario, 5% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

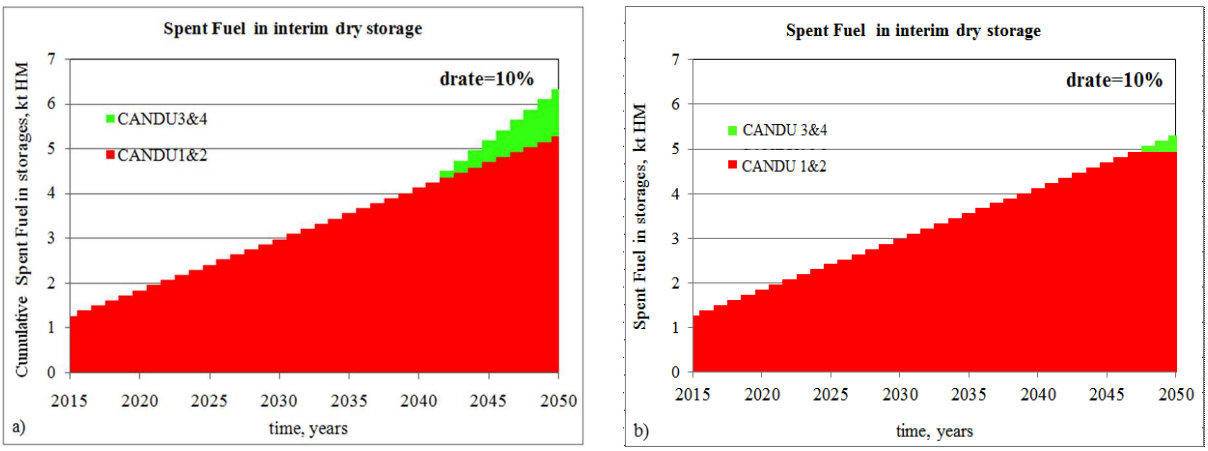

FIG. V-37. Cumulative spent fuel in storages, ktHM
NESA - basic scenario, 10% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

In the case of pessimistic scenarios (Pes1 and Pes2) for the demand evolution, the results are similar and shown that, for all the discount rates considered in the study, both Unit 3 and Unit 4 from Cernavoda NPP are still considered to be built, except for the case of 10% discount rate and short lifetime of CANDU 1&2 when is added only one new CANDU reactor after 2040.

For 8% discount rate, the Unit 3 and 4 will be built in: 2035 and 2046 for 40 years lifetime of CANDU 1&2; 2030 and 2041 for 35 years lifetime of CANDU 1&2. The cumulative U consumption was estimated as follows: Pes1 – 7.9 ktHM and 6.0 ktHM for 40 years and 35 years lifetime of CANDU 1&2, respectively; Pes2 – 7.9 ktHM for both CANDU 1&2 lifetimes. Regarding the cumulative volume of Spent Fuel in storages, for both Pes1 and Pes2 demand evolution scenarios the following amounts were estimated: 40 years lifetime of CANDU 1&2 - 5.26 ktHM SNF from CANDU 1&2 and 1.06 ktHM SNF from CANDU 3&4; 35 years lifetime of CANDU 1&2 - 4.92 ktHM SNF from CANDU 1&2 and 1.63 ktHM SNF from CANDU 3&4.

For 5% discount rate, the Unit3 and 4 will be built in: 2024 and 2027 for 40 years lifetime of CANDU 1&2; 2027 and 2030 for 35 years lifetime of CANDU 1&2. The cumulative U consumption was estimated as follows: Pes1 – 10.93 ktHM and 9.34 ktHM for 40 years and 35 years lifetime of CANDU 1&2, respectively; Pes2 – 9.82 ktHM and 9.34 ktHM for 40 years and 35 years lifetime of CANDU 1&2, respectively. Regarding the cumulative volume of Spent Fuel in storages the following amounts were estimated: 40 years lifetime of CANDU 1&2 - 5.26 ktHM SNF from CANDU 1&2 and 2.31 ktHM SNF from CANDU 3&4 (Pes1) and 5.26 ktHM SNF from CANDU 1&2 and 1.97 ktHM SNF from CANDU 3&4 (Pes2); 35 years lifetime of CANDU 1&2 - 4.92 ktHM SNF from CANDU 1&2 and 1.97 ktHM SNF from CANDU 3&4 (both Pes1 and Pes2).

For 10% discount rate, the new CANDU reactors construction resulted as follows: 40 years lifetime of CANDU 1&2 – 2035 and 2046 for both Pes1 and Pes2 scenarios; 35 years lifetime of CANDU 1&2 – only one new CANDU unit will be built in 2042 (Pes1) or 2041 (Pes2). The cumulative U consumption was estimated to 7.90 ktHM and 5.91 ktHM for 40 years and 35 years lifetime of CANDU 1&2 in both Pes 1 and Pes2 scenarios. Regarding the cumulative volume of Spent Fuel in storages the following amounts were estimated: 40 years lifetime of CANDU 1&2 - 5.26 ktHM SNF from CANDU 1&2 and 1.06 ktHM SNF from CANDU 3&4 (both Pes1 and Pes2); 35 years lifetime of CANDU 1&2 - 4.92 ktHM SNF from CANDU 1&2 and 0.26 ktHM SNF from CANDU 3&4 (Pes1) and 4.92 ktHM SNF from CANDU 1&2 and 0.38 ktHM SNF from CANDU 3&4 (Pes2).

In the Basic Scenario for nuclear energy development and considering a discount rate of 8%, from the present study can be highlighted the following conclusions:

- The annual electric energy produced by the nuclear capacities assures about 1.3 GW(e) by operation of two CANDU reactors (Unit 1&2 till 2030 or 2035, Unit 2&3 till 2041 or 2046 and Unit 3&4 after that); the nuclear energy share in Romanian energy mix decreases from initial 22% to 14% in 2050.
- At the end of 2050, the cumulative consumption of Uranium was estimated to about 8 kt (larger than domestic RAR+IR, about 1.2 ktHM being assured from the prognosticated and speculative resources), the annual Uranium requirements being of 0.2 ktHM. It can be taken into account to use Uranium or Uranium technical concentrates or even Uranium Fresh Fuel from import, if these solutions are sustained by the economical advantages.
- The volume of Spent Fuel in interim dry storage was estimated to 6.33 – 6.55 ktHM, from which about 5 ktHM is SNF produced by the operation of CANDU Unit 1&2.

V-4.2. Nuclear generation optimistic scenario

Figures V-38 – V-70 present the interest parameters evolution during the period of modelling for the nuclear generation optimistic scenario, in the conditions of NESA scenario for the electricity demand, considered discount rate values and CANDU 1&2 different lifetimes. Two options for addition of new advanced PWR/HWR (bound and no bound) have been also taken into account in the following.

The annual total electric energy generation and the nuclear electric energy production growth are presented in Fig. V-38 – V-49. Figures V-50 – V-55 present the new installed nuclear capacity and the corresponding investment evolution. Figures V-56 – V-61 present the annual U requirements and the corresponding cumulative U consumption, respectively. The fresh fuel requirements are illustrated in Fig. V-62 – V-64. Figures V-65 – V-67 and V-68 – V-70 present the amount of spent fuel annually discharged from the reactors core and the cumulative volume of spent fuel in interim dry storage, respectively.

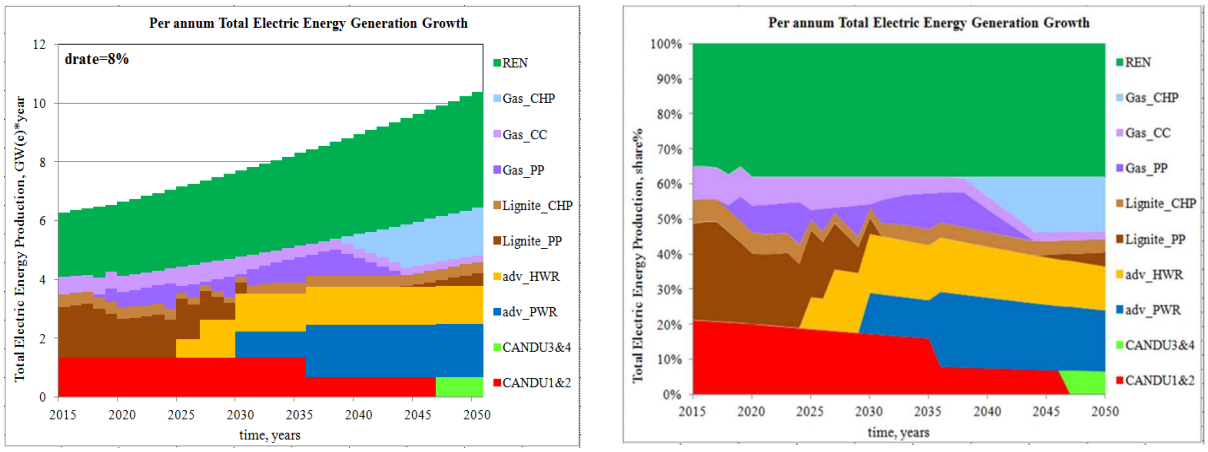

*FIG. V-38. Annual total electric energy generation growth, GW(e)*year, %share NESA - optimistic scenario, 8% discount rate, 40 years lifetime for CANDU 1&2 bound on advanced PWR /HWR addition.*

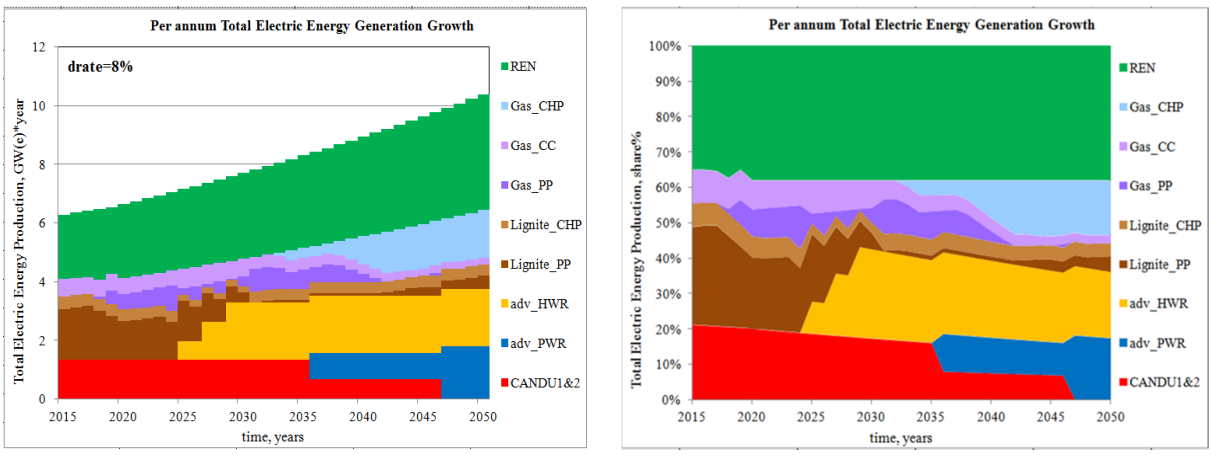

*FIG. V-39. Annual total electric energy generation growth, GW(e)*year, %share NESA - optimistic scenario, 8% discount rate, 40 years lifetime for CANDU 1&2 no bound on advanced PWR /HWR addition.*

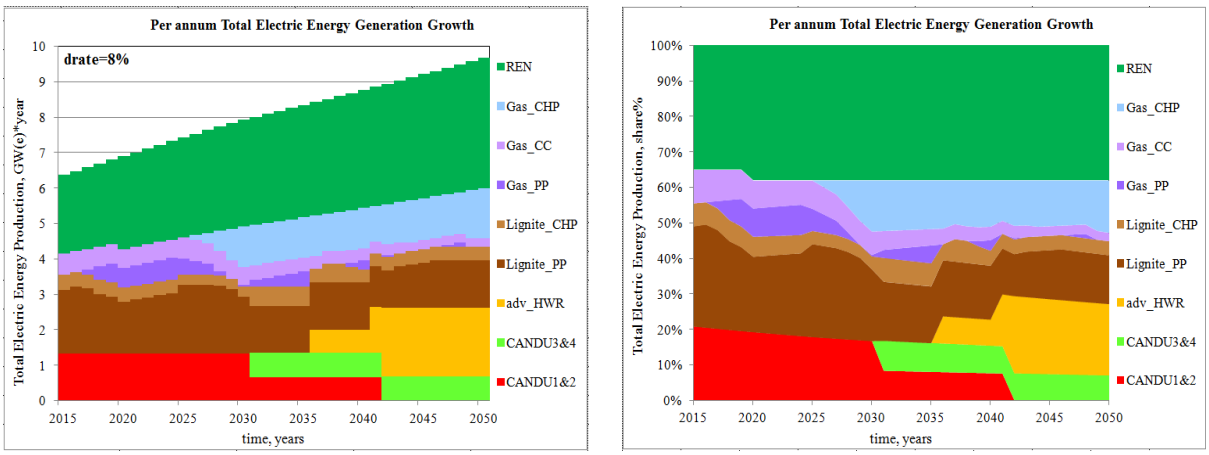

*FIG. V-40. Annual total electric energy generation growth, GW(e)*year, %share NESA - optimistic scenario, 8% discount rate, 35 years lifetime for CANDU 1&2.*

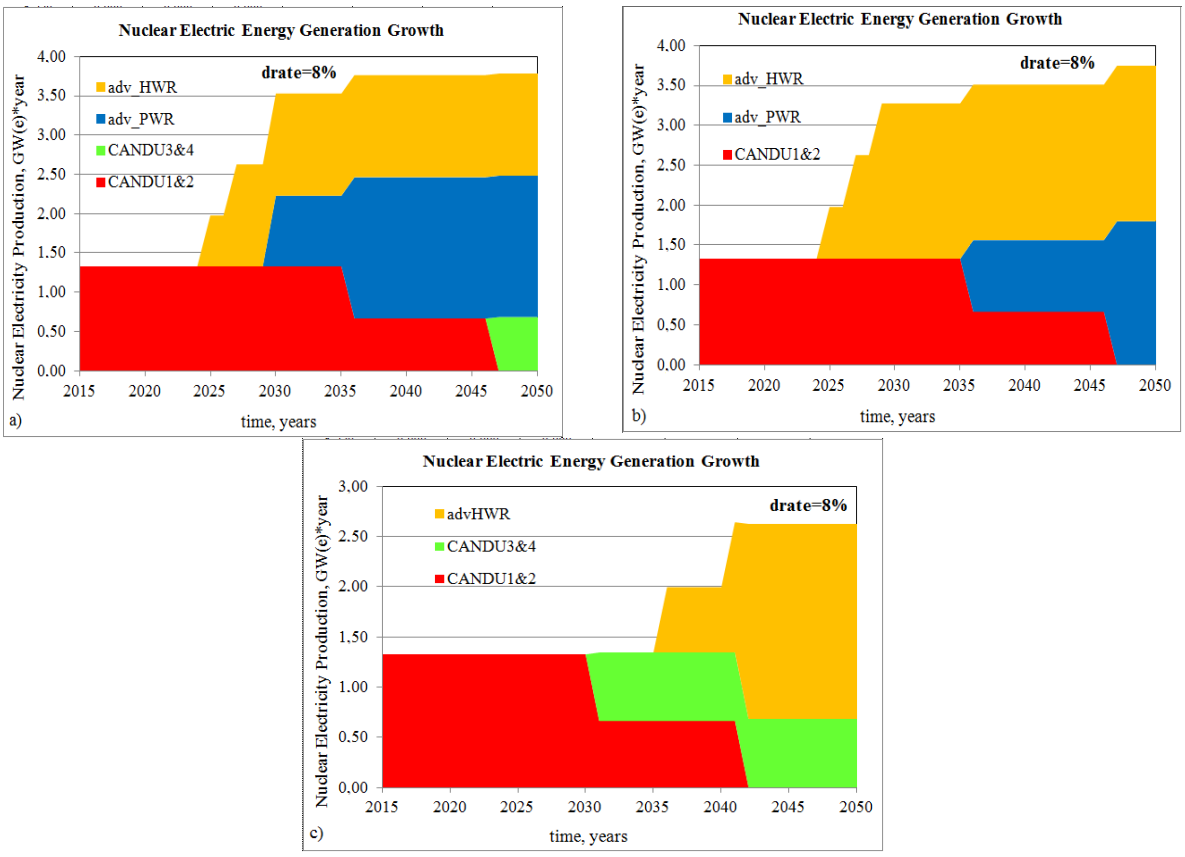

*FIG. V-41. Annual nuclear electricity production, GW(e)*year*
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

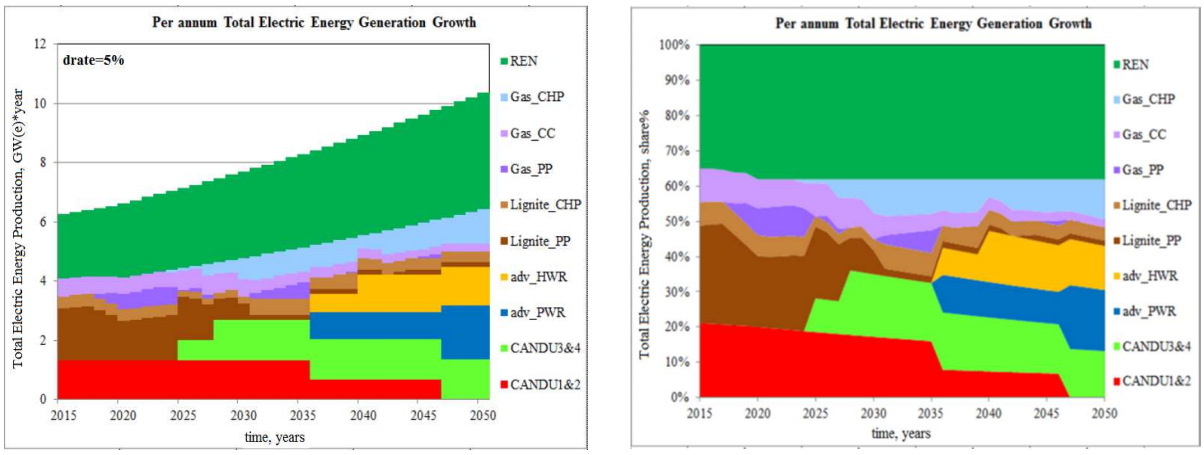

*FIG. V-42. Annual total electric energy generation growth, GW(e)*year, %share*
NESA - optimistic scenario, 5% discount rate, 40 years lifetime for CANDU 1&2 bound on advanced PWR /HWR addition.

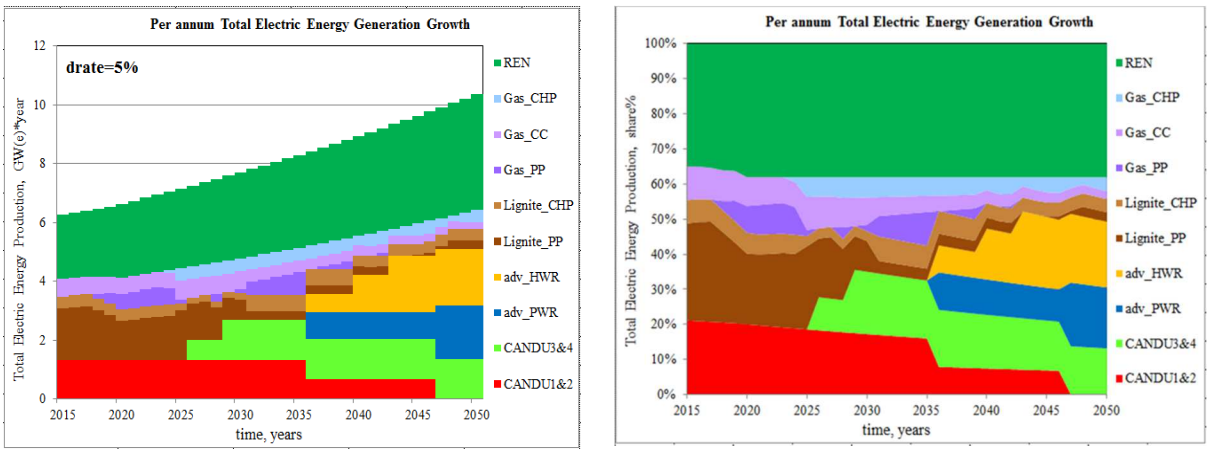

*FIG. V-43. Annual total electric energy generation growth, GW(e)*year, %share NESA - optimistic scenario, 5% discount rate, 40 years lifetime for CANDU 1&2 no bound on advanced PWR /HWR addition.*

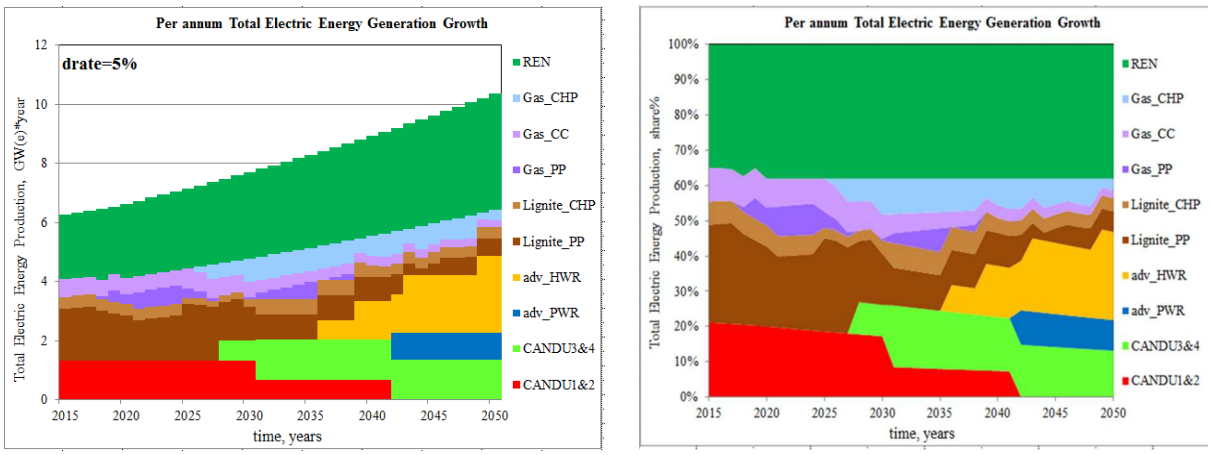

*FIG. V-44. Annual total electric energy generation growth, GW(e)*year, %share NESA - optimistic scenario, 5% discount rate, 35 years lifetime for CANDU 1&2*

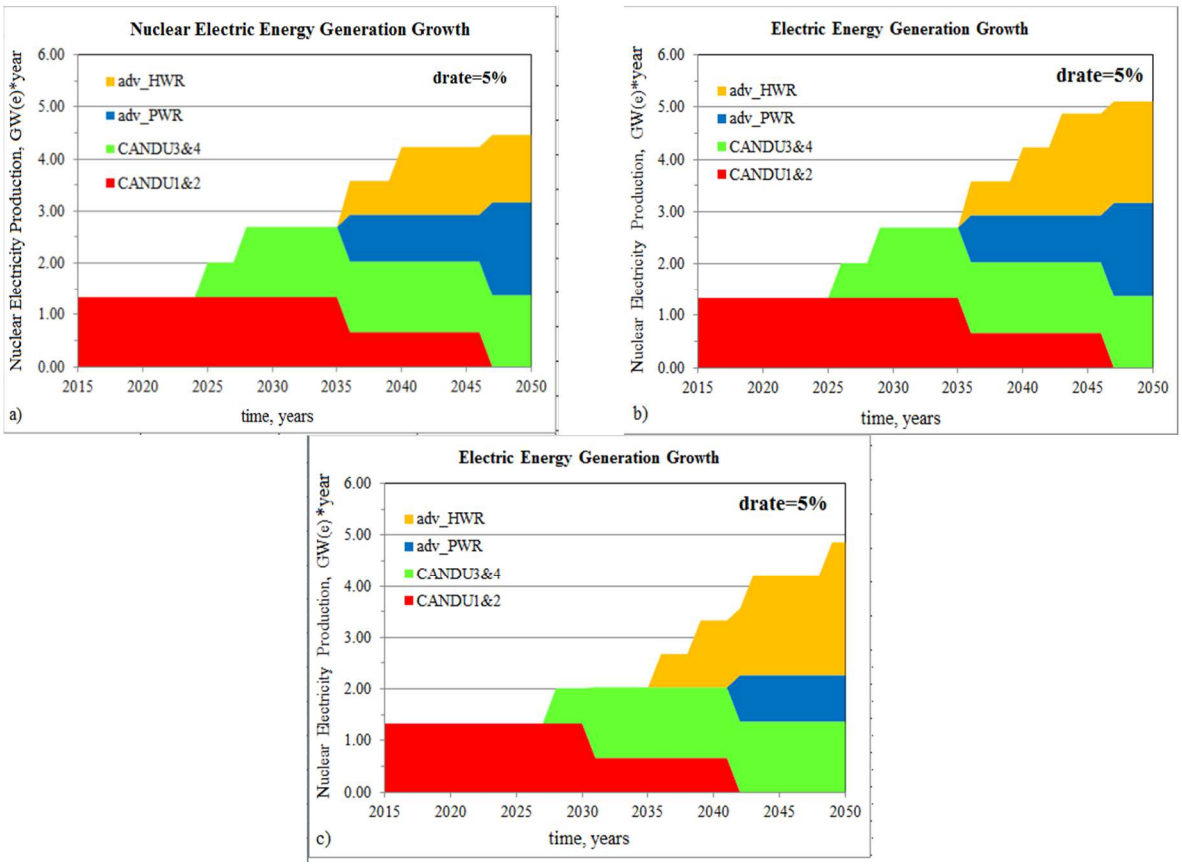

FIG. V-45. Annual nuclear electricity production, GW(e)∗year
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

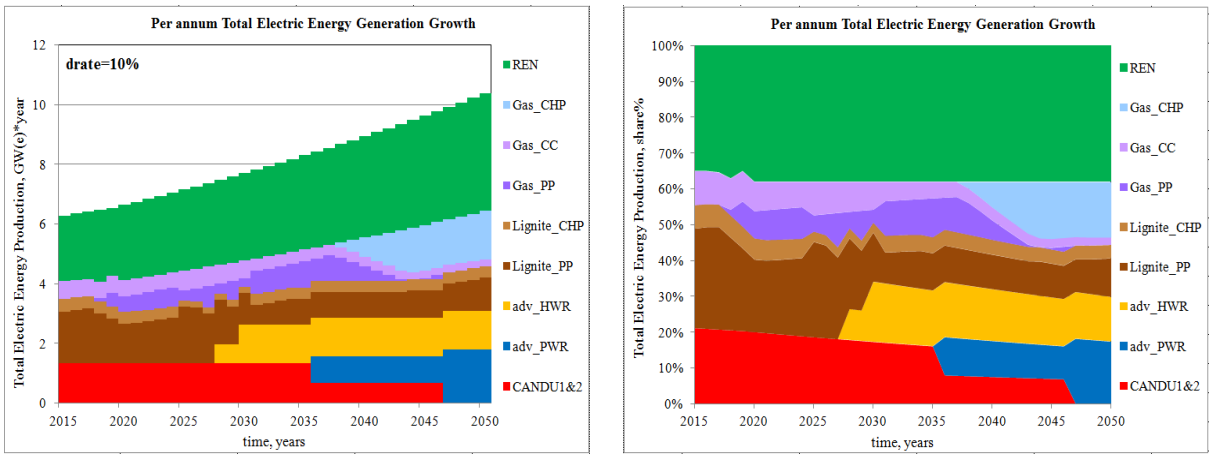

FIG. V-46. Annual total electric energy generation growth, GW(e)∗year, %share
NESA - optimistic scenario, 10% discount rate, 40 years lifetime for CANDU 1&2 bound on advanced PWR /HWR addition.

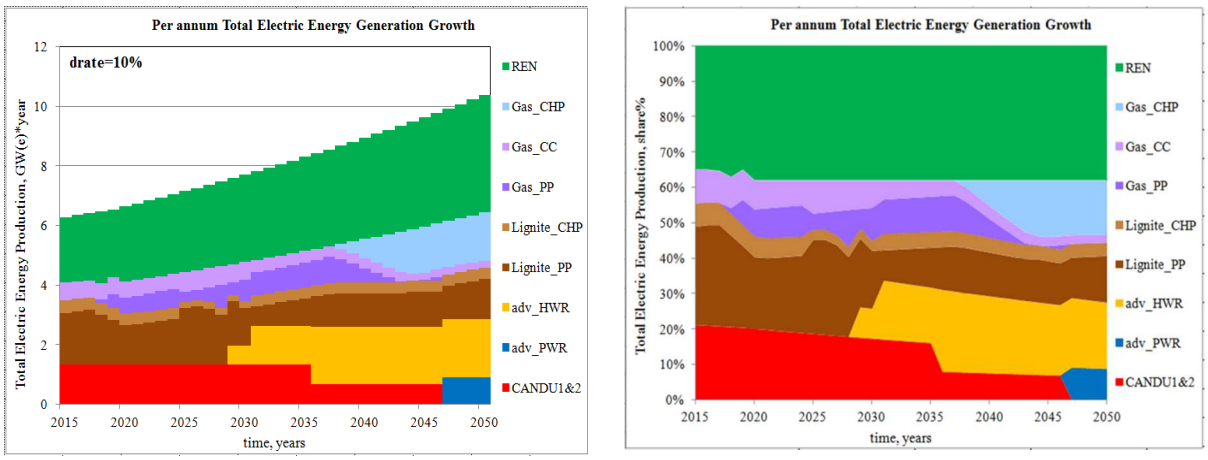

*FIG. V-47. Annual total electric energy generation growth, GW(e)*year, %share NESA - optimistic scenario, 10% discount rate, 40 years lifetime for CANDU 1&2 no bound on advanced PWR /HWR addition.*

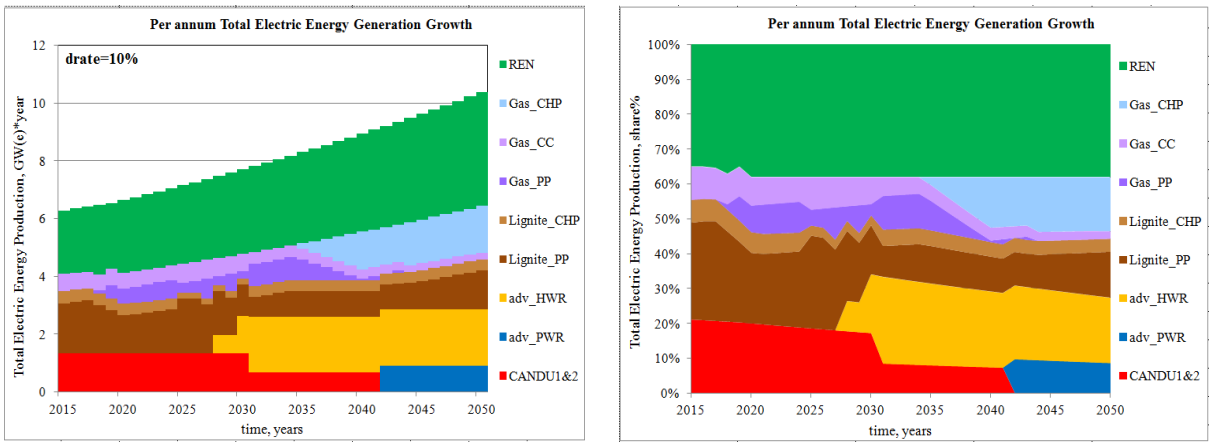

*FIG. V-48. Annual total electric energy generation growth, GW(e)*year, %share NESA - optimistic scenario, 10% discount rate, 35 years lifetime for CANDU 1&2.*

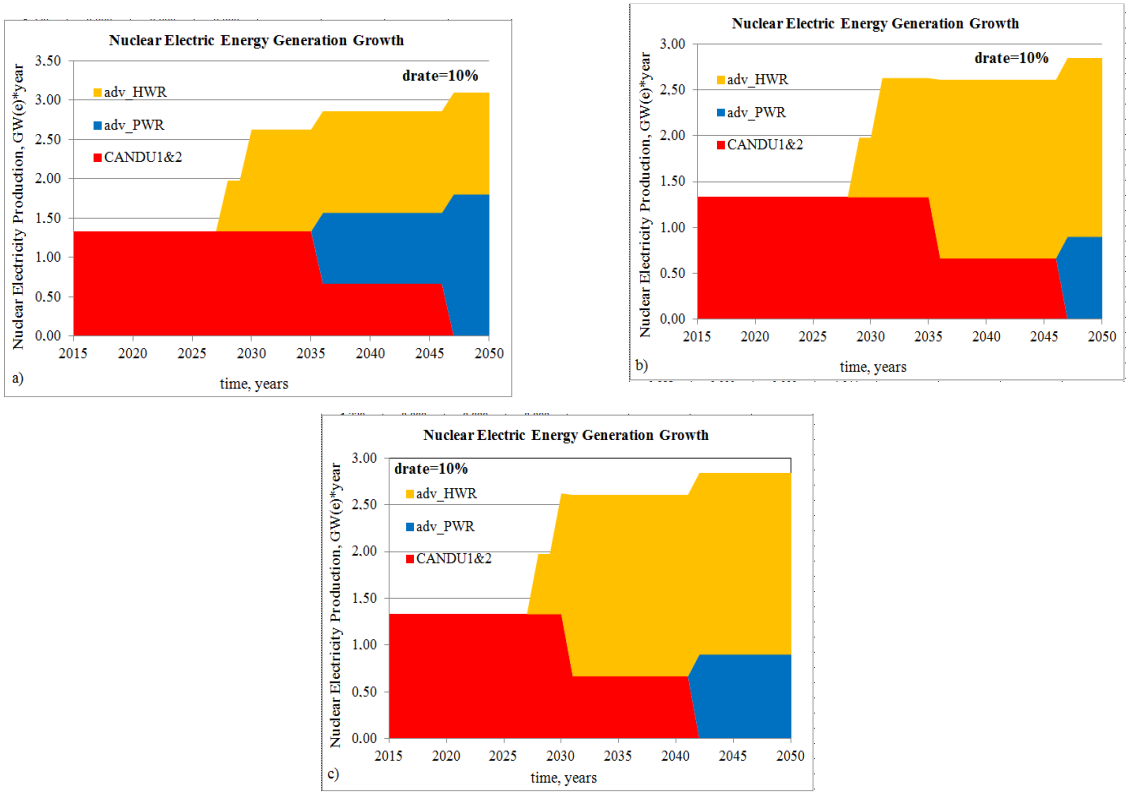

FIG. V-49. Annual nuclear electricity production, GW(e)∗year
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

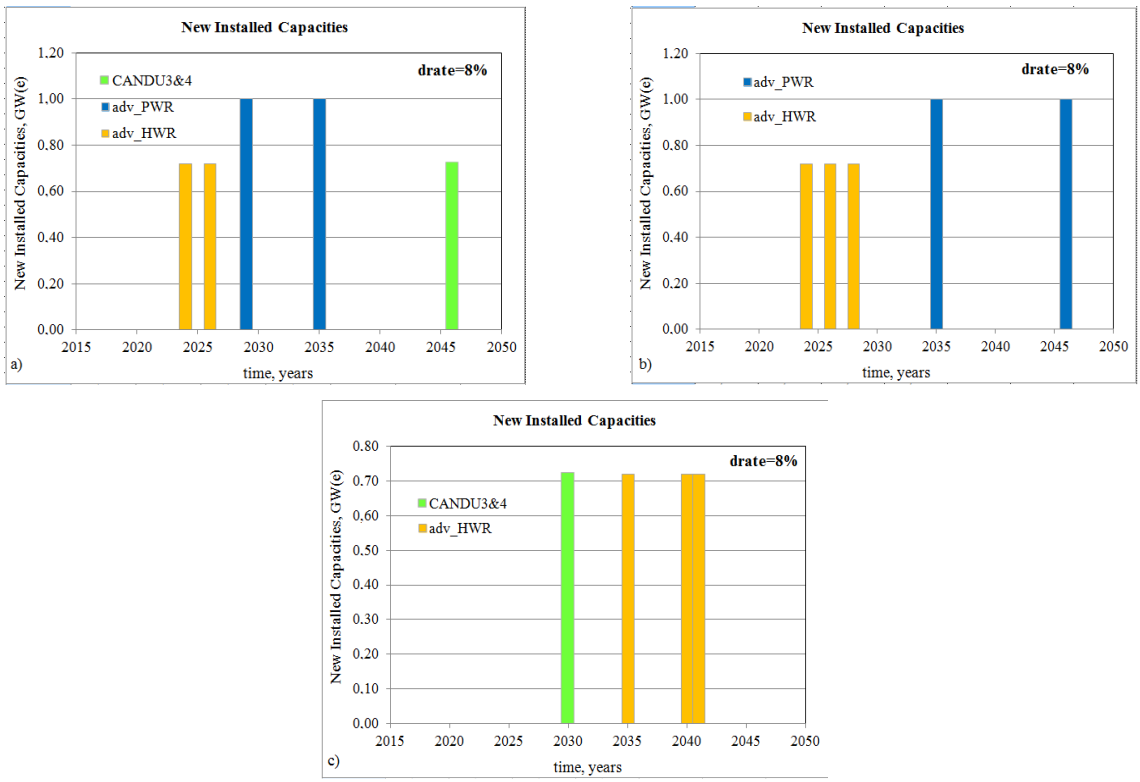

FIG. V-50. New installed nuclear capacities, GW(e)
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

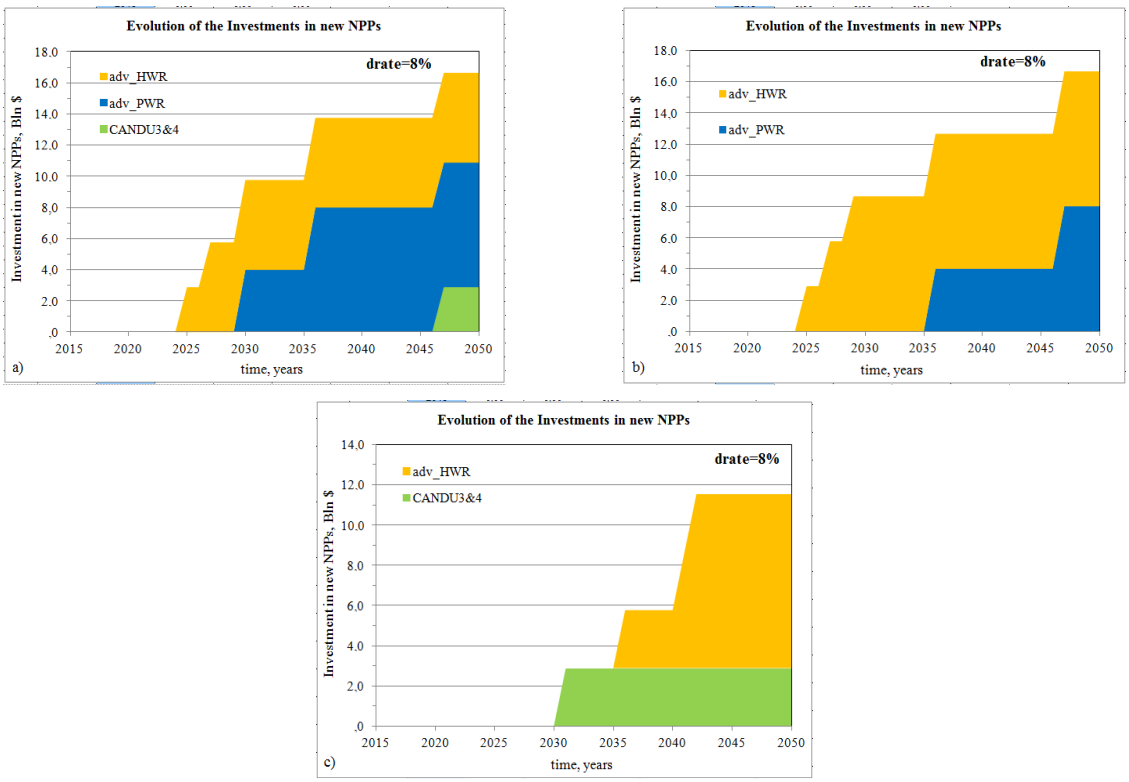

FIG. V-51. Investments in nuclear energy capacities, bln. $
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

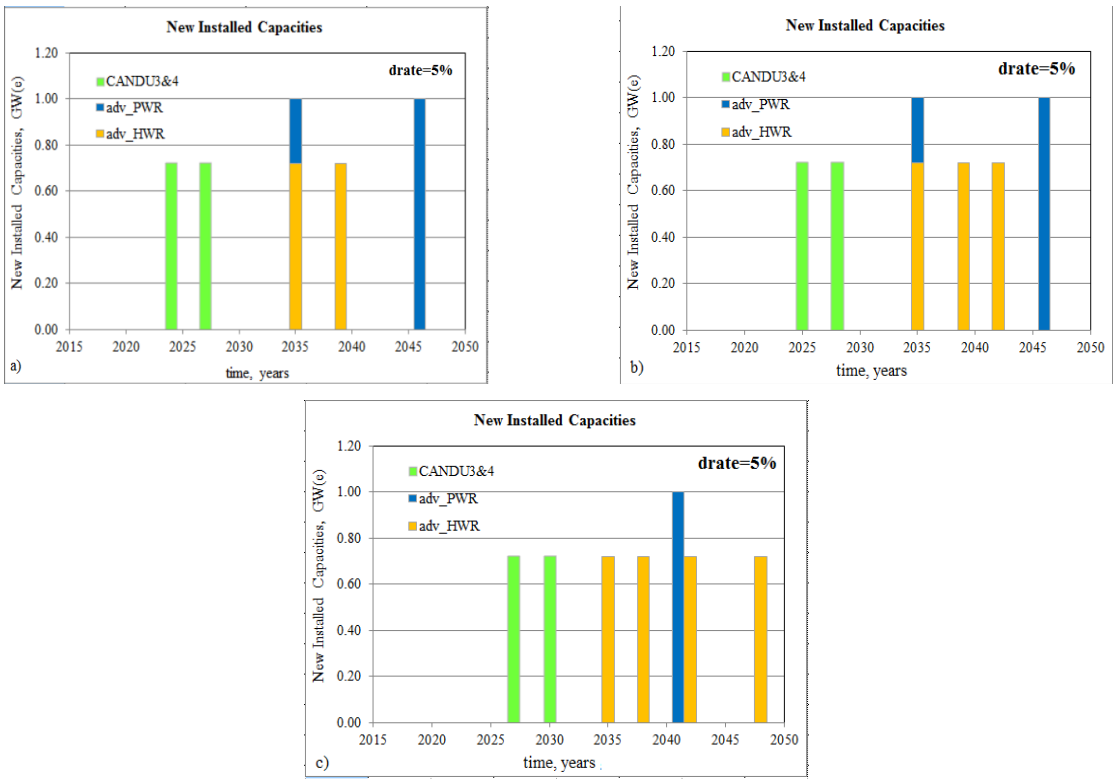

FIG. V-52. New installed nuclear capacities, GW(e)
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

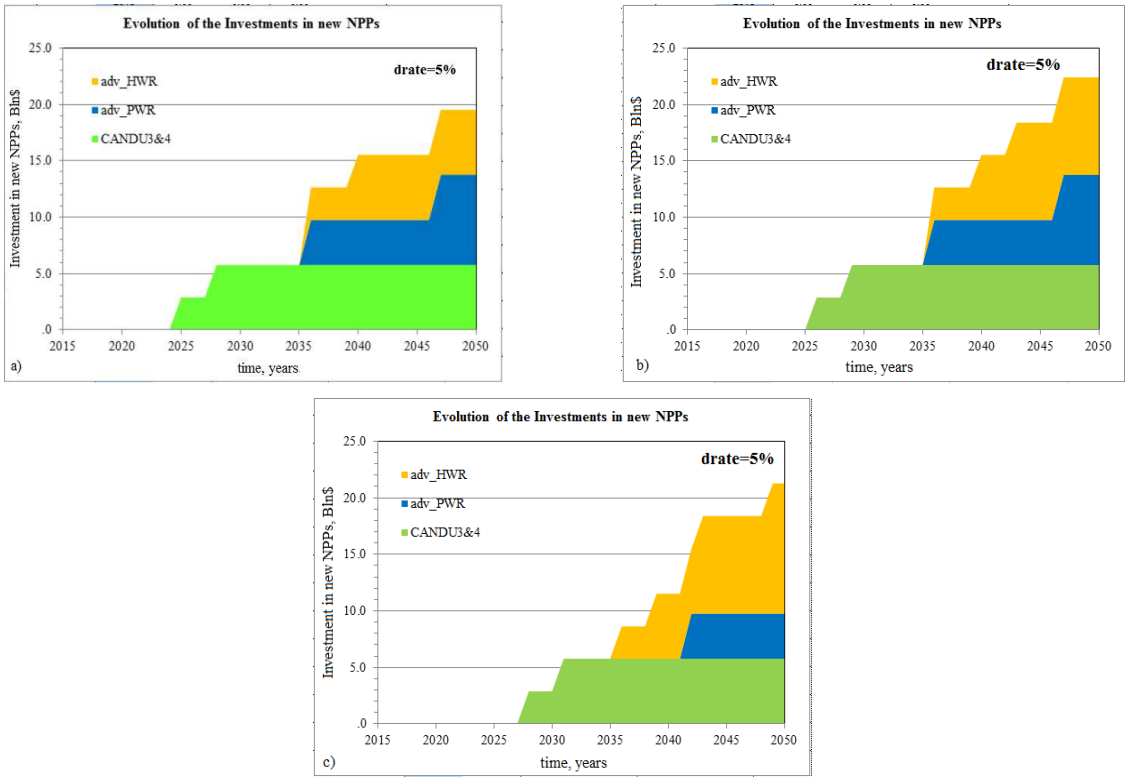

FIG. V-53. Investments in nuclear energy capacities, bln. $
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

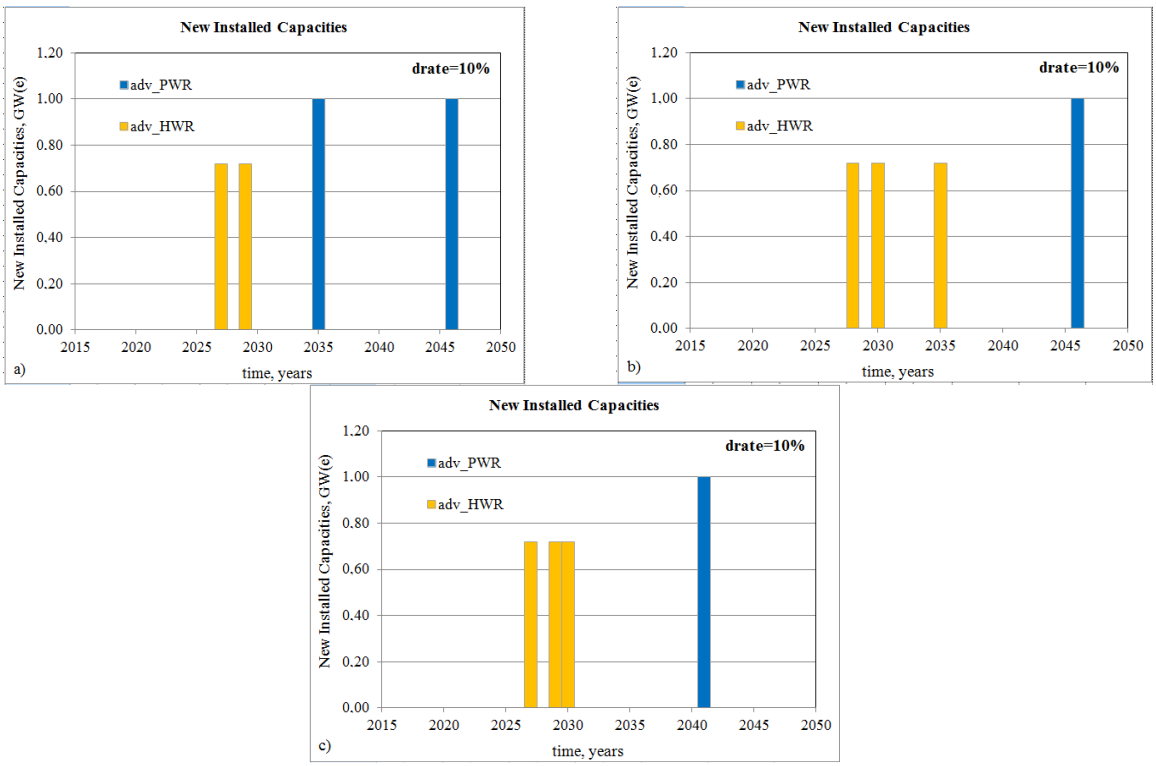

FIG. V-54. New installed nuclear capacities, GW(e)
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

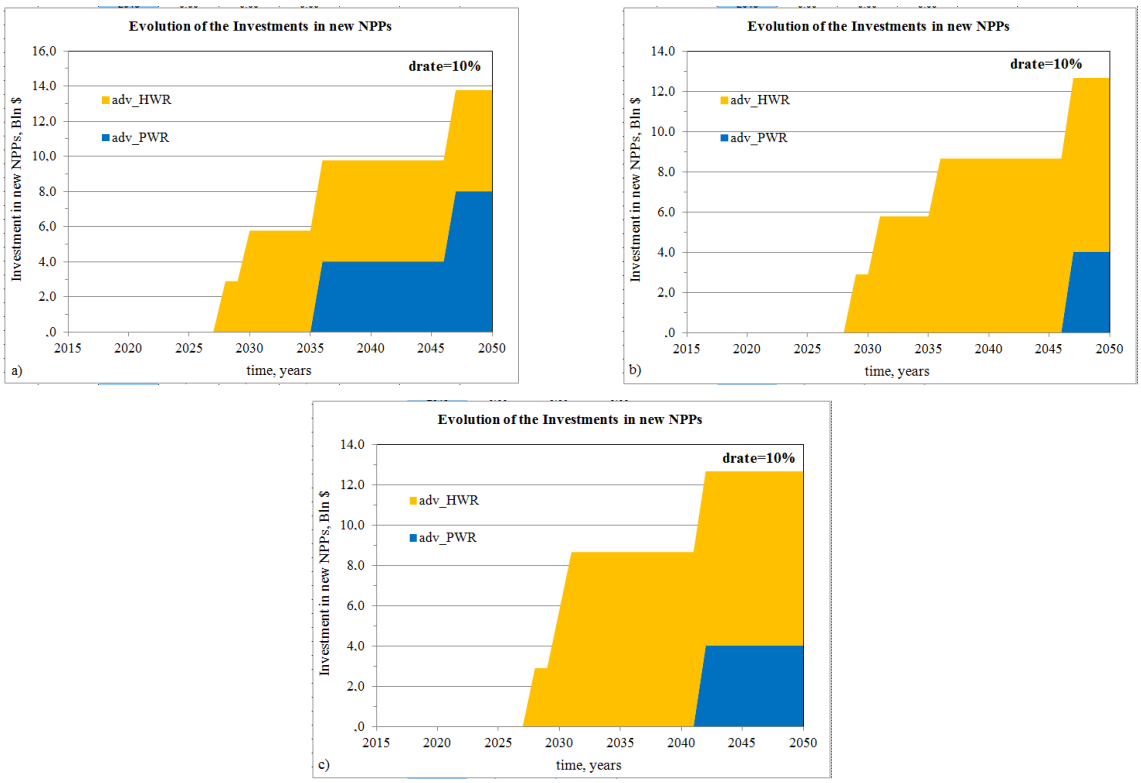

FIG. V-55. Investments in nuclear energy capacities, bln. $
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2:a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

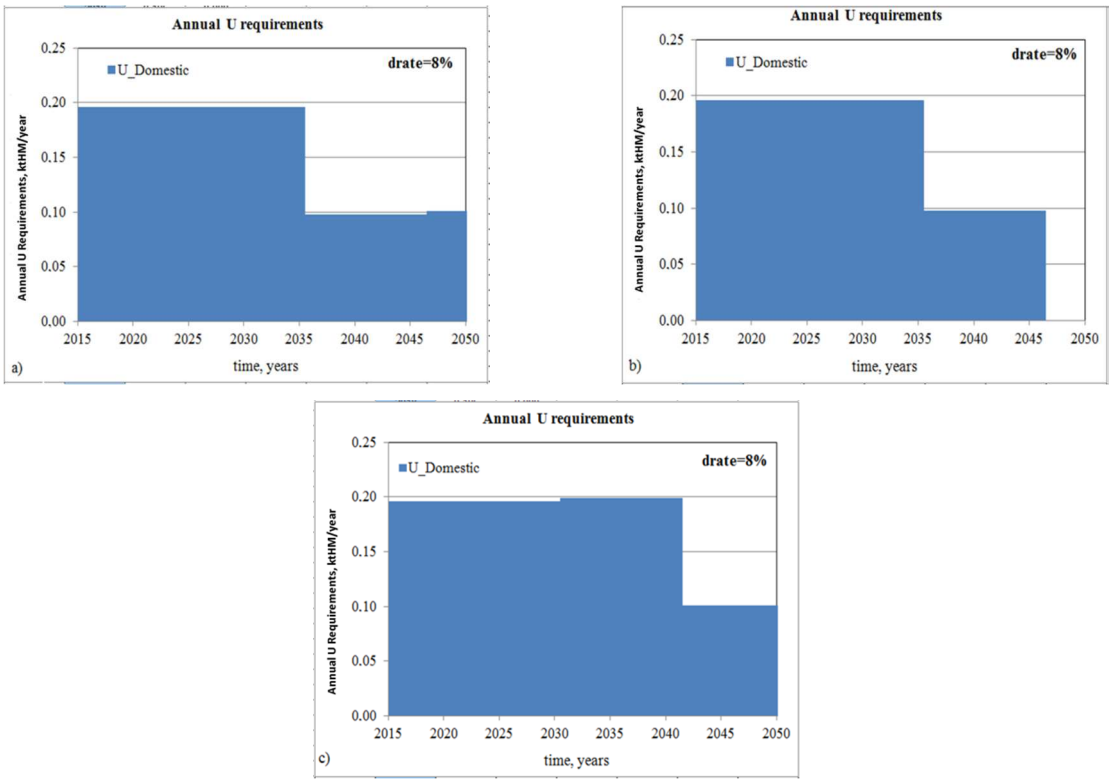

FIG. V-56. Annual U requirements, ktHM /year
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

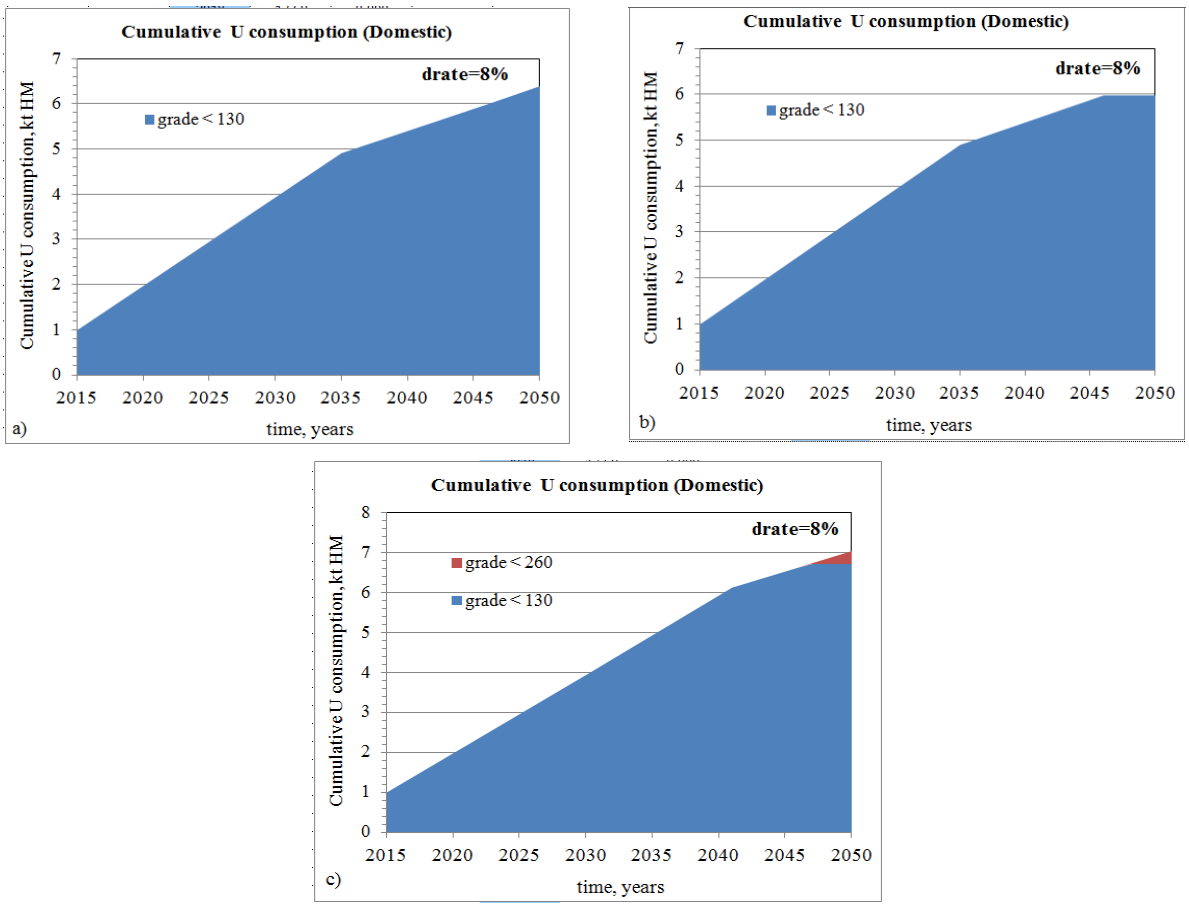

FIG. V-57. Cumulative U consumption, ktHM
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

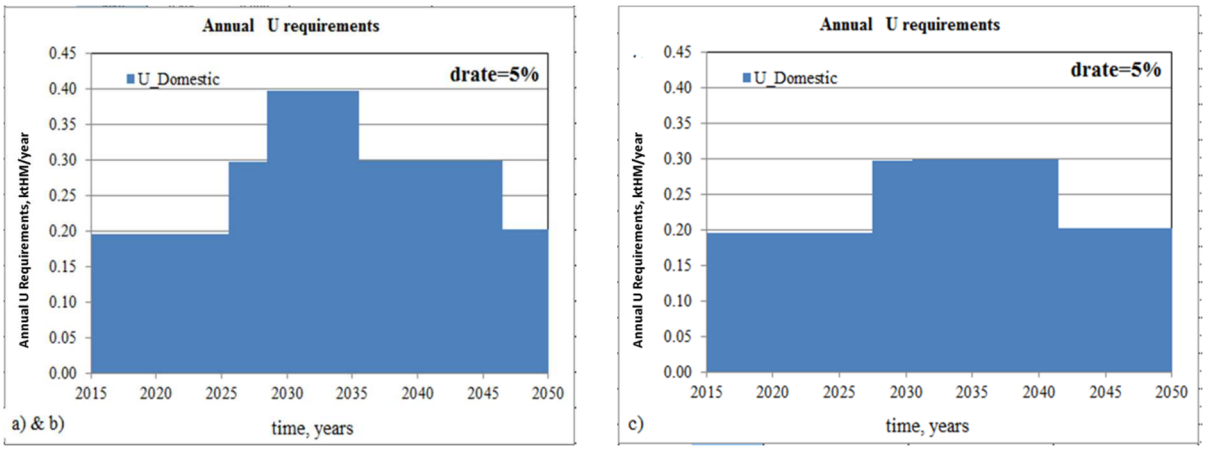

FIG. V-58. Annual U requirements, ktHM /year
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

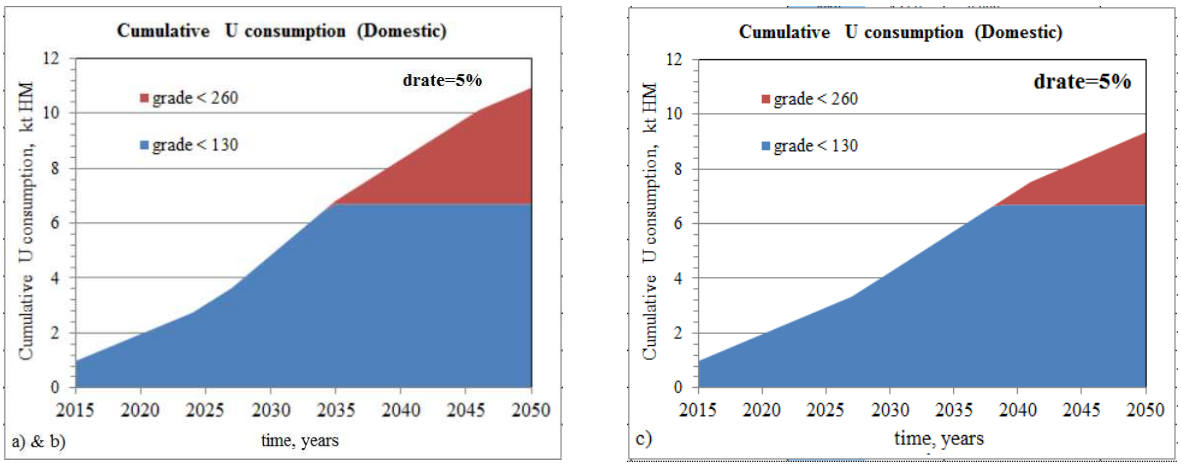

FIG. V-59. Cumulative U consumption, ktHM
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

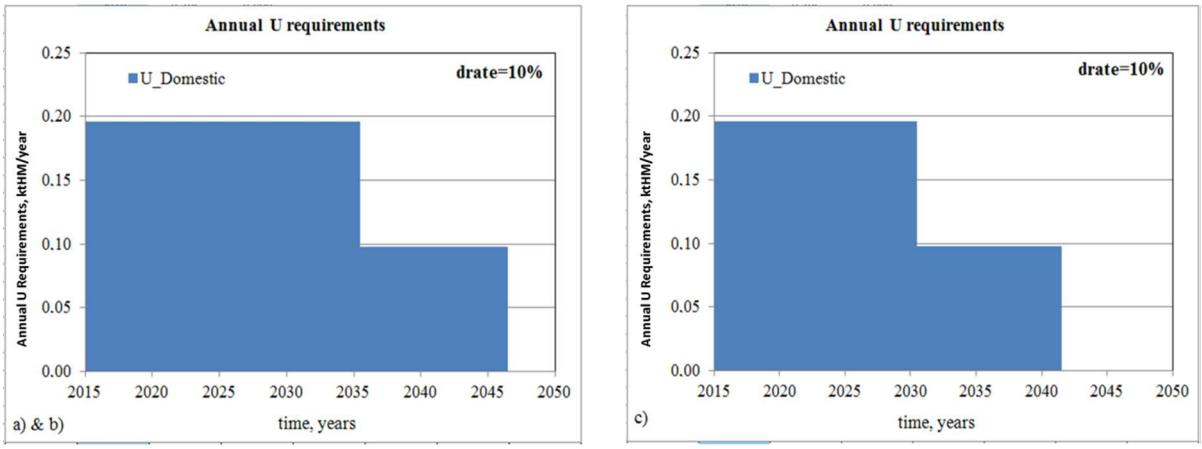

FIG. V-60. Annual U requirements, ktHM /year
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

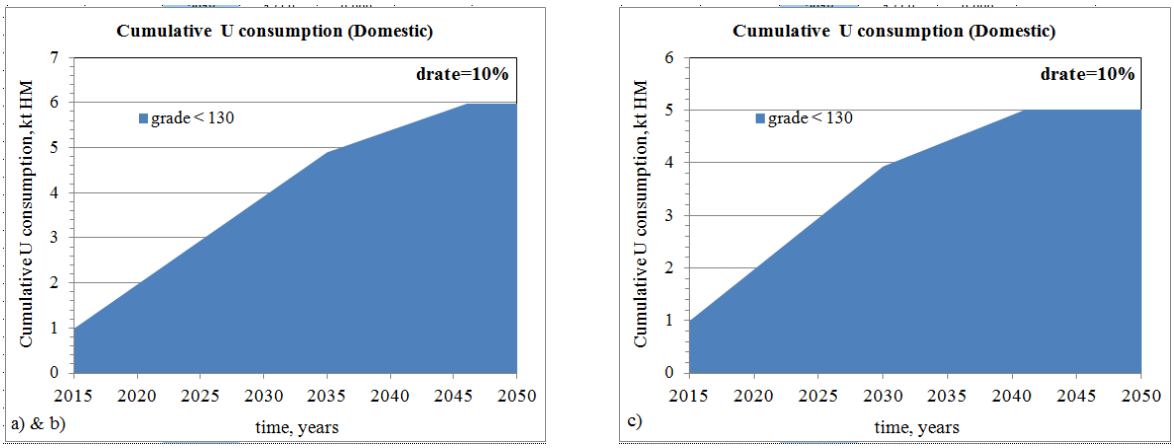

FIG. V-61. Cumulative U consumption, ktHM
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

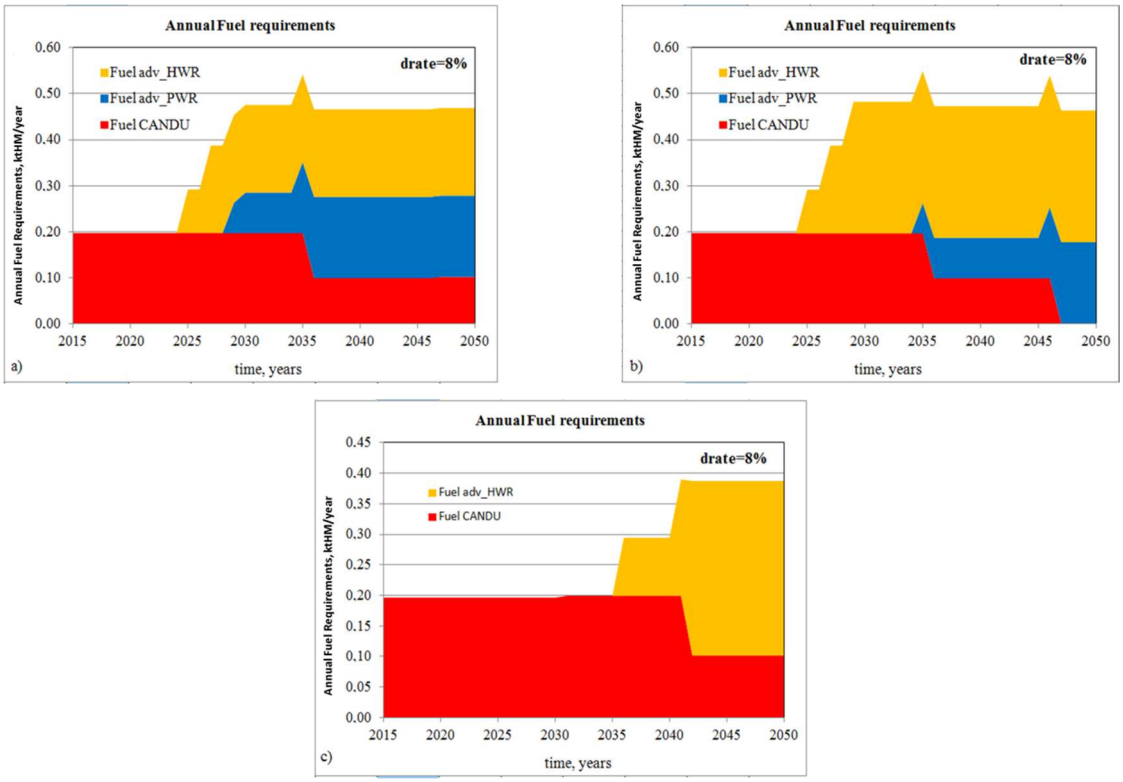

FIG. V-62. Fresh fuel annual requirements, ktHM /year
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

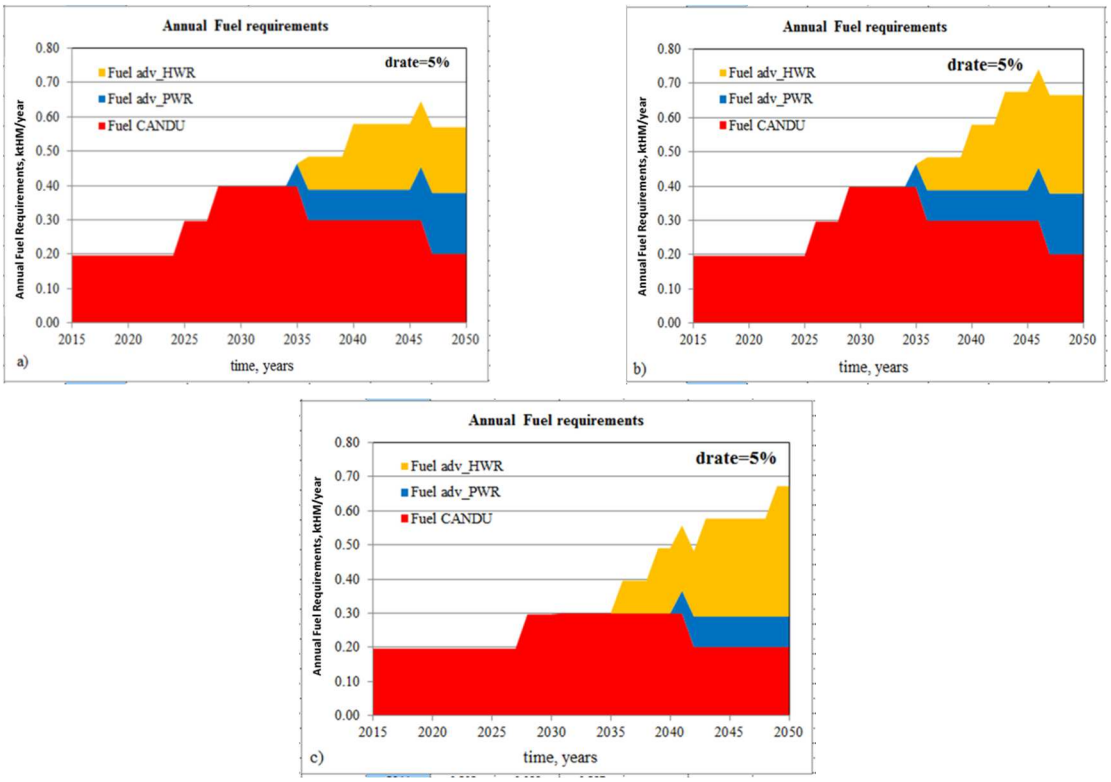

FIG. V-63. Fresh fuel annual requirements, ktHM /year
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

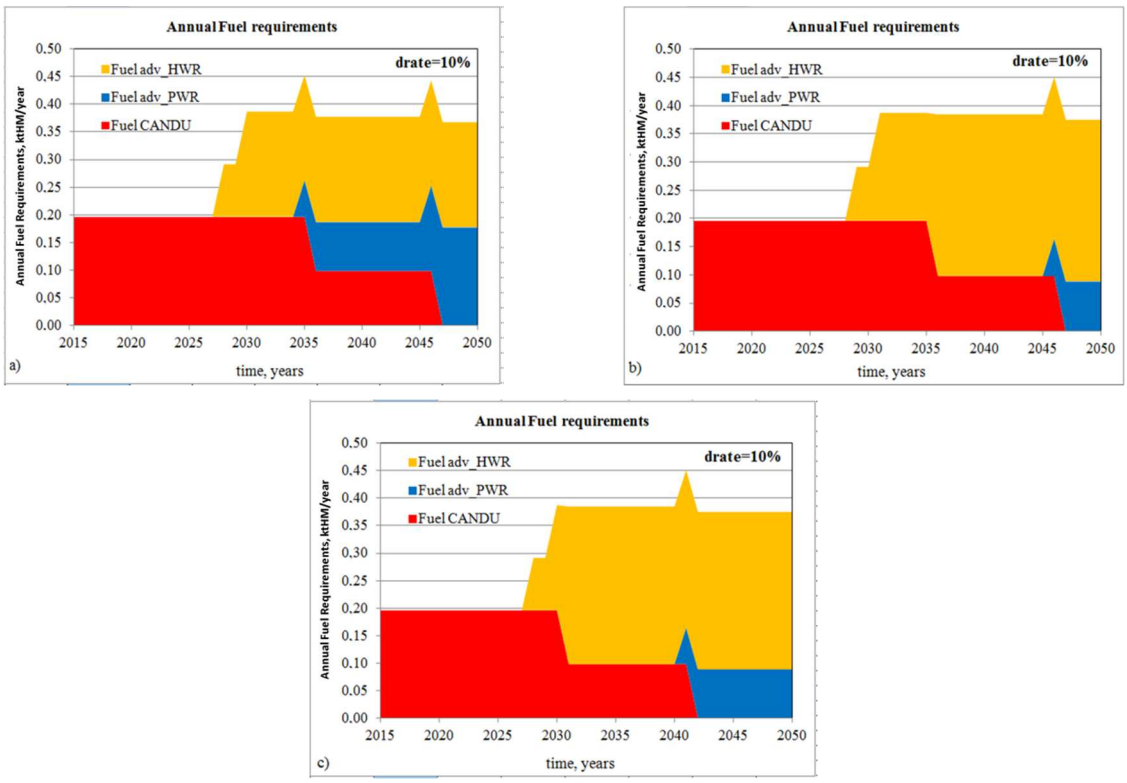

FIG. V-64. Fresh fuel annual requirements, ktHM /year
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

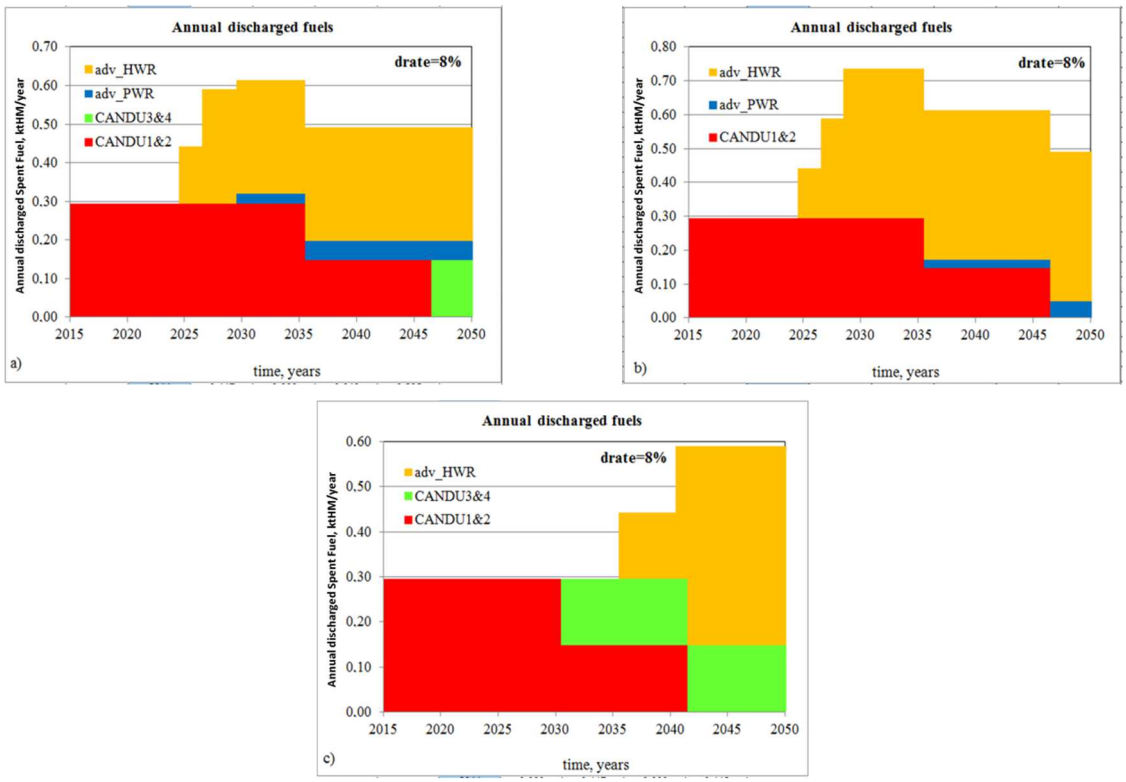

FIG. V-65. Spent fuel discharged from reactor core, ktHM/year
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

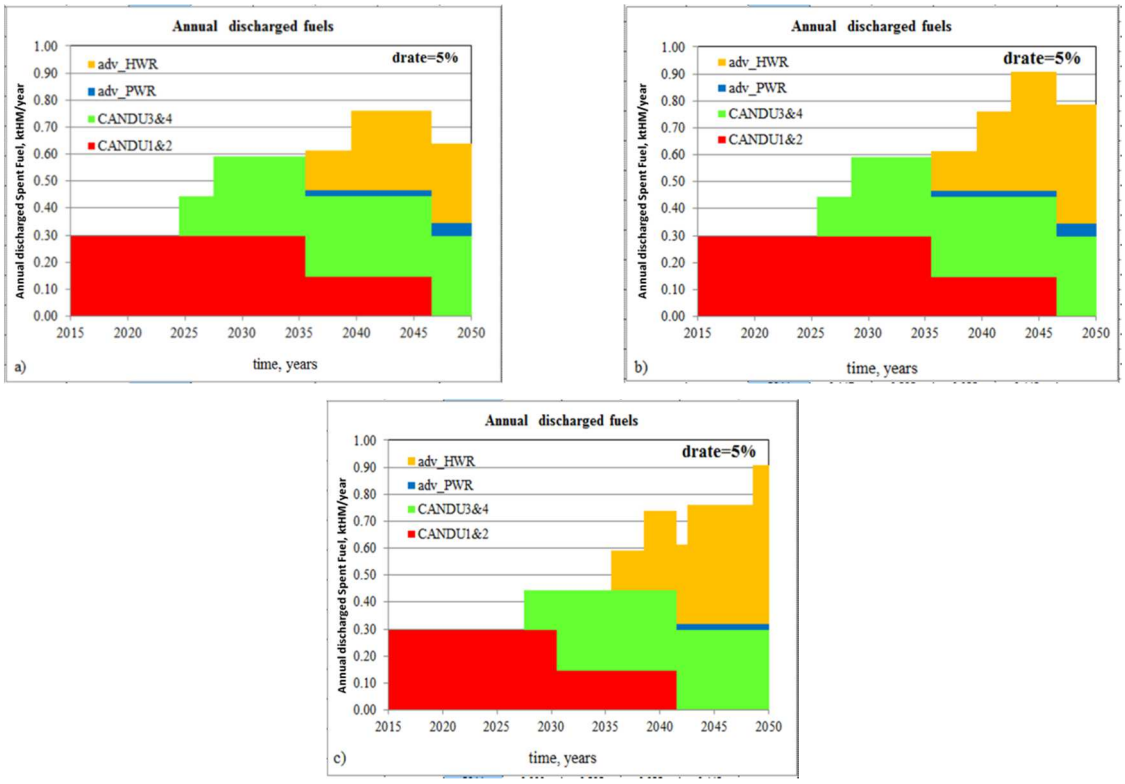

FIG. V-66. Spent fuel discharged from reactor core, ktHM/year
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

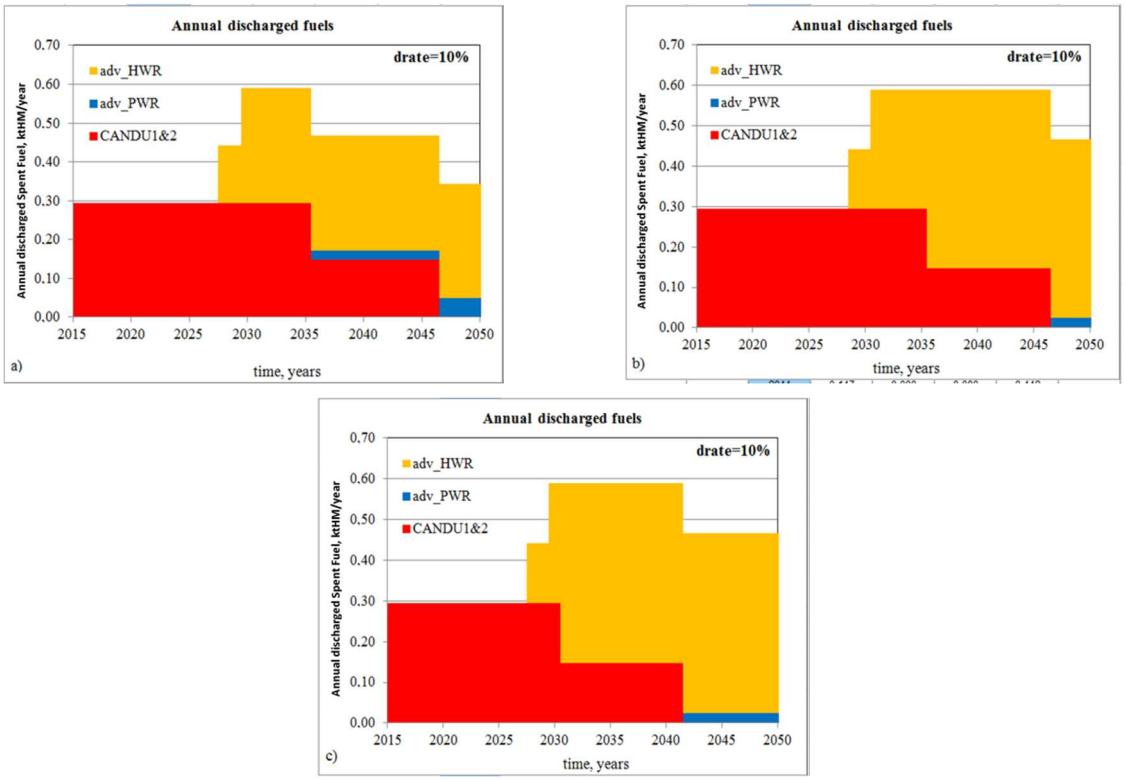

FIG. V-67. Spent fuel discharged from reactor core, ktHM/year
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

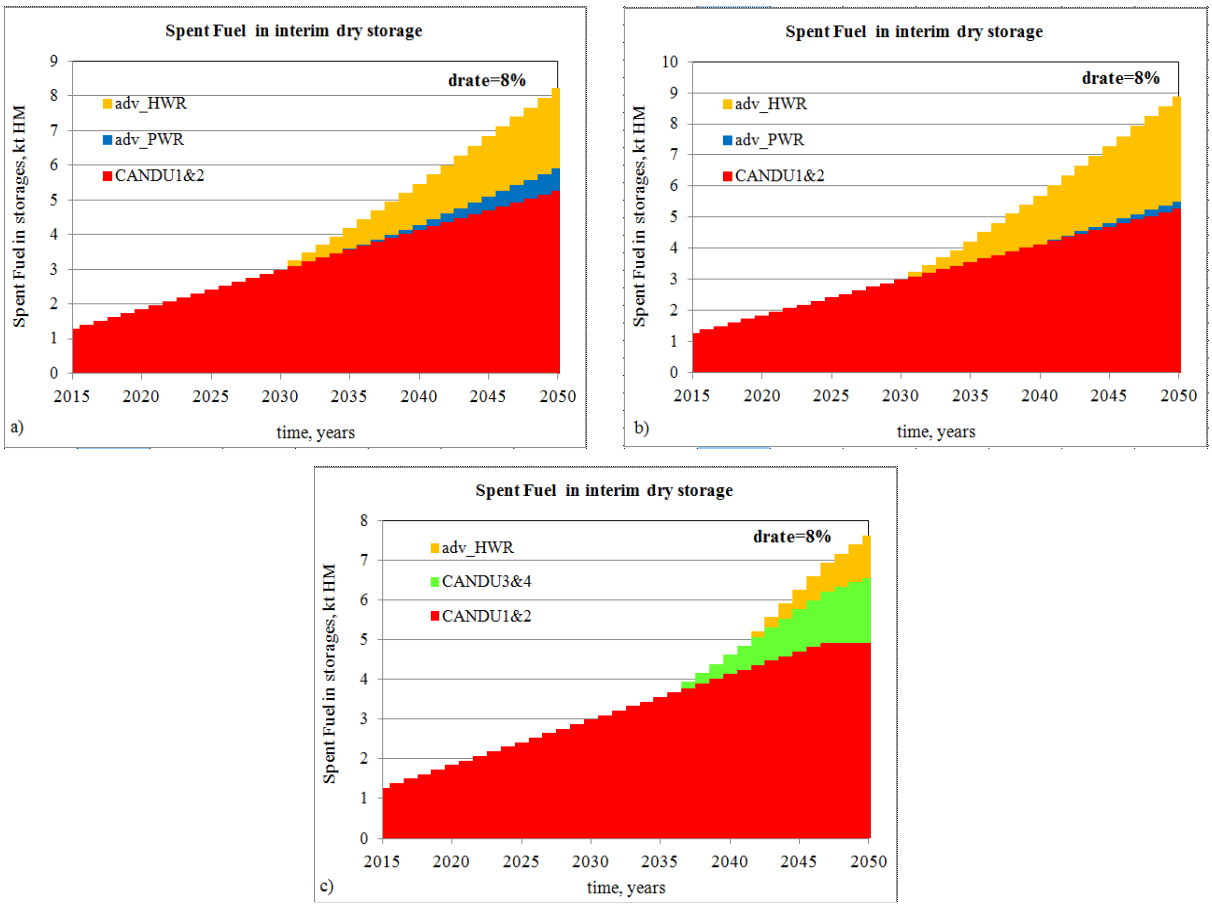

FIG. V-68. Cumulative spent fuel in storages, ktHM
NESA - optimistic scenario, 8% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

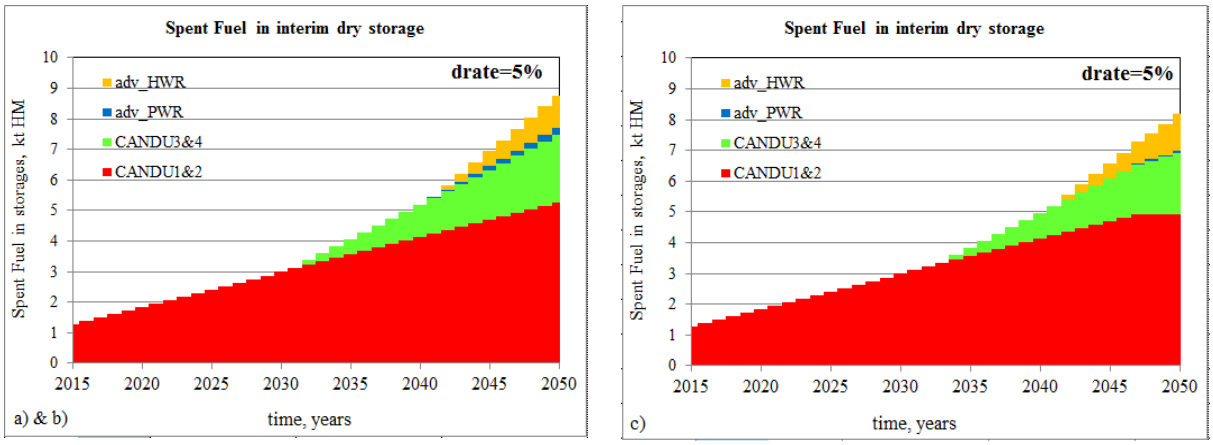

FIG. V-69. Cumulative spent fuel in storages, ktHM
NESA - optimistic scenario, 5% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

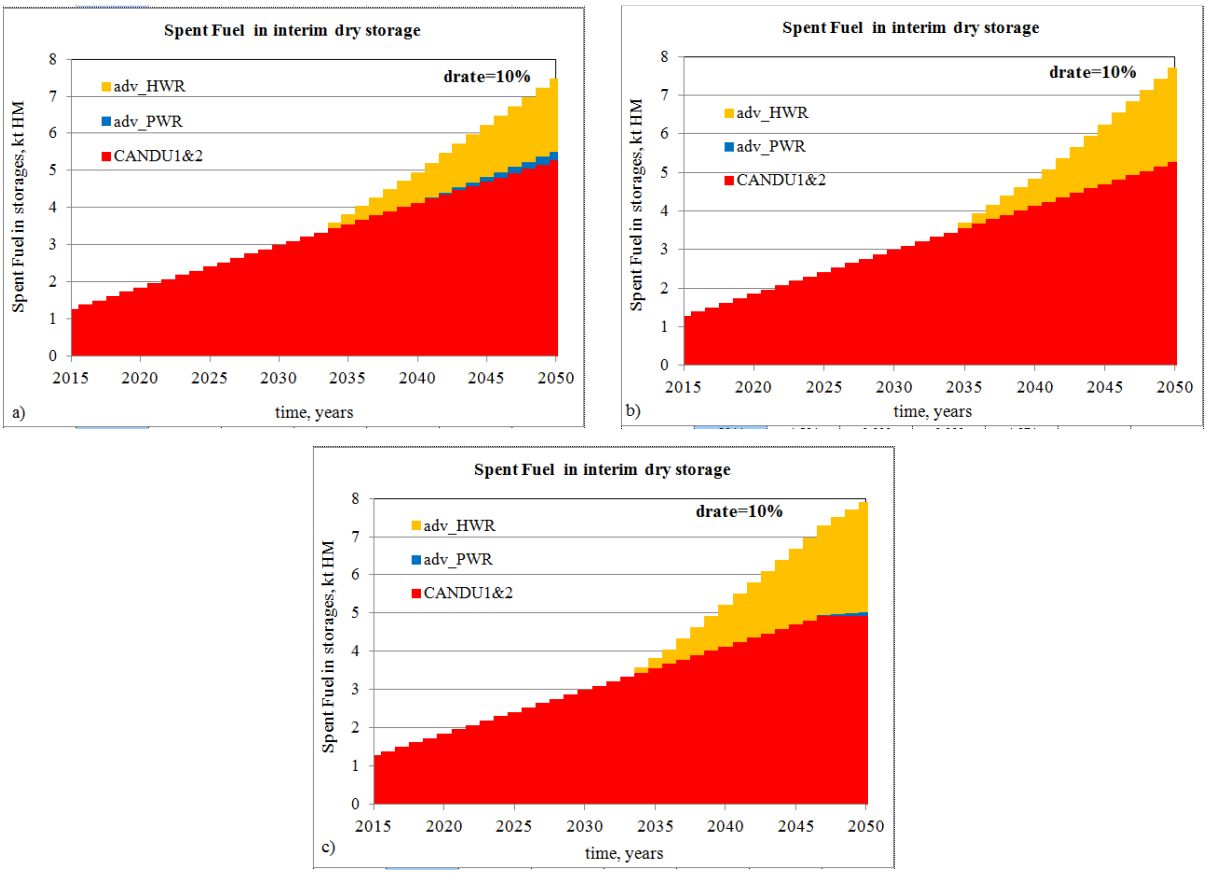

FIG. V-70. Cumulative spent fuel in storages, ktHM
NESA - optimistic scenario, 10% discount rate, 40 years lifetime CANDU 1&2: a) bound; b) no bound on advanced PWR /HWR addition; c) 35 years lifetime CANDU 1&2.

In the case of pessimistic scenarios (Pes1 and Pes2) for the demand evolution, the results are similar and shown that both Unit3 and Unit4 from Cernavoda NPP are considered to be built only for drate = 5%; for drate =8 % only one CANDU reactor will be built, and for drate = 10% no CANDU new reactor will be built, the economic considerations conducting to the selection for advanced HWR reactors to cover the electricity needs.

For 8% discount rate, the CANDU new reactor will be built in 2029 (Pes1) or 2030 (Pes2). It must to be mentioned here the construction of 3 advHWR (Pes1 – 2035, 2038 and 2046; Pes2 - 2024, 2027 and 2029) and 2 advPWR in 2035 and 2046 (Pes2). The cumulative U consumption was estimated as follows: Pes1 – 8.20 ktHM and 7.00 ktHM for 40 years and 35 years lifetime of CANDU 1&2, respectively; Pes2 – 5.98 ktHM for both CANDU 1&2 lifetimes. Regarding the cumulative volume of Spent Fuel in storages, the following amounts were estimated: Pes1 - 5.26 ktHM SNF from CANDU 1&2 (Pes1 and Pes2), 1.74 ktHM SNF from CANDU 3&4 (Pes1), 1.06 ktHM (Pes1) and 3.24 ktHM (Pes2) SNF from advHWR, 0.25 ktHM SNF from advPWR (Pes2).

For 5% discount rate, the Unit3 and 4 will be built in: 2024 and 2027 for 40 years lifetime of CANDU 1&2; 2027 and 2030 for 35 years lifetime of CANDU 1&2. The simulation selected to built also advHWR (4 reactors starting from 2035) and one advPWR after 2045. The cumulative U consumption was estimated as follows for both pessimistic scenarios: 10.93 ktHM and 9.34 ktHM for 40 years and 35 years lifetime of CANDU 1&2, respectively. Regarding the cumulative volume of Spent Fuel in storages the following amounts were estimated: 5.26 ktHM SNF from CANDU 1&2 (Pes1 and Pes2), 2.31 ktHM (Pes1) and 1.97 ktHM (Pes2) SNF from CANDU 3&4 and 1.39 ktHM (Pes1) and 1.19 ktHM (Pes2) SNF from advHWR.

For 10% discount rate, no new CANDU reactors will be constructed; instead, 3 advHWR (2028, 2030 and 2035) and one advPWR (2046) will cover the electricity demand needs. The cumulative U consumption was estimated to 5.98 ktHM. Regarding the cumulative volume of Spent Fuel in storages, the following amounts were estimated: 5.26 ktHM SNF from CANDU 1&2 (Pes1 and Pes2), 1.97 ktHM (Pes1) and 2.56 ktHM (Pes2) SNF from advHWR.

In the case of Optimistic scenario for NES development in Romania with bound on the commissioning of advPWR and/or advHWR (after 2035), the present study led to the following conclusions:

- The annual nuclear electricity production can reach up to 2.6 GW(e) – commissioning of only CANDU Unit3 in 2030 and another three advHWR in 2035-2045; CANDU Unit4 construction is delayed after 2050 due to economic reasons; the nuclear share in Romanian energy mix reaches 30%.
- The cumulative uranium consumption was estimated to be about 6.7 kt, without exceeding the existing RAR+IR. It must be mentioned here that the study assumption was to assure from import the Fresh Fuel needed for advHWR operation, in order to respect the national regulations regarding the interdiction of U enrichment and SNF reprocessing activities. The annual Fuel requirements were estimated to 0.4 ktHM, from which about 0.2 ktHM are used for CANDU reactors operation.
- The volume of SNF in interim dry storage reaches about 7.5 ktHM, from which about 5 ktHM is SNF produced by CANDU reactors operation.

The Optimistic Scenario for NES development in Romania with no bound on the commissioning of advPWR/advHWR (after 2035), has led to the following conclusions:

- The annual nuclear electricity production reaches up to 3.8 GW(e) after 2035 – two advHWR (till 2025) and two advPWR (after 2025) and only CANDU Unit 3 (after 2045); CANDU Unit 4 construction is delayed after 2050 due to economic reasons; the nuclear share in Romanian energy mix can reach about 45%.
- The cumulative Uranium consumption was estimated to be about 6.7 kt, without exceeding the existing RAR+IR. The Fresh Fuel needed for advPWR and advHWR operation is issured from import, with respect to national regulations regarding the interdiction of U enrichment and SNF reprocessing activities. The annual Fuel requirements were estimated to 0.5 ktHM, from which about 0.1 ktHM are used for CANDU reactors operation.
- The volume of SNF in interim dry storage reaches about 8 ktHM, from which about 5 ktHM is SNF produced by CANDU reactors operation. To be mentioned that the study assumed that the SNF from advPWR will be stored outside the country in a regional storage facility.

V-4.3. Nuclear generation pessimistic scenario

In the following, the results obtained for the nuclear Pessimistic scenario will be presented, considering the NESA energy demand evolution scenario, 8% discount rate two options for the operating CANDU Unit 1 and Unit 2, Cernavoda NPP (35 and 40 years, respectively).

Figures V-71–V-76 illustrate the evolution of the interest parameters for nuclear energy

domain during the considered period of modelling. The annual electricity production from nuclear capacities is presented in Fig. V-71. Figures V-72 and V-73 present the annual U requirements and the corresponding cumulative U consumption. The annual fresh fuel requirement evolution is illustrated in Fig. V-74; Figures V-75 and V-76 present the amount of spent fuel annually discharged from the reactors core and the volume of spent fuel in interim dry storage, respectively.

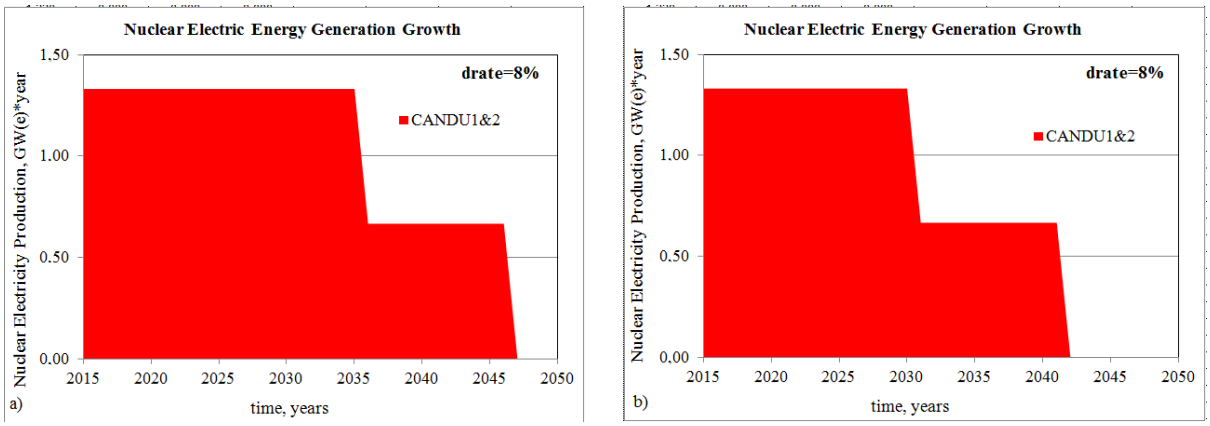

*FIG. V-71. Annual nuclear electricity production, GW(e)*year*
NESA - pessimistic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

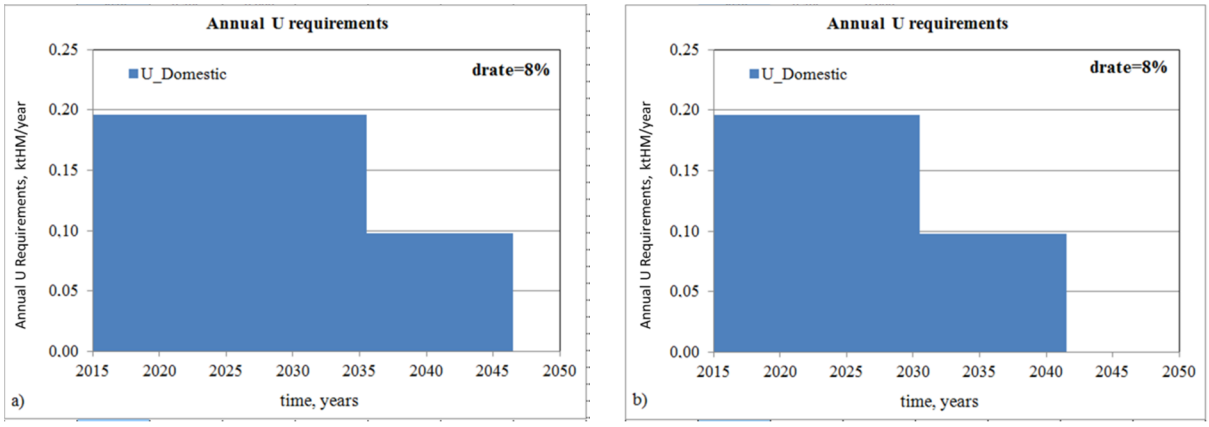

FIG. V-72. Annual U requirements, ktHM /year
NESA - pessimistic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

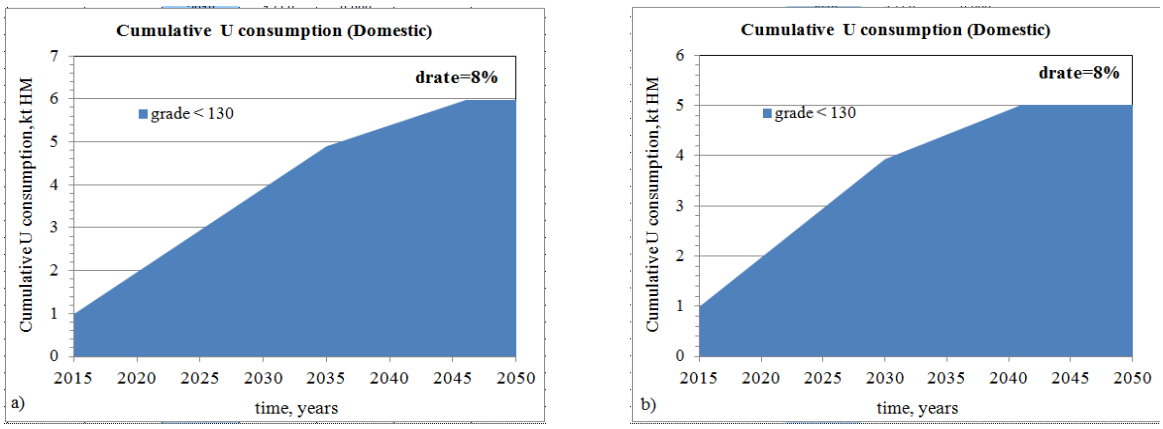

FIG. V-73. Cumulative U consumption, ktHM
NESA - pessimistic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

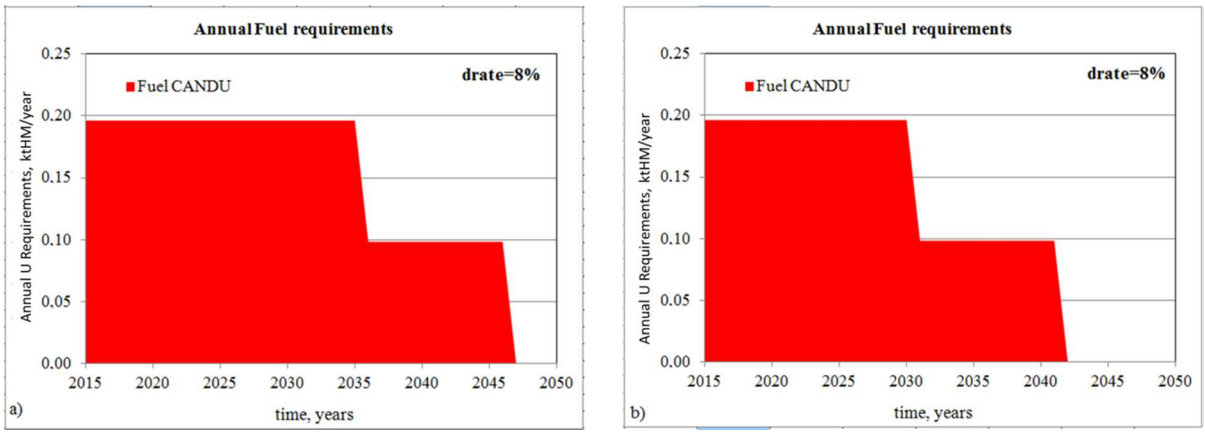

FIG. V-74. Fresh fuel requirements, ktHM/ year
NESA - pessimistic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

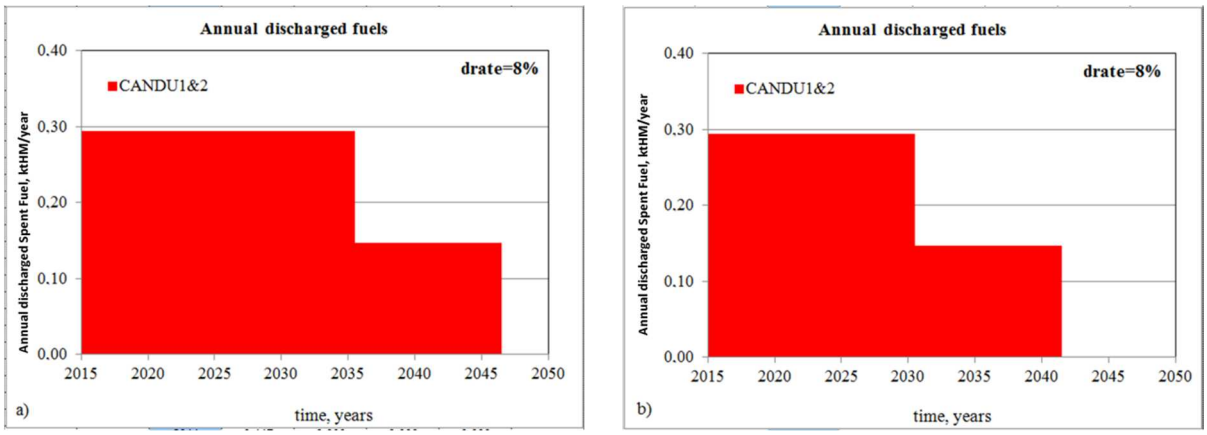

FIG. V-75. Spent fuel discharged from reactor core, ktHM/ year
NESA - pessimistic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

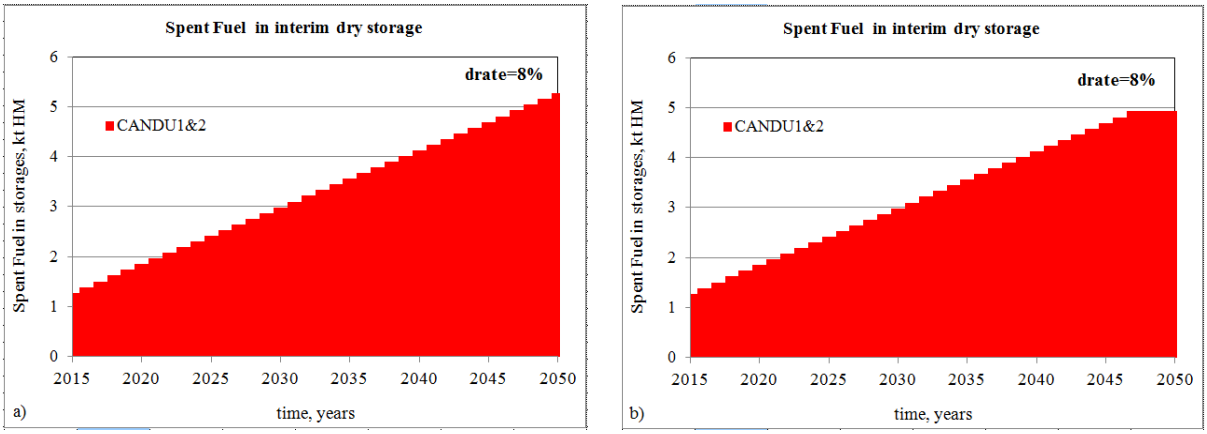

FIG. V-76. Spent fuel in interim dry storage, ktHM
NESA - pessimistic scenario, 8% discount rate, lifetime for CANDU 1&2: a) 40 years; b) 35 years.

In the case of nuclear development Pessimistic scenario, the other considered values for discount rate (5% and 10%, respectively) led to results similar with those obtained for 8% discount rate.

Considering the pessimistic energy demand scenarios, the results were similar with the NESA scenario, in the study being observed that Pes1 and Pes2 scenarios influence is noticed for Nuclear Development in the considered Basic and Optimistic Scenarios.

For the NES Pessimistic Scenario, following conclusions can be extracted:

- The annual nuclear electric energy production is about 1.3 GW(e) (with both CANDU Units 1&2 in operation), reduces to 0.6 GW(e) after 2030 or 2035 (shutdown of CANDU Unit 1) and there is no nuclear electricity produced after 2040 or 2045 (shutdown of CANDU Unit 2). The national electricity demand in the Romanian energy mix has to be assured by increasing the share of renewable capacities or building classic thermal capacities with improved technologies for preserving the low CO_2 emissions required level.
- The cumulative Uranium resources consumption was estimated to about 6 kt, this amount being assured by the estimated domestic RAR+IR.
- The volume of SNF in interim dry storage reaches 5.26 ktHM.

V-5. ECONOMIC ANALYSIS FOR NUCLEAR ENERGY COST COMPETITIVENESS ASSESSMENT

The economic analysis included in Romania study case was performed in order to evaluate the nuclear energy cost competitiveness against alternative energy sources. The study final goal proposes to search solid arguments sustaining the nuclear power plants comparatively with the classical fossil fuel plants, highlighted by the evolution of specific economic indicators (*Levelized Unit Energy Cost* - LUEC, *Internal Rate of Return* - IRR, *Return on Investment* - ROI, *Net Present Value* – NPV, *Total investment/Investments limit*). Both for nuclear and classic non-nuclear technologies advanced solutions have been considered.

In the comparative economic study, three types of technologies were considered, as follows: NPP (advanced PWR and advanced PHWR), Coal-fired power plant (PP) (power plant using lignite fossil fuel, with carbon capture) and Gas-fired power plant (power plant operating on combined cycle, with carbon capture), respectively.

The electricity generation costs calculated are plant-level costs, at the station, and do not include transmission and distribution costs.

TABLE V-10. COUNTRY SPECIFIC ECONOMIC INPUT PARAMETERS

Parameters	units	PWR	HWR	Coal-fired PP	Gas-fired PP
Discount rate	1/year	0.1	0.1	0.1	0.1
Price of unit electricity sold	mills[1]/kWh	80	80	80	80
Tax rate	%/100	0.6	0.6	0.6	0.6
Market income	M$/year	3000	3000	3000	3000
Market share	%/100	1	1	1	1
Profit margin	%/100	0.3	0.3	0.3	0.3
Time of growth	years	4	4	2	2
Adjusting coefficient	%/100	1	1	1	1

[1] There are 1000 mills in a US$.

In Tables V-10, V-11, V-12 and V-13, respectively, the basic assumptions for the comparative economic study are given. The values presented in the tables have been collected from [V-10, V-15, V-16 and V-23 – V-32] and were used as initial input values for the NEST code calculations. In order to calculate the economic parameters for the considered energy sources, in the comparative study the formula provided in [V-27] were used.

In the comparative study, for the initial capital investment the uniform investment schedule has been used for all the considered energy sources.

TABLE V-11. POWER PLANT SPECIFIC TECHNICAL INPUT PARAMETERS

Parameters	units	PWR	HWR	Coal-fired PP	Gas-fired PP
Net electric power	MW(e)	1000	720	400	400
Construction time	years	6	6	4	2
Life time	years	60	60	40	30
Load factor	%/100	0.9	0.9	0.9	0.9
Net thermal efficiency	%/100	0.33	0.33	0.39	0.55

TABLE V-12. POWER PLANT SPECIFIC ECONOMIC INPUT PARAMETERS

Parameters	units	PWR		HWR		Coal-fired PP		Gas-fired PP	
Overnight Construction Cost	$/kWe	2550		2250		704		509	
Contingency Cost	$/kWe	510		450		80		58	
Owners Cost	$/kWe	340		300		736		532	
Capital investment schedule	%/100	0	0	0	0	0	0	0	0
	%/100	0.16	-1	0.16	-1	0.25	-1	0.5	-1
	%/100	0.16	-2	0.16	-2	0.25	-2	0.5	-2
	%/100	0.17	-3	0.17	-3	0.25	-3		-3
	%/100	0.17	-4	0.17	-4	0.25	-4		-4
	%/100	0.17	-5	0.17	-5		-5		-5
	%/100	0.17	-6	0.17	-6		-6		-6
Decommissioning cost	mills/kWh	1		0.03		0		0	
Fixed O & M cost	$/kWe	50		55		25		18	
Variable O & M cost	mills/kWh	0.9		0.9		5		2	
Fuel price	$/GJ	*		*		4		8	
Real fuel price annual escalation rate	%/100	-		-		0.01		0.01	

* Nuclear fuel costs are calculated directly, using additional NPP specific technical parameters (TABLE V-13).

TABLE V-13. ADDITIONAL NPP SPECIFIC TECHNICAL INPUT PARAMETERS

Parameters	units	PWR	HWR
Spent nuclear fuel average burnup	MWday/kg	40	15
Reactor first core average power density	kW/kg	28.89	23.5
Natural U purchase cost	$/kgU$_{nat}$	80	80
U conversion cost	$/kgHM	8	8
U enrichment cost	$/SWU	110	0
Nuclear fuel fabrication cost	$/kgHM	275	80
Nuclear fuel backend cost	$/kg	400	80

The results obtained after performing the comparative analysis of considered energy sources (NPPs, Coal-fired PP and Gas-fired PP) are presented in the following. As it was mentioned before, in the initial (base) calculations performed using NEST code, 8% discount rate was considered.

TABLE V-14. COMPARATIVE STUDY FOR NUCLEAR AND ALTERNATIVE ENERGY SOURCES – DISCOUNT RATE 8% LEVELIZED UNIT ENERGY COSTS [10^{-3} $/kWh]

Technology	Net capacity GW(e)	Overnight costs * $/kW(e)	Investment costs ** $/kW(e)	Total investment *** M$	LUEC 10^{-3} $/kWh
Advanced PWR	1.000	3400	4503	4503	46.52
Advanced HWR	0.720	3000	3973	2861	38.14
Coal-fired PP	0.400	1520	1841	740	63.09
Gas-fired PP	0.400	1099	1234	494	71.33

* Overnight costs include pre-construction (owner's), construction (engineering, procurement and construction) and contingency costs, but not interest during construction (IDC);

** Investment costs include Overnight costs and the interest during construction (IDC);

*** Total investment is given by the Investment costs multiplied by power plant net capacity

TABLE V-15. COMPARATIVE STUDY FOR NUCLEAR AND ALTERNATIVE ENERGY SOURCES – DISCOUNT RATE 8% ADDITIONAL ECONOMIC PARAMETERS

Technology	Net capacity GW(e)	IRR	ROI	NPV $/kW(e)
Advanced PWR	1.000	0.13	0.39	3529
Advanced HWR	0.720	0.15	0.46	4411
Coal-fired PP	0.400	0.15	0.35	1717
Gas-fired PP	0.400	0.16	0.27	831

The advanced HWR NPP is the best economic option for the considered initial data. It follows advanced PWR NPP with ~20% higher LUEC value, Coal-fired PP with ~37% higher LUEC value and, respectively, Gas-fired PP with ~ 50% higher LUEC value (advanced HWR

LUEC value is taken as reference value for the comparison). The electricity produced by NPPs is cost competitive against coal and gas fired power plants electricity.

Private sector investors will be attracted by a competitive Internal Rate of Return (IRR), corresponding to associated risks. However, Net Present Value (NPV) of cash flows may be more suitable for government investors because this financial figure take into account other benefits such as security of energy supply and technology development. Return on investment (ROI) may be attractive as an indicator that is complimentary to IRR.

IRR values for the considered competing technologies were almost equal, the lowest IRR value, IRR=0.13, being obtained for Adv_PWR; next IRR value, IRR=0.15, was equally obtained for Adv_HWR and Coal_fired PP, so very small difference comparatively to leader.

ROI values for NPPs were better tha those for classic technologies, the leader being this time Adv_HWR, ROI=0.46, against Adv_PWR, ROI=0.39.

NPV values for the nuclear technologies were higher than those for the alternative classic ones. In conclusion, for all the considered figures of merit (IRR, ROI, NPV) the nuclear technology proven to be more attractive for investors than the fossil fuel classic technology improved to reduce greenhouse gases (GHG) emissions.The comparative study considered also the sensitivity analysis on the cost competitiveness for the defined nuclear and alternative energy sources. The sensitivity calculations were performed by considering the effect on LUEC due to the variation in the following parameters: discount rate, fixed O&M, Overnight costs, load factor, lifetime, construction time, investment schedule. The sensitivity analysis results are presented in the following figures and tables.

The sensitivity of LUEC to discount rate variation considered the following discount rates per year: 5%, 8%, 10%, 12% and 15%, respectively. Table V-16 and Fig. V-77 present the results.

TABLE V-16. SENSITIVITY OF LUEC ($/MWh) TO ANNUAL DISCOUNT RATE VARIATION

Technology	5%	8%	10%	12%	15%
Advanced PWR	31.26	46.52	59.00	73.20	97.62
Advanced HWR	25.02	38.14	48.93	61.22	82.42
Coal-fired PP	58.72	63.09	66.89	71.30	78.89
Gas-fired PP	69.06	71.33	73.27	75.49	79.27

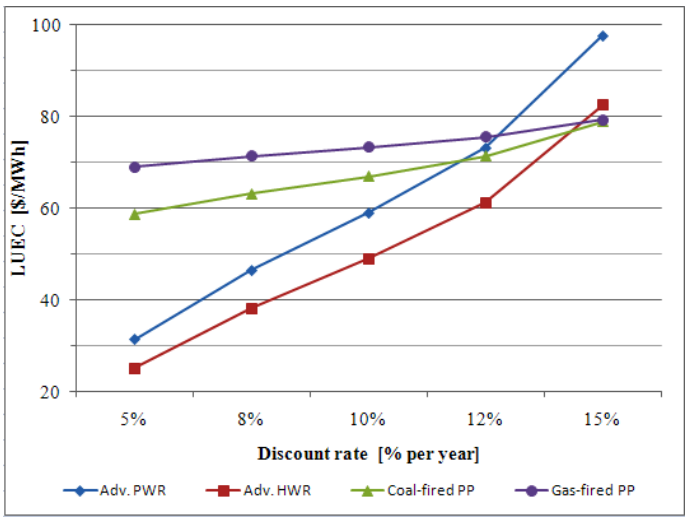

FIG. V-77. Impact of discount rate variation on LUEC, $/MWh.

LUEC increases the most for capital intensive technologies (see also Fig. V-2), as the assumed discount rate becomes higher. The impact is greatest for the nuclear technologies and lowest for the Coal-fired PP. We note that in most of the sensitivities examined, advanced HWR continues to have the lowest LUEC. For 15% discount rate per year, non-nuclear technologies (coal and gas) become competitive with advanced HWR.

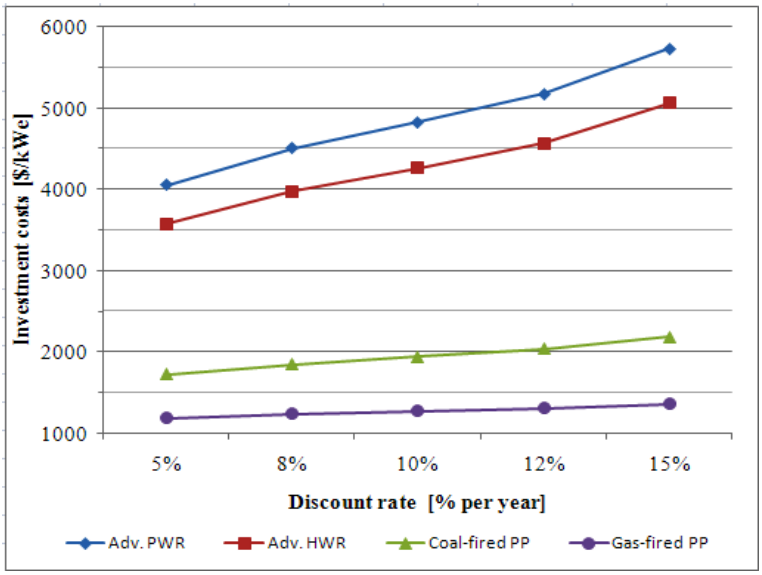

FIG. V-78. Impact of discount rate variation on Investment costs, $/kW(e).

The investments costs (include overnight costs and IDC) for the nuclear technologies are more rapidly increasing (by 11%) as the discount rate becomes higher comparatively with the ones characterizing the non-nuclear sources of energy (by 8% for Coal-fired PP and by 4% for Gas-fired PP, respectively).

The sensitivity of LUEC to fixed O&M costs variation was obtained considering a variation of ±5%, ±10% and ±15%, respectively, comparatively with the initial assumed fixed O&M costs. Tables V-17 and V-18 show that the LUEC value for all considered technologies has small changes with variation of the fixed O&M costs, but for different discount rates the changes in LUEC value are higher for nuclear technologies than for the non-nuclear ones. Considering the discount rates of 10% and 5% per year, the higher changes are obtained for advanced HWR technology (LUEC reduces by 96%), the lowest ones being obtained for the Gas-fired technology (LUEC reduces by only 2%), as can be seen also in Fig. V-79. In all sensitivity cases considered, the lowest LUEC value was obtained for advanced HWR.

TABLE V-17. SENSITIVITY OF LUEC ($/MWh) TO FIXED O&M COSTS VARIATION – DISCOUNT RATE 10%

Technology	-15%	-10%	-5%	0	+5%	+10%	+15%
Advanced PWR	58.05	58.37	58.68	59.00	59.32	59.64	59.95
Advanced HWR	47.88	48.23	48.58	48.93	49.28	49.63	49.98
Coal-fired PP	66.41	66.57	66.73	66.89	67.05	67.21	67.37
Gas-fired PP	72.93	73.04	73.15	73.27	73.38	73.50	73.61

TABLE V-18. SENSITIVITY OF LUEC ($/MWh) TO FIXED O&M COSTS VARIATION – DISCOUNT RATE 5%

Technology	-15%	-10%	-5%	0	+5%	+10%	+15%
Advanced PWR	30.31	30.63	30.95	31.26	31.58	31.90	32.22
Advanced HWR	23.98	24.32	24.67	25.02	25.37	25.72	26.07
Coal-fired PP	58.24	58.40	58.56	58.72	58.88	59.04	59.19
Gas-fired PP	71.33	71.45	71.56	71.68	71.79	71.91	72.02

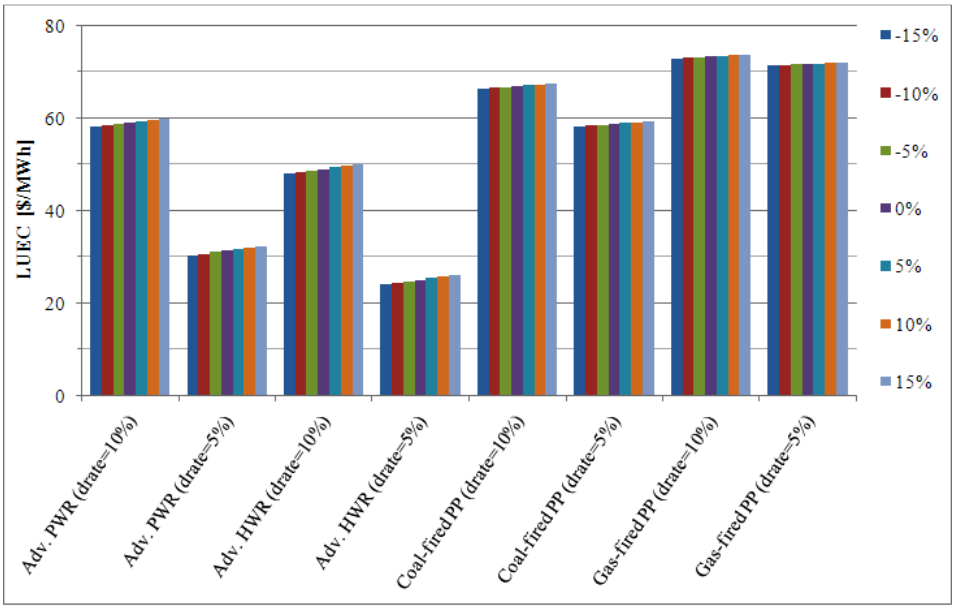

FIG. V-79. Impact of fixed O&M costs variation on LUEC ($/MWh), for different discount rates.

The sensitivity of LUEC (for 10% annual discount rate) to Overnight costs variation by ±5%, ±10% and ±15%, respectively, comparatively with the initial assumed Overnight costs, was studied. The results are presented in Table V-19 and Fig. V-80.

TABLE V-19. SENSITIVITY OF LUEC ($/MWh) TO OVERNIGHT COSTS VARIATION

Technology	-15%	-10%	-5%	0	+5%	+10%	+15%
Advanced PWR	52.46	54.64	56.82	59.00	61.06	63.37	65.55
Advanced HWR	43.19	45.08	47.00	48.93	50.85	52.78	54.71
Coal-fired PP	64.17	65.08	65.98	66.89	67.80	68.70	69.61
Gas-fired PP	71.37	72.07	72.67	73.27	73.86	74.46	75.06

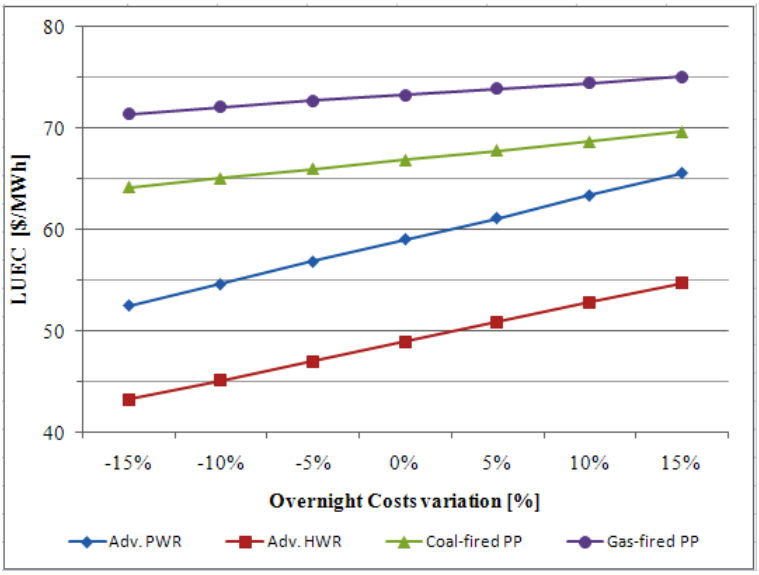

FIG. V-80. Impact of Overnight costs variation on LUEC, $/MWh.

LUEC increases the most for the nuclear technologies, as the assumed Overnight costs become higher. The greatest impact is obtained for the nuclear technologies (LUEC increases by 12% for 15% increasing in Overnight costs), the lowest one being for Gas-fired PP (LUEC increases by 2% for 15% increasing in Overnight costs). In all of the sensitivities examined, advanced HWR technology continues to have the lowest LUEC.

The impact of load factor variation on LUEC (for 10% annual discount rate) was obtained by considering in the sensitivity computations the following load factor values: 80%, 85%, 90%, 93% and 95%, respectively. To be mentioned that 90% was the initial assumed load factor for the comparative economic analysis of the nuclear and non-nuclear energy sources. The results are presented in Table V-20 and Fig. V-81.

TABLE V-20. SENSITIVITY OF LUEC ($/MWh) TO LOAD FACTOR VARIATION

Technology	80%	85%	90%	93%	95%
Advanced PWR	65.42	62.02	59.00	57.35	56.30
Advanced HWR	54.65	51.62	48.93	47.45	46.52
Coal-fired PP	69.55	68.14	66.89	66.20	65.77
Gas-fired PP	75.05	74.11	73.27	72.81	72.52

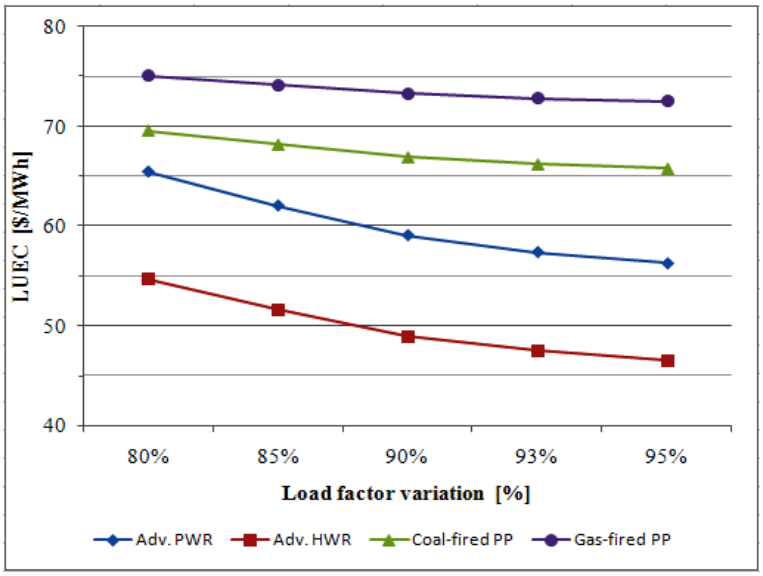

FIG. V-81. Impact of load factor variation on LUEC, $/MWh.

LUEC decreases with load factor improving for all the considered energy generating technologies, the higher impact being observed for the nuclear technologies (for 5% increasing in load factor value, the LUEC value reduces by 5%). For the non-nuclear energy producing technologies the impact of load factor improving on LUEC is smaller, namely for 5% improving of load factor, LUEC reduces by 2% for Coal-fired PP and only by 1% for Gas-fired PP. In all sensitivity cases considered for load factor variation, the lowest LUEC was obtained for advanced HWR technology.

The impact of selected technologies lifetime variation on LUEC (for 10% annual discount rate) was obtained by considering a variation in power plants life time of ±5% and ±10%, respectively, comparatively with the initial assumed life times. The results are presented in Table V-21.

TABLE V-21. SENSITIVITY OF LUEC ($/MWh) TO LIFETIME VARIATION

Technology	-10 years	-5 years	0	+5 years	+10 years
Advanced PWR	59.24	59.09	59.00	58.95	58.92
Advanced HWR	49.14	49.01	48.93	48.88	48.85
Coal-fired PP	67.18	66.98	66.89	66.86	66.85
Gas-fired PP	73.59	73.31	73.27	73.32	73.39

It can be noticed that for all considered technologies the power plants lifetime variation has a very low impact (less than 0.5% for a discount rate of 10% per year) on LUEC. Considering different values for the annual discount rate, the impact of power plants lifetime on LUEC was still very low, LUEC value changing by less than 3% for 5% discount rate, and less than 0.01% for 15% discount rate, respectively. The lowest LUEC value was obtained for advanced HWR technology.

The sensitivity of LUEC (for 10% annual discount rate) to construction time variation by ±6 months and ±12 months, respectively, comparatively with the initial assumed construction times, was studied. For the LUEC sensitivity compilations, the construction time variation determined consequently the corresponding investment schedule modification. The results are presented in Table V-22 and Fig. V-82.

TABLE V-22. SENSITIVITY OF LUEC ($/MWh) TO CONSTRUCTION TIME VARIATION

Technology	-12 months	-6 months	on time	+6 months	+12 months
Advanced PWR	55.99	57.91	59.00	61.05	63.14
Advanced HWR	46.27	47.97	48.93	50.74	52.58
Coal-fired PP	64.72	66.53	66.89	67.73	68.09
Gas-fired PP	72.53	73.25	73.27	73.89	74.06

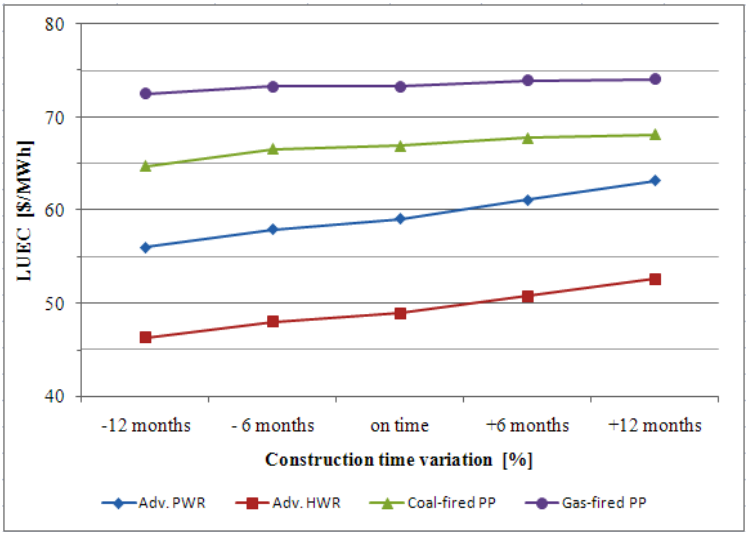

FIG. V-82. Impact of construction time variation on LUEC, $/MWh.

LUEC increases the most for the nuclear technologies, as the construction is delayed. The greatest impact is obtained for capital intensive technologies (nuclear technologies), as follows: 6 months delay in construction lead to LUEC increasing by 3-4%, 12 months delay in construction leading to LUEC increasing by 7%; construction time shorter than the initially assumed one is translated in LUEC decreasing by 2% for 6 months shorter construction time and by 5-6% for 12 months shorter construction time, respectively. For non-nuclear technologies, the impact of construction time on LUEC is rather small, namely: LUEC value increases/decreases by 1% for 6 months delay/shorter time and by 2% for 12 months delay/shorter time, respectively. Gas-fired technology is characterized by the lowest impact of construction time on LUEC. Advanced HWR technology continues to have the lowest LUEC.

In order to examine the impact of investment schedule on LUEC (for 10% annual discount rate), different investment schedule options (ISO) were considered beside the initially assumed uniform investment schedule, [V-23, V-27] as shown in Table V-23. The additional ISO were, as follows: the investment schedules selected in a Canadian study on nuclear technology competitiveness comparatively with Coal- and Gas-fired PP [V-24], the option with 80% from investment in the first half of construction period and the rest of 20% in the second half, the option to do all investment from the beginning of PP construction, the option with 20% from investment in the first half of construction period and the rest of 80% in the second half. Table V-24 and Fig. V-83 present the results obtained in studying the LUEC sensitivity to Investment.

TABLE V-23. OPTIONS CONSIDERED FOR THE INVESTMENT SCHEDULE (share/year)

Investment option / Technology	Year before operation						
	0	1	2	3	4	5	6
Uniform investment schedule, [V-23, V-27] (ISO-1)							
Nuclear technologies	0	0.16	0.16	0.17	0.17	0.17	0.17
Coal-fired PP	0	0.25	0.25	0.25	0.25		
Gas-fired PP	0	0.5	0.5				
Investment schedule given in [V-24] (ISO-2)							
Nuclear technologies	0.051	0.072	0.120	0.196	0.271	0.210	0.080
Coal-fired PP	0	0.159	0.341	0.308	0.161	0.031	
Gas-fired PP	0	0.5	0.5				
80% of investment in 1st half of construction period; 20% in the 2nd half (ISO-3)							
Nuclear technologies	0	0.06	0.06	0.06	0.27	0.27	0.28
Coal-fired PP	0	0.1	0.1	0.4	0.4		
Gas-fired PP	0	0.2	0.8				
All investment done in the beginning of construction (ISO-4)							
Nuclear technologies	0	0	0	0	0	0	1
Coal-fired PP	0	0	0	0	1		
Gas-fired PP	0	0	1				
20% of investment in 1st half of construction period; 80% in the 2nd half (ISO-5)							
Nuclear technologies	0	0.28	0.27	0.27	0.06	0.06	0.06
Coal-fired PP	0	0.4	0.4	0.1	0.1		
Gas-fired PP	0	0.8	0.2				

TABLE V-24. SENSITIVITY OF LUEC ($/MWh) TO INVESTMENT SCHEDULE

Technology	ISO-1	ISO-2	ISO-3	ISO-4	ISO-5
Advanced PWR	59.00	58.74	63.92	72.84	53.70
Advanced HWR	48.93	48.70	53.27	61.14	44.25
Coal-fired PP	66.89	67.01	68.19	70.26	65.59
Gas-fired PP	73.27	73.27	73.71	74.01	72.82

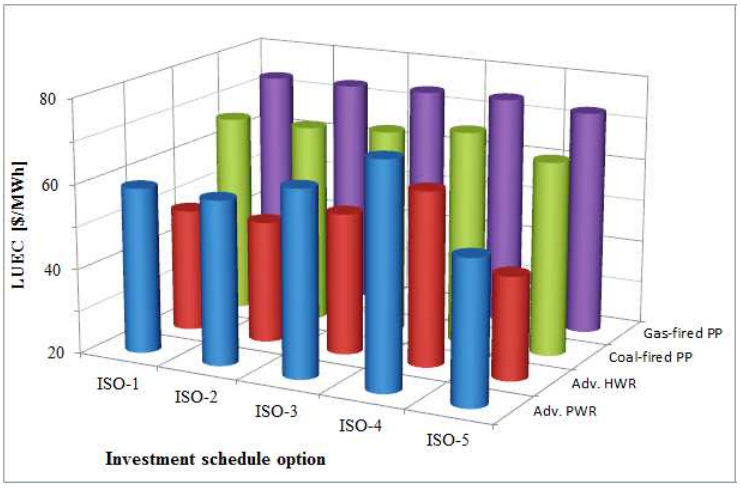

FIG. V-83. Impact of investment schedule option on LUEC, $/MWh.

For ISO-1 (uniform investment schedule) and ISO-2 (investment schedule proposed by Canadian Energy Research Institute in the study on LUEC comparison of alternate technologies for baseload generation in Ontario, [V-24]), the difference between LUEC values is very small, less than 0.5% for nuclear technologies and less than 0.2 for Coal-fired PP; for Gas-fired PP the proposed investment schedule being the same, LUEC obtained is the same.

LUEC increases the most for the capital intensive technologies (see also Fig. V-84), as the investment share becomes higher in first half of the construction period, the greatest LUEC values being obtained for the ISO-4 (assumes that all investment is done from the beginning, in 1st year of construction).

In nuclear technologies case, LUEC for ISO-4 is ~25% greater than LUEC characterizing ISO-1 and ISO-2, LUEC for ISO-3 being ~ 9% greater than LUEC characterizing ISO-1 and ISO-2. In the case of Coal-fired PP, LUEC for ISO-4 is 5% greater than LUEC characterizing ISO-1 and ISO-2, LUEC for ISO-3 being only 1% greater than LUEC characterizing ISO-1 and ISO-2. The lowest changes in LUEC value for different options of Investment schedule are obtained in the case of Gas-fired technology: LUEC for ISO-4 is 1% greater than LUEC for ISO-1 and ISO-2; LUEC for ISO-3 is 0.6% greater than LUEC for ISO-1 and ISO-2.

LUEC lowest values were obtained for ISO-5 (assumes that only 20% of investment is done in the first half of construction period, the rest of 80% being inserted in the second half). In the nuclear technologies case, LUEC for ISO-5 is reduced by 10% comparatively with LUEC obtained considering ISO-1 and ISO-2.

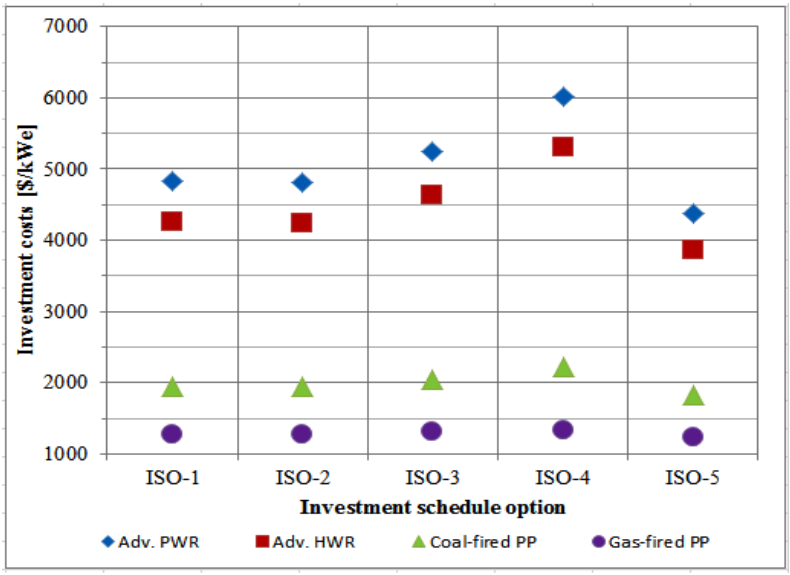

FIG. V-84. Impact of investment schedule option on Investment costs, $/kW(e).

Considering ISO-4 applicable, the investment costs (include overnight costs and IDC) for the nuclear technologies are more rapidly increasing (by 25%) comparatively with the ones characterizing the non-nuclear sources of energy (by 15% for Coal-fired PP and by 5% for Gas-fired PP, respectively). The lowest investment costs are obtained for all considered technologies, if apply ISO-5.

The sensitivity analysis was performed for the defined alternate technologies considering the variation of discount rate, fixed O&M costs, Overnight costs, load factor, Life time, construction time and investment schedule. For all considered parameters, the highest impact was obtained for capital intensive technologies, advanced PWR and advanced HWR,

the lowest impact being obtained for Gas-fired PP. In most of the sensitivity cases, the lowest LUEC value was obtained advanced HWR.

The variation of annual discount rate has the highest impact on LUEC. Considering as reference the initially assumed discount rate (10% per year), the impact of variation of discount rate on calculated LUEC was, as follows: for a discount rate of 5% per year, LUEC characterizing the nuclear technologies was 90%-95% smaller, LUEC for Coal-fired PP was 14% smaller and LUEC for Gas-fired PP was 0.6% smaller than LUEC reference value, respectively; for a discount rate of 15% per year, LUEC characterizing the nuclear technologies was 70% greater, LUEC for Coal-fired PP was 18% greater and LUEC for Gas-fired PP was 0.8% greater than LUEC reference value, respectively.

The lowest impact on LUEC is due to PP life time variation, the difference in calculated LUEC for nuclear technologies being less than 3% for a discount rate of 5% per year, less than 0.5% for a discount rate of 10% per year and less than 0.01% for a discount rate of 15% per year, respectively.

REFERENCES TO ANNEX V

[V-1] Terms of Reference for INPRO collaborative project "Synergistic nuclear energy regional group interactions evaluated for sustainability" (SYNERGIES)

[V-2] ROMANIAN GOVERNMENT Decision no. 1259, National Strategy for the Development of the Nuclear Field in Romania and the Plan of Action for the Implementation of this Strategy, Official Bulletin no. 851 / 26.11.2002.

[V-3] ROMANIAN GOVERNMENT Decision no. 1069, Romanian Energy Strategy for 2007-2020, Ministry of Economy and Finances, Official Bulletin no. 781 / 19.11.2007.

[V-4] Energy Roadmap for Romania, approved by ROMANIAN GOVERNMENT Decision no. 890/2003, 2003.

[V-5] Strategy for Using Renewable Energy Sources, approved by ROMANIAN GOVERNMENT Decision no. 1535/2003, 2003.

[V-6] National Renewable Energy Action Plan - Romania, transposing Directive No. 2009/28/EC of the EUROPEAN PARLIAMENT AND COUNCIL of 23 April 2009 on promotion of use of energy from renewable sources, 2010.

[V-7] Overview of the Romanian Electricity Sector: Development and Investment Opportunities, report prepared by KPMG Romania, March 2012.

[V-8] ROMANIAN ENERGY REGULATORY AUTHORITY reports on Electricity market monitoring, available on the official website: www.anre.ro

[V-9] INSTITUTE OF ENERGETIC STUDIES AND DESIGNS, Study regarding collection/selection and systematization of data needed for sustainability comparative evaluation for alternative scenarios of Romania's nuclear infrastructure development on long and very long term, elaborated in the framework of national project "Nuclear Energy System Assessment in Romania using INPRO Methodology", code 8118/2014-1-S0071921-B2, ISPE (2014).

[V-10] EUROPEAN UNION, EU Energy in Figures, Statistical pocketbook 2014, ISSN 1977-4559, EU, 2014.

[V-11] ROMANIAN GOVERNMENT Decision no. 1069, Romanian Energy Strategy for 2007-2020, Ministry of Economy and Finances, Official Bulletin no. 781 / 19.11.2007.

[V-12] ROMANIAN NATIONAL ENERGY REGULATORY AUTHORITY, The Energy

Sector in Romania. Present and future, RNERA, 2012.

[V-13] MINISTRY OF ECONOMY OF ROMANIA, Elements of Energy Strategy for 2011-2035, under public debate, 2014: https://www.iaea.org/INPRO/8th_Dialogue_Forum/Breakout_Resource_04_Margeanu.pdf

[V-14] "Study regarding the development directions of Romanian Electricity Transport Network for 2011-2035 – as part of the national energy strategy ", elaborated by Institute of Energetic Studies and Designs (ISPE), 2012

[V-15] ORGANISATION OF ECONOMIC COOPERATION AND DEVELOPMENT, NUCLEAR ENERGY AGENCY, AND INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2011: Resources, Production and Demand, NEA No.7059, ISBN 978-92-64-17803-8, 2012.

[V-16] ORGANISATION OF ECONOMIC COOPERATION AND DEVELOPMENT, NUCLEAR ENERGY AGENCY, AND INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2014: Resources, Production and Demand, NEA No.7209, ISBN 978-92-64-17803-8, 2014.

[V-17] Romania has more Uranium than it was presumed, "Truth" newspaper, May 2013.

[V-18] INTERNATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Fuel Cycle Profiles", Second edition, IAEA Technical Report Series No. 425, Vienna (2005).

[V-19] INTERNATIONAL ATOMIC ENERGY AGENCY, Romania – Country Nuclear Power Profile, updated 2012, IAEA official website: www.iaea.org

[V-20] NATIONAL AGENCY FOR MINERAL RESOURCES, NATIONAL URANIUM COMPANY, Strategy for Mining Industry for the period 2012-2035, elaborated by Ministry of Economy, Commerce and Business Environment, 2012.

[V-21] Declaration of the Nuclear Fuel Plant Manager, "Bursa" newspaper, 2009.

[V-22] NuclearElectrica National Society website, Nuclear Fuel Plant Pitesti: www.nuclearelectrica.ro

[V-23] ORGANISATION OF ECONOMIC COOPERATION AND DEVELOPMENT NUCLEAR ENERGY AGENCY AND INTERNATIONAL ENERGY AGENCY, Projected Costs of Generating Electricity, 2010 Edition, ISBN 978-92-64-08430-8, Paris (2011)

[V-24] CANADIAN ENERGY RESEARCH INSTITUTE, Levelised Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario, CERI (2004).

[V-25] ORGANISATION OF ECONOMIC COOPERATION AND DEVELOPMENT NUCLEAR ENERGY AGENCY, Nuclear Energy Today, 2nd Edition, NEA No.6885, ISBN 978-92-64-99204-7, Paris (2012).

[V-26] ORGANISATION OF ECONOMIC COOPERATION AND DEVELOPMENT NUCLEAR ENERGY AGENCY "The Economics of the Back End of the Nuclear Fuel Cycle", NEA No.7061, Paris (2013).

[V-27] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics, IAEA Nuclear Energy Series No. NG-T-4.4, Vienna (2014).

[V-28] G. VALCEREANU, Performance, cost and emission reference data for electric power plants, prepared for IAEA in the frame of Contractual Service Agreement (CSA) 200844163 (30 December 2008 - 31 May 2009).

[V-29] D.E. SHROPSHIRE ET AL, Advanced fuel cycle cost basis 2009, Idaho National

Laboratory Report INL/EXT-07-12107 (2009): www.inl.gov/technicalpublications/Documents/4536700.pdf

[V-30] NUCLEARELECTRICA NATIONAL SOCIETY, Management Plan, 2013: http://www.nuclearelectrica.ro/wp-content/uploads/2014/06/Nuclearelectrica-Management-Plan.pdf

[V-31] ROMANIAN NATIONAL INSTITUTE OF STATISTICS, Energy Balance and Energy Equipment structure for 2010, ISSN 2067-1245, ISSN-L 1584-7691, 2011.

[V-32] ROMANIAN NATIONAL INSTITUTE OF STATISTICS, Energy Balance and Energy Equipment Structure for 2012, ISSN 2067-1245, ISSN-L 1584-7691, 2013.

[V-33] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling Nuclear Energy Systems with MESSAGE: A Users' Guide. IAEA Nuclear Energy Series No. NG-T-5.2, Vienna (2016).