ANNEX XV.

STUDY ON SENSITIVITY ANALYSIS OF THE SHARES OF NG1/NG2 COUNTRY GROUPS IN GAINS SCENARIOS

The current study is based on widely used and recommended framework developed in the INPRO GAINS collaborative project. The GAINS framework classifies non-personified countries into three country groups according to their nuclear fuel cycle strategies: NG1 countries pursue fast reactor programme and perform recycling of SNF; NG2 countries either directly dispose of the SNF or send it to NG1 for reprocessing; and NG3 countries are LWR based newcomer countries that send the SNF back to NG1 or NG2. The analysis methodology in this study is based on varying the allocation of future nuclear energy generation share of each country group as function of time for assessment of different scenarios, in comparison to the GAINS studies where the NG1:NG2:NG3 ratio was kept fixed at 40:40:20.

The objective of this sensitivity analysis is to study the behavior of global nuclear energy system in terms of its key parameters and stress limits under variations in country group shares. The GIANS framework was employed for investigating impact of various growth rates of NGs. This study explores possibility of transition of NG1 and NG2 groups under changes in NG1:NG2 proportion. The study also assesses impact of NG3 share variation on NG1/NG2 front end and back end fuel cycle requirements. Description and major details of GAINS approach for dynamic NES modelling are provided in appendix 3.

XV-1. SCENARIOS OF GLOBAL NUCLEAR ENERGY SYSTEM DEVELOPMENT FOR SYNERGIES STUDIES

Scenarios of global nuclear energy with Moderate and High capacity growth include modeling of the Base case scenario (40%-40%-20%) and four additional scenarios having different nuclear power shares of NG1/NG2 and keeping fixed nuclear power in NG3. The scenarios explore non-synergistic and synergistic nuclear energy development to consider the mutual benefits and issues of cooperation. Total scenario number is thirty including 3 NG groups, 5 scenarios and 2 (Moderate and High) nuclear power growth options.

Nuclear power distribution for the different scenarios and groups of countries with Moderate and High power growth of global nuclear energy are presented in Tables XV-1—XV-2.

XV-2. ANALYSIS OF THE MODELLING RESULTS

The study compares simulation results for synergistic and non-synergistic group development. There are five scenarios considered for Moderate and five for High growth by 2100 (see Tables XV-1—XV-2).

TABLE XV-1.SCENARIOS FOR MODERATE GROWTH OF NUCLEAR POWER

Moderate scenario 2500 GW(e)*year in 2100				
Nominal case (40%, 40%, 20% in 2100) scenario 3				
Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	286	286	29	600
2050	454	454	91	1000
2100	1000	1000	500	2500
Sensitivity studies:				
Minimal direct disposal (NG2 25% to 10%) scenario 1				
Year	NG1	NG2	NG3	Total
2008	224	75	0	298
2030	443	128	29	600
2050	727	182	91	1000
2100	1750	250	500	2500
High NG1 growth (from 50% to 65%) scenario 2				
Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	307	264	29	600
2050	568	340	91	1000
2100	1625	375	500	2500
High NG2 growth (from 50% to 65%) scenario 4				
Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	264	307	29	600
2050	340	568	91	1000
2100	375	1625	500	2500
Minimal recycle (ng1 35% to 10%) scenario 5				
Year	NG1	NG2	NG3	Total
2008	104	194	0	298
2030	174	397	29	600
2050	236	673	91	1000
2100	250	1750	500	2500

TABLE XV-2. SCENARIOS FOR HIGH GROWTH OF NUCLEAR POWER

High scenario 5000 GW(e)*year in 2100				
Nominal case (40%, 40%, 20% in 2100) scenario 3				
Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	333	333	33	700
2050	682	682	137	1500
2100	2000	2000	1000	5000
Sensitivity studies:				
Minimal direct disposal (ng2 25% to 10%) scenario 1				
Year	NG1	NG2	NG3	Total
2008	224	75	0	298
2030	517	150	33	700
2050	1091	272	137	1500
2100	3500	500	1000	5000
High NG1 growth (from 50% to 65%) scenario 2				
Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	358	308	33	700
2050	853	510	137	1500
2100	3250	750	1000	5000
High NG2 growth (from 50% to 65%) scenario 4				
Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	308	358	33	700
2050	510	853	137	1500
2100	750	3250	1000	5000
Minimal recycle (ng1 35% to 10%) scenario 5				
Year	NG1	NG2	NG3	Total
2008	104	194	0	298
2030	203	463	33	700
2050	354	1009	137	1500
2100	500	3500	1000	5000

Key indicators for each scenario include:

- Nuclear capacities;
- Natural uranium consumption;
- Separation work unit;
- Fresh fuel production;
- Reprocessing of spent nuclear fuel (SNF);
- Plutonium accumulation and consumption;
- SNF storage facilities (for cooled fuel).

The minimal amount of SNF in Scenario 1 and a minimal amount of reprocessing facilities in Scenario 5 define upper and lower nuclear energy limits in NG1 and in NG2 by 2100. NG3 group keeps reference scenario share.

Following key indicators were calculated for each group:

– Thermal and fast reactors share in NG1 (Fig. XV-1—XV-3);
– Natural Uranium consumption in NG1, NG2, NG3 (Fig. XV-3—XV-4);
– Annual SWU in NG1, NG2, NG3 and summary (total), see Fig. XV-5—XV-12;
– SNF accumulation in NG1, NG2, NG3 and summary (total), see Fig. XV-13—XV-20;
– Annual loading of reprocessing facilities in NG1 (Fig. XV-21—XV-22).

These results are shown in Fig. XV-1—XV-22. For convenience, the graphic information of each scenario corresponds to a diagram number (from left to right) and caption (from top to bottom). Numbers are identical to the numbers of scenarios presented in Tables XV-1— XV-10. NG1/NG2 share in 2100 considers five possible scenarios:

1. Minimum SNF. Low share of capacity in NG2. Maximum reprocessing in NG1.
2. High growth in NG1. Nuclear power growth in NG1 countries from 50% in 2008 to 65% by 2100.
3. Base case (40% NG1, 40% NG2, 20% NG3 in 2100).
4. High growth in NG2. Nuclear power growth in NG2 countries from 50% in 2008 to 65% by 2100.
5. Minimum SNF reprocessing. Low share of capacity in NG1. Maximum of SNF in the NG2.

There are two interconnected bar charts with the same color representing the results of calculations, from the left to right on the charts: (a) the independent development of nuclear energy in each group of countries, and (b) interaction between groups of countries (synergy).

In case of no difference between synergistic and non-synergistic scenarios, the results will coincide and bar charts of both scenarios will merge to form a single column of single color, as illustrated by Fig. XV-1 for the 2050 case. However, if cooperation has certain impact on the results, the columns height will change and a ‘step’ will appear, which is clearly visible for the 2100 case.

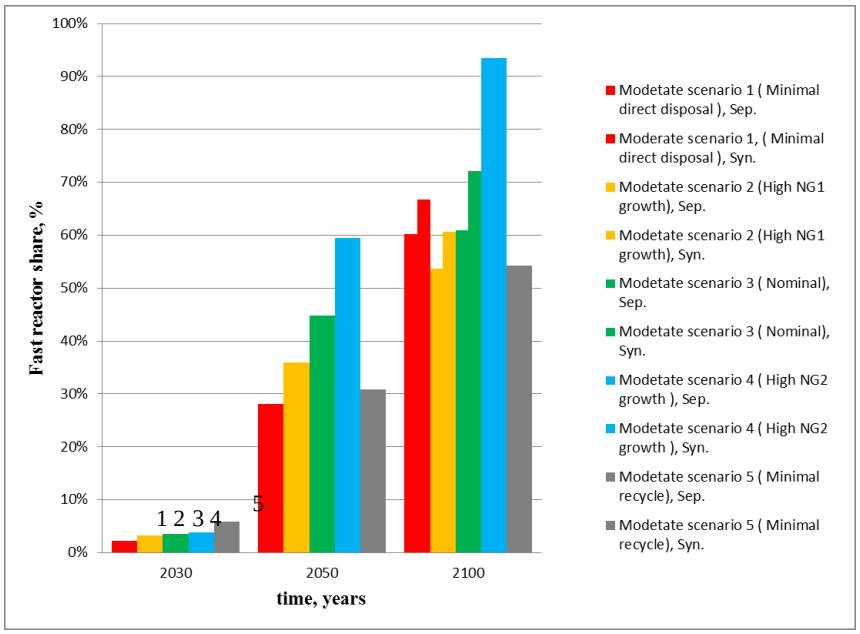

FIG. XV-1. Fast reactors share in NG1, moderate scenario (Option I).

However, there is synergistic effect provoked increase in the fast reactors share in NG1 after 2050 in the scenarios 1, 2 and 3. The difference between the synergistic and non-synergistic scenarios in these three scenarios is 7%, 7% and 11%, respectively, in 2100. The proportion of fast reactors strongly depends on capacity increase in NG1, as well as on the development of Nuclear System in NG2 as shown in the Fig. XV-1.

This trend is even more significant in the case of global Nuclear Energy Development for Option II (Fig. XV-2). So from Scenario 4 analysis (high capacity growth in NG2) it can be concluded that the share of fast reactors in NG1 reaches 53—55% (without or with the interaction) by 2050, and 71—93% respectively in 2100, i.e. the proportion of synergism reaches 22% in 2100.

Thus, in accordance with the proposed mathematical model of fast reactor, technology development depends on the nuclear energy in NG1 and the growth in the capacity of NG2.

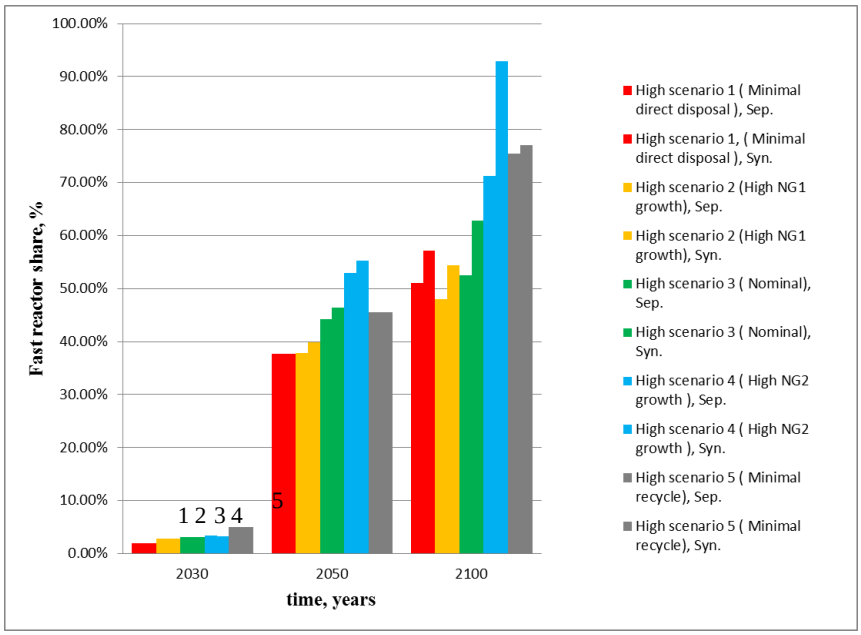

FIG. XV-2. Fast reactors share in NG1, high scenario (Option II).

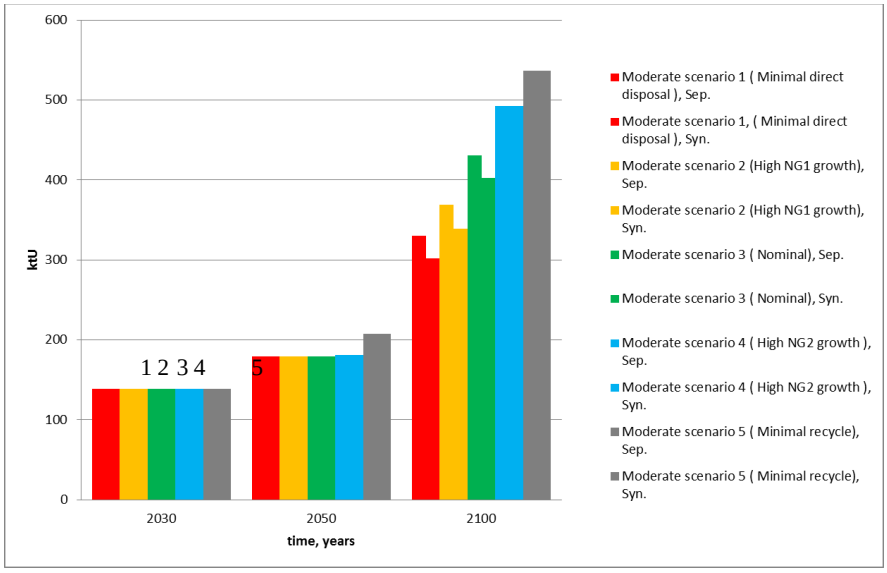

FIG. XV-3. Annual natural uranium consumption of NG1, NG2, NG3 (Option I).

Figures XV-3 and XV-4 present the annual consumption of natural uranium in the group of countries with Moderate and High scenarios of NE. The consumption is the lowest in Scenario 1 "Minimal direct disposal (25% to 10%)" and maximum in Scenario 5 “Minimal recycle (35% to 10%)” Natural uranium consumption is steadily increasing to the end of the century.

In both cases of world nuclear energy development synergistic effect reduces the annual natural uranium consumption by about 30—40 ktU, if any. The absolute annual consumption is maximum for the High fifth scenario reaching 1050 ktU (Fig. XV-4).

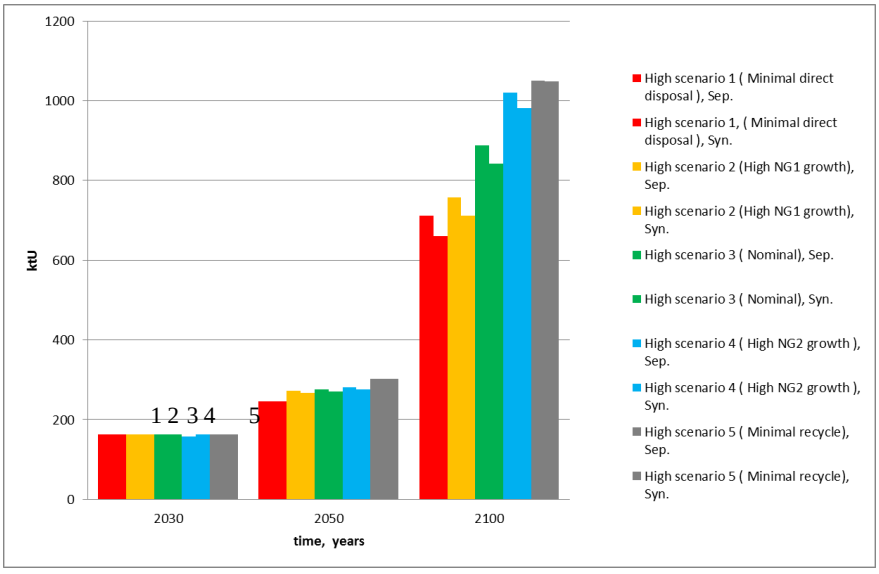

FIG. XV-4. Annual natural uranium consumption of NG1, NG2, NG3 (Option II).

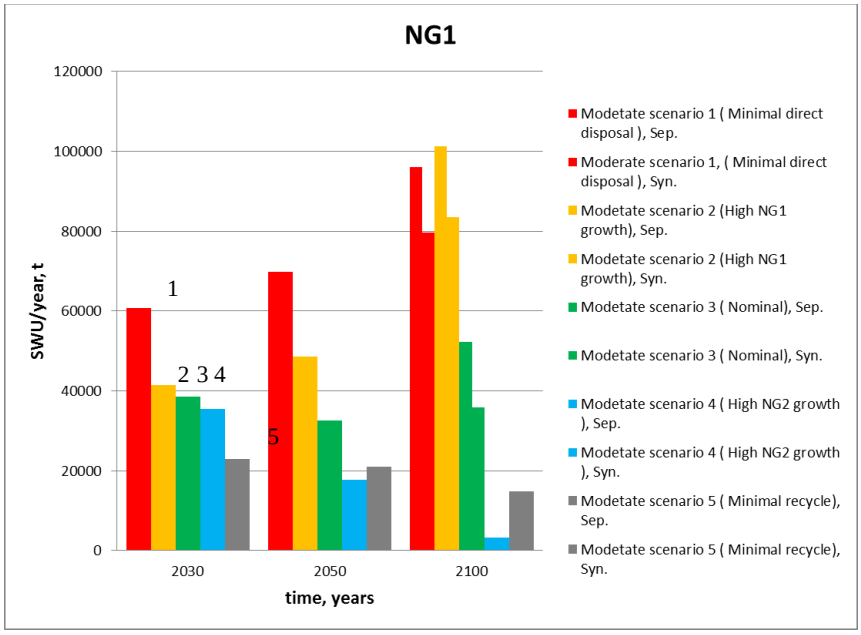

FIG. XV-5. SWU NG1, moderate case (Option I).

Figure XV-5 shows the variation of SWU/year for NG1 countries in the Moderate case. The independent development of country groups for Scenario 1 (Minimal direct disposal (25% to 10%)) in 2050/2100 accounts for 69835/96079 SWU/year. In scenario 4 "High

growth in NG2" NG1 has the minimum SWU for all time segments: 35413/17692/3168 SWU/year in 2030, 2050 and 2100, respectively. Synergistic effect takes place in the first three scenarios after 2050.

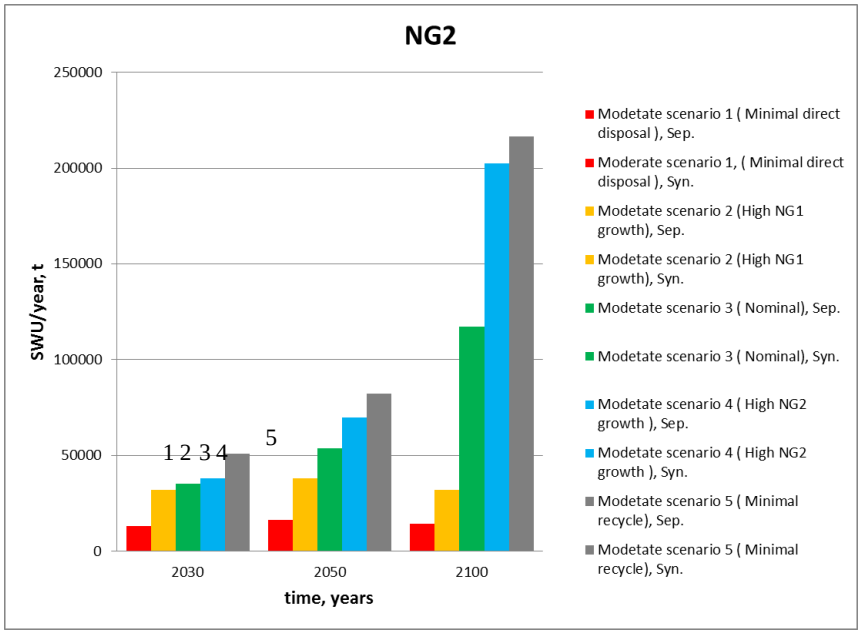

FIG. XV-6. SWU NG2, moderate case (Option I).

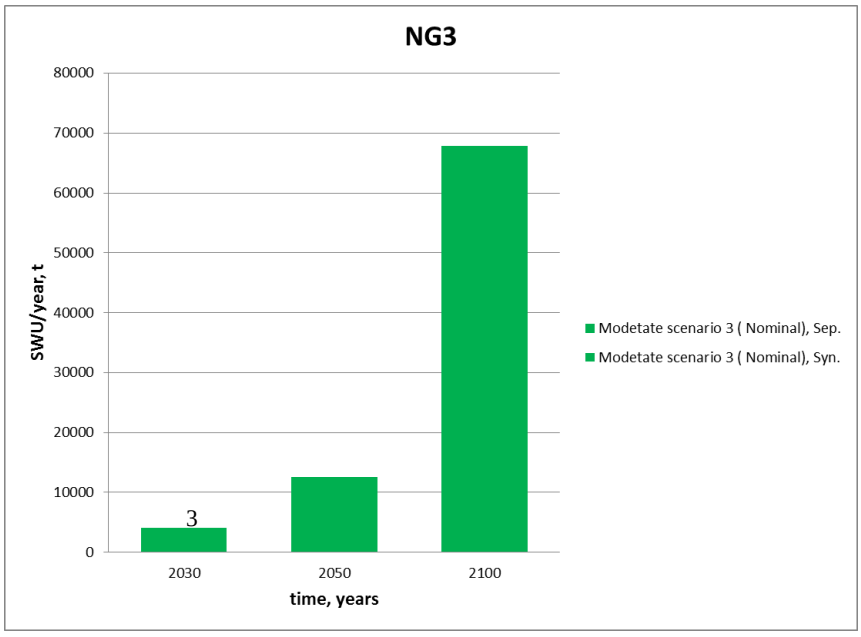

FIG. XV-7. SWU NG3, moderate case (Option I).

Figures XV-6 and XV-7 present SWU/year in NG2 and NG3 under Moderate case. All these regions develop proportionally to power increase (because of once-through fuel cycle). For NG2 the minimum SWU requirement is 14335 SWU/year in 2100 for Scenario 1 "Minimal Direct Disposal (25% to 10%)", and maximum is 217,538 SWU/year for Scenario 5 "Minimum SNF reprocessing". Scenarios capacity growth dynamics for NG3 is shown in Fig. XV-7.

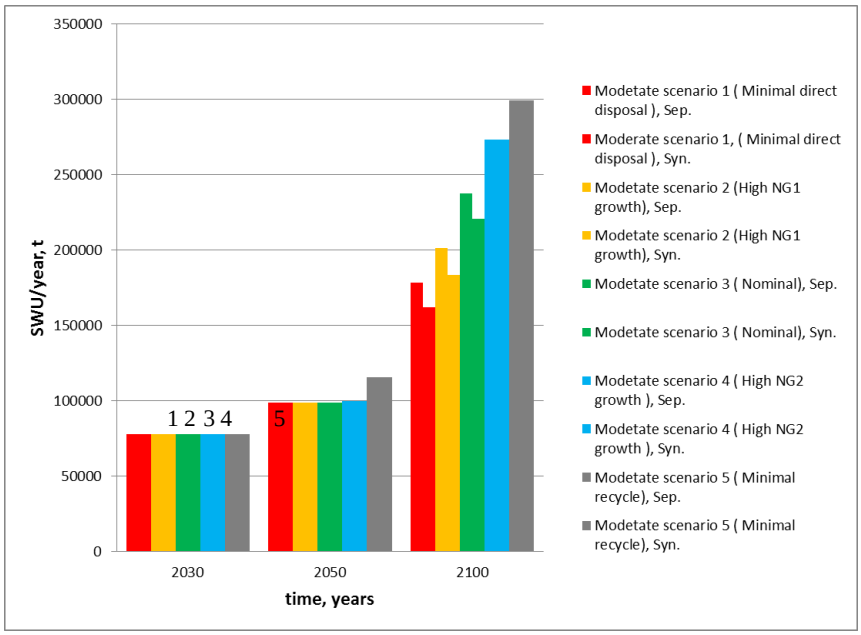

FIG. XV-8. SWU NG1, NG2, NG3, moderate case (Option I).

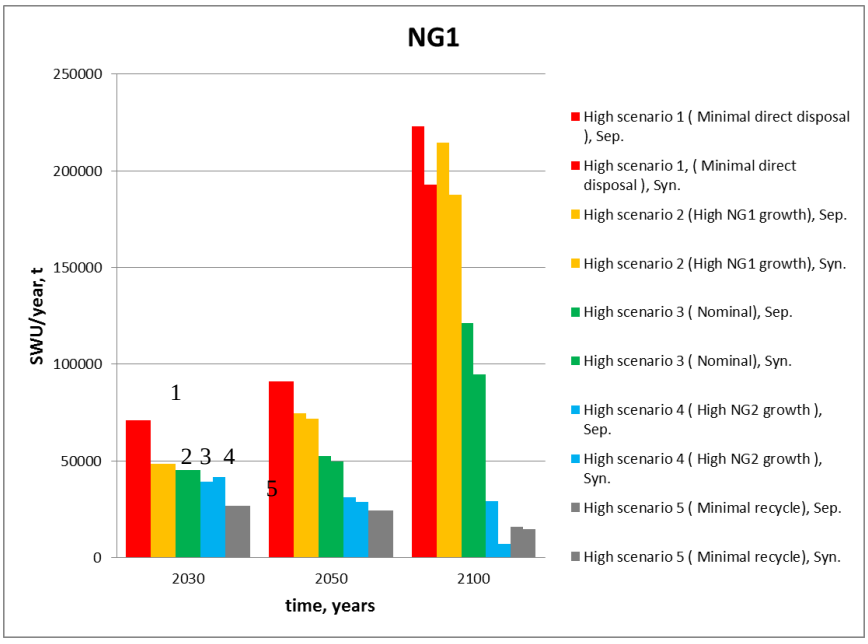

FIG. XV-9. SWU NG1, high case (Option II).

The same trend can be observed for High case for nuclear power development.

Synergistic effects appear in all high Scenarios after 2050 (Fig. XV-9) and before 2050 in Scenarios 2 "High growth in NG1", 3 "Base case" and 4 "High growth in NG2". Before 2030 synergism occurs for 4th scenario only. There is no synergy effect in NG2 and NG3 (Fig. XV-10, XV-11).

Figures from XV-8 to XV-12 show the total SWU for the three regions.

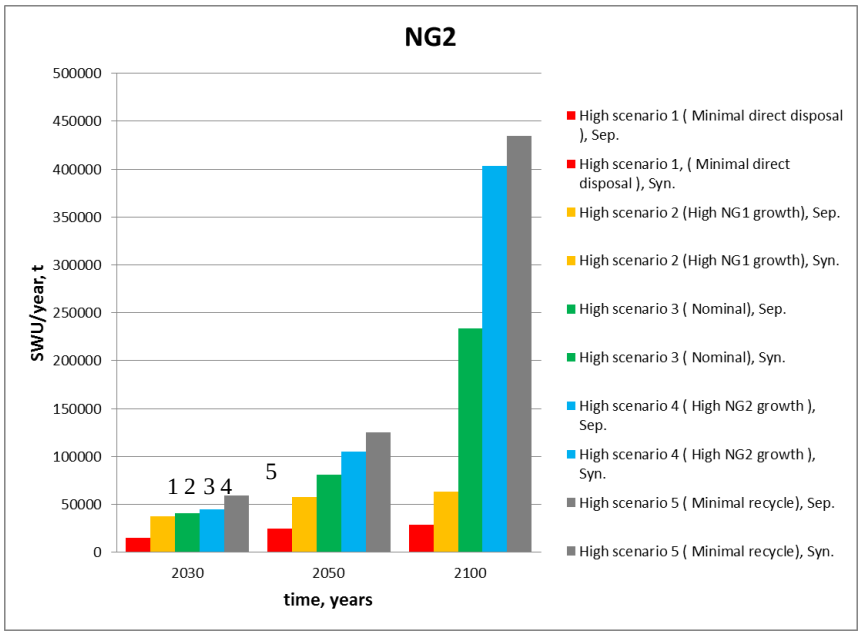

FIG. XV-10. SWU NG2, high case (Option II).

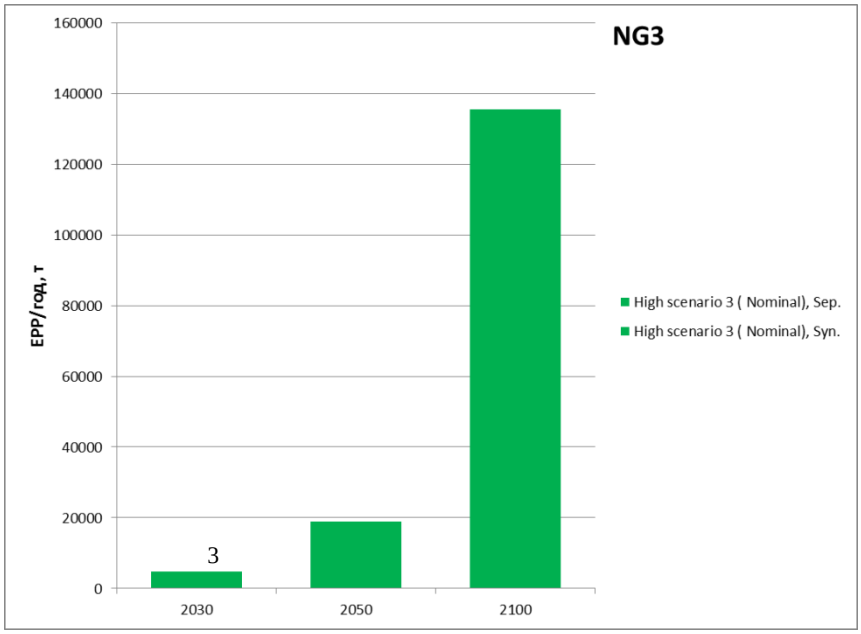

FIG. XV-11. SWU NG3, high case (Option II).

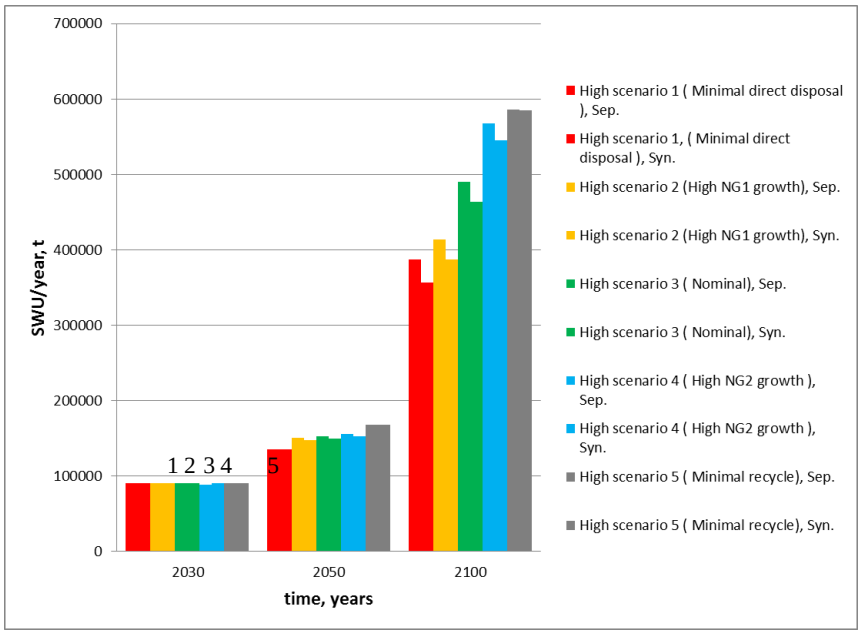

FIG. XV-12. SWU NG1, NG2, NG3, high case (Option II).

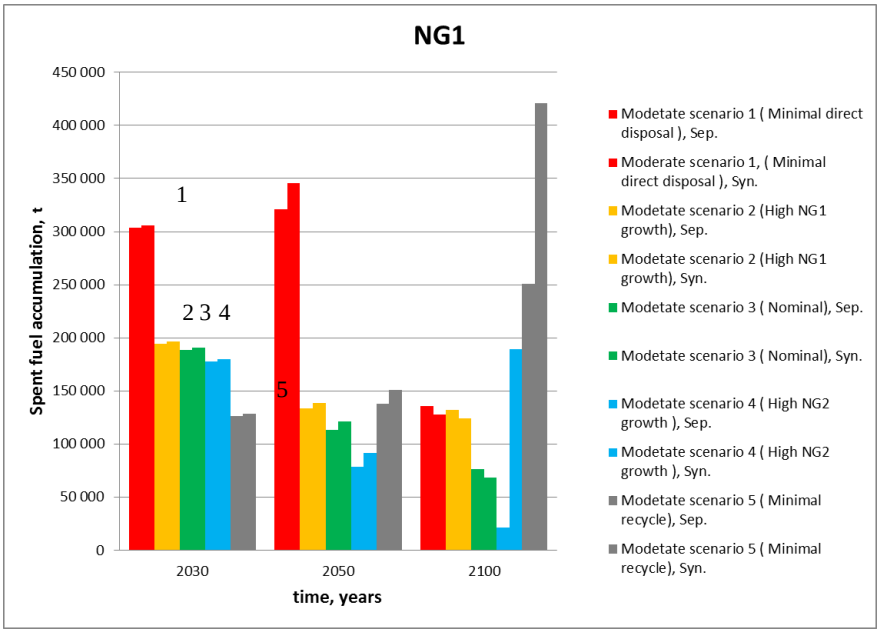

FIG. XV-13. SNF accumulation in NG1, moderate case (Option I).

Figure XV-13 shows the dynamics of SNF accumulation in NG1 at different time intervals for Moderate (Option I) case.

As can be seen from the diagram, irradiated nuclear fuel is accumulated in storages in different ways. For the first four scenarios a trend can be observed of accumulated SNF reduction from Scenario 1 to 4 respectively. The most considerable synergistic effect appears in 2100 for the Scenario 4. The accumulated amount of irradiated fuel increases in 9-fold compared with that of independent development regions and exceeding its level of 2030.

However, the most dangerous trend in terms of accumulation of SNF occurs is Scenario 5 "Minimum SNF reprocessing". The amount of accumulated SNF is relatively small in 2030 (125 kt) and stays unchanged until 2050. The strong growth of irradiated fuel stocks in storages starts after 2050, reaching 250 kt in 2100 in NG1 region in case of separate

development and 420.5 kt in synergistic case. This is the maximum amount of SNF in comparison with other scenarios.

In general, Scenarios 1 "Minimum SNF", 2 "High growth in NG1» and 3 "Base case" Moderate (Option I) hold a favorable trend to reduce the amount of SNF in storages.

If the extreme cases in the form of scenarios 1 "Minimum SNF" and 5 "Minimum SNF reprocessing" are not considered, the amount of SNF by 2100 is expected to be 124377/68454/189060 t for scenarios 2, 3 and 4, respectively, in the synergetic case. For independent development of the regions, the SNF amount reaches 132146/76158/21822 tons for the second, third and fourth scenarios, respectively.

Figure XV-14 shows SNF data for NG2 with a Moderate scenario. Countries of NG2 have similar ways of development and SNF amount increases much faster for synergistic case than for separate case.

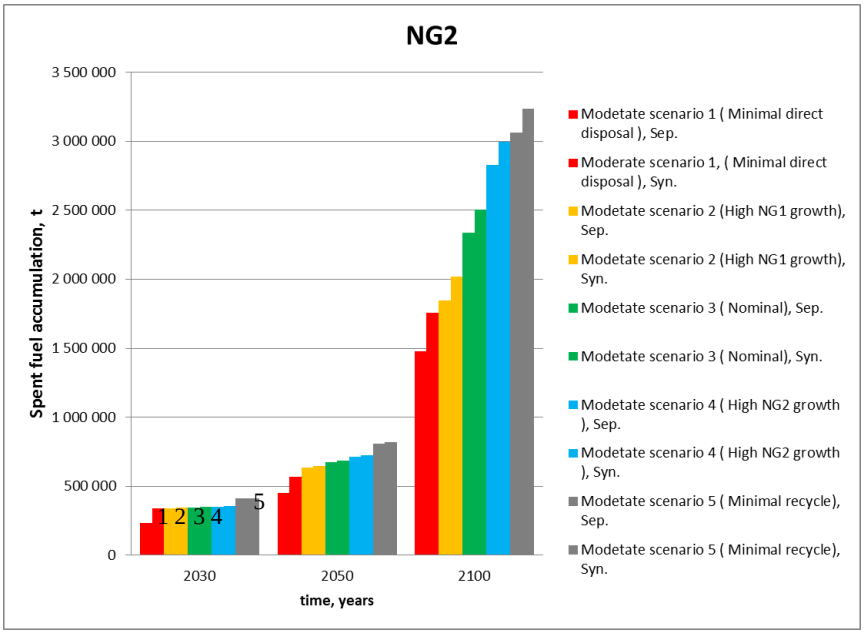

FIG. XV-14. SNF accumulation in NG2, moderate case (Option I).

Synergism starts from 2030 in Scenario 1 "Minimum SNF" and continues in all scenarios in NG2, representing half of NG3 SNF.

Figure XV-15 shows the SNF amount in NG3 group. The amount of SNF in synergetic case is minimal after transportation to the regions of NG1 and NG2and it is stored in cooling pools. In 2100 the amount of SNF in storage pools is expected to be 60 kt.

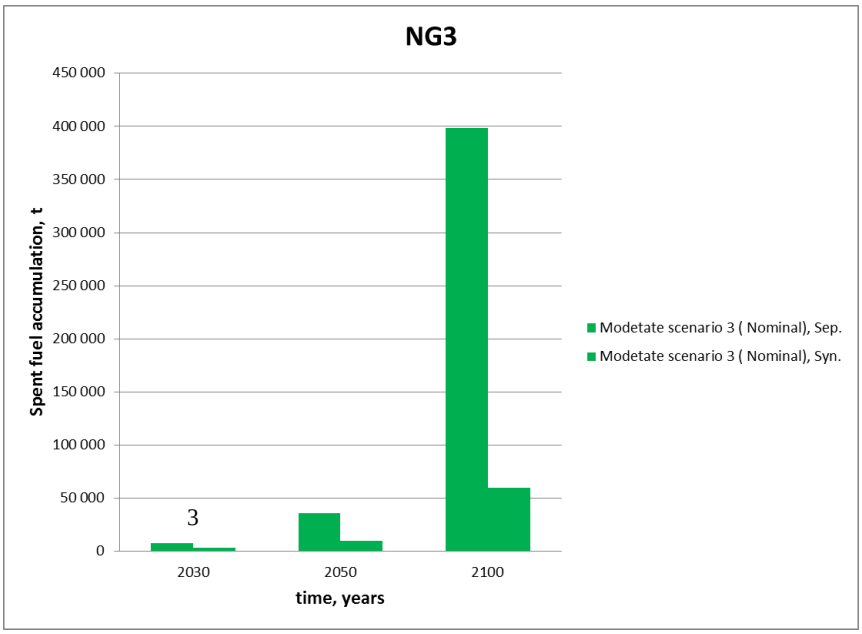

FIG. XV-15. SNF accumulation in NG3, moderate case (Option I).

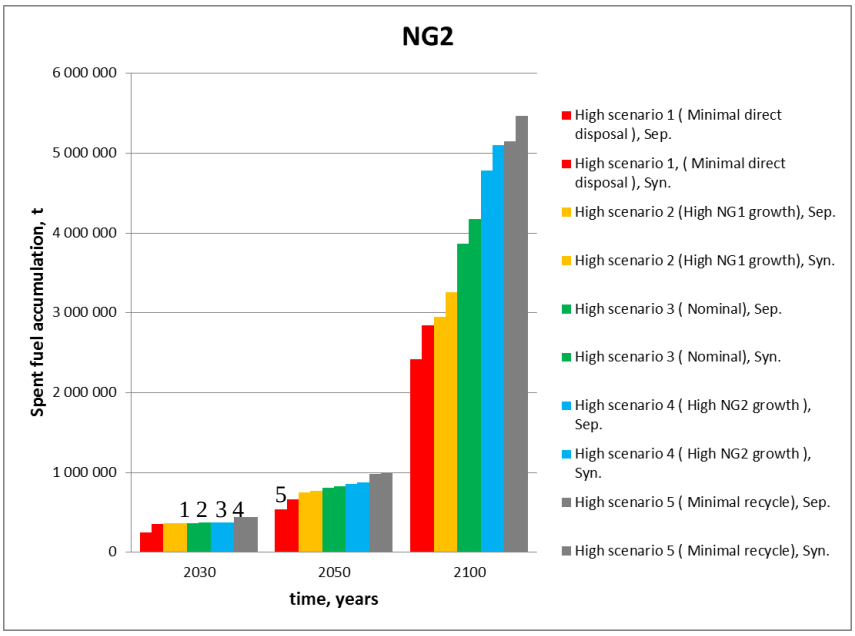

FIG. XV-16. SNF accumulation in NG1, high case (Option II).

Figure XV-16 shows the accumulation of SNF in storages for High case in NG1. Comparison with the Moderate case (Fig. XV-13) indicates the following: the amount of SNF in scenarios 1, 2, 3 and 4 in 2100 is greater than in 2050. This can be explained by an increase in the NG1 nuclear capacities due to the large share of fast reactors (Fig. XV-2). SNF that cannot be technologically recycled because of the retention time (cooling time) also has impact. Other trends are similar to those shown in Fig. XV-13.

Figure XV-17 shows the accumulation of SNF data for NG2 region in High case, which is similar to the Moderate Scenario case shown in Fig.XV-14. NG2 countries are developing in a similar way. SNF amount increases much faster in synergistic case. SNF accumulation in

NG3 storage (Fig. XV-18) is similar to that in the case of moderate (Option I) development of nuclear energy (Fig. XV-15) with the only difference in the scale of values.

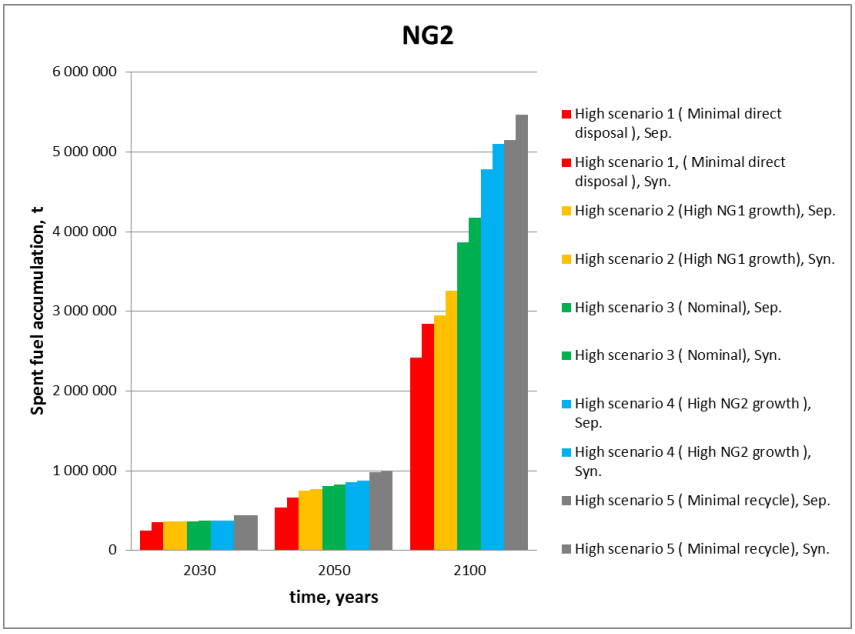

FIG. XV-17. SNF accumulation in NG2, high case (Option II).

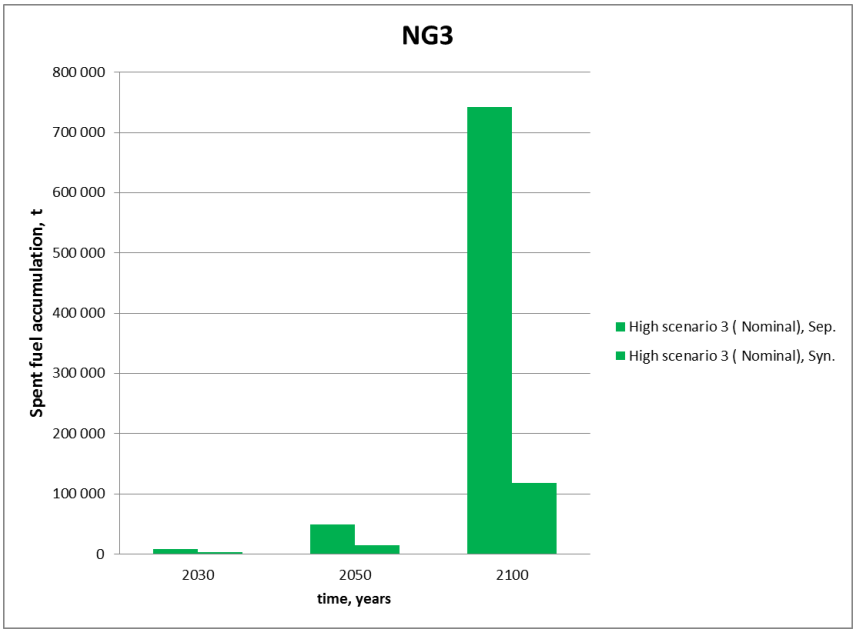

FIG. XV-18. SNF accumulation in NG3, high case (Option II).

Figures XV-19 and XV-20 show total amount of SNF in NG1, NG2 and NG3 for Moderate and High cases. Trends for High and Moderate options are similar: decrease in capacity in NG1 leads to increase of SNF amount by 2100.

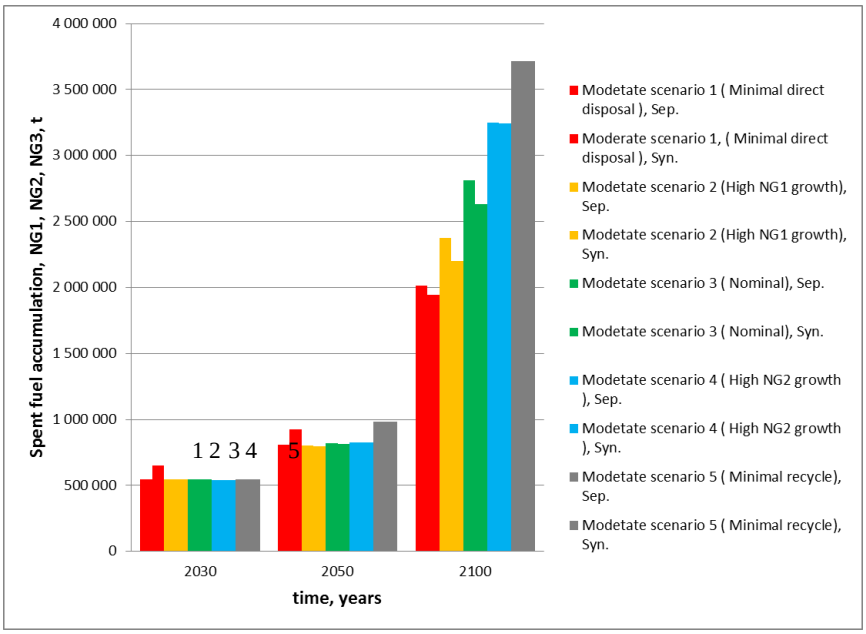

FIG. XV-19. SNF accumulation in NG1, NG2, NG3, moderate case (Option I).

Figure XV-20 shows a slight increase of 117 000 tons of SNF in 2050 for synergistic case in the first scenario. However, by 2100 accumulated SNF decreases by 71000 tons in synergistic scenario in comparison with non-synergistic case. Thus, synergism provides gradual decrease of SNF accumulation.

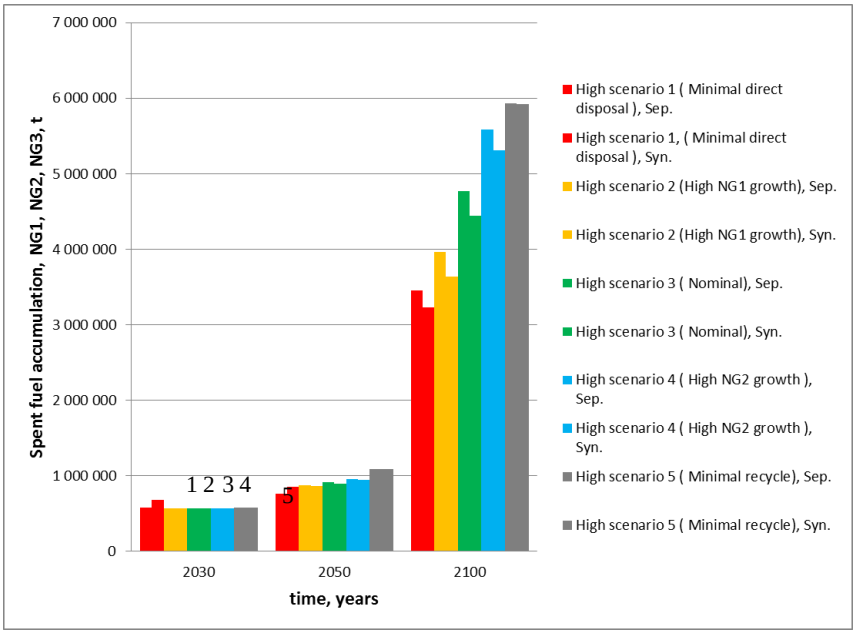

FIG. XV-20. SNF accumulation in NG1, NG2, NG3, high case (Option II).

Figures XV-21 and XV-22 show the capacity of reprocessing facilities in different scenarios for Moderate (I) – Fig. XV-21 – and High (II) – Fig. XV-22 – scenarios of the global nuclear energy development. The dashed line denotes the capacity of reprocessing facilities with a synergism.

FIG. XV-21. Capacity of recycle facilities in NG1, moderate case (Option I).

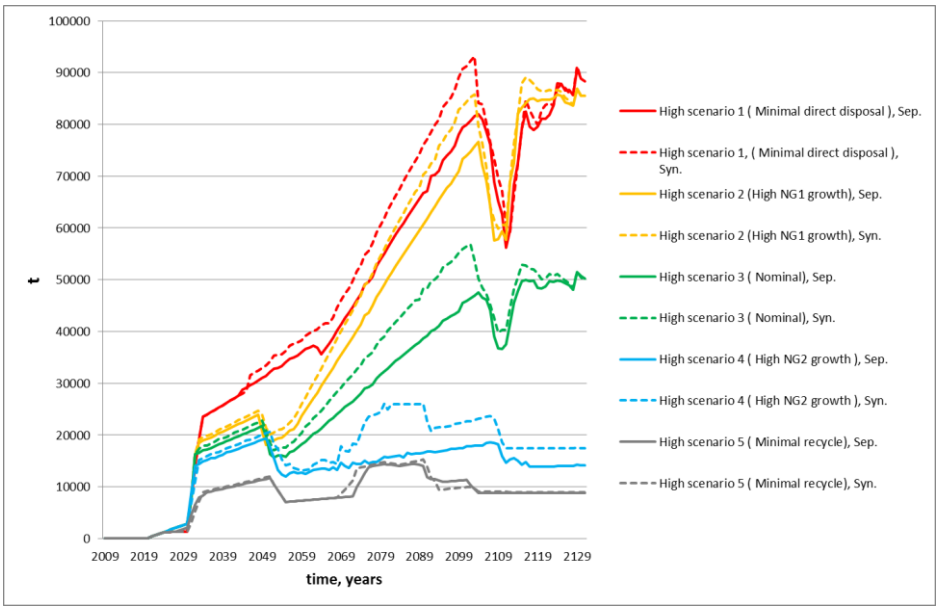

FIG. XV-22. Capacity of recycle facilities in NG1, high case (Option II).

XV-3. CONCLUSIONS

The scenarios considered are interdependent and are formulated in such a way that the total power of nuclear energy capacities in all scenarios for NG1, NG2 and NG3 is considered constant and equal to 5000 GW∗year for the High and 2,500 GW∗year for the Moderate case by 2100. Countries in NG3 region (newcomers) have the same nuclear capacities in both cases. An increase of capacity in NG1 leads to its decrease in NG2 and vice versa. The difference among scenarios is discussed below:

Fast reactors share in the first region (NG1) depends not only on the growth rate of installed capacity in this region, but also on the capacity growth in NG2 countries.

For Moderate option in 2100:

- The proportion of fast reactors in the High NG2 growth (from 50% to 65%), synergistic scenario is 93.47% (349 877 GW(e)*year). This is the maximum value, and the minimum value is 53.72% (861519 GW(e)*year) for the High NG1 growth (from 50% to 65%) non-synergistic scenario.

For High option:

- The proportion of fast reactors in the High NG2 growth (from 50% to 65%) synergistic scenario is 92.83% (691758 GW(e)*year). This is the maximum value, and the minimum value is 47.94% (1 523590 GW(e)*year) for the High NG1 growth (from 50% to 65%) non-synergistic scenario.

In synergistic scenarios the share of fast reactors is higher than in the individual cases. The average difference between the synergistic and the non-synergistic is 4.93% for Moderate case and 9.19% for the High case.

SNF accumulation is reduced only in NG1, and it is growing in NG2 and NG3 for the non-synergistic case. In synergistic scenarios in the second group of countries the SNF inventory is growing faster than in the individual development cases. The maximum differences are in the Minimal direct disposal (25% to 10%) scenario. In the Moderate case the differences are 107917t/118769t/275146t in 2030/2050/2100, respectively. In the High case the differences are 108280t/122905t/417956t in 2030/2050/2100, respectively. Therefore there is a need to plan for additional storage facilities. Reduction of the total amount of SNF in the world in the independent development case is possible only for NG1 due to the need of a reprocessing technology. The volume of SNF in the third region in the synergistic scenario is minimized and depends on retention time of the SNF.

The decrease in natural uranium consumption due to introduction of fast reactors in NG1 makes use of uranium more cost effective for the second and the third regions.

The summary of the results for NG1, NG2, NG3 is as follows:

- The total amount of SNF in all regions in 2100 will be minimal in Scenario 1 "Low NG2 share". Minimal direct disposal (25% to 10%) for the Moderate option it is 1 942 006 t and for the High option it is 3 232 889 t. High growth in the first region has a significant impact on the reduction of the total amount of SNF.
- Total consumption of natural uranium will be minimal in the High case (Option I) in the first region.
- Cooperation in the development of nuclear energy will undoubtedly be beneficial and will eventually lead to significant savings in natural uranium and a gradual reduction of the global SNF amount.

Some intermediate results of study were presented at GLOBAL- 2013 [XIV-7].

REFERENCES TO ANNEX XV

[XV-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability, Final Report of the INPRO Collaborative Project on Global Architectures of Innovative Nuclear Energy Systems with Thermal and Fast Reactors and a Closed Nuclear Fuel Cycle (GAINS), IAEA Nuclear Energy Series NP-T-1.14, Vienna (2013)

[XV-2] Kuznetsov, V., Fesenko, G., Poplavskaya, E. "Sensitivity analysis of synergistic collaborative scenarios towards sustainable nuclear energy systems", GLOBAL - 2013 "Nuclear energy at a crossroads", Proceedings of Global 2013, 29 September -3 October 2013, Salt Lake City, Utah, USA, 2013.