ANNEX XIII.

SCENARIO WITH THE VVER-FR COLLABORATIVE DEPLOYMENT

XIII-1. INTRODUCTION

The research work was performed by experts at the Energoatom Scientific and Technical Centre "SE NNEGC" in Kiev, Ukraine according to Task 1 of the collaborative project (CP) SYNERGIES.

The general objective is the elaboration of proposals for areas of international cooperation for the development of the NES in Ukraine in the mid- and long-term, using Generation III+ and Generation IV reactors, SNF reprocessing, and international centres for long-term SNF storage and/or disposal.

XIII-2. OBJECTIVE AND PROBLEM FORMULATION

About 47% of the electricity in Ukraine is produced through nuclear generation on Ukrainian soil. The current NES is based on an open fuel cycle featuring four NPPs (13 VVER-1000s and 2 VVER-440s) and transport of SNF abroad for long-term storage and (potential) reprocessing. One NPP (Zaporizhzha) features a dry storage facility for the long-term storage of spent fuel for up to 50 years. Fuel management is performed according to a "wait and see" strategy. Accordingly, the government has approved the construction of a centralized SNF dry storage facility with a capacity of 5 650 ton HM. In addition, five LWRs with UOX-fuel are to be commissioned by 2030 in accordance with the basic scenario of the updated energy strategy of Ukraine. A large amount of SNF will be accumulated by 2100.

The main objectives of this study are to develop a way for Ukraine to decrease SNF accumulation through implementation of fast reactors within the Ukrainian nuclear infrastructure. Proposals for a revised spent fuel management strategy are under development.

XIII-3. ASSUMPTIONS

XIII-3.1. General assumptions

The modelling is performed under the following boundary conditions:

- energy system of Ukraine is modelled by generation forms independently of specific power units and regional features. Nuclear generation, however, is represented by different reactor types.
- economic parameters (price for resources, capital construction, etc.) are given in momentary prices (overnight cost).

The modelling of non-nuclear energy is performed under the following boundary conditions:

- solar power plants and bio-energy make very small contribution to electricity production and do not affect significantly the energy mix of the country. A&R are represented in the model by hydropower, wind and solar power;
- renewable energy resources (hydropower, wind) are unlimited in volume and cost

nothing; only commissioning rate of the generation capacities is limited;
- coal reserves are sufficient to cover energy needs in full scope and thus are considered to be unlimited; the mining rate is also unlimited; coal import is allowed, if necessary;
- gas for energy generation is imported, therefore its reserves are assumed to be unlimited. Supply rate is also unlimited;
- electric power losses in the grids are to be decreased in accordance with the draft of the updated Energy Strategy till 2030and then to remain unchanged till 2050;
- modelling period – till 2100.

The modelling of the nuclear energy system of Ukraine is performed using the following boundary conditions and assumptions:

- the initial condition of the nuclear energy sector of Ukraine is the beginning of 2012;
- nuclear generation is represented absolutely as a basic component of the energy system of Ukraine;
- nuclear share in the energy mix of Ukraine should not exceed 50%;
- approved NFC technologies which have the potential to be used commercially and are in the conceptual development stage.

XIII-3.2. Assumptions for the NFC analysis

- 5 light-water reactors with UOX-fuel are commissioned by 2030 in accordance with the basic scenario of the energy strategy of Ukraine on 2013);
- closed NFC based on FR is possible after 2030 (FR is a developed technology but nowadays it is not widely used; it is assumed that FR and related technologies will have been approved by 2030);
- there is a possibility to commission annually no more than 1 reactor of any type after 2030;
- commissioning of LWR with UOX-fuel, LWR with MOX-fuel, HWR with regenerated uranium and FR is defined by the model after optimization;
- LWR and FR SNF reprocessing is possible;
- MOX-fuel application is possible after 2030. 25% of the core will be loaded with this type of fuel;
- the commissioning of HWR with ReU[1]-fuel is possible after 2030;
- an opportunity for LWR SNF disposal is considered (600 USD/kg(HM)), with no constraints regarding the repository capacity;
- an opportunity for spent MOX-fuel disposal is considered (600 USD/kg(HM)), with no constraints regarding the repository capacity;
- HWR SNF (ReU-fuel) is transported for disposal at the cost of 600 USD/kg(HM), the repository capacity is not limited;
- the possibility of SNF reprocessing is admitted starting from the modelling period;
- in case the optimized modelling demonstrates that a technology “is squeezed” from the system, a “prioritized” (compelled) technology is allowed to be used in the model; for partially-closed NFC a “prioritized” introduction is assumed to be applied to MOX-fuel and FR deployment as the key technologies (reprocessing appears, additional energy source, necessity to dispose of other SNF types and products derived from reprocessing); 1 MOX-reactor will be commissioned in order for the model with

[1] Reprocessed uranium.

optimal way of system development to be selected; a compulsory introduction is set up in the longterm in 2050, if the model does not demonstrate the viability of technology introduction in the near term.

XIII-4. METHODS, CODES AND INPUT DATA USED

XIII-4.1. Codes and methods

The modelling of the energy system is performed with the MESSAGE software [XIII-1]. MESSAGE methodology is based on optimization of target function addressing specific set of constraints. MESSAGE is aimed at achieving the given parameters of electricity generation at minimum cost of the entire system with constraints of resources, fuel availability and market situation, investments, waste accumulation, etc.

MESSAGE provides two approaches to description of system components:

- INS component is modelled as “technology”, i.e., production deployed on the territory of Ukraine;
- INS component is modelled as “service”, purchased either at domestic market or imported.

To describe components in terms of “technology” the following minimum input data is required:

- material balance of raw materials and end product;
- capital costs, construction period and operating lifetime;
- fixed operating & maintenance costs independent of actual output (salary, water, electricity, expendable materials, rent, loans, etc.);
- variable production costs (raw materials, fuel, etc.).

To describe components in terms of “service” the following input data is required:

- material balance of raw materials and end product;
- cost of service.

The compliance of established model with actual conditions and, hence, forecast probability significantly depends on completeness and reliability of input data on technologies or, more specifically, on implementation status of related INS components.

XIII-5. SUMMARY PRESENTATION OF THE RESULTS

In the present chapter two scenarios of FR implementation in Ukrainian nuclear fuel cycle are considered:

- Implementation of FR after 2050;
- Substitution of LWR by FR after 2030.

Introduction of thermal and fast reactors (with MOX-fuel for FR) and CANDU reactors with reprocessed uranium is under consideration. Reprocessed LWR SNF and FR fuel are

planned to be used in the Ukrainian fast reactors and ReU-fuel is planned to be used in Ukrainian HWR.

Centralized Spent Nuclear Fuel Dry Storage Facility is supposed to be commissioned in 2015 (Nuclear Energy Strategy on 2013).

XIII-5.1. Implementation of FR after 20505 light-water reactors with

The configuration considers the commissioning of reactors of all types: LWR with UOX and MOX-fuel, HWR with ReU-fuel and FR with MOX-fuel. The model considers the possibility of LWR SNF disposal.

The electricity generation structure and generation share with Closed Nuclear Fuel Cycle option are shown in Figs XIII-1 and XIII-2.

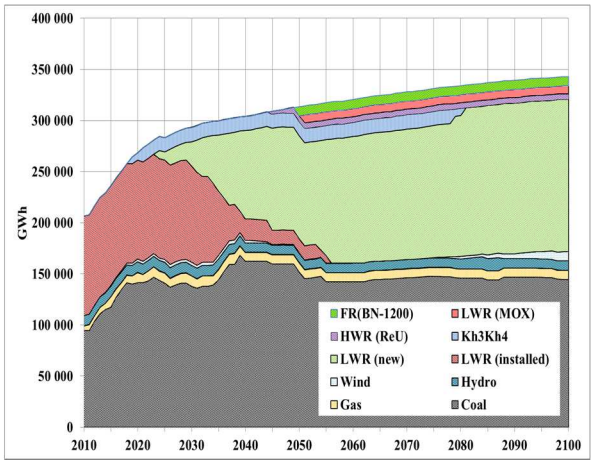

FIG. XIII-1. Electricity generation structure.

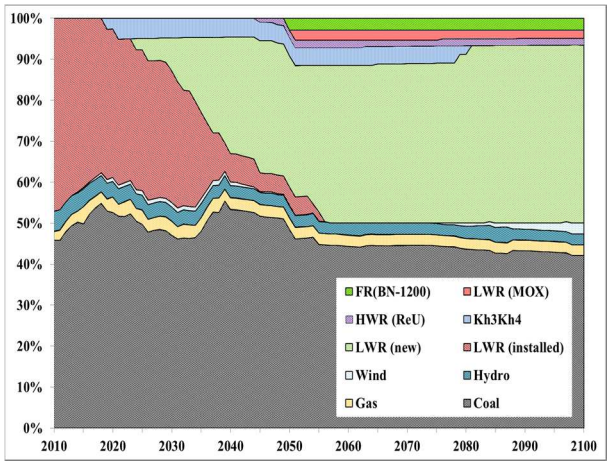

FIG. XIII-2. Generation share.

The total installed nuclear capacity and Schedule of new capacities to be commissioned are presented in Figs XIII-3 and XIII-4.

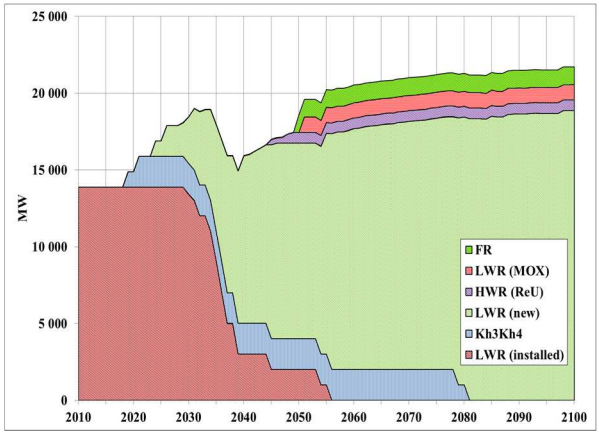

FIG. XIII-3. Total installed capacities.

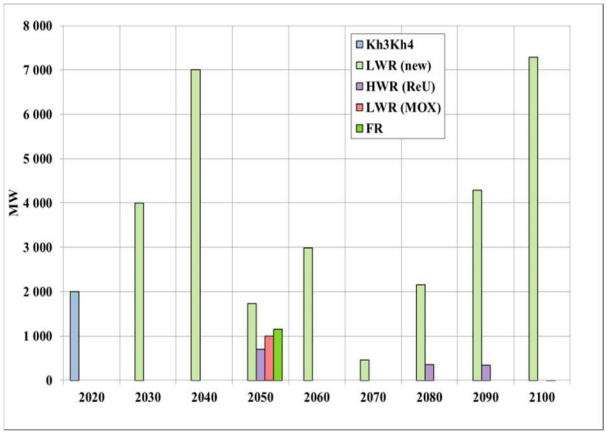

FIG. XIII-4. Schedule of new capacities to be commissioned.

The accumulation of SNF and of fission products resulted from reprocessing is presented in Figs XIII-5 and XIII-6 with specified accumulated volumes of extracted plutonium (Putot), minor actinides (Mac) and fission products (FPr) indicated.

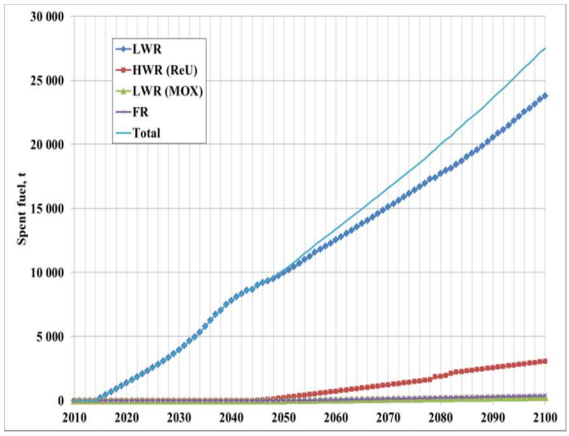

FIG. XIII-5. SNF accumulation.

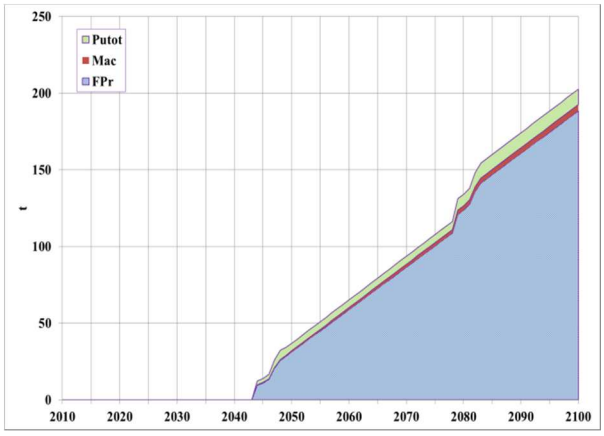

FIG. XIII-6. Accumulation of products resulted from reprocessing.

Natural uranium recourses exhaustion are presented in Fig. XIII-7.

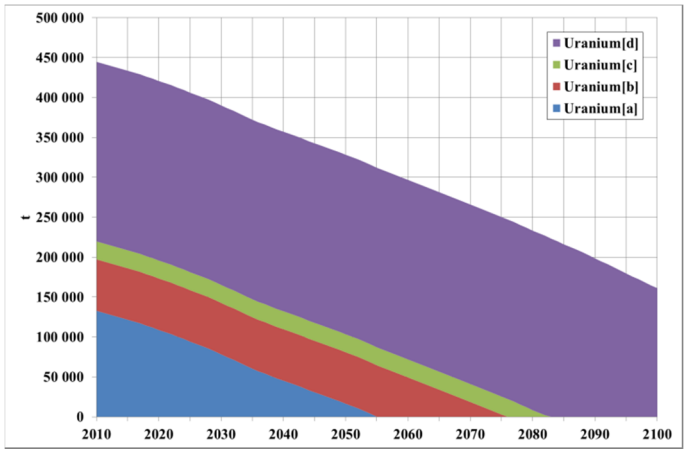

FIG. XIII-7. Residual natural uranium resources.

Price categories of uranium reserves Uranium[a], Uranium[b], Uranium[c], Uranium[d] refer to 100 USD/kg, 120 USD/kg, 150 USD/kg, 260 USD/kg respectively.

XIII-5.2. Substitution of LWR by FR after 2030

Feasibility study of FR large-scale deployment in NFC with multi-recycling of plutonium is presented in this section. LWR replacement by FR and SNF reprocessing are considered to be services. CSNFSF with capacity of 5 650 t(HM) is supposed to be commissioned in 2015When CSNFSF is full an additional storage facility with capacity of 2 000 t(HM) will be commissioned. 5 LWR will be commissioned by 2030. After that only FR will be commissioned.

LWR construction costs make up 5 000 USD/kW, FR – 6000 USD/kW. LWR SNF reprocessing costs amount to 2 000 USD/kg, FR SNF reprocessing costs – 2 400 USD/kW, reprocessing is considered to be service.

The electricity generation structure and generation share with Closed Nuclear Fuel Cycle option and multi-recycling option are shown in Figs XIII-8 and XIII-9.

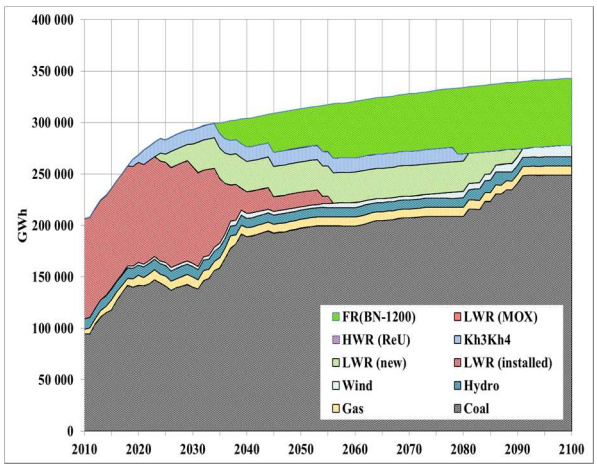

FIG. XIII-8. Electricity generation structure

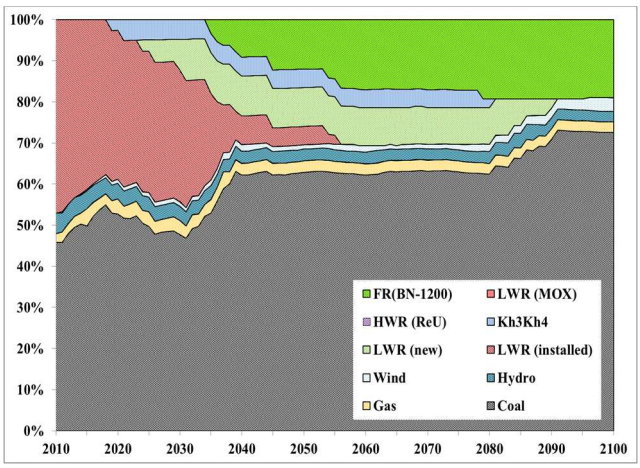

FIG. XIII-9. Share of electricity generation.

The total installed nuclear capacity and Schedule of new capacities to be commissioned are presented in Figs XIII-10 and XIII-11.

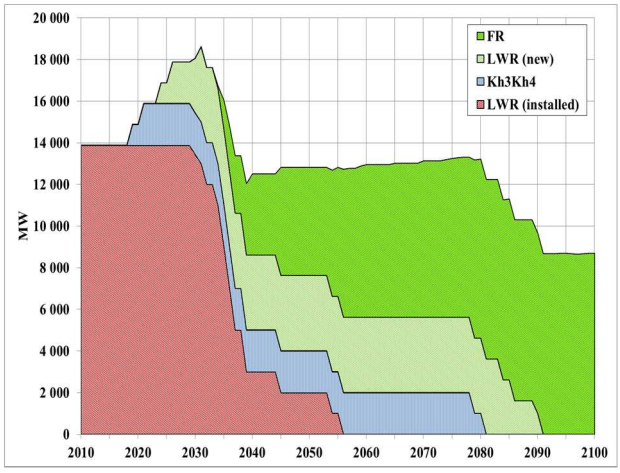

FIG. XIII-10. Total installed capacities.

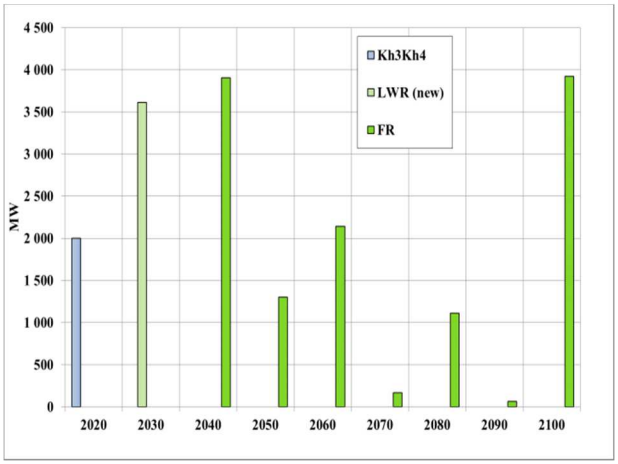

FIG. XIII-11. Schedule of new capacities to be commissioned.

The accumulation of SNF and of products resulted from reprocessing are presented in Figs XIII-12 and XIII-13 with specified accumulated volumes of extracted plutonium (Putot), minor actinides (Mac) and fission products (FPr) indicated. RedepU[2] is uranium regenerated from FR SNF; ReU – uranium regenerated from LWR SNF; Putot – total amount of accumulated plutonium; Mac – minor actinides; FPr – fission products.

[2] Depleted uranium from reprocessing/

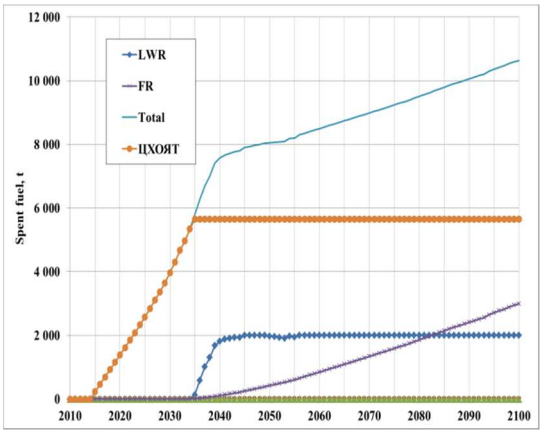

FIG. XIII-12. SNF accumulation

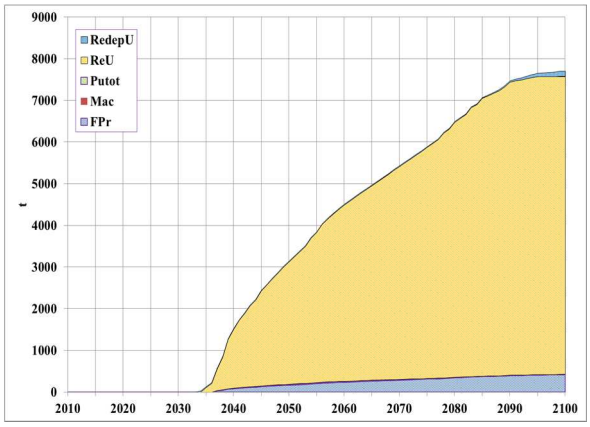

FIG. XIII-13. Accumulation of products resulted from reprocessing.

The assessment of fission products structure from reprocessing is presented in Fig. XIII-14.

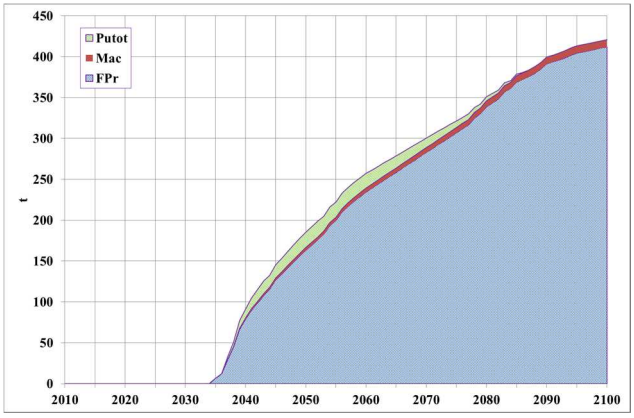

FIG. XIII-14. Accumulation of products resulted from reprocessing with specified accumulated volumes of extracted plutonium (Putot), minor actinides (Mac) and fission products (FPr).

Natural uranium recourses exhaustion is shown in Fig. XIII-15.

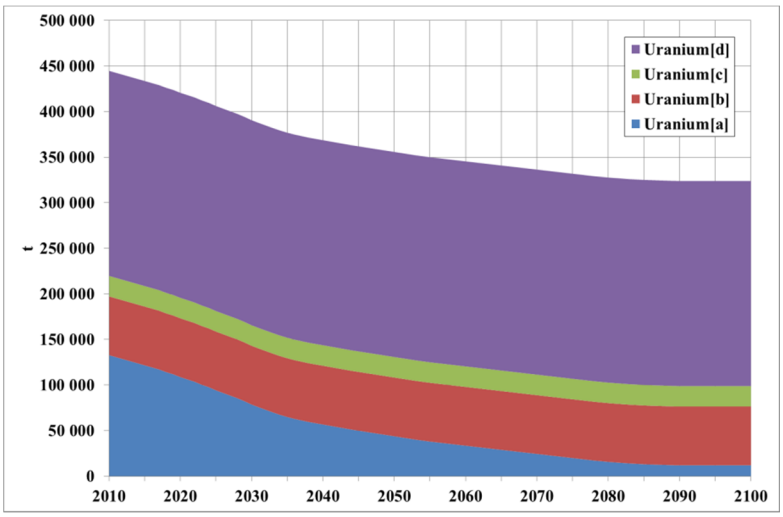

FIG. XIII-15. Natural uranium reserves exhaustion.

XIII-6. ANALYSIS OF THE RESULTS

XIII-6.1. Deployment of FR after 2050

The modelling results show that there are only LWR in the system if the selected initial conditions and assumptions are considered. It happens because of the low capital costs of their commissioning, low cost of UOX-fuel fabrication, high costs of SNF reprocessing services and considerable reserves of natural uranium. To assess a potential impact of MOX-fuel and FR deployment on the system an obligatory commissioning of one LWR with MOX-fuel and one FR is planned by 2050. LWR with UOX-fuel remains the main reactor type in the system.

Considering the model requirement that refers to the necessity of LWR SNF reprocessing for MOX-fuel fabrication to be used in this LWR, NFC is automatically complemented with HWR with ReU-fuel that can be commissioned not earlier than 2030.

The modelling results show the reduction of nuclear share down to 40-43% from the existing level due to the decommissioning of reactors currently in operation and low tempo of their replacement by new reactors, which is described in the Updated energy strategy of fuel and energy sector development in Ukraine till 2030 (Figs XIII-1, XIII-2). This result complies with the obtained results for once-through NFC and partially-closed NFC that proves the model correctness.

A condition to maintain 50% of nuclear share in the energy system of Ukraine requires commissioning of significant amount of nuclear capacities in 2030-2040 that imposes a significant financial burden on the country's economy and cannot be considered a realistic scenario. Total installed capacity of new light-water reactors is expected to make up 7 GW in this period.

The operation of reactors with MOX-fuel and one FR with plutonium fuel in 2050 requires LWR SNF reprocessing and one HWR with ReU-fuel deployment in NFC in the indicated period (Fig. XIII-4). It should be noted that there is no limitations regarding the number of LWR with MOX-fuel and FR in the model of this study. However, taking into account the technical and economical parameters of a reactor and NFC mentioned in the Annex, the commissioning of these reactors is performed at the minimal level. It is related to the absence of restrictions regarding the amount of accumulated LWR SNF, natural uranium prices and its reserves.

The results regarding accumulation of SNF and reprocessing products are similar to the option based on partially-closed NFC due to the small share of FR in NFC. Total amount of accumulated SNF will amount to 28 thousand t(HM) including 4 thousand t(HM) of HWR SNF and 24 thousand t(HM) of LWR SNF. Total amount of accumulated spent MOX-fuel and FR SNF will make up less than 1 thousand t(HM) by 2100 (Fig. XIII-5).

Small amount of reprocessed LWR SNF corresponds to the small amount of obtained reprocessing products (up to 200 t(HM)). The amount of extracted plutonium is about 20 t(HM).

The discounted cost of electricity for this type of NFC based on 1 LWR with MOX-fuel, 1 FR and 1 HWR with ReU-fuel at zero cost makes up 14.08 USD/MWh that complies with the cost in once-through NFC.

Natural uranium reserves in the amount of 447 000 t(HM) will be sufficient till 2150 that complies with the results of partially-closed NFC.

XIII-6.2. Substitution of LWR by FR after 2030

The modelling demonstrates that share of nuclear power in electricity generation will decline to 20% by 2100 (Figs XIII-8 and XIII-9). It is related to the high cost of closed NFC

technologies. When storage facilities are filled (approximately in 2035) SNF reprocessing will start.

Total installed capacity of new reactors will make up 4 GW in 2030-2040. Additionally, up to 4 GW will be commissioned in 2040-2080 (Fig. XIII-11).

Fresh fuel for fast reactors is fabricated from plutonium extracted from LWR SNF as a result of reprocessing. LWR SNF reprocessing will be stopped when last LWR is decommissioned (in 2090). Termination of LWR SNF reprocessing can also be seen in the graph that shows the accumulation of regenerated uranium (Fig. XIII-13): regenerated uranium produced after LWR SNF reprocessing is planned to be accumulated only till 2090, after 2090 the accumulation of regenerated uranium obtained from FR SNF will start. FR SNF reprocessing will start after 2090 since it involves more plutonium (accumulation of regenerated uranium from FR SNF). The model considers FR SNF accumulation till 2100.

Total amount of accumulated SNF will amount to 11 000 t(HM) including 2 000 t(HM) of LWR SNF and 3 000 t(HM) of FR SNF. Due to the considerable amount of SNF subject to reprocessing total amount of reprocessing products will amount to 8 000 t(HM) including 7 000 t(HM) of regenerated uranium.

This option of NFC does not consider plutonium accumulation. All plutonium will be used till 2100. It may be considered as a significant benefit of the cycle that involves SNF reprocessing.

The economy of this NFC should be studied separately. However, in case of significant reduction of number of nuclear reactors in the system by 2100 and utilization of plutonium extracted from FR SNF the discounted cost of electricity generation will equal 12 USD/MWh that is much lower than in case of once-through NFC. However, this result cannot be considered as a representative one.

The depletion of natural uranium reserves during the whole period of study in this type of NFC is presented in Fig. XIII-15. It should be noted that reduction of uranium reserves is not observed neither till 2100 or in the future. In 2100 uranium reserves will amount to 340 000 tons regardless of further reduction rate of uranium reserves. It confirms the energy system sustainability in accordance with the IAEA sustainability concept.

XIII-7. CONCLUSIONS

In the framework of activities under the international IAEA project SYNERGIES (Task 1) analysis of Ukrainian NES concentrated on closed NFC based on fast reactors with FR construction after 2050 and substitution of LWR by FR after 2030.

The commissioning of fast reactors is deferred for later term due to sufficient amount of uranium resources available, high cost of fast reactors and high reprocessing costs. According to optimization estimates and considering restrictions and input data provided in Annex, the closed NFC based on FRs is assumed to be not feasible for Ukrainian power grid until 2100 and is therefore deferred for more distant prospect. The major reasons are as follows:

a) availability of large uranium reserves;
b) high cost of FR construction;
c) high cost of SNF reprocessing;
d) high cost of fresh fuel fabrication for FR.

For the closed NFC under Ukrainian conditions the specific features would be a significant amount of LWRs on UOX fuel, lack of economic attractiveness of LWRs on MOX

fuel, commissioning of one FR and a number of HWRs on regenerated uranium depending on the scope of SNF reprocessing.

In case of closed NFC the change of NPP share in electricity generation falls within a range from 43% to 33% from the total electricity generation in the period of 2030-2050 and is induced by significant capital expenditures for FR deployment as well as for infrastructure of closed NFC. Long-term cooperation with other countries on regional level might be considered a favorable option for optimizing capital expenditures.

The share of NPPs in power generation is primarily increased by HWRs on regenerated uranium, and this case requires separate studies to be performed. Insofar as economics of NFC is concerned, significant amounts of regenerated uranium by zero cost allow to increase the NPP share up to 50%, as well as to reduce the rate of new reactor capacities commissioning in the period of 2030-2040 down to 4.5 GW that could be considered a more feasible scenario.

As the accumulated SNF amount is limited, reprocessing of SNF starting from 2045is required, which is a prerequisite for commissioning of FRs, LWRs on MOX fuel (plutonium utilization) as well as HWRs on regenerated uranium in 2050.

It would be reasonable to ensure reprocessing of FR SNF due to its higher level of fissile materials. The closing of NFC based on FR will significantly decrease amount of accumulated SNF.

The transition to closed NFC could be impeded by limited capacities for SNF disposal (limited storage capacities), decrease of uranium reserves and of costs of closed NFC technologies.

The input data on cost (price range) of FRs and reprocessing should be discussed with manufacturers and service suppliers. The modelling results depend significantly on price parameters. In addition, the sensitivity analysis concerning costs of technologies and services should be performed.

To provide one FR with fuel requires reprocessed SNF from 10 LWRs. However, reprocessing of SNF increases the cost of fuel cycle. From the analysis results it becomes obvious that reprocessing of SNF from FRs (instead of SNF from LWRs) is feasible owing to much higher level of fissile material.

The levelized cost of electricity makes up 14.08 USD/MWh for implementation of one FR and 12 USD/MWh for the case with substitution of LWR by FR after 2030. The capital cost of reactors built before 2012 is not taken into account.

In this case the most potentially productive way is to develop international cooperation in several areas of the NFC back-end listed below:

- reprocessing of SNF from LWRs;
- fabrication of MOX and ReU fuel.

APPENDIX A. INPUT DATA

A.1. NUCLEAR GENERATION AND NFC

A.1.1. Front-end

A.1.1.1. Uranium

For energy system modelling purposes natural uranium resources of Ukraine are accounted for 477 thousand tons. NPP uranium demand is covered by domestic reserves [XIII-2].

TABLE XIII-A1. PRICE BRACKETS OF URANIUM RESOURCES IN UKRAINE.

Price bracket, USD/kg	Resources, thousand tons
80	135
100	64.5
120	22.5
150	255

A.1.1.2. Uranium conversion and enrichment

For the modelling purposes the cost of conversion services in 2013 equals 10 USD/kg(HM) [XIII-3]. The uranium conversion phase is considered to be service.

Uranium enrichment is also considered to be service with cost of 130 USD/SWU and is purchased at the global market, which is assumed to be unlimited [XIII-3].

A.1.2. Fresh fuel fabrication

A.1.2.1. Fresh nuclear fuel fabrication for LWR

Fresh fuel fabrication is considered to be service that is purchased at 300 USD/kg(HM). In 2008 average PWR nuclear fuel fabrication costs made up 250 USD/kg(HM). MOX-fuel fabrication for LWR is considered to be service purchased at 1500 USD/kg.

A.1.2.2. Blanket fabrication for FR

The cost of blanket fabrication based on depleted uranium makes up 300 USD/kg(HM).

A.1.2.3. Fresh nuclear fuel fabrication for FR core

MOX-fuel is used in FR core, as fabricated from depleted uranium derived from uranium enrichment tailings and plutonium resulting from SNF reprocessing.

The cost of MOX-fuel fabrication for FR cores is 2000 USD/kg(HM).

TABLE XIII-A2. FUEL FABRICATION COST, USD/KG(HM).

LWR(UOX)	LWR(MOX)	HWR(ReU)	FR(BN-800)	FR(BN-1200)
300	1500	200	300 – blanket, 2000 – core	300 – blanket, 2400 – core

A.2. REACTORS

TABLE XIII-A3. TECHNICAL AND ECONOMICAL PARAMETERS OF THE REACTORS.

Parameter	VVER–1000	ALWR	LWR (MOX)	FR	HWR
Thermal capacity, MW(t)	3000	3200	3200	2900 [XIII-4]	2064
Electrical capacity, MW(e)	1000	1120	1120	1200 [XIII-4]	728
Efficiency factor, %	33	35	35	1200 [XIII-4]	35.3
Capacity factor, %	78	90	90	90 [XIII-4]	90
Fuel enrichment, %	4.7	4.7	7% (Pu)	18.2 (Pu) [XIII-4]	0.9(5)
Average burn-up in fuel assembly, GW×day/t	60	60	60	113 [XIII-4]	13 [XIII-5]
First load, t(HM)	72.844(1)	72.844(1)	17.78 (MOX)(3), 53.35 (UOX)(4)	Total / Pu 41.5/ 7.802 [XIII-4]	88
Annual reload, t(HM)	16.088(2)	16.088(2)	3.,93 (MOX)(3), 11.78 (UOX)(4)	Total / Pu 8.05 / 1.513 [XIII-4]	52.113 (4)
Construction costs, USD/kW	3400 - Kh3Kh4	5000	5000	6000 (estimation by experts, no ref.)	4000
Fixed costs, USD/kW [XIII-6]	69.3	69.3	69.3	69.3	55.0
Variable costs, USD/MW×h [XIII-**Error! Bookmark not defined.**]	0.50	0.50	0.50	0.50	0.50
Operation lifetime, year	50	60	60	60 [XIII-**Error! Bookmark not defined.**]	35
Construction period	6	6	6	6	5
Fresh nuclear fuel fabrication, USD/kg	300 [XIII-7, XIII-8]	300 [XIII-7, XIII-8]	1500 [XIII-7, XIII-8, XIII-9]	2400 [XIII-4, XIII-9]]	200
SNF disposal costs, USD/kg	600 [XIII-7, XIII-9, XIII-10, XIII-11]	600 [XIII-7, XIII-9, XIII-10, XIII-11]	600 [XIII-7, XIII-9, XIII-10, XIII-11]	-	600 [XIII-7, XIII-9, XIII-10, XIII-11]
Reprocessing costs, USD/kg	2000 [XIII-7, XIII-9, XIII-11]	2000 [XIII-7, XIII-9, XIII-11]	-	2200 [XIII-4, XIII-8, XIII-9]	-
Disposal costs of the products derived from SNF reprocessing (MA, FP), USD/kg	10 000 [XIII-12]	10 000 [XIII-12]	10 000 [XIII-12]	10 000 [XIII-12]	10 000 [XIII-12]

(1) 163 fuel assemblies x 545 kg x 0.85 = 72 844 kg
(2) 36 fuel assemblies x 545 kg x 0.85 = 16 088 kg
(3) 25% MOX-fuel is loaded into the core
(4) as calculated
(5) ^{235}U containment

A.3. SNF MANAGEMENT

A.3.1. Centralized spent nuclear fuel storage facility

TABLE XIII-A4. CSNFSF DESIGN CAPACITY.

Reactor type	Number of fuel assemblies
WWER-1000	12 010
WWER-440	4 519
Total design capacity	16 529

The above mentioned centralized SNF storage facility may be used as temporary one (until postponed decision is implemented) [XIII-13]. The cost will make up 350 USD/kg(HM). The cost includes capital costs, O&M costs and decommissioning costs. The commissioning of centralized SNF storage facility with 5 650 t capacity is planned in 2015.

The cost of direct SNF disposal is estimated at 400-1000-1600 USD/kg(HM). The Ukrainian NFC modelling considers SNF disposal to be service with estimated cost of 600 USD/kg(HM).

A.3.2. LWR SNF reprocessing for utilization in CANDU

LWR SNF reprocessing is considered to be a purchasable service that costs 2000 USD/kg [XIII-7, XIII-8, XIII-9, XIII-11].

A.3.3. LWR SNF reprocessing for utilization in FR

LWR SNF is reprocessed with a purpose to extract plutonium and fabricate MOX-fuel to be used in fast reactors. LWR SNF reprocessing for FR fuel fabrication is considered to be a purchasable service that costs 2000 USD/kg(HM).

A.3.4. FR SNF reprocessing for reutilization in FR

After being exposed to radiation in FR, SNF may be reprocessed for repeated extraction of plutonium and MOX-fuel fabrication to be loaded in the FR core.
The following assumptions are made in relation to SNF from fast reactors:

- all FR SNF is reprocessed and its disposal is not considered;
- after SNF reprocessing plutonium is used for FR fuel fabrication;
- after FR SNF reprocessing uranium is subject to storage for unlimited period of time;
- there is no difference between SNF of the core and SNF of the blanket in the model;
- after SNF reprocessing minor actinides and fission products are subject to final disposal.

FR SNF reprocessing for further application in fast reactors is considered to be a purchasable service that costs 2200 USD/kg [XIII-14].

A.3.5. Disposal of high-level products resulted from reprocessing

The model assumes the following:

- the repository capacity is not restricted;
- the cost of HLW disposal ranges from 2 500 to 12 500 USD/kg(FP) [XIII-12], 10 000 $/kg(FP) was chosen for the present model.

Non-nuclear generation and electricity consumption

A.3.6. Projected electricity consumption in Ukraine till 2100

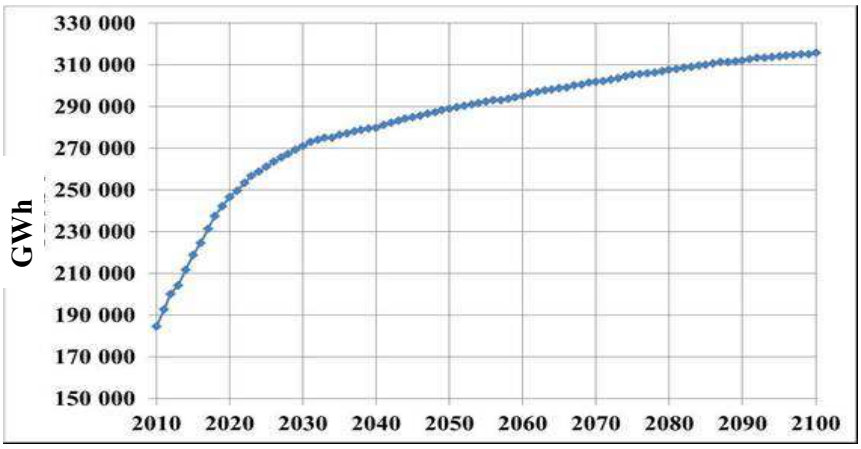

FIG XIII-A1. Projected electricity consumption in Ukraine till 2100.

A.3.7. Electricity production

The installed capacities structure as for 31 December 2011 [XIII-15] and generation structure [XIII-16] in Ukraine are presented in Tables XIII-A5 and XIII-A6. Coal-fuelled power plants have the biggest share in the installed capacities – about 50%, nuclear power plants cover about 25%. The share of solar and wind power plants makes up 0.25% and 0.23% respectively.

It should be noted that the majority of thermal power plants were commissioned from 1960 to 1980 [XIII-16] and their modernization should be started in the coming years. The commissioning of nuclear power plants occurred in 1980-1990s.

Nowadays the activities on lifetime extension of nuclear power units are carried out.

TABLE XIII-A5. INSTALLED CAPACITIES STRUCTURE IN UKRAINE.

Generation type	Capacity, MW	Share, %
NPP	13 835	25.95
TPP (coal)	27 272	51.16
CHP and other TPP	6 429,8	12.05
HPP	5 465	10.26
Solar power plants	187.5	0.35
Wind farms	121.1	0.23

Most electricity is generated at nuclear power plants (45-47%), fossil fuel burning power plants produce 43-49% of electricity and hydro power plants amount to 6-7%.

TABLE XIII-A6. ELECTRICITY GENERATION STRUCTURE IN UKRAINE.

Type	2010		2011		2012	
	bln. kW×h	%	bln. kW×h	%	bln. kW×h	%
NPP	89,2	47	90,2	46	90,1	45
TPP	86,5	46	93,6	48	97,1	49
HPP	13,2	7	10,9	6	11,0	6
Total	188,8	100	194,9	100	198,9	100

A.3.8. Non-nuclear energy

Ukraine exploits almost all fossil and renewable primary energy resources, however their power potential is very different.

A.3.9. Coal-fuelled power plant

Since 2000 the coal consumption for electricity generation was 40-50 mln. tons of r.f. that corresponds to the mining capabilities of Ukraine. However the coal reserves in Ukraine are difficult to access and a lot of investments is required for new technologies deployment that could make the coal mining less expensive.

Coal-fuelled power plants are presented in the model as a technology with the following parameters:

- capacity factor – about 55%;
- capital construction costs – 1600 USD/kW;
- construction period – 4 years;
- fixed costs – about 57 USD/kW of installed capacity per year;
- variable costs – about 4,5 USD/kW×h of generated electricity at specific coal price correlated with generated energy and estimated at 107 USD/kW×year (100 USD/t).
- construction and modernization pace of coal-fuelled power plants does not exceed 2000 MW per year.

A.3.10.Gas-fuelled power plant

Natural gas application for commercial generation is restricted by its limited reserves and considerable increase of import prices. Taking into account that gas-fuelled power plants are the most suitable for responding to peak loads, capacity factor is assumed to be about 32% (gas-fuelled power plants are supposed to be highly-maneuverable facilities capable to respond to the peak loads). Some other economic parameters include:

- capital construction costs – 1300 USD/ kW;
- construction period – 3 years;
- fixed costs – about 20 USD/kW of installed capacity per year;
- variable costs – about 15 USD/kW×h of generated electricity. The gas price is about 350 USD/kW×year (corresponds to the purchase price of 400 USD/thousand m^3).

A.3.11.Hydro power

The energy potential of large rivers makes up 7,0 mln. tons of r.f./year and is almost exhausted. The energy potential of small rivers is low and amounts to 1,4 mln. tons of r.f./year and therefore cannot be considered as a significant factor for base-load generation. Hydro power plants have high energy potential in regulating peak loads and when it is necessary to reimburse the collapse of energy consumption.

The main economic parameters of hydro power used in the model are listed below:

- capacity factor – about 25%;
- capital construction costs – 2200 USD/kW;
- construction period – 10 years;
- fixed costs – about 14 USD/kW of installed capacity per year;
- variable costs – about 2,4 USD/kW×h of generated electricity.

A.3.12.Wind energy

The following parameters of wind power are used in the model of the energy system of Ukraine:

- capacity factor – 26%;
- capital construction costs – 1900 USD/kW;
- construction period – 1 year;
- fixed costs – about 31 USD/kW of installed capacity per year.

A.3.13.Solar energy

The following parameters of solar energy are used in the model of the energy system of Ukraine:

- capacity factor – 16%;
- capital construction costs – 5000 USD/kW;
- construction period – 1 year;
- fixed costs – about 15 USD/kW of installed capacity per year.

REFERENCES TO ANNEX XIII

[XIII-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE), 2009

[XIII-2] ORGANISATION OF ECONOMIC COOPERATION AND DEVELOPMENT NUCLEAR ENERGY AGENCY, AND INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2007: Resources, Production and Demand, Paris (2012).

[XIII-3] UxC web site: http://www.uxc.com/

[XIII-4] I.A. KUZNETSOV, V.M. POPLAVSKIY, Safety of NPPs with fast reactors, IzdAT, Moscow (2012), (in Russian).

[XIII-5] INTERNATIONAL ATOMIC ENERGY AGENCY, Heavy Water Reactors: Status and Project Development, IAEA Technical Report Series No. 407, Vienna (2002)

[XIII-6] S. KAPLAN, Power plants: characteristics and costs, CRS Report for Congress, Order Code RL34746 (2008): https://www.fas.org/sgp/crs/misc/RL34746.pdf

[XIII-7] ORGANISATION OF ECONOMIC COOPERATION AND DEVELOPMENT NUCLEAR ENERGY AGENCY, Advanced Nuclear Fuel Cycles and Radioactive Waste Management, OECD Nuclear Development (2006): https://www.oecd-nea.org/ndd/pubs/2006/5990-advanced-nfc-rwm.pdf

[XIII-8] INTERNATIONAL ATOMIC ENERGY AGENCY, Spent fuel reprocessing options, IAEA TECDOC Series No. 1587, Vienna (2008)

[XIII-9] D. SHROPSHIRE, Advanced fuel cycle economic analysis of symbiotic light water reactor and fast burner reactor system, INL, 2009.

[XIII-10] 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)

[XIII-11] INTERNATIONAL ATOMIC ENERGY AGENCY, Spent fuel reprocessing options, IAEA TECDOC Series No. 1587, Vienna (2008)

[XIII-12] Terms of Reference for INPRO collaborative project "Synergistic nuclear energy regional group interactions evaluated for sustainability" (SYNERGIES)

[XIII-13] MINISTRY OF ENERGY AND COAL INDUSTRY OF UKRAINE, ENERGOATOM SCIENTIFIC AND TECHNICAL CENTRE "SE NNEGC", Analytical survey of the materials of a feasibility study on centralized repository for spent nuclear fuel of VVER reactors of the Ukraine nuclear power plants: http://www.kmu.gov.ua/control/en/publish/article?art_id=89307

[XIII-14] Workshop on elaboration of common approaches to the assessment of national nuclear power deployment in the framework of regional cooperation in solving NFC issues (within INPRO-SYNERGIES project)», Kyiv, 16-17 May 2013.

[XIII-15] NATIONAL POWER COMPANY "UKRENERGO", Changes of installed capacities in the Joint energy system of Ukraine in 2011, Kiev (2011): http://www.ukrenergo.energy.gov.ua/Pages/main.aspx

[XIII-16] STATE STATISTICS SERVICE OF UKRAINE, Annual statistical digest of Ukraine in 2012, Kiev (2013).