ANNEX I.

ASSESSMENT OF IMPACT OF FUEL CYCLE BACK END OPTIONS ON LEVELIZED UNIT ELECTRICITY COST OF PRODUCED ELECTRICITY BASED ON NUCLEAR FUEL CYCLE IN ARMENIA

I-1. INTRODUCTION

Spent nuclear fuel management is an important part of the nuclear fuel cycle (NFC) development. Nowadays, different options for treatment of spent nuclear fuel (SNF) are offered. An important factor for selecting a strategy for final SNF management is the economic evaluation that allows a comparative analysis of different scenarios of NFC and/or reveals the influence of the different components of the NFC on the entire fuel cycle cost.

Finding a solution for SNF may determine the direction of implementation of the national strategy for the further development of nuclear power generation. Due to the amounts of accumulated SNF and the lack of generally accepted solutions for its optimal final management long-term assessment is necessary to determine the impact on the cost of electricity produced by NPPs in the various NFC scenarios.

Common approaches for assessing the impact of the final stage of nuclear fuel cycle on the levelized unit electricity cost (LUEC) of electricity when considering "idealized model" are presented in the OECD report [I-1]. It is shown that the assessment of the final stage impact of the NFC requires determining the value of the entire fuel cycle, including the construction costs of nuclear power plants, nuclear fuel procurement, maintenance, storage and disposal of spent nuclear fuel.

This study is performed under the SYNERGIES Task 1 scenario “Russia, Ukraine and Armenia study on the VVER-FR collaborative deployment scenarios aimed at solving the problem of accumulating spent fuel inventory to match FR deployment needs”.

In accordance with the decisions made on the regional meeting on SYNERGIES project in Armenia Yerevan, November 2013 in this study an economic evaluation of impact of configuration options of final stage of NFC on the LUEC was carried out.

For the reference scenario an option for long-term storage of spent fuel at the NPP site with no restrictions on SNF accumulation has been considered.

For sensitivity analysis the study considers the options for removal of SNF from the NPP site to another country for reprocessing and final disposal with different transportation types (truck, railway, air transport).

I-2. OBJECTIVES OF THE STUDY

In accordance with decisions made on the regional meeting on SYNERGIES project in Yerevan (Armenia, November 2013), as well as based on some discussions done later the following objectives have been finally formulated:

- Collection and analysis of baseline information on the current status and projections of the development of nuclear power in Armenia;
- Development of a model for NFC options, including:
  - SNF storage at the NPP site;

- SNF storage at the NPP site and transfer of SNF from NPP site to geological disposal;
- SNF storage at the NPP site and Export of SNF from Armenia with different transportation types (truck, railway, and air transport) for reprocessing and final disposal in another country.

– Assessment of the impact of SNF management cost on the cost of electricity produced by NPP.
– Development of potential recommendations on optimizing the cost of spent nuclear fuel management, and for sustainable development of nuclear generation in Armenia.

The main goal is to analyse the impact of the NFC options on the LUEC of electricity produced by the NPP in Armenia.

Chapters below are shortly describing current situation of Armenian Energy System, briefly introducing demand forecast for 21st century and power plants expected for covering that demand, and presenting the main results and obtained findings of this study.

I-3. BRIEF DESCRIPTION OF ARMENIAN ENERGY SYSTEM

I-3.1. Energy resources

Hydro resources are the main domestic energy carrier. Their theoretical potential is valued at 21.8 billion kWh, with the technically available potential of 7-8 billion kWh and economically sound hydro potential of about 3.6 billion kWh. 1.5 billion kWh of that potential is already applicable, and implementation of the rest part is expected during the next 15 years.

Another source of energy in Armenia is wind power. Theoretical potential is assessed to be 10.7 GWh, technically available potential in case of 10% of power ratio is about 1.1 GWh. Implementation of wind energy potential is expected for realization during the following 15-20 years.

The potential of solar energy is great. Utilization of that kind of energy, especially with the purpose of thermal energy generation can significantly decrease the need of imported energy carriers. The average annual inflow of solar energy per square unit of horizontal surface is 1 720 kWh/m^2, and one fourth of the Republic's territory is exposed to 1 850 kWh/m^2 intensity of solar energy annually.

Utilization in Armenia of biomass, as the source of energy, is not widely spread yet.

Utilization of geothermal resources in Armenia is rather perspective. In case of the positive results of ongoing investigation and potential assessment of geothermal resources as renewable energy resource, it can become attractive either for private investors or for International financial organizations.

The process of investigation of oil and gas availability lasting from 1947 till nowadays, hasn't reveal any of oil or gas mines on the territory of Armenia.

Geological investigations show that there is a certain quantity of fossil fuel on the territory of Armenia, which has no industrial importance for the whole energy sector because its caloricity is rather low, and it can be used for limited demand.

Energy saving is referred to as the own energy reserve. According to the approximate assessment, the application of its full potential can save 20% of the energy consumed. According to the Law on Energy Saving and Renewable Energy, as well as to the programs

of its development and implementation, the application of energy saving is of great importance for the country.

I-3.2. Power sector

I-3.2.1. Power plants

The total installed capacity in Power Sector is about 3 079 MW, of which 2 937 MW is available. System internal peak in 2013 was 1523 MW. The summary of available capacities of power plants in Armenian Power System is presented in the Table I-1.

TABLE I-1. AVAILABLE CAPACITIES OF THE POWER PLANTS IN ARMENIA

Power plant	Capacity, MW(e)
Armenian NPP	375
Hrazdan TPP	720
Yerevan CCGT	220
Sevan-Hrazdan Cascade of HPPs	550
Vorotan cascade of HPPs	400
Small HPPs (<30 MW)	222
Wind Power Plant	2.6

I-3.2.2. Electricity transmission and distribution networks

The Transmission Network consists of 1527 km of 220 kV overhead lines (OL) and 14 substations, as well as 3083 km of 110 kV overhead lines and 119 substations. According to the administrative-economic affiliation, the 220 kV network, as well as about 580 km of 110 kV overhead lines and 18 substations are operated by the High Voltage Network CJSC, and the remaining part of the 110 kV network is operated by the Electric Networks of Armenia CJSC. The Transmission Network is well developed, with a circular structure and is characterized by its extensive capacity. The 220-110 kV networks of Armenia are capable to transmit all the energy within the domestic market and have sufficient potential to wheel significant power within a regional market. Armenia has interconnections with all neighbouring countries.

The country's interconnection with Iran through a new 400 kV double circuits overhead line (HrazdanTPP Tabriz) will be completed at the end of 2018 (with 1000 MW transmitting capacity). In the same period another 400 kV one circuit overhead line (600 MW) between Armenia and Georgia (HrazdanTPP Ksani) will be constructed.

The Distribution Network includes 101 110 kV substations, 110/35/10/6/0.4 kV overhead lines and cables, 278 35 kV substations, 10,625 10(6)/0.4 kV substations and 120 transformers with 1000 kVA and more installed capacity.

I-3.3. Gas distribution system

The gas transmission and distribution systems (including the Abovian Underground Gas Storage facility) are operated by the GaspromArmenia, a Closed Joint Stock Company fully owned by Gazprom of Russia. GaspromArmenia is responsible for import, transportation, storage and supply of gas in the whole territory of Armenia.

The Abovian Underground Gas Storage facility is located near to Yerevan and occupies a site of 140 hectares. Its construction began in 1962 and it has a design capacity of about 190

million m3. It is used mainly for seasonal regulation of the gas supply. The gas is stored in caverns leached in underground salt layers. A total of eighteen wells were drilled. The compressor station has a design injection pressure of 125 atmospheres.

I-3.4. Fuel cycle and waste management

Armenia has no nuclear fuel cycle industry and uses an open nuclear fuel cycle scheme. Up to now, all the nuclear fuel has been supplied by Russia. The ANPP is operating with a three-year fuel cycle. The spent nuclear fuel, before its transfer to the dry storage, is kept in wet nuclear fuel storage cooling pools in the reactor building.

In 2000, the construction of the first stage of the spent fuel dry storage was completed. The construction was commissioned by the French firm Framatom and financed by the French Government. The spent fuel dry storage facility has been put into operation, and all the transfers of spent fuel is performed according to the requirements of the license given by the Armenian Nuclear Regulatory Authority. Now, all the volume of the first stage of storage is filled with spent fuel.

In 2005, an agreement was signed with French company TN International for construction of the additional three stages of the dry storage facility. The financing was allocated from the State budget of RA. The second stage was completed and put into operation in spring 2008 and the first part of the spent nuclear fuel has been transferred into dry storage. The third stage of spent fuel dry storage construction is planned to be started in 2015.

The final spent fuel and high-level radioactive waste treatment and disposal concept will be developed and included in the ANPP Decommissioning Program.

According to the ANPP design, the annual radioactive waste generation in Unit 2 is: 308 m3 of solid LLW; 1.5 m^3 of solid MLW; 0.3 m^3 of solid HLW; 108 m^3 of liquid MLW. At the ANPP site, there are storages for both solid and liquid radioactive waste.

High-level waste is stored in a special area of the Reactor building. The storage area consists of 380 cells. The storage capacity is 78.34 m^3.

Medium-level radioactive waste is stored in the Special Building. Storage capacity is 1001.22 m^3. Also, the deep evaporating facility containers are stored temporarily on the upper unheated floor of the Special Building. Its effective storage volume is 655 m^2 (3 000 containers).

Liquid waste is stored in the Special Building. Liquid wastes (evaporator residues) generated in the evaporators during drain water reprocessing are collected in the evaporator residue tank.

The storage facility for low-level radioactive waste consists of two compartments, each measuring 27x36x8.9 m. The total storage volume is about 17 050 m^3.

I-4. ARMENIAN DEMAND FORECAST FOR 21ST CENTURY AND POWER TECHNOLOGIES CONSIDERED FOR INVESTIGATION

To analyze a long term fuel cycle strategy it is necessary to predict the possible over-long term demand of the country, to consider export/import opportunities of power system, to identify the technologies by the use of which that demand and interconnection flows can be covered, etc. This chapter represents the forecast of Armenian electricity demand over 21st century and available/ considered electricity generation technologies to meet the consumption requirements.

Historically, the average annual growth rate of electricity consumption in Armenia during the last 10 years (2003-2013) was recorded at the level of 3.72%/year. This rate has

been accepted as a base rate for the projection years but with de-escalation rate of "minus" 0.05% per annum. Based on this assumption, the calculated average annual demand growth rate for whole planning period (up to 2100) is equal to 1.54% per year.

Today, Armenia has signed a long-term swap agreement with Iran according to which Armenia should export electricity to Iran at the level of 6 900 million kWh per year instead of imported natural gas from Iran till 2027. It is assumed that this agreement will be prolonged up to the end of the simulation period. So after 2027, export to Iran will be kept at the level of the last contractual year. In the same time, it is assumed that import of the electricity from Georgia will be constant at the level of 2013.

The results of calculations made according to the above assumptions are summarized in Fig.I-1.

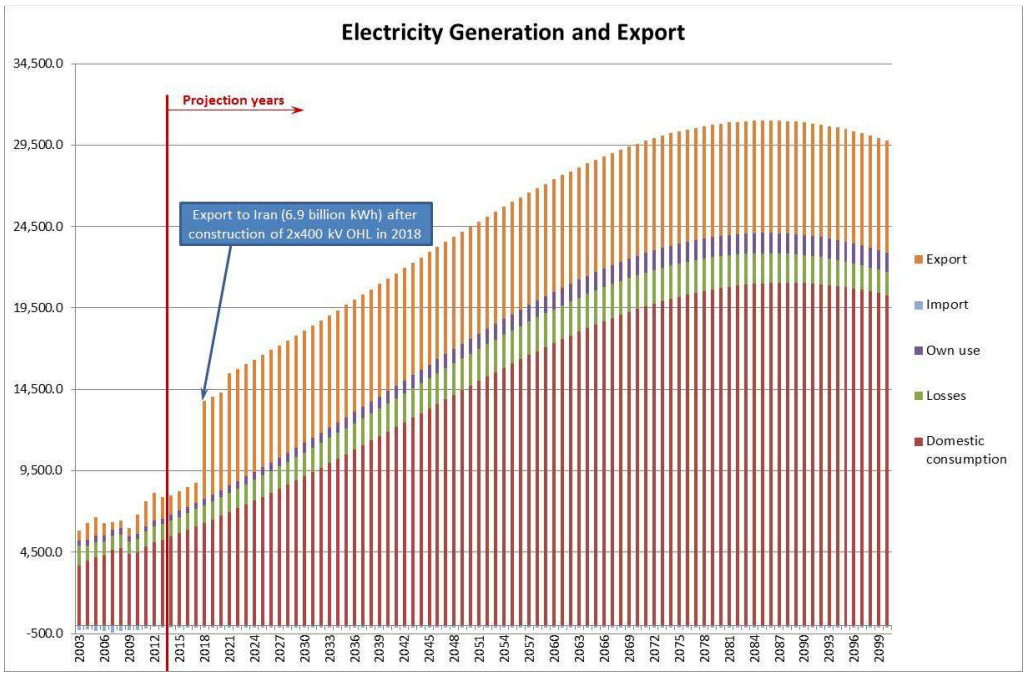


FIG. I-1. Structure of electricity generation.

To ensure all the needs of domestic consumption, as well as to secure obligations of electricity export during this century around 3340 MW of additional capacities will be required. Three types of generation capacities are foreseen for Armenia, namely thermal (natural gas-fired) plants, renewables and nuclear technologies.

Today, existing gas transportation system is under-loaded and additional gas pipelines are not foreseen for construction. It is expected that existing capacities will be used to cover growing domestic natural gas demand. Due to this it is assumed that old thermal units will be replaced by the same capacities and no additional thermal units will be installed.

As it was mentioned before, Armenia has very limited domestic sources for electricity generation which are only renewables. According to the Power system development national strategy all of national economically feasible renewable energy sources (RES) should be utilized in Armenia till 2035 (Fig. I-2). Table I-2 provides the list of proven RES and their implementation time-frame. Figure I-1 presents structure of RES generation over the period of their introduction into the system (till 2035). It is assumed that such a structure will be kept up to the end of whole planning period (the end of 21st century). As it can be seen from Table

I-2, only 714 MW of new renewable energy sources from the requested 3340 MW additional capacities are available in the country.

TABLE I-2. LIST OF NEW RENEWABLE ENERGY SOURCES

Technology	Installed capacity, MW(e)	Annual generation potential, mln. kWh/year	Implementation year
Solar PV	40 30	98 32	Up to 2020 Up to 2035
Small HPPs	148	71	Up to 2021
Wind Farms	200	480	Up to 2027
Shnokh HPP	70	270	2021
Loriberd HPP	66	212	2021
Meghri HPP	130	720	2032
Geothermal PP	30	194	2021
Total	714	1960	

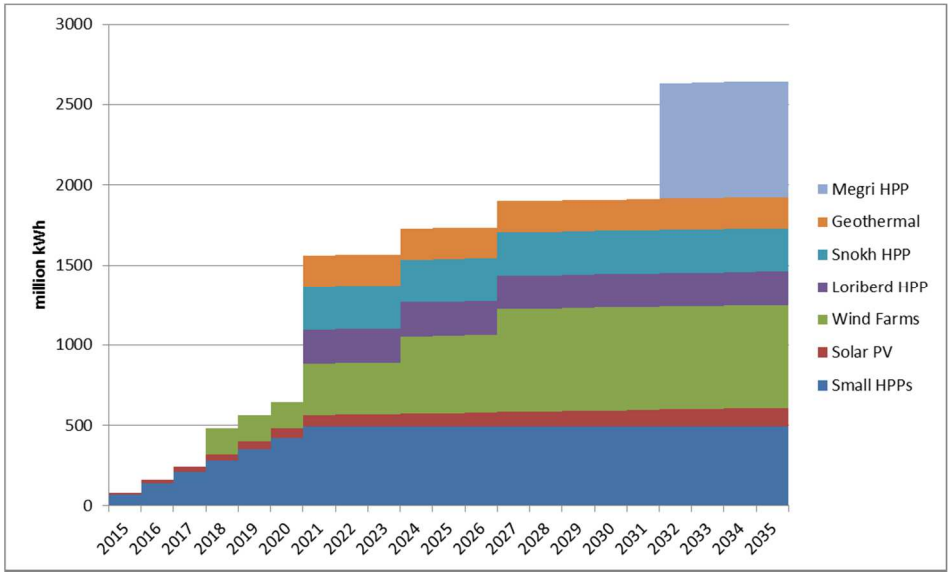


FIG. I- 2. Structure of electricity generation by RES.

Finally, to cover the growing electricity demand and to provide the contractual obligations with Iran only the implementation of nuclear technologies can be proposed. It is assumed that VVER-1000 unit will replace the existing Armenian NPP in 2026. Starting from 2035 six reactors of VBER-300 will come into operation for each decade. The last (sixth) VBER-300 will be introduced into the power system in 2095.

So, based on the above-mentioned issues, the structure of electricity generation by different types of power plants for a whole planning period will have a shape as shown in Fig. I-3 below.

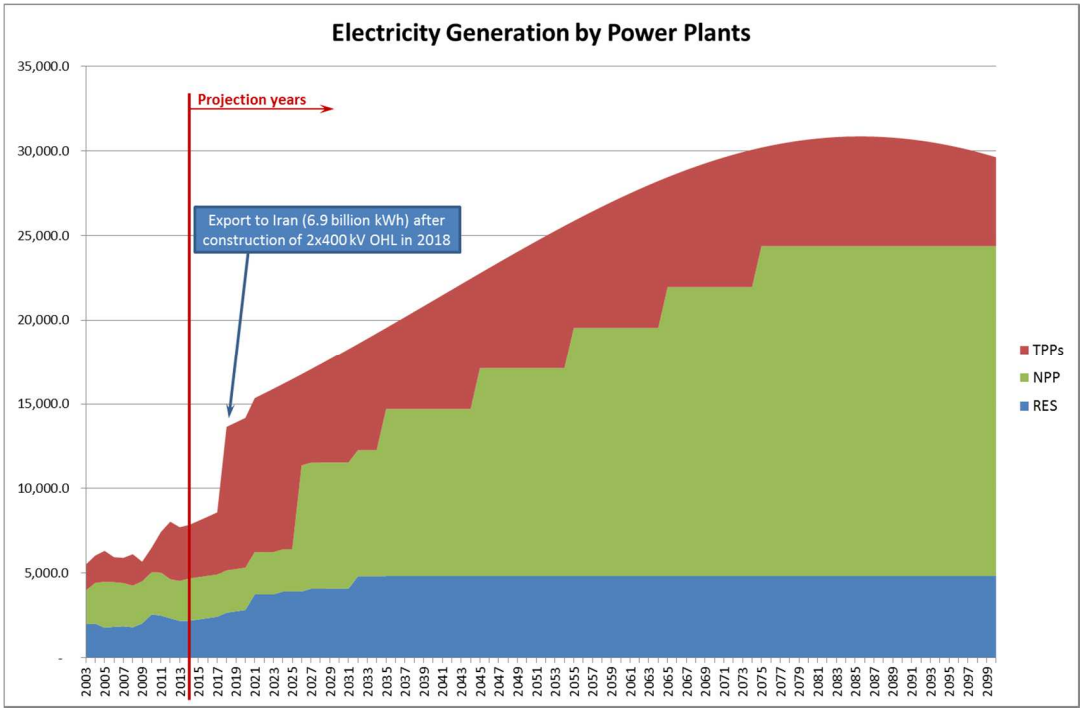


FIG. I-3. Generation of electricity by types of power plants.

I-5. APPROACHES AND ASSUMPTIONS TO THE ASSESSMENT OF THE REALIZATION OPTION IMPACT OF NFC FINAL STAGE ON THE PRESENT VALUE OF ELECTRICITY

I-5.1. Spent fuel

Currently, the spent fuel of VVER-440 reactor is stored in the Spent Fuel Dry Storage (SFDS) stage 1 with capacity of 616 spent nuclear fuel assemblies and in SFDS stage2 with capacity 560 spent nuclear fuel assemblies. 304 nuclear fuel assemblies are located in the cooling pool of the first unit and 305 spent nuclear fuel assemblies in the cooling pool of the second unit. Totally there are 1785 nuclear fuel assemblies from which 1176 spent nuclear fuel assemblies of SNF are located in the SFDS that is 205.632 tons(HM) (1785 × 115.2 = 205 632 kg).

SFDS-1 and SFDS-2 have the design capacity of 616 and 672 assemblies respectively. SFDS-3 is being built with capacity of 672 assemblies. After 2020 it is need to input in operation SFDS-4 with capacity of 672 spent nuclear fuel assemblies. The last “lot” is going to be stored in SFDS-5 with capacity of 560 spent nuclear fuel assemblies.

I-5.2. Nuclear fuel cycle options

I-5.2.1. Open fuel cycle

Light water VVER-440 reactor will operate till 2026 and in 2026 VVER-1100 will be put into operation. Enrichment of VVER-440 fuel is 3.82%. It is assumed that Unit Capability Factor (UCF) is 72% and permitted maximum electrical capacity is 92% of installed capacity 407.5 MW.

New unit will be put into operation in 2026 and it is expected UCF will be at 85 %. The following different management options of SNF are under the consideration (Table I-3).

The LUEC of nuclear generation is determined in the scenarios depending on the final stage in each option.

The models structures for NFC options (Table I-3) are presented in Figs. I-4 - I-7:

- the diagram of model for the option with the “Construction of SFDS” is shown in Fig. I-4;
- the option with the “Construction of SFDS at the NPP site and after 50 years SNF storage, for reprocessing and disposal export of SNF from the NPP site to another country” is presented in Fig. I-5;
- the scheme for the option of “Construction of SFDS at the NPP site and after 50 years SNF storage, transfer SNF to geological disposal” is given in Fig. I-6;
- configuration of “For reprocessing and final disposal in another country, export of SNF from the NPP site”, new/old fuel, construction of small reactors” is shown in Fig. I-7.

Variable parameters and the variation range of those parameters are shown in Table I-5.2.

TABLE I-3. SNF MANAGEMENT CONFIGURATION OPTIONS

Management of SNF without construction small reactors	Construction of SFDS at the NPP site (*Reference Scenario)* Construction of SFDS at the NPP site and export of SNF from the NPP site to another country by railway for reprocessing and disposal of SNF after 50 years storage at the NPP site Construction of SFDS at the NPP site and transfer SNF to geological disposal after 50 years SNF storage at the NPP site	○ VVER-440, fuel enrichment 3.82%; burn-up 42.66 MW·day/t; ○ SNF of VVER-440 is located in SFDS after the interim cooling in the cooling pool (5 years); ○ VVER-1000, fuel enrichment 4.7%; burn-up 60 MW·day/t; ○ SNF of VVER-1000 will be located in SFDS after the interim cooling in the cooling pool (12 years); ○ operation time of SFDS is unlimited; ○ volume of SFDS is limited by numbers of SNF assemblies of VVER-1000 + VVER-440;
Management of SNF without construction small reactors	Construction of SFDS at the NPP site (*Reference Scenario)* Construction of SFDS at the NPP site and export of SNF from the NPP site to another country by railway for reprocessing and disposal of SNF after 50 years storage at the NPP site Construction of SFDS at the NPP site and transfer SNF to geological disposal after 50 years SNF storage at the NPP site	○ VVER-440, fuel enrichment 3.82%; burn-up 42.66 MWday/t; ○ SNF of VVER-440 is located in SFDS after the interim cooling in the cooling pool (5 years); ○ VVER-1000, fuel enrichment 4.7%; burn-up 60 MW·day/t; ○ SNF of VVER-1000 will be located in SFDS after the interim cooling in the cooling pool (12 years); ○ operation time of SFDS is unlimited; ○ volume of SFDS is limited by numbers of SNF assemblies of VVER-1000 + VVER-440;

TABLE I-3. SNF MANAGEMENT CONFIGURATION OPTIONS (cont.)

Export of SNF from the NPP site to another country by different types transportation for reprocessing and final disposal, old modification fuel, construction of small reactors	Export of SNF by track Export of SNF by railway Export of SNF by air transport	o VVER-1000, fuel enrichment 4,28%, burn-up 48 MWday/t; o removal after the interim storage of SNF in the cooling pool (5 years) and 50 years storage in SFDS; o return of radioactive waste is not considered; o removal rate of SNF corresponds to the annual loading of the reactor(s) (or to the total annual load of the reactors); o construction of small reactors is envisaged.
Export of SNF from the NPP site to another country by different types transportation for reprocessing and final disposal, new modification fuel, construction of small reactors	Export of SNF by truck Export of SNF by railway transport Export of SNF by air transport	o VVER-1000, fuel enrichment 4,7%, o burn-up 60 MWday/t; o removal after the interim storage of SNF in the cooling pool (12 years) and 50 years storage in SFDS; o return of radioactive waste is not considered; o removal pace of SNF corresponds to the annual loading of the reactor(s) (or to the total annual load of the reactors); o construction of small reactors is envisaged.

TABLE I-4. VALUE OF PARAMETER AND THE RANGE OF VARIATION

Parameter	Value
Transportation:	
by truck	100 - 125 USD/kgHM
by railway	40 - 60 USD/kgHM
by air transport	400 - 700 USD/kgHM
Cost of the SFDS construction [I-4], [I-5], [I-6], [I-7]	120 - 170 USD/kgHM
Cost of the geological disposal of SNF [I-4], [I-5], [I-6], [I-7]	500 - 650 USD/kgHM
Cost of the processing without the return of processing waste [I-8]	1500 - 2500 USD/kgHM

Planning period is from 2013 until the unloading year of the last spent nuclear fuel assemblies from SFDS.

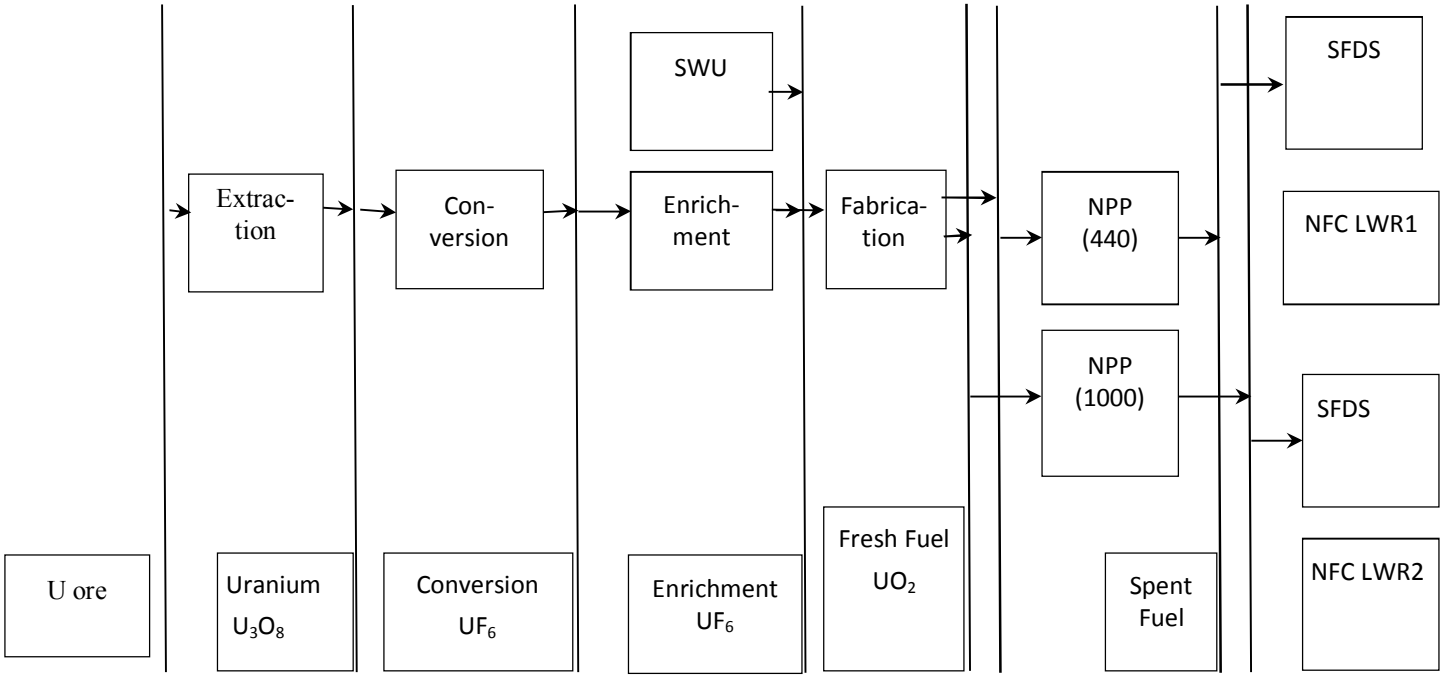


FIG. I-4. Structure of the model "Construction SFDS at the NPP site".

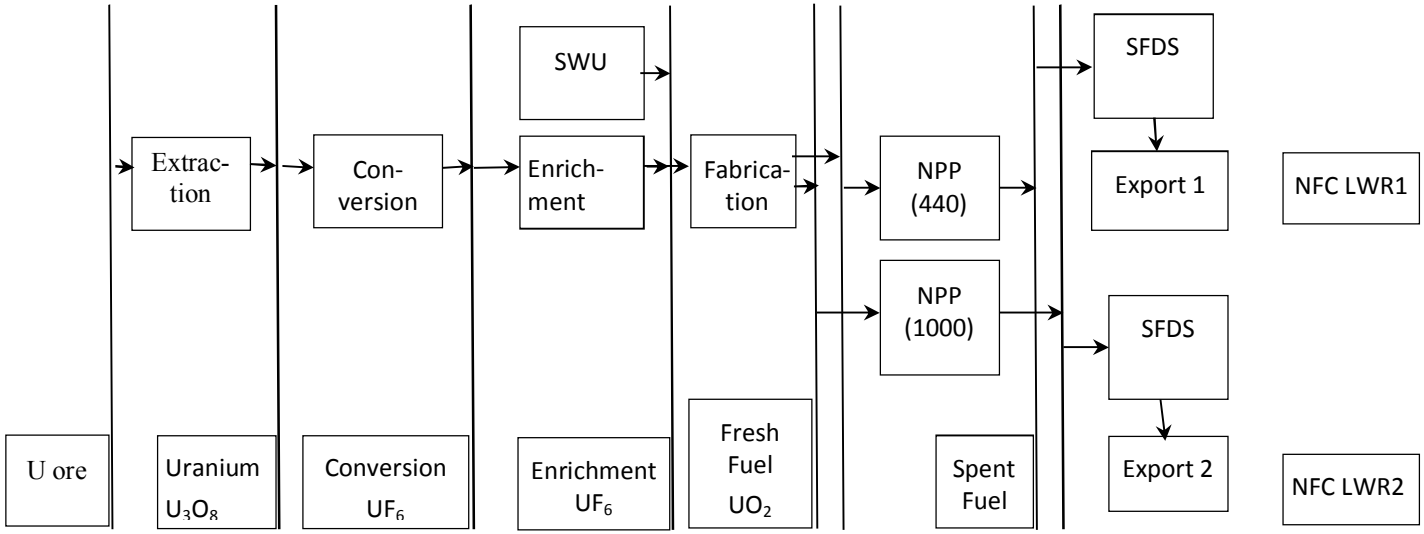


FIG. I-5. Structure of the model "Construction SFDS at the NPP site and export of SNF".

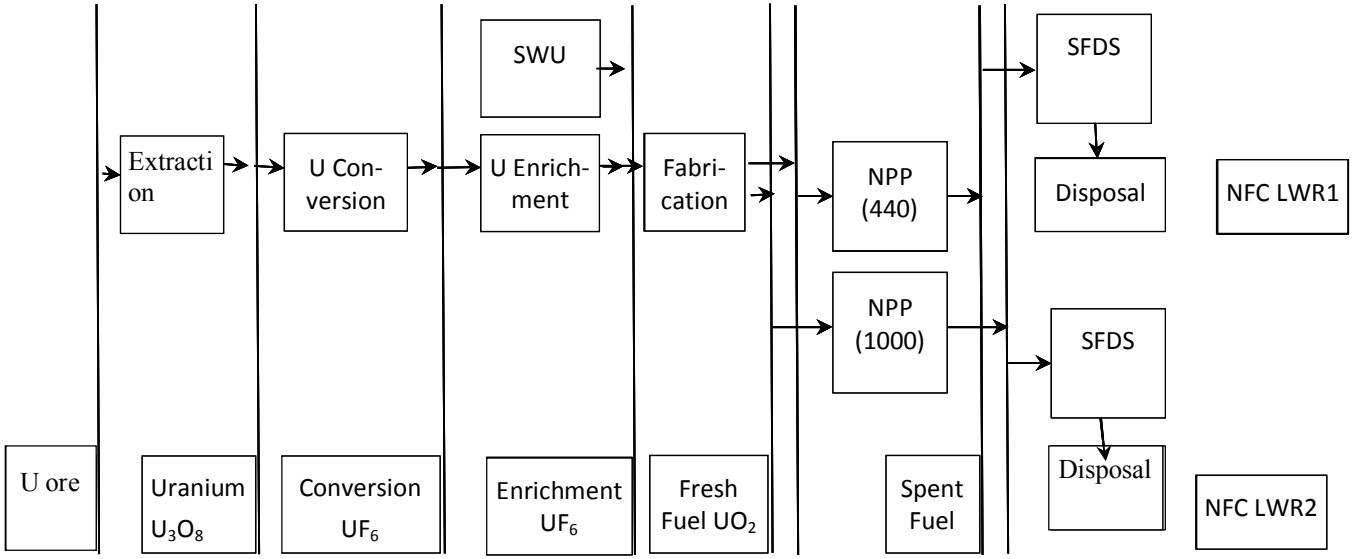


FIG. I-6. Structure of the model "Construction SFDS at the NPP site and transfer of SNF to geological disposal".

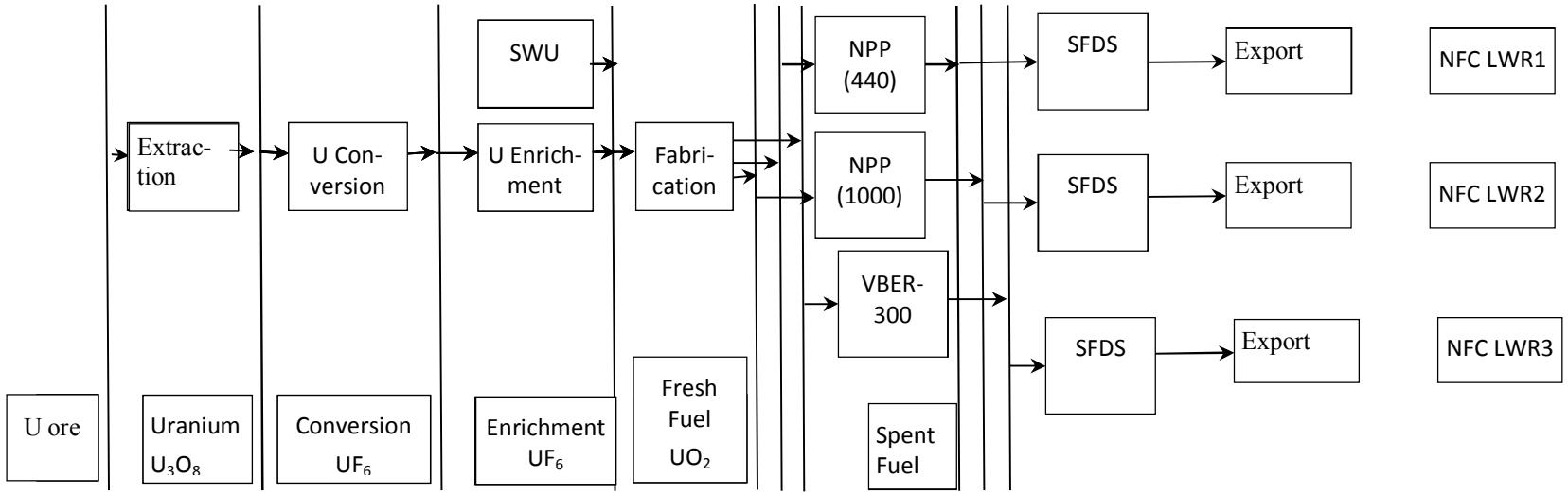


FIG. *I-7.* *Structure of the model "Construction SFDS at the NPP site and export of SNF, (old/new modification of fresh fuel, commissioning of small reactors)".*

I-6. INITIAL DATA

I-6.1. Initial stage of NFC

I-6.1.1. Uranium resources

Uranium resources are considered to be unlimited during the modelling period. The cost of natural uranium is considered at 110 USD/kg.

I-6.1.2. Conversion and enrichment

Historically, the cost of conversion services was varied between 8-15 USD/kgHM [I-2]. This value is assumed to be 7.5 USD/kgHM in the model. Uranium conversion stage is considered as a service.

The process of uranium enrichment is considered as a service with cost 160 USD/SWU purchased on the world market [I-2]. It is assumed that the global market for uranium enrichment services is not limited. Tails assay is 0.25%.

I-6.1.3. Fuel fabrication

Fabrication of fresh fuel for light water reactors is considered as service purchased at the price of 300 USD/kgHM. Average world prices of fuel fabrication for pressurized water reactors were 250 USD/kgHM in 2008 [I-3].

For VVER-440 unit were used real economic data from tariff.

I-6.2. Light water reactors

Three types of light water reactors are considered in the scenarios: VVER-440, VVER-1000 (Project B-392), and VBER-300. It is planned to commission only one VVER-1000 reactor in 2026. After that a series of small reactors (VBER-300) are expected to be implemented up to the end of the century. The technical and economic data of considered reactors are presented in Table I-5 [I-9].

TABLE I-5. TECHNICAL AND ECONOMIC PARAMETERS OF THE REACTORS USED IN THE MODEL

Parameter	VVER-440	VVER-1000	VBER-300
Heat capacity, MW	1375	3000	912
Electric capacity, MW	375	1060	325
Efficiency, %	32	35	
ICUF, %	72	85	85
Fuel enrichment,%	3.82	4.28/4.7	5%
Average burn-up for fuel assemblies, GWday/t	42.66	48/60	60
The first load, tHM	40.2048(3)	68.4437/72.844(1)	22.2144
Annual reload, tHM	8.9856(3)	20.155/16.088(2)	4.44
Overnight cost USD/kW	-	5000	5500
Fixed costs, USD/kW	50	50	50
Variable costs, USD/MWh	1	1	1
Operation lifetime, years	13(4)	60	60
Construction period, years	-	6	5
Fuel fabrication, USD/kg	300	300	300
Construction of SFDS, USD/kg	150	150	150
The cost of disposal of spent nuclear fuel, USD/kg	600	600	600

(1) The first load: Old Fuel - 163 pcs. x 494 kg x 0.85 = 68 443.7 kg; New Fuel - 163 pcs. x 545 kg x 0.85 = 72 844.0 kg
(2) Annual reload: Old Fuel - 36 pcs. x 545 kg x 0.85 = 16 088 kg; New Fuel - 48 pcs. x 494 kg x 0.85 = 20 155kg
(3) The first load: 115.2 kg × 349 pcs = 40 204.8 kg; Annual reload: 115,2 × 78 pcs = 8985.6 kg
(4) From the starting year (2013) to the decommissioning year (2026) of the modelling.

Four different nuclear fuels have been modelled in this study. Their parameters are presented in Table I-6 [I-9].

TABLE I-6. VALUE OF THE NUCLEAR FUEL PARAMETERS USED IN THE MODEL

Item	VVER-440	VVER-1000 (new)	VVER-1000 (old)	VBER-300
Average enrichment,%	3.82%	4.7%	4.28%	5%
Burn-up, MWday/kg	42.66	60.0	48.0	60.0
Weight of UO2 in fuel assemblies, kg	115.2	545	494	N/A
Number of assemblies in the reactor, pieces	349	163	163	N/A
Fuel assemblies annual load, pieces	78	36	42	N/A

The following schedule of implementation of new nuclear units (TABLE I-7.) is proposed in Chapter 4 which is based on the requirement to cover the forecasted demand.

TABLE I-7. SCHEDULE OF NEW NUCLEAR CAPACITIES COMMISSIONING

Reactor	Year of commissioning
VVER-1000	2026
VBER-300	2035, 2045, 2055, 2065, 2075, 2095

In this assessment, discount rate is taken at 10% for all the considered scenarios.

I-6.3. Management of spent nuclear fuel

I-6.3.1. Current status

Currently, 616 assemblies are stored in SFDS-1 and 560 assemblies are stored in SFDS-2. In the cooling pool (CP) of the first unit there are 304 assemblies and in the cooling pool of the second unit 305 assemblies. So, the total number of stored SNF assemblies amounts to 1785 units. To simplify the model, it is assumed that the weight of uranium in the assembly is 115.2 kg, it is assumed that 1785 × 115.2 = 205 632 kgHM has already accumulated.

I-6.3.2. Spent nuclear fuel dry storage

It is assumed that storage will be exploited for the whole volume of SNF from VVER-440 and VVER-1000. The SFDS construction cost is considered to be at the level of 150 USD/kgHM.

It is planned that removal of SNF of VVER-440 from SFDS will start in 50 years from the date of its loading and before placing in SFDS the fuel is kept 5 years.

After the unloading of spent fuel with enrichment of 4.7% from VVER-1000 it is cooled for 12 years. For the nuclear fuel enriched by 4.28% the cooling time is considered as 5 years. From cooling pool the fuel is goes to SFDS for storing 50 years.

In the model, enrichment of fuel for VBER-300 is taken equal to 5%; the reactor's SNF is stored in cooling pool for 12 years, and from cooling pool it goes to SFDS for storing 50 years.

I-6.3.3. Geological disposal

The cost of directly geological disposed spent fuel is given in references [I-4, I-5, I-6, and I-7]. For modelling the NFC, geological disposal of SNF for base case is considered as a service, with approximate cost of 600 USD/kgHM.

I-6.3.4. Transportation of SNF

The following three cases of SNF transportation are considered:

- by railway - 50 USD/kgHM;
- by truck 112.55 USD/kgHM;
- by air transport 500 USD/kgHM.

I-6.3.5. SNF export for reprocessing

There is another scenario when considering the possibility of SNF export for reprocessing and disposal without its return to Armenia [I-8]. Cost of reprocessing and disposal for 1 kg of HM is 2000 USD/kgHM.

I-6.4. Simulation time interval

In this study, the start year of simulation period is 2013, and the end year is the year of unloading of the last spent nuclear fuel assemblies from SFDS. Due to this, the model does not take into account the investments made before 2013.

I-7. RESULTS

This Chapter summarizes the results of economic analyses of NFC scenarios modelled according to Table I-3.

I-7.1.1. Management of SNF without construction of small reactors with SNF storage at the NPP site

This scenario assumes the existing VVER-440 reactor will produce electricity till 2026. After decommissioning of the existing unit a new VVER-1000 type reactor will be introduced to start electricity generation for the period from 2026 to 2086. Installed capacities of the nuclear reactors and electricity generation by NPP are given in Fig. I-8 and Fig. I-9.

Numbers of SNF assemblies will have been accumulated from VVER-440 will be 3148 fuel assemblies which amounts to 362.6496 tons. Specified number includes:

a. 1785 (205.632 tons) assemblies already accumulated by 2013;

b. 1014 (116.8128 t) (78 assemblies × 13 years = 1014) assemblies will be accumulated in 13 years (from 2013 to 2025); and

c. 349 assemblies resulted in complete unloading from reactor core which will be unloaded from CP in 2026.

3148 SNF assemblies will have been accumulated from VVER-440, which amounts to 362.649 tons. SNF from VVER-440 will be removed after 5 years of storage in a cooling pool.

The total accumulation of SNF from the VVER-1000 will be 1 022.036 tons (16.088 t × 59 years + 72.844 tons). Spent nuclear fuel assemblies will be unloaded after 12 years of storage in a cooling pool. The first group of spent nuclear fuel assemblies will be unloaded from cooling pools in 2039, and the last one in 2099. In total, 1384.685 t of SNF will have

been accumulated from VVER-440 and VVER-1000 nuclear units by 2100. Figure I-10 shows the picture of SNF accumulation over the planning period.

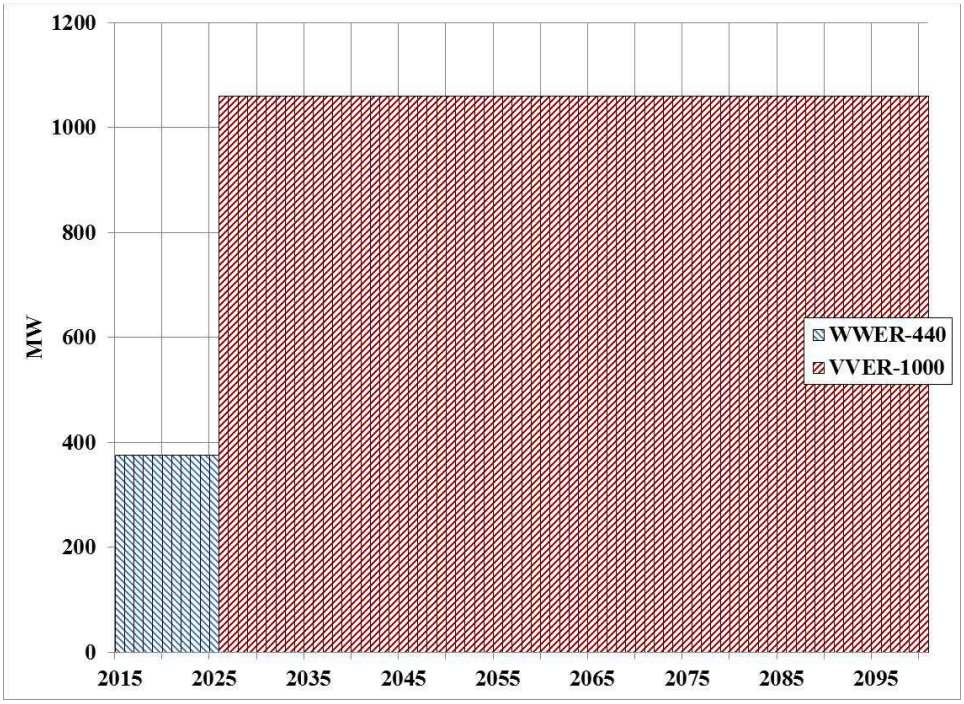


FIG. I-8. Installed capacities of nuclear reactors.

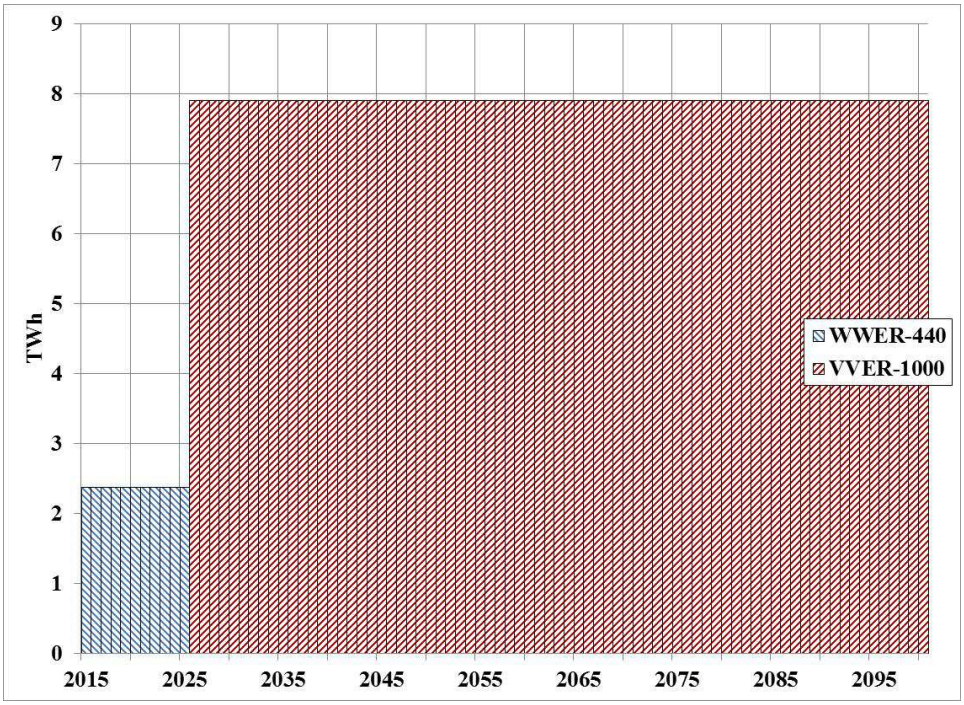


FIG. I- 9. Generation of electricity by NPPs.

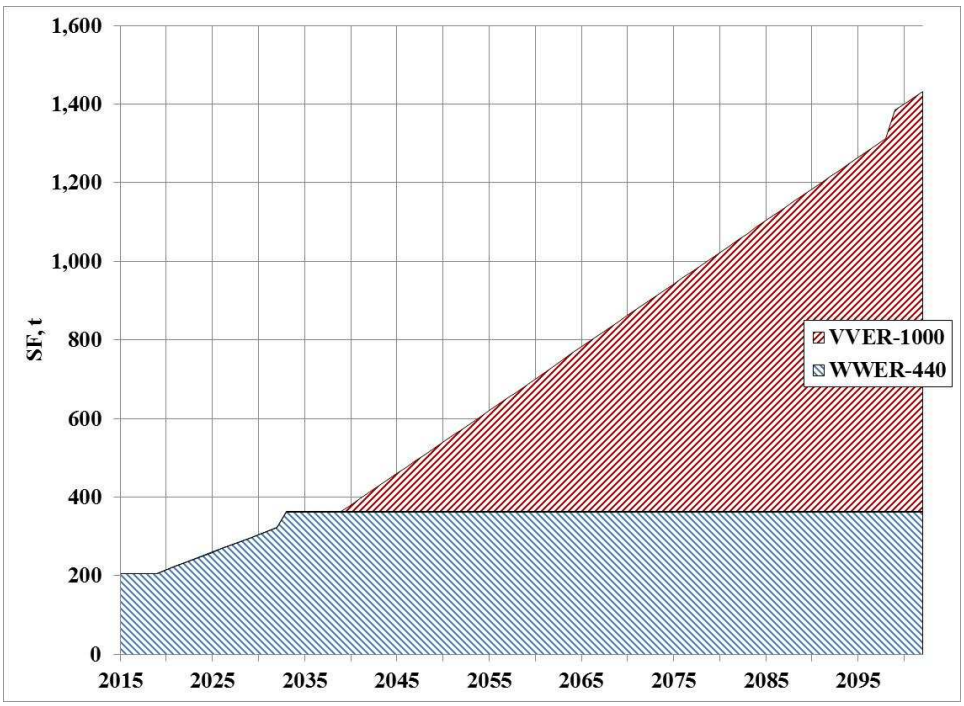
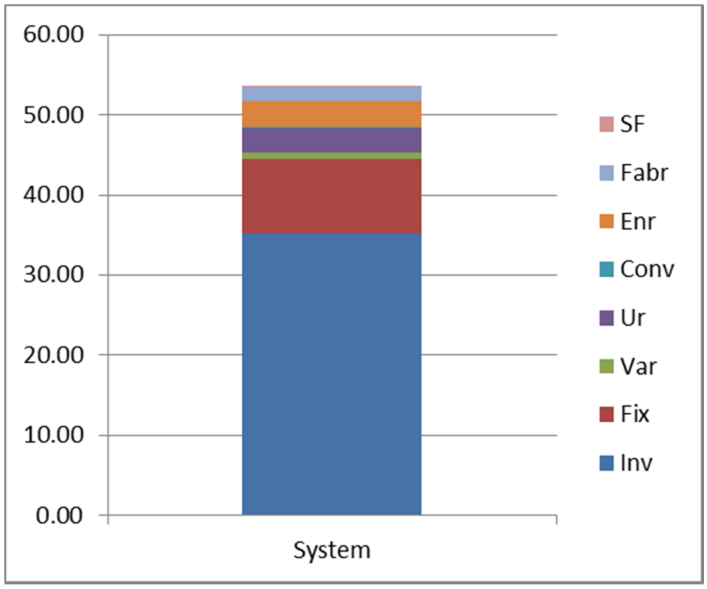


FIG. I-10. Accumulation of SNF over the planning period.

The LUEC for the specified scenario is estimated at 53.69 USD/MWh, and its structure is presented in Fig. I-11 and Table I-8.



SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

FIG. I-11. Structure of the LUEC

TABLE I-8. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Components	USD/MWh
Investment component costs	35.25
Fixed costs	9.25
Variable costs	0.81
Uranium price	3.02

TABLE I-8. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST (cont.)

Costs Components	USD/MWh
Conversion costs	0.21
Enrichment Costs	3.22
Fabrication costs	1.71
SNF Management Costs	0.23
LUEC	53.69

I-7.1.2. Construction of SFDS and export of SNF from the NPP site to another country

This scenario considers construction of dry type of SNF storage and subsequent export of SNF by railway transportation. In this scenario, SNF export starts after its 50 years placement in SFDS.

Figure I-12 shows the dynamics of accumulation and removal of VVER-440 SNF from SFDS. It is assumed that 205.632 tons of SNF accumulated before 2013 will be exported by 2063 (2013 + 50). If SNF is removed at rate of 8.9856 tons/year (an annual load of VVER-440), then the start of SNF removal produced until 2013 should be scheduled up to 2051. SNF from the VVER-440 - which will be moved to SFDS after 2013 will begin to be exported in 2068 and will be completely removed by 2086 (Fig. I-12). The blue colour relates to the SNF from the VVER-440, which had been accumulated before 2013; the brown colour is associated with SNF from the VVER-440, which will be produced after 2013. In total 362.65 tons of SNF will be produced. The export of SNF from the VVER-440 is shown in Fig. I-13.

The dynamics of accumulation and removal of SNF from VVER-1000 are shown in Fig. I-14. In consideration of the removal 850 tons of SNF will be accumulated. Removal of SNF from the VVER-1000 will begin in 2089 (2027 + 12 + 50) and will be completed by 2152. SNF annual removal is limited by the amount of annual loading/unloading of VVER-1000 fuel, which is 16.088 tons/year. The export of SNF from the VVER-1000 is shown in Fig. I-15. In total 1 022.036 tons of SNF will be produced.

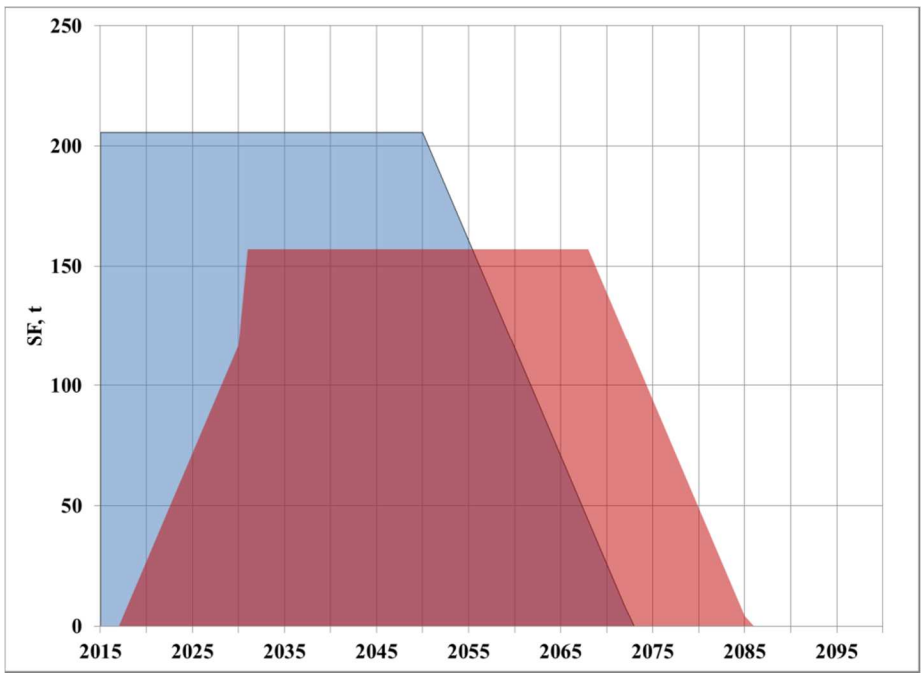


FIG. I-12. Removal of VVER-440 SNF from SFDS.

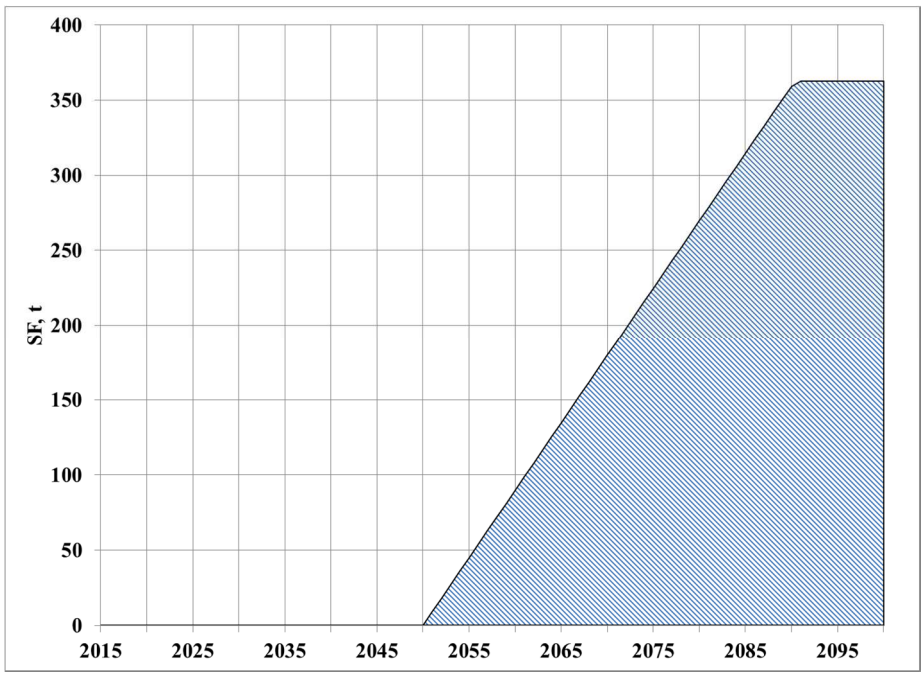


FIG. I-13. Export dynamics of VVER-440 SNF from SFDS.

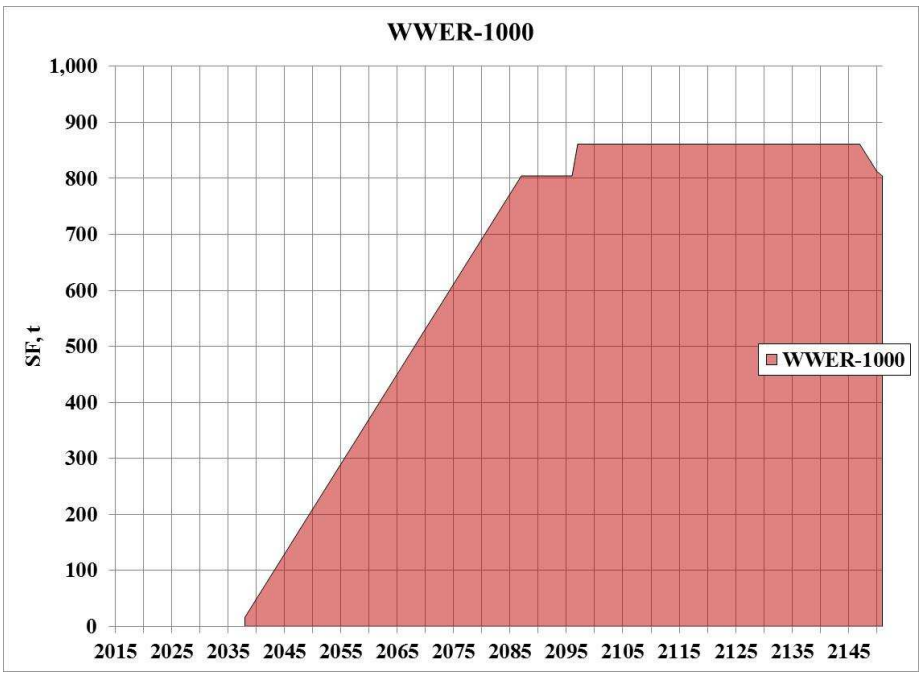


FIG. I-14. Change of volume of SNF from VVER-1000 stored in SFDS.

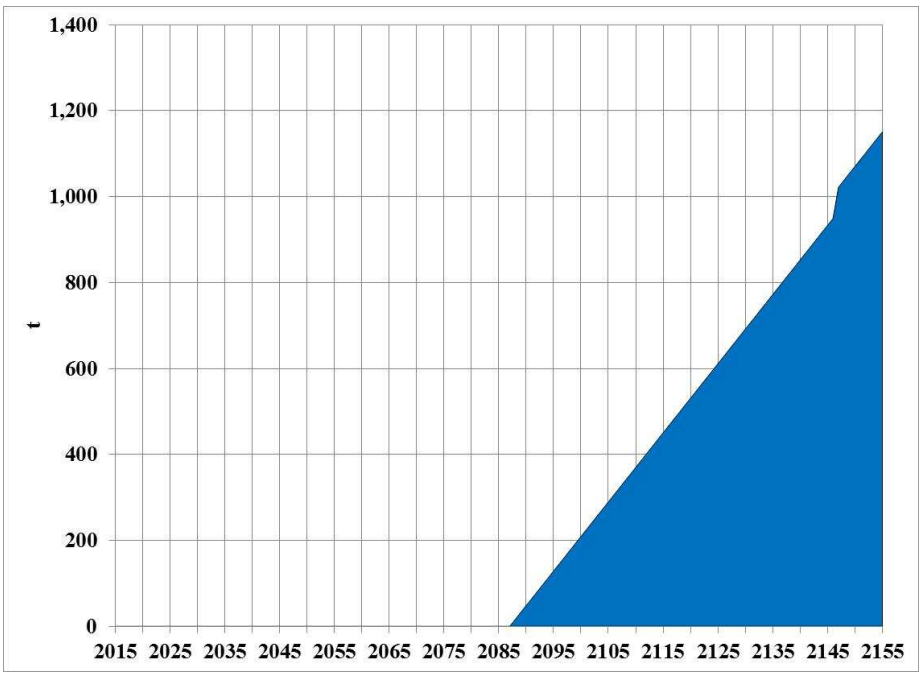
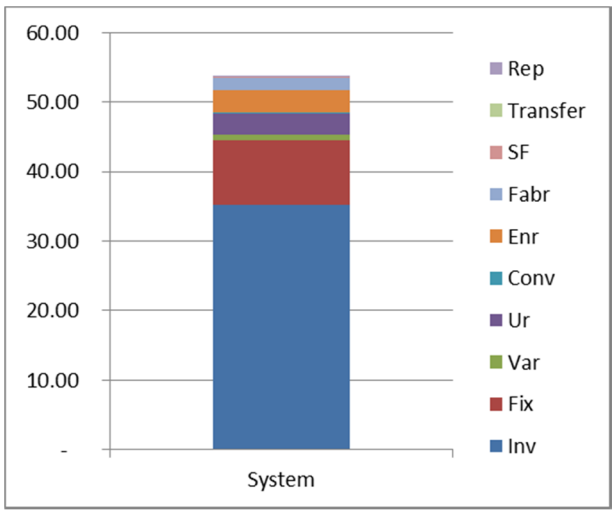


FIG. I-15. Export dynamics of VVER-1000 SNF from SFDS.

The LUEC for the specified scenario is estimated at 53.82 USD/MWh, and its structure is presented in Fig. I-16 and in Table I-9.



Rep - costs of reprocessing and final disposal in another country
Transfer - SNF transportation costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

FIG. I-16. Structure of the LUEC.

TABLE I-9. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Components	USD/MWh
Investment component costs	35.25
Fixed costs	9.25
Variable costs	0.81
Uranium price	3.02
Conversion costs	0.21

TABLE I-9. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST (cont.)

Costs Components	USD/MWh
Enrichment costs	3.22
Fabrication costs	1.71
SNF Management costs	0.23
Transfer costs	0.0031
Cost of the processing without the return of processing waste	0.12
LUEC	53.82

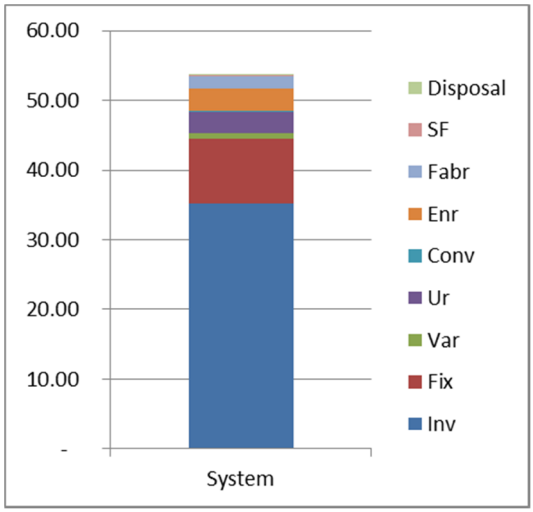
I-7.1.3. Construction of SFDS and transfer SNF from the NPP site to geological disposal

This scenario considers the construction of dry-type storage for spent fuels from VVER-440 and VVER-1000, as well as the construction of a geological repository for disposal of SNF. It is assumed that SNF at the initial stage will be stored in SFDS. After 50 years SNF will be transferred to a geological repository.

Dynamics of the accumulation of SNF from VVER-440 in a centralized storage and dynamics of SNF replacement into a geological repository are shown in Fig. I-12 and Fig. 13.

Accumulation of SNF from VVER-1000, its removal and placement in a geological repository are shown in Fig. I-14 and Fig. I-15. According to the scenario SNF removal from dry storage and placement in a geological repository will begin in 2089. SFDS will be fully emptied in 2152.

The LUEC for the specified scenario is estimated at 53.73 USD/MWh, and its structure is presented in Fig. I-17 and in Table I-10.



Disposal - SNF Disposal costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

FIG. I-17. Structure of the LUEC.

TABLE I-10. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Components	USD/MWh
Investment component cost	35.25
Fixed costs	9.25
Variable costs	0.81
Uranium price	3.02
Conversion costs	0.21

TABLE I-10. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST (cont.)

Costs Components	USD/MWh
Enrichment costs	3.22
Fabrication costs	1.71
SNF management cost	0.23
Disposal costs	0.04
LUEC	53.73

I-7.2. Construction of small reactors, export of SNF from the NPP site to another country (old fuel modification)

This scenario considers the grid connection of VVER-1000 in 2026, as well as construction of a series of small VBER-300 reactors in 2035, 2045, 2055, 2065, 2075, and in 2095.

The scenario considers the operation of the VVER-1000 reactor with fuel enrichment of 4.28% (old fuel modification).

The structure of installed nuclear capacity and electricity generation until 2100 is given in Fig. I-18 and Fig. I-19. Total installed capacity in 2080 will increase to 2,625 MW (1,000 MW - VVER-1000 and 1625 MW - 5xVBER-325).

Amounts of SNF are shown in Fig. I-20 and Fig. I-21. Approximately 2376 tons of SNF will be produced up to 2100. In total, there will be 1592 tons of SNF in SFDS collected from all the reactors considering the export of SNF (Fig. I-22). Rates of spent fuel export from dry storage are taken at the level of annual loads for both VVER-440 and VVER-1000 reactors and the rates of export for small reactors equal to SNF supply rate.

SNF export is shown in Fig. I-23. There will be exported only 784 tons of SNF by 2100 (Fig. I-23). The volume of exported SNF from VVER-1000 will be 403 tonnes for the period up to 2100 (Fig. I-23).

Amounts of SNF exports for VVER-440 and VVER-1000 are limited by the amount of annual loads for the respective reactors. The export of SNF from VBER-300 is determined by the volume of SNF unloaded from all reactors in a given year.

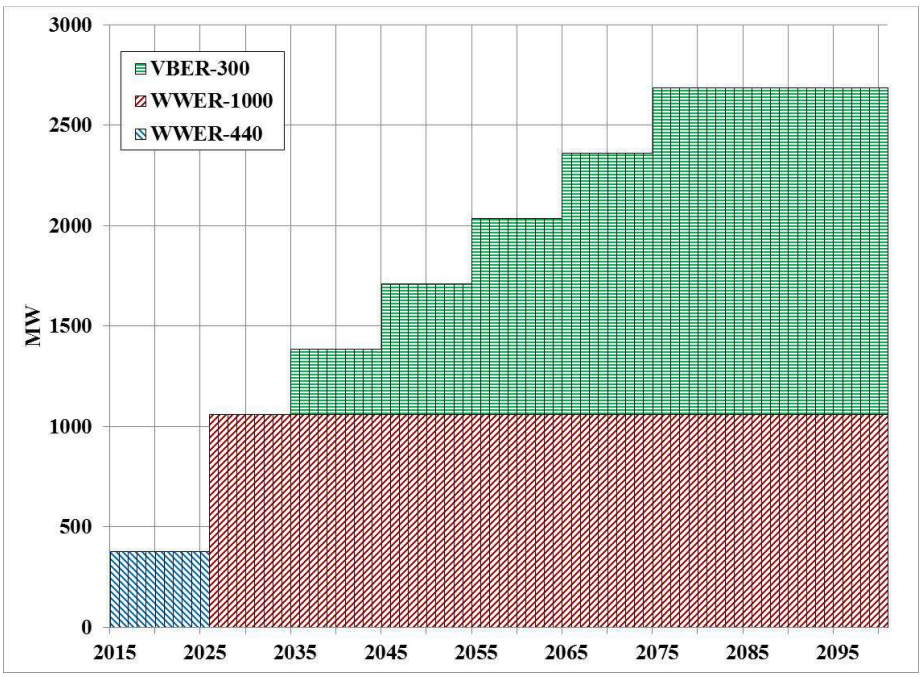


FIG. I-18. The structure of installed capacities of reactors.

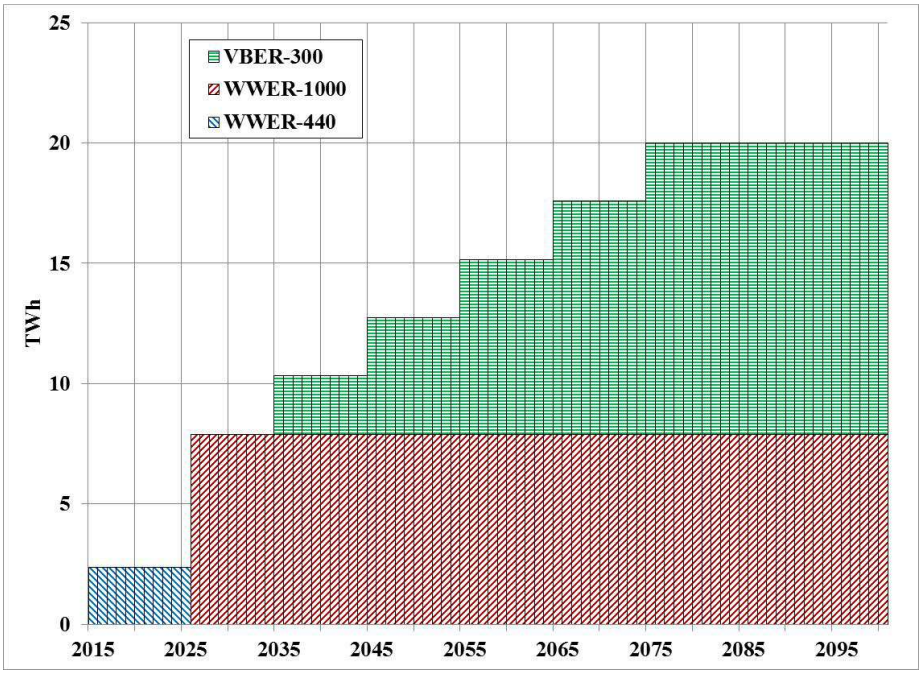


FIG. I-19. The structure of electricity generation by nuclear power plants.

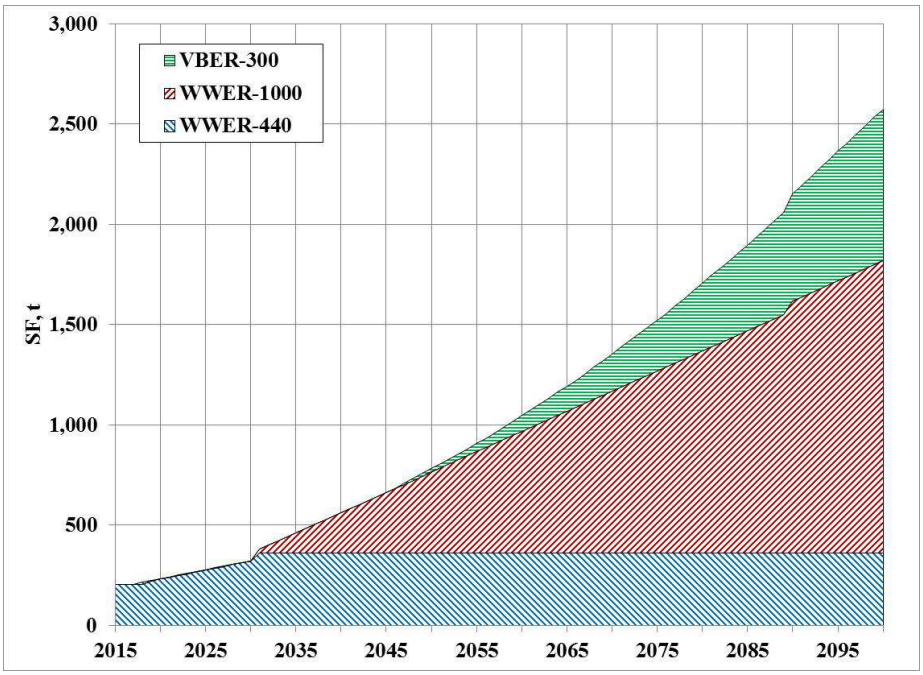


FIG. I-20. Amount of SNF without export (total).

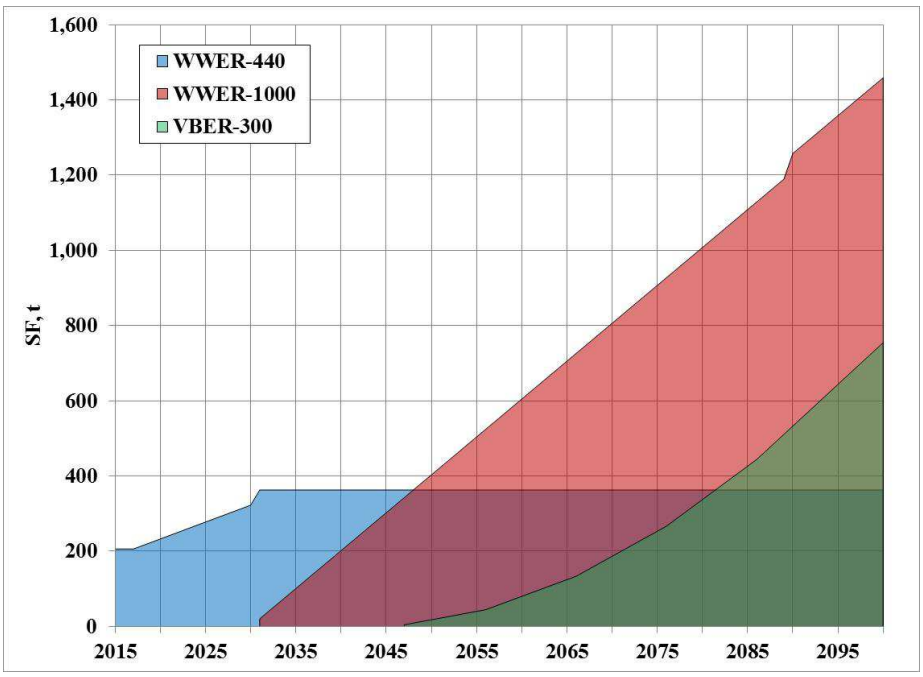


FIG. I-21. Amount of SNF without export (by reactor type).

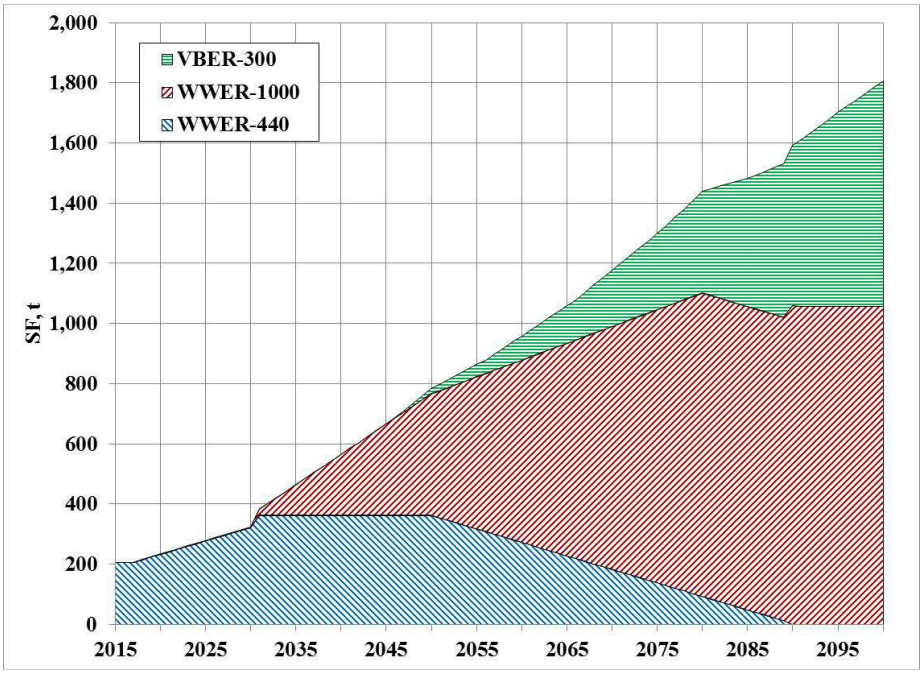


FIG. I-22. SNF in storages considering export (total).

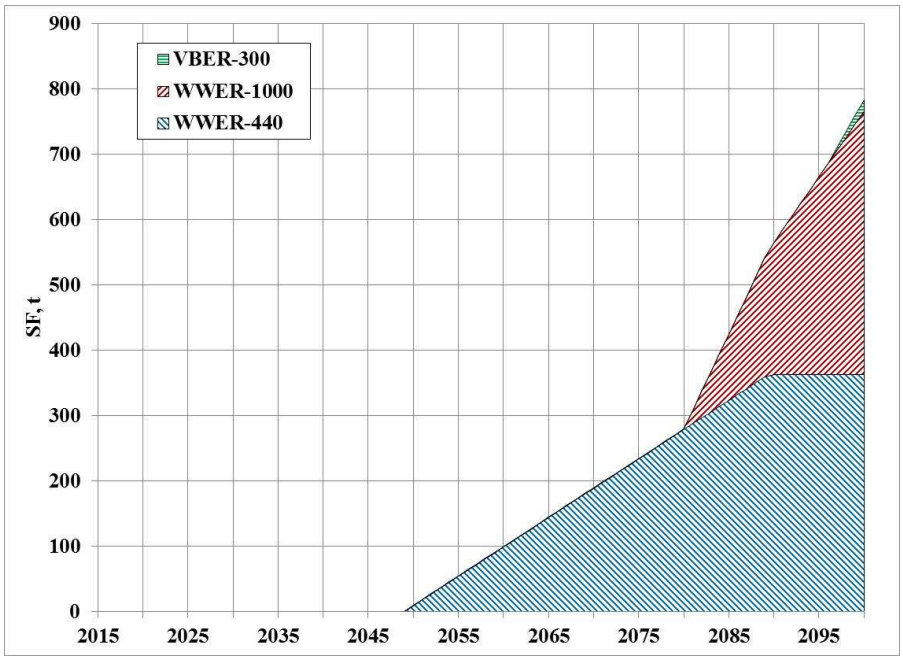
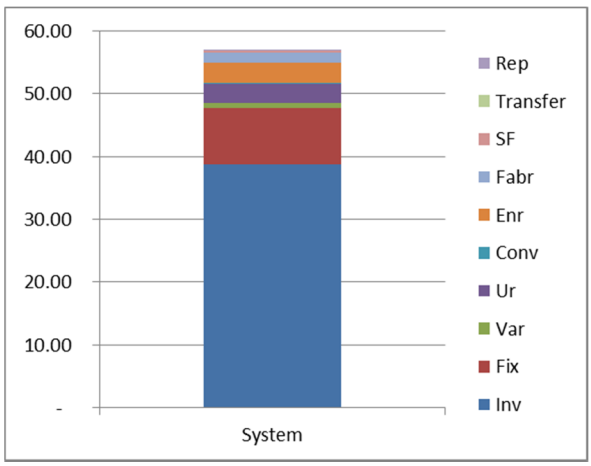


FIG. I-23. Export of SNF (total).

I-7.2.1. Export by railway transport

In this scenario, the cost of export by railway is set as 50 USD/tHM. The LUEC will be 57.153 USD/MWh. The structure of the LUEC is shown in Fig. I- 24 and in Table I-11.



Rep - cost of reprocessing and final disposal in another country
Transfer - SNF transportation costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

FIG. I-24. Structure of the LUEC.

TABLE I-11. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Components	USD/MWh
Investment component costs	38.73
Fixed costs	8.98
Variable costs	0.83
Uranium price	3.07
Conversion costs	0.21

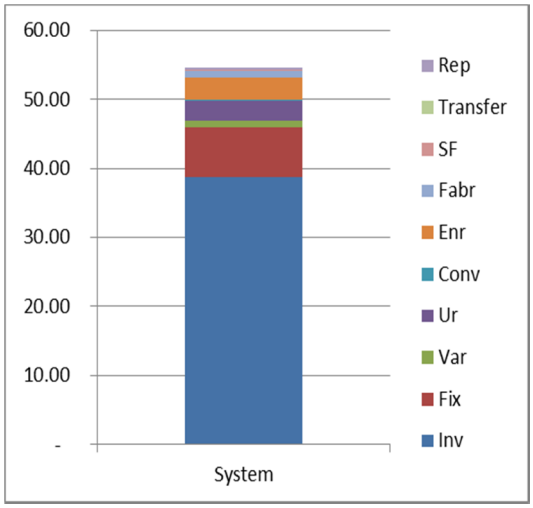
TABLE I-11. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST (cont.)

Costs Components	USD/MWh
Enrichment costs	3.24
Fabrication costs	1.67
SNF management costs	0.29
Transfer costs	0.0032
Cost of the processing without the return of processing waste	0.13
LUEC	57.153

I-7.2.2. Export by truck

The cost of SNF transportation by freight transport is considered at 112.5 USD/kgHM.

The LUEC for this case will be 57.157 USD/MWh, and its structure is presented in Fig. I-25 and in Table I-12.



Rep - cost of reprocessing and final disposal in another country
Transfer - SNF transportation costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

FIG. I-25. Structure of the LUEC.

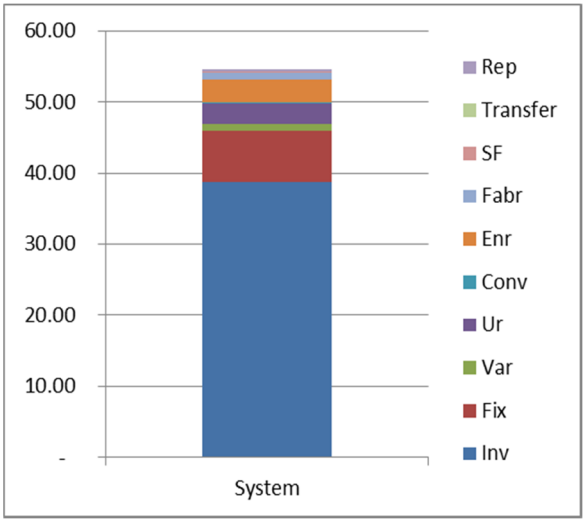
TABLE I-12. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Components	USD/MWh
Investment component costs	38.73
Fixed costs	8.98
Variable costs	0.83
Uranium price	3.07
Conversion costs	0.21
Enrichment costs	3.24
Fabrication costs	1.67
SNF Management costs	0.29
Transfer costs	0.0072
Cost of the processing without the return of processing waste	0.13
LUEC	57.157

I-7.2.3. Export by air transport

Cost of SNF transportation by air transport is taken at the level of 500 USD/kgHM.

Present value of electricity generation for this case will be 57.18 USD/MWh, and its structure is presented in Fig. I-26 and in Table I-13.



Rep - cost of reprocessing and final disposal in another country
Transfer - SNF transportation costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

FIG. I-26. Structure of the LUEC.

TABLE I-13. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Components	USD/MWh
Investment component costs	38.73
Fixed costs	8.98
Variable costs	0.83
Uranium price	3.07
Conversion costs	0.21
Enrichment costs	3.24
Fabrication costs	1.67
SNF Management costs	0.29
Transfer costs	0.0322
Cost of the processing without the return of processing waste	0.13
LUEC	57.18

I-7.3. Construction of small reactors, export of SNF from the NPP site to another country (new fuel modification)

This scenario considers the implementation of VVER-1000 reactor and a series of small VBER-300 reactors. Operation of VVER-1000 reactor is modelled with fuel enrichment to 4.7%.

Figure I-22 and Fig. I-23 show the structure of installed capacities and electricity generation by nuclear power plants, respectively.

All reactors until 2100 will be produced 2 140 tHM of SNF until 2100 (Fig. I-27 and Fig. I-28).

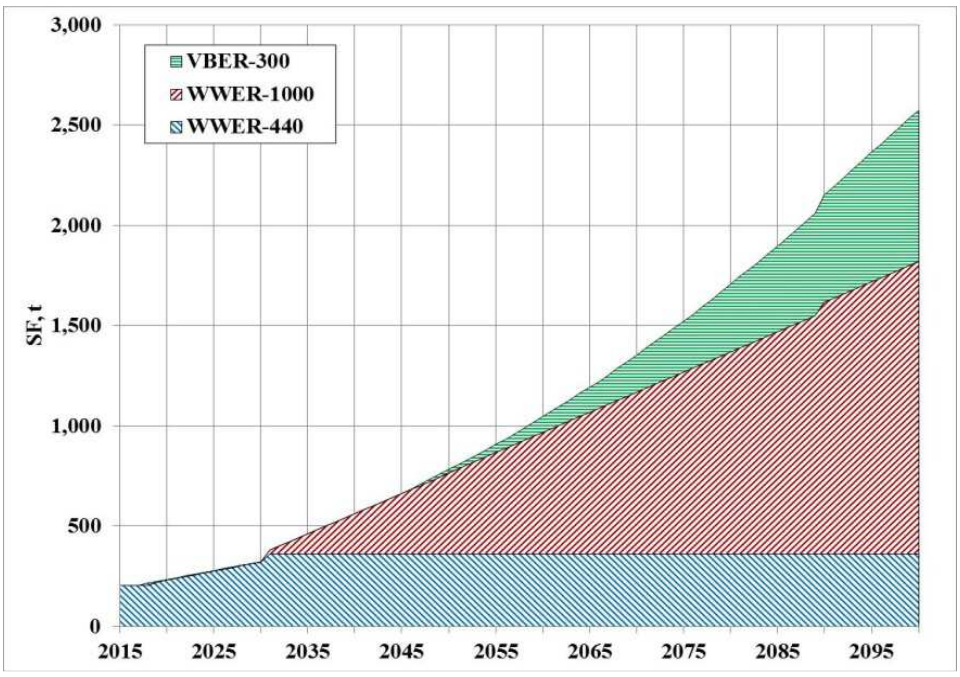


FIG. I-27. Total amount of SNF (excluding export).

FIG. I-28. Amount of SNF (excluding export) by reactor types.

Accumulation of SNF into the storage for the period up to 2100 is shown in Fig. I-29 (with export).

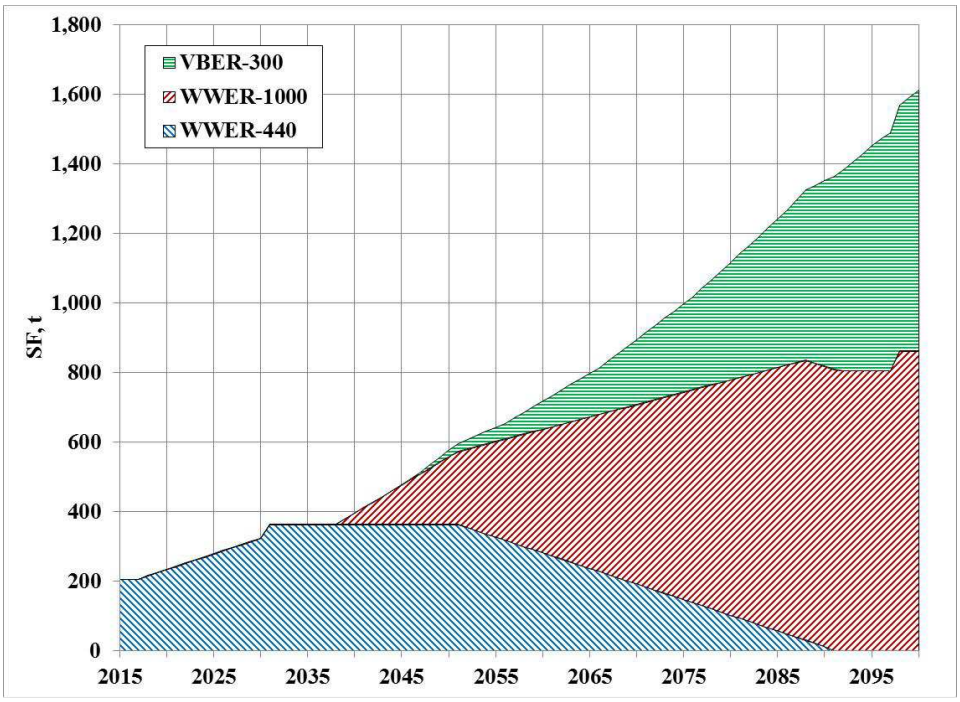


FIG. I-29. Total accumulation of SNF in storage (with export).

SNF export is shown in Fig. I-30. According to the accepted scenario there will be exported 635 tons of SNF from all reactors till 2100.

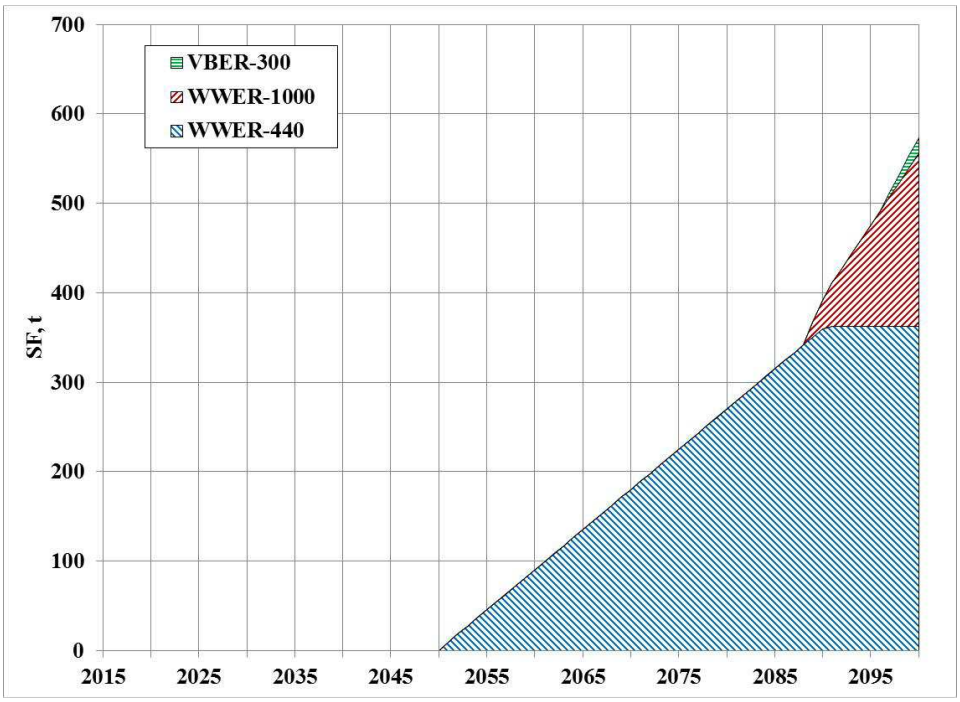
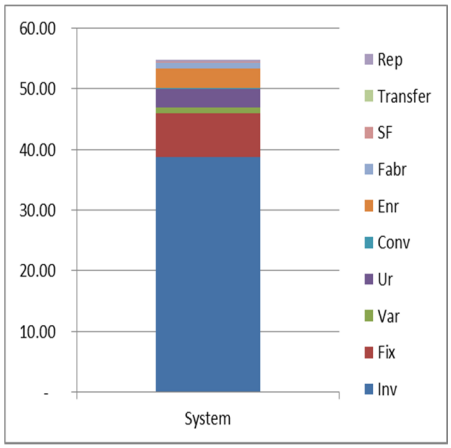


FIG. I-30. Total exported SNF.

I-7.3.1. Export by railway transport

The levelized unit electricity cost for this case will be 56.893 USD/MWh, and its structure is presented in Fig. I-31 and in Table I-14.



Rep - cost of reprocessing and final disposal in another country
Transfer - SNF transportation costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

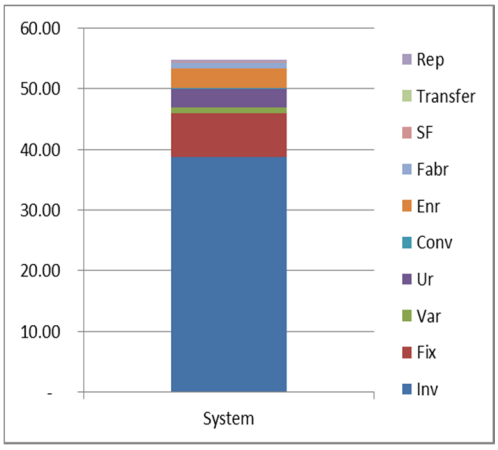
FIG I-31. Structure of the LUEC.

TABLE I-14. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Components	USD/MWh
Investment component costs	38.73
Fixed costs	8.98
Variable costs	0.83
Uranium price	3.00
Conversion costs	0.20
Enrichment costs	3.21
Fabrication costs	1.60
SNF management costs	0.21
Transfer costs	0.0027
Cost of the processing without the return of processing waste	0.11
LUEC	56.893

I-7.3.2. Export by truck

The LUEC for this case will be 56.896 USD/MWh, and its structure is presented in Fig. I-32 and in Table I-15.



Rep - cost of reprocessing and final disposal in another country
Transfer - SNF transportation costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

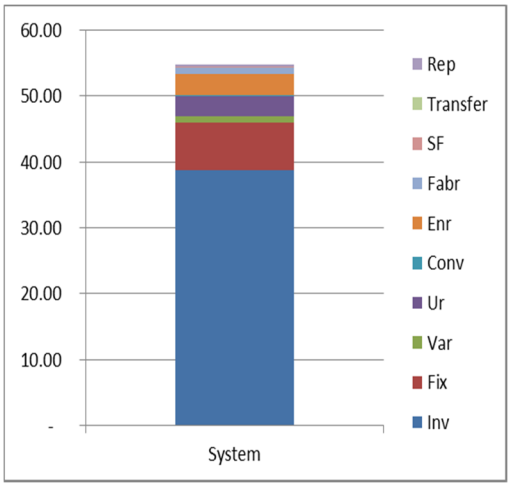
FIG. I-32. Structure of the LUEC.

TABLE I-15. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Component	Present Value, USD/MWh
Investment component costs	38.73
Fixed costs	8.98
Variable costs	0.83
Uranium price	3.00
Conversion costs	0.20
Enrichment costs	3.21
Fabrication costs	1.60
SNF management costs	0.21
Transfer costs	0.0062
Cost of the processing without the return of processing waste	0.11
LUEC	56.896

I-7.3.3. Export by air transport

The LUEC for this case will be 56.92 USD/MWh, and its structure is presented in Fig. I-33 and in Table I-16.



Rep - cost of reprocessing and final disposal in another country
Transfer - SNF transportation costs
SF - SNF management (SFDS) costs
Fabr - Fuel fabrication costs
Enr - Uranium enrichment costs
Conv - Uranium conversion costs
Ur - Uranium price
Var - Variable costs
Fix - Fixed costs
Inv - Investment component costs

FIG. I-33. Structure of the LUEC.

TABLE I-16. STRUCTURE OF THE LEVELIZED UNIT ELECTRICITY COST

Costs Component	Present Value, USD/MWh
Investment component costs	38.73
Fixed costs	8.98
Variable costs	0.83
Uranium price	3.00
Conversion costs	0.20
Enrichment costs	3.21
Fabrication costs	1.60
SNF management costs	0.21
Transfer costs	0.0274
Cost of the processing without the return of processing waste	0.11
LUEC	56.92

I-8. CONCLUSIONS

The low sensitivity of the present value of electricity to the modification of the scenarios' conditions relates (Table I-17) to the following factors:

- small contribution of the final stage of NFC in the overall structure of the present value;
- small exported amounts of SNF in the period under review;
- extended period of SNF removal (until 2150);
- postponement for the later export or disposal;
- lack of the consideration of SFDS operational costs and geological storage in the model.

In the structure of the present value of electricity the share corresponding to the final stage of the NFC, is a small part (4%). Changes in the price of SNF management have an insignificant effect changes in the present value of electricity.

The option with the construction of SFDS at the base conditions is an acceptable solution to the management of SNF. However, given the need of SNF management after the project period of the storage in SFDS, export of SNF may be more attractive after its discharge from the cooling pool.

TABLE I-17. THE LEVELIZED UNIT ELECTRICITY COST IN DIFFERENT SCENARIOS, USD/MWh

Management of SNF without construction of small reactors	53.69 SNF dry storage	53.82 SNF export by railway transport	53.73 SNF transfer to geological disposal
Construction of small reactors, export of SNF from the NPP site to another country (old fuel modification)	57.153 SNF export by railway transport	57.157 SNF export by truck	57.18 SNF export by air transport
Construction of small reactors, export of SNF from the NPP site to another country (new fuel modification)	56.893 SNF export by railway transport	56.896 SNF export by truck	56.92 SNF export by air transport

REFERENCES TO ANNEX 1

[I-1] ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT NUCLEAR ENERGY AGENCY, The Economics of the Back End of the Nuclear Fuel Cycle, Paris (2013).

[I-2] Ux Consulting Company web site: http://uxc.com

[I-3] Ux Consulting Company, "Fabrication market outlook,", UxC (2008).

[I-4] SHROPSHIRE D., Advanced fuel cycle economic analisys of symbiotic lightwater reactor and fast burner reactor system, Idaho National Laboratory (2009).

[I-5] ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT NUCLEAR ENERGY AGENCY, Advanced Nuclear Fuel Cycles and Radioactive Waste Management, Paris (2006).

[I-6] INTERNATIONAL ATOMIC ENERGY AGENCY, Spent fuel reprocessing options, IAEA TECDOC Series No.1587, Vienna (2008).

[I-7] INTERNATIONAL ATOMIC ENERGY AGENCY, Role of Thorium to Supplement fuel cycles of future nuclear energy systems, IAEA Nuclear Energy Series No. NF-T-2.4, Vienna (2012).

[I-8] High Level Waste & Spent Fuel Monitor, Russia's MINATOM begins compain to get Duma ok for taking in spent fuel, March 13, 2000.

[I-9] INTERNATIONAL ATOMIC ENERGY AGENCY Status of advanced light water reactor designs, IAEA TECDOC Series No. 1391, Vienna (2004).

ABBREVIATIONS

INPRO	International project on innovative nuclear reactors and fuel cycles
FNF	Fresh nuclear fuel
HM	Heavy metal
LWR	Light water reactor
LUEC	Levelized unit electricity cost
NFC	Nuclear fuel cycle
RES	Renewable energy source(s)
SFDS	Spent fuel dry storage
SNF	Spent nuclear fuel
CP	cooling pool
SYNERGIES	"Synergistic nuclear energy regional group interactions evaluated for sustainability", INPRO collaborative project
UOX-fuel	Uranium oxide fuel
VBER	Modular pressurized water reactor (water-water modular energy reactor)
VVER	Water-water energy reactor (pressurized water reactor)
WWER	Same as VVER
UCF	Unit capacity factor