ANNEX VIII.

GLOBAL SCENARIOS WITH THE INTRODUCTION OF A NUMBER OF FAST REACTORS UNDER UNCERTAINTIES IN THE SCALE OF NUCLEAR ENERGY DEMAND AND IN THE NUCLEAR POWER STRUCTURE

VIII-1. INTRODUCTION

INPRO is striving to promote a global vision of nuclear energy sustainability for the 21st century by conducting NES assessment studies at global level as well as regional and national levels [VIII-1–VIII-4]. The INPRO collaborative project GAINS particularly developed an architecture for global nuclear energy sustainability by addressing related technical, organizational and institutional issues. The GAINS also developed a comprehensive framework that provides a common platform with methodologies for assessment of nuclear energy systems, keeping in view assumptions and different boundary conditions.

This study uses the GAINS framework and provides assessment of global energy scenarios with introducing fast reactors into the energy mix with different uncertainties in demand and structure of nuclear energy. The case study is related to the SYNERGIES Task 1 on evaluation of synergistic collaborative scenarios for fuel cycle infrastructure development. Short description of GAINS approach for assessing transition scenarios to sustainable nuclear energy systems is given in Section 2 of the report.

VIII-2. UNCERTAINTIES IN SCALE AND TIMING OF NUCLEAR ENERGY DEMAND GROWTH PROJECTIONS

There are wide variations in forecast of nuclear energy demand growth for the current century, varying from huge demand growth to assumptions of nuclear phase-out by the end of century. The GAINS project has selected high and moderate scenarios for projection of nuclear energy demand growth. The high scenario of GAINS rises nuclear energy generation to 5000 GW(e).year whereas the moderate scenario climbs to 2500 GW(e).year energy generation by the end of 2100 and flattening afterwards.

Nuclear energy evolution for medium term duration is comprehensively described by high projection case of the IAEA [VIII-5]. The IAEA high growth projection remains very close to the moderate scenario of 600 GW(e).year of the GAINS till 2030, but goes lower before 2050. The IAEA low growth projection of nuclear power generation is further lower and reaches only 350 GW(e).year in 2030. The IAEA projections of nuclear power generation and capacity growth are based on present nuclear power projects, policies and future plans of the IAEA Member States. The individual country to country studies are consolidated in a bottom-up approach and nuclear power projections are presented at regional and global levels.

Low demand projections have historically been very near to the actual curve of nuclear power growth. An analysis of low and high projections of global nuclear power capacity growth since 1985 have shown that the realization rate for low estimate was much higher, being 70% as compared to the realization rate of high estimate standing at 50% for the year 2000. It shows that long term plans of nuclear power capacity expansion could not be realized and have been reduced significantly in subsequent revisions.

These observations lead to the plausible expectation that low scenario of nuclear power capacity growth is more likely to prevail in near future (until 2030). Therefore, the present study focusses on low nuclear power demand growth and corresponding nuclear power structure. The future nuclear power structure of NES considerably depends on the power

demand growth. Fig. VIII-1 shows the low demand curve extrapolated to 2100 and GAINS demand curves adjusted to the IAEA projections.

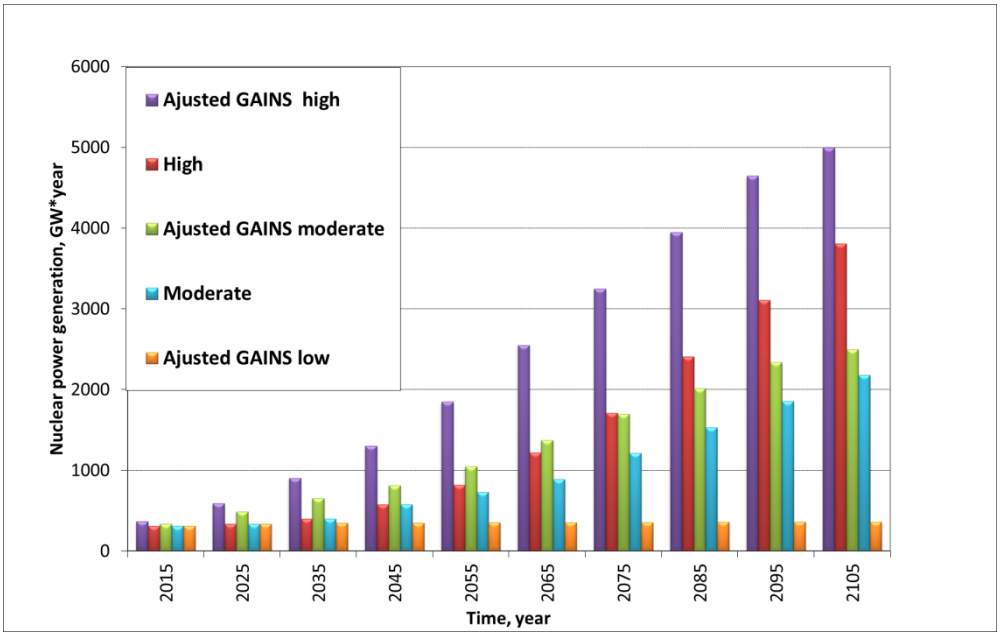

FIG. VIII-1 GAINS demand curves adjusted to IAEA projections.

This study focuses on transition scenarios of nuclear energy systems for sustainability under uncertainties in nuclear energy demand and power structure. The study is based on framework of GAINS collaborative project. The study considers nuclear energy demand assumptions of the GAINS framework along with a low demand scenario "L" with possible delays in moderate demand scenario "M" and high demand scenario "H" as shown in Fig. VIII-2. The L scenario is assumed to be near term and up to 2030 for all scenarios under consideration. The M scenario starts in 2030 with a delay of 15 years whereas the H scenario starts in 2050 with delay of 22 years against medium and high growth scenarios of the GAINS project as shown in Fig. VIII-1 and Fig. VIII-2.

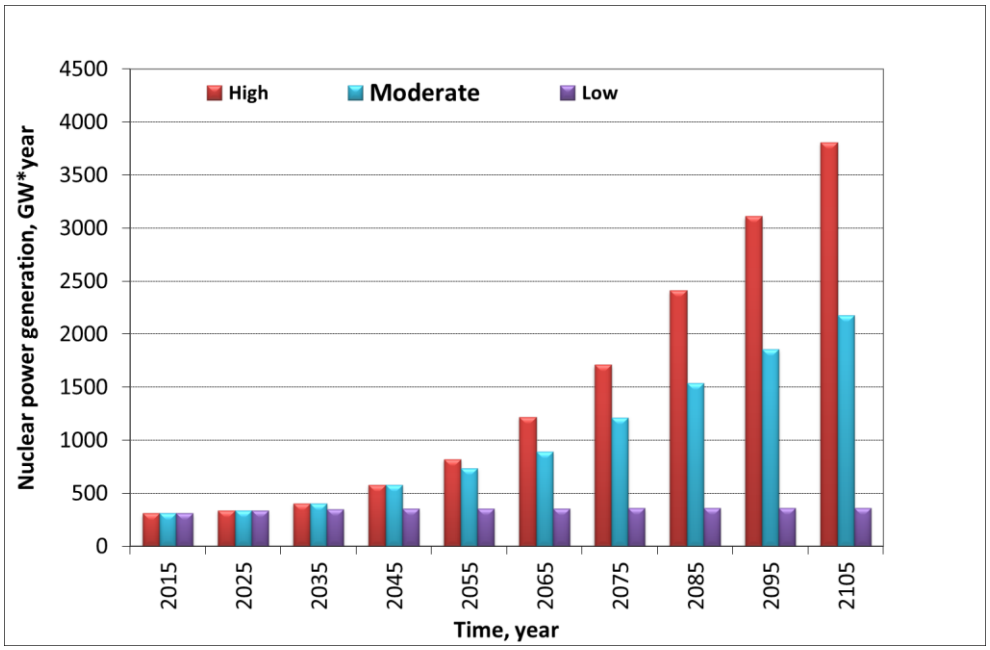

FIG. VIII-2. Low, moderate and high scenarios with possible delay in moderate and high demand growth.

The current study uses nominal grouping of global nuclear power structure based on NFC strategies adopted by the countries as developed in GAINS framework and called as NG groups. According to this division, the synergistic collaboration takes place between counties such that NG1 countries pursue fast reactor programme and recycle SNF, NG2 countries either directly dispose SNF or send it to the NG1 for reprocessing and NG3 countries send their SNF to NG1 or NG2 countries for recycling or disposal. The nominal GAINS scenario considers fixed share of nuclear energy generation by the groups with ratio of NG1:NG2:NG3 at 40:40:20 by the end of the century.

VIII-3. APPROACH AND INPUT DATA FOR THE ANALYSIS

SNF accumulation from LWRs and effective utilization of natural uranium are certain issues to be addressed for scenario realization. In the GAINS framework it is considered that fast reactors are introduced after 2030 in order to optimize the uranium fuel utilization and reduction of SNF. These large-scale FRs utilize plutonium from reprocessed SNF of LWRs as their loading.

TABLE VIII-1 REACTOR CHARACTERISTICS

Parameter	LWR	FR1	FR
Fuel type	UOX	Pu_depleted U	Pu_depleted U
Eelectric capacity, MW	1000	500	870
Thermal efficiency	0.33	0.40	0.42
Load factor	0.85	0.85	0.85
Average burnup, MW*d/kg HM	45	76.5	65.9
Life time, years	60	60	60
Uranium enrichment, %	4	-	-

The present study uses reactor data from the GAIN database as shown in the Table VIII-1. The reactor data includes:

— LWR: Low burnup light water reactor;

— FR: Break-even fast reactor with breading ratio (BR) ~1.0, generalized from BN-800 FR design technology of the Russian Federation;

— FR1: Medium breeding ratio fast reactor with BR~1.2, exemplified by Indian prototype fast breeder reactor.

The uncertainty in nuclear energy demand and delays in introduction of FRs on large scale into the energy mix in future may lead to drastic SNF accumulation from LWRs as late as after the middle of this century.

Reprocessing of SNF may be considered as one option to cope with such situation. This option would consider separating uranium and plutonium to manufacture MOX-fuel for single time recycle in presently operating thermal reactors and ultimate geological disposal of high level waste. Such option may help in partially resolving the SNF accumulation problem by decreasing the current annual volumes of SNF by a factor of 6 to 7, but it will create another problem of accumulation of spent MOX fuel.

A more viable option to reduce accumulating SNF in near future is shown in Fig. VIII-3 and involves use of existing LWRs and fast reactors with MOX-fuel. According to this option, all SNF discharged from UOX-fuel loaded LWRs is reprocessed and MOX-fuel will be fabricated from the separated plutonium. This MOX-fuel would not be directly used in existing LWRs; instead it would be used in existing FRs for utilizing the plutonium present in the SNF of LWRs during the low demand scenario implementation. In this way, all LWR SNF would be utilized effectively during first phase of L scenario.

The reprocessed uranium (REPU) would be accumulated during such scenario. However, it is feasible since REPU can be recycled effectively in LWRs and PHWRs, and may also be used in FRs and some other reactor types. The present study assumes that REPU from LWRs is converted, re-enriched individually or blended with enriched uranium and finally fabricated into UOX-fuel. Such use of REPU helps in removing reprocessed uranium from the stock and reducing natural uranium utilization, leading towards nuclear energy sustainability. The depleted uranium occurring in tails of enrichment process of REPU can be consumed up in FRs in addition to reprocessed uranium from FRs. The reprocessed waste stock will only accumulate minor actinides and fission products in this way.

The prospects of future SNF utilization from FRs using MOX-fuel during implementation of second phase of L scenario depend upon demand for nuclear energy, market feasibility for construction of NPPs after 2030 and readiness of closed fuel cycle technologies and fast reactors. These uncertainties in nuclear energy demand and timeline for innovative FR introduction lead towards considering delays in medium and high scenarios of nuclear power in the present study. Such scenarios are modelled using the MESSAGE tool.

VIII-4. LOW SCENARIO WITH INTRODUCTION OF FAST REACTORS SUPPORTING THE MULTI-RECYCLE OF PLUTONIUM IN LWRs AND FRs

Slow growth of nuclear energy demand is represented by L scenario. The problem of utilization of SNF from FRs using MOX-fuel is considered using existing structure of nuclear energy system for this scenario. A suitable solution is introduced in Fig. VIII-3 which involves reprocessing of SNF of MOX-fuel based FRs and multiple recycling of plutonium in the existing FRs and LWRs in the form of MOX-fuel.

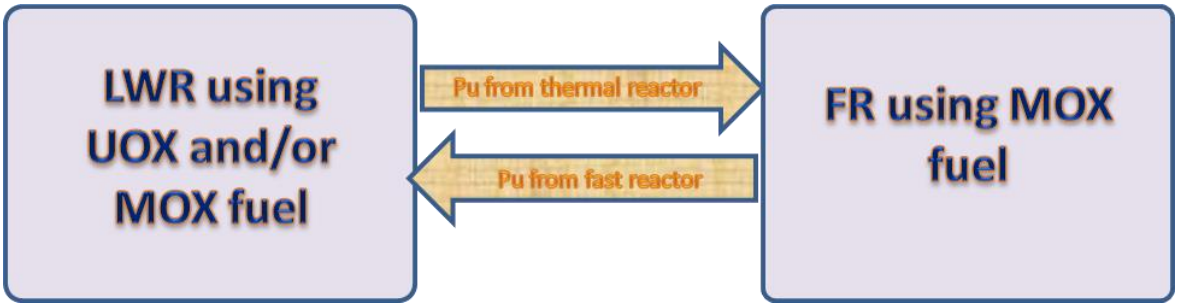

FIG. VIII-3. Multiple recycling of plutonium in the form of MOX fuel both, in the existing fast reactors and in the operating LWR reactors.

Two cases of collaboration are analyzed and compared for consumption of natural uranium, SNF accumulation and nuclear fuel cycle infrastructure requirements. The first case is shown in Fig. VIII-4 and involves cooperation between NG1 and NG3 such that NG1 supplies UOX-fuel to NG3 without return of spent fuel (back end separate case). The second case involves synergistic collaboration shown in Fig. VIII-5 such that NG1 supplies fresh fuel to NG3 including its MOX-fuel with return of spent fuel (back end synergistic case).

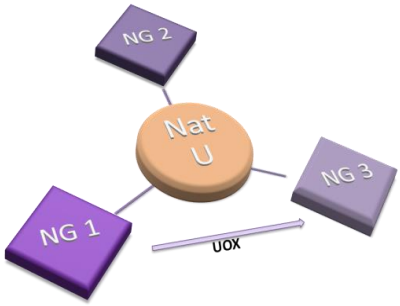

FIG. VIII-4. Back-end separate case.

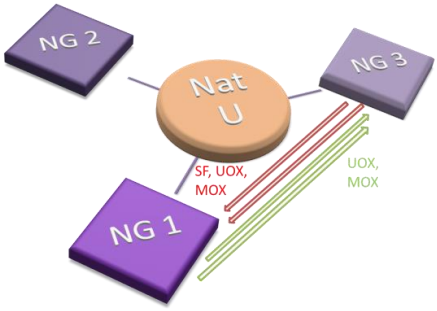

FIG. VIII-5. Back-end synergistic case.

VIII-4.1. Back-end separate case

The nuclear power production growth structure in NG1 is shown in the Fig. VIII-6 for back end separate case. The share of FRs increases steadily to 18% and is maintained after 2070. Fig. VIII-7 shows corresponding SNF storage requirements. The SNF accumulation from

LWRs stabilizes be the end of century at same level as beginning of the century, with 18% share of the FRs in NES. The cooling time of LWR SNF is assumed as 6 years in accordance with GAINS framework. Although longer LWR SNF storage time makes its reprocessing more economical and simpler due to mature reprocessing technology, however longer storage time of SNF causes accumulation of large quantity of radiotoxic minor actinide ^{241}Am from decay of ^{241}Pu. In France, optimal time of storage before reprocessing of SNF from PWRs is realized to be 4-5 years. The ^{241}Am can be separated from SNF during reprocessing and discarded in vitrified high level waste along with other minor actinides and fission products. Thus plutonium can be extracted in relatively pure form during reprocessing of UOX SNF and MOX-fuel for use in FRs can be fabricated avoiding radiotoxic environment.

In the current case, the nuclear power evolution structure in NG1 is not severely affected by the spent fuel cooling time, which can be increased to existing 15-20 years without significant loss of FR share. The spent fuel is however distributed such that larger amount stays in the NPP pools and lesser amount is present in the long term storages.

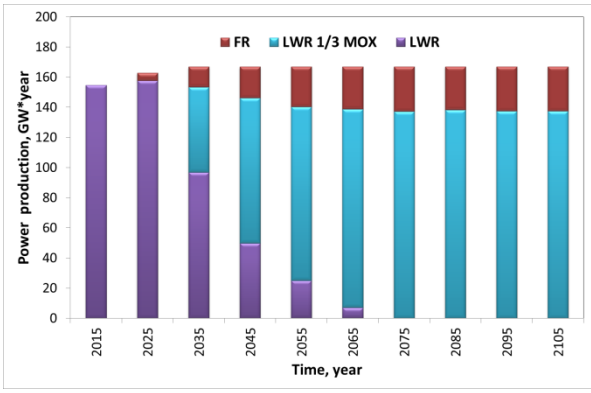

FIG. VIII-6. Structure of power production growth in NG1 (back-end separate case).

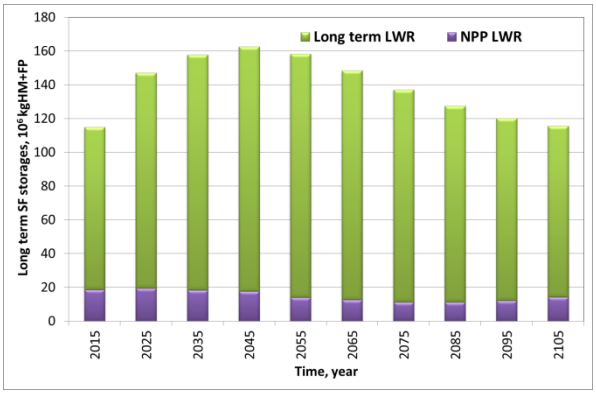

FIG. VIII-7. Storages of LWR spent nuclear fuel in NG1 (back-end separate case).

The upgradation of fuel cycle infrastructure for utilizing SNF from LWRs would be required in back end separate case in the form of additional stages for reprocessing of spent MOX-fuel and re-fabrication of MOX-fuel for use in both FRs and LWRs (Fig VIII-8 and Fig. VIII-9).

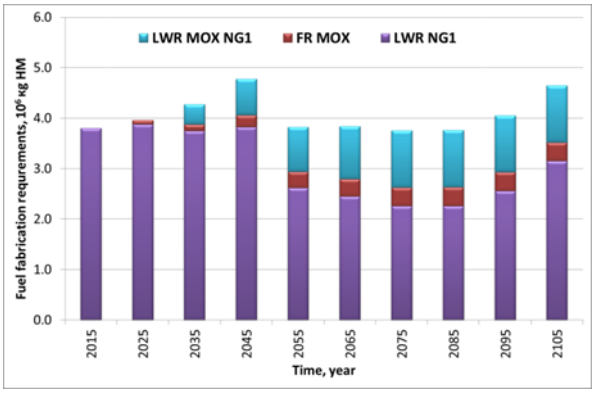

FIG. VIII-8. Fuel fabrication (back-end separate case).

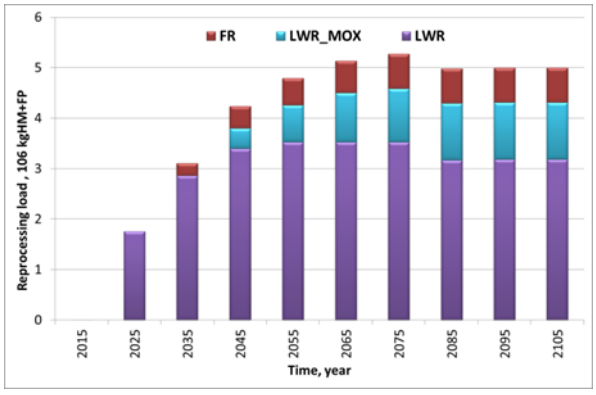

FIG. VIII-9. Reprocessing load (back-end separate case).

Multiple recycling of Pu is possible due to presence of limited number of FRs in the nuclear energy system. It is achieved by separating low grade plutonium from SNF of MOX-fuelled LWRs and fabricating MOX-fuel for FRs which can utilize this reduced quality plutonium

effectively. NG1 and NG3 can also opt for cooperation in this scenario for utilization of NG3 spent fuel. NG1 can take back SNF from NG3 for reprocessing and fabrication of MOX fuel for use in FRs. NG1 can consider adding few additional FRs for utilizing the plutonium from NG3 and can also supply MOX-fuel to NG3 for loading in LWRs (back end synergistic case, Fig. VIII-5).

VIII-4.2. Back-end synergistic case

The back end synergistic case involves NG1 providing fresh fuel including MOX-fuel to NG3 for LWRs, and taking back UOX and MOX spent fuel from NG3 (Fig. VIII-5).
The electrical energy generation from FRs for both cases is shown in Fig. VIII-10. The FR share in the NES increases to 21% for the back end synergistic case from previously described 18% share for back end separate case. The slight increase in FRs is observed which utilize plutonium from SNF of LWRs of NG3.
Long term storage requirements for SNF for the back end synergistic case are shown in Fig. VIII-11. The on-site cooling time for LWR spent fuel is considered as 6 years. The long term storage facilities of NG1 also receive UOX and MOX spent fuel from NG3 for reprocessing. There is a negligible increase in long term SNF storage requirements in the back end synergistic case when compared to the back end separate case.

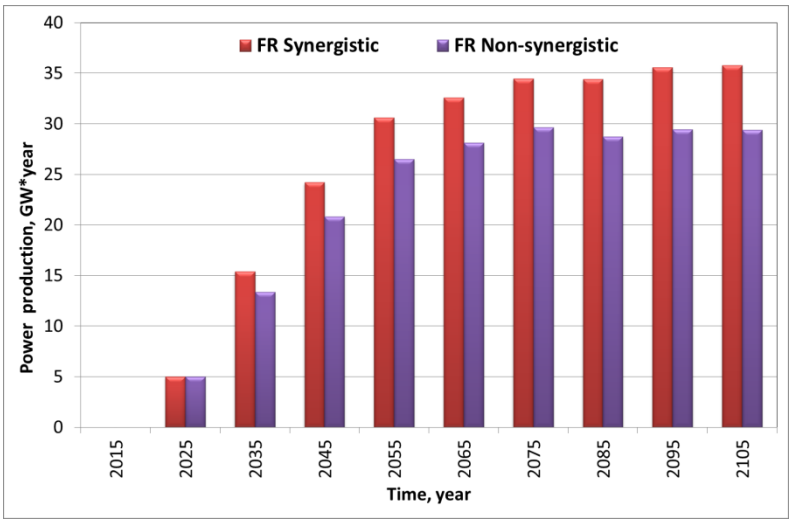

FIG. VIII-10. Electric energy production from FRs for the back-end separate and the back end synergistic cases.

The fuel fabrication and reprocessing load at NG1 is considerably increased in the back end synergistic case for providing fabrication and reprocessing services to the NG3, as shown in VIII-12 and Fig. VIII-13. The transport of UOX and MOX fresh and spent fuel between NG1 and NG3 pose an additional issue which is not considered in this analysis.

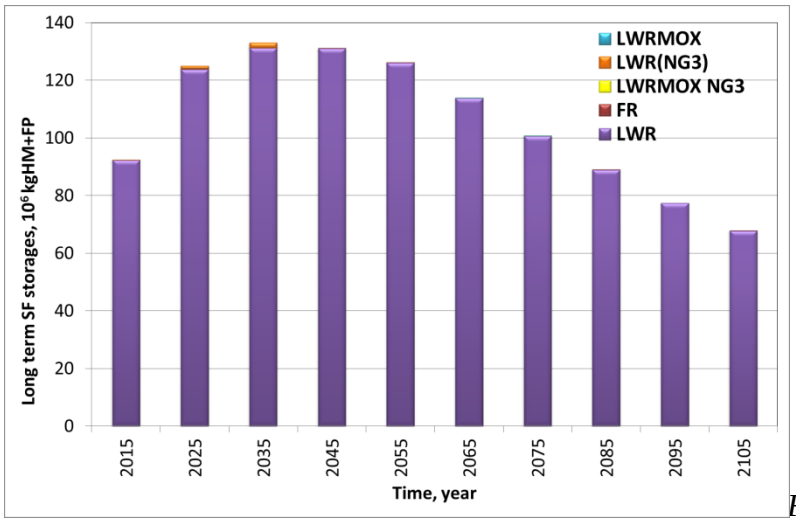

FIG. VIII-11. Long term storages of LWR spent nuclear fuel in NG1 (back-end synergistic case).

VIII-4.3. Transition to Moderate and High scenarios

Nuclear energy demand can rise in medium or long term depending upon favorable market conditions making NES transition towards medium or high demand scenarios. The M scenario is represented by low growth of nuclear energy demand until 2030 and medium energy demand growth continued after 2050. The H scenario suggests low demand growth until 2030, medium demand growth until 2050 and high demand growth afterwards (Fig. VIII-14 and Fig. VIII-15).

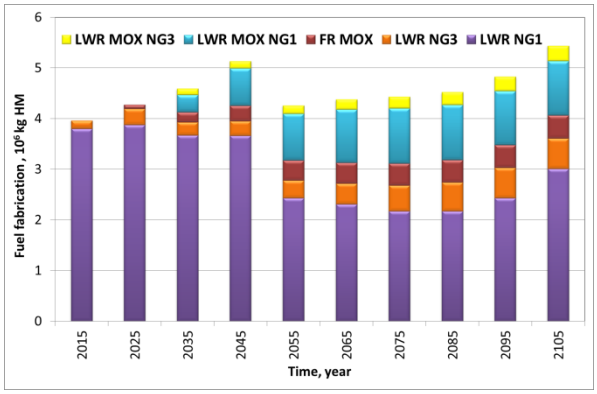

FIG. VIII-12. Fuel fabrication (back-end synergistic case).

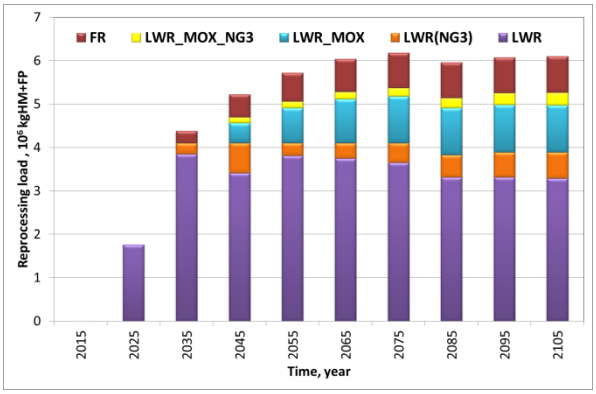

FIG. VIII-13. Reprocessing load (back-end synergistic case).

The increased energy demand growth can be met by MOX-fuelled FR1 type fast reactors (BR=1.16) in these scenarios. FR1 reactors can utilize SNF produced by MOX-fuelled FR during implementation of first phase of the L scenario. The SNF of MOX-fuelled FR can be reprocessed and extracted plutonium can be used in fabrication of MOX-fuel for utilization in FR1 operating in a closed fuel cycle. However further upgradation of nuclear fuel cycle facilities would be required for reprocessing of SNF from MOX-fuelled FR1 reactors and refabrication of MOX-fuel from the extracted plutonium for FR1 reactors.

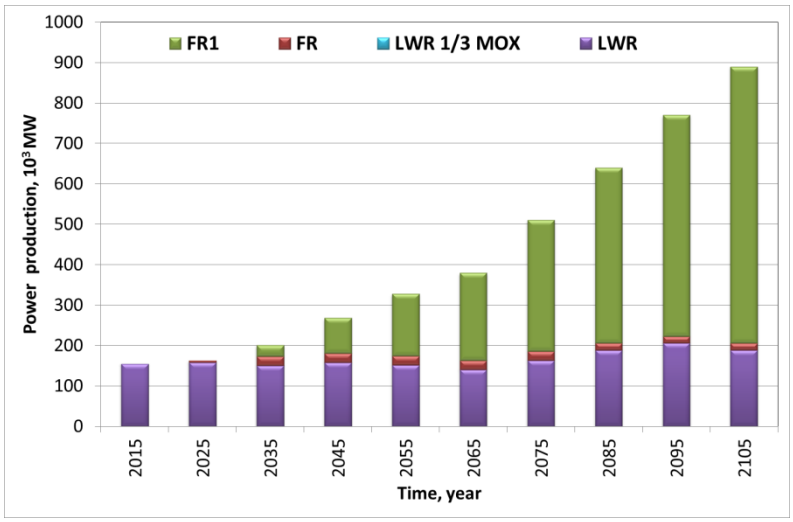

FIG. VIII-14. Structure of power production growth (M-Scenario).

VIII-4.4. Economic considerations for Pu recycling in thermal and fast reactors

The GAINS framework proposed LUEC as one of key indicators for assessment of transition scenarios of sustainable nuclear energy systems. The LUEC calculations are performed using NEST tool developed at INPRO [VIII-6]. Although overnight capital cost and O&M costs are major constituents of the LUEC, the present study focusses on fuel cycle cost component of the LUEC. The fuel cycle cost component includes costs of all fuel cycle steps from mining to ultimate waste disposal in a nuclear fuel cycle scheme. The reference data used in the study for calculating the fuel cycle cost component of LUEC is presented in the Table VIII-2.

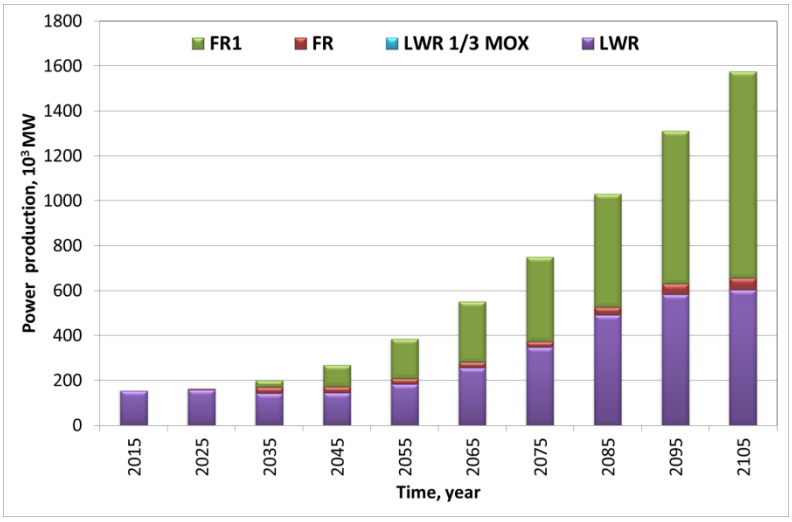

FIG. VIII-15. Structure of power production growth (H-Scenario).

TABLE VIII-2. FUEL CYCLE REFERENCE SERVICE COST [VIII-7]

* SNF – spent nuclear fuel, HM – heavy metals, SWU – separative work units; HLW – high level waste

Fuel cycle step	Range of service cost	Reference service cost
Uranium, $/kgHM	80-450,	80-450
Conversion, $/kgHM	5-10-15	10
Enrichment, $/SWU	8-110-120	110
Fuel UOX, $/kgHM	200-275-300	275
FR1 SNF storage, $/kgHM	200	200
LWR SNF direct disposal, $/kgHM	400-800-1600	800
HLW direct disposal, $/kgHM	400	400

The economy of scale plays significant role in per kg cost depending on size of new facilities, as shown in Fig. VIII-16 [VIII-8–VIII-9]. Therefore, large commercial facilities can be considered for deployment. As shown in the VIII-3, the fuel cycle facilities with high costs are scaled to National facility "N" for a smaller power programme (4-6 GW(e)) and to International facility "I" for synergistic large scale nuclear power programme (140-170 GW(e)). The Reference facility "R" represents a reference size fuel cycle facility for big national nuclear power programme (20-30 GW(e)). The correlated cost changes due to facility size variation are provided in the Table VIII-3.

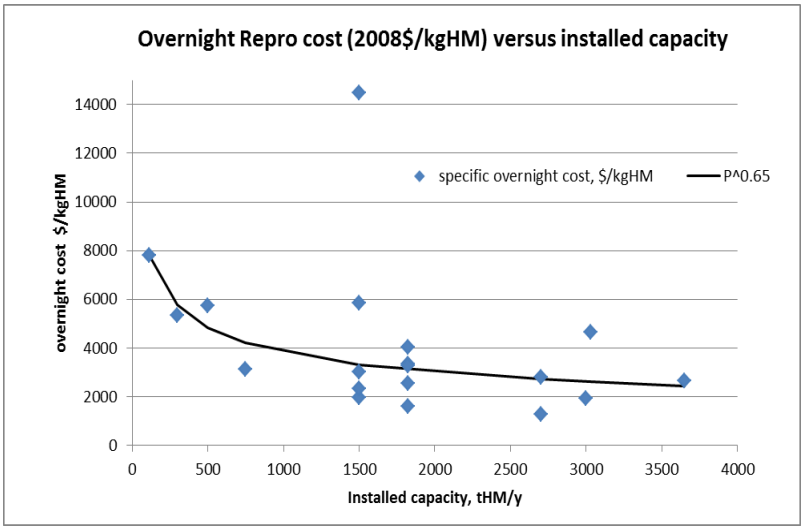

FIG. VIII-16. Overnight reprocessing cost (2008 $/kgHM) versus installed capacity.

TABLE VIII-3. FUEL CYCLE COST FOR NATIONAL FACILITY-REFERENCE FACILITY-INTERNATIONAL CENTER, (N-R-I) COST

Fuel cycle service	Facility capacity, N_R_I	Nuclear capacity N_R_I	Service cost, N_R_I

Enrichment	0.5-3-20, mln. SWU/year	4-22-145, GW(e)	110, $/kg SWU
Fuel fabrication, MOX	50-250-1500, tHM/year	4.5-23-140 GW(e)	3000-1500-750, $/kgHM
Reprocessing, UOX	100-500-3000, tHM/year	5-25-145, GW(e)	2700-1300-580, $/kgHM
Reprocessing MOX and FR1 blankets	100-500-3000, tHM/year	5.7-29-170, GW(e)	3000-1500-750, $/kgHM

The fuel cycle component of LUEC for all fuel cycle steps of uranium mining, reprocessing, fuel first load and reload fabrication, SNF disposal and HLW disposal are calculated using reference cost units and international cost units as shown in Fig. VIII-17 and Fig. VIII-18. The calculations are done for both options of once through open fuel cycle based on LWRs and a closed fuel cycle utilizing multiple recycling of plutonium with LWRs and FRs. The spent nuclear fuel reprocessing at an international center would reduce the reprocessing costs and increase economic competitiveness of closed NFC option.

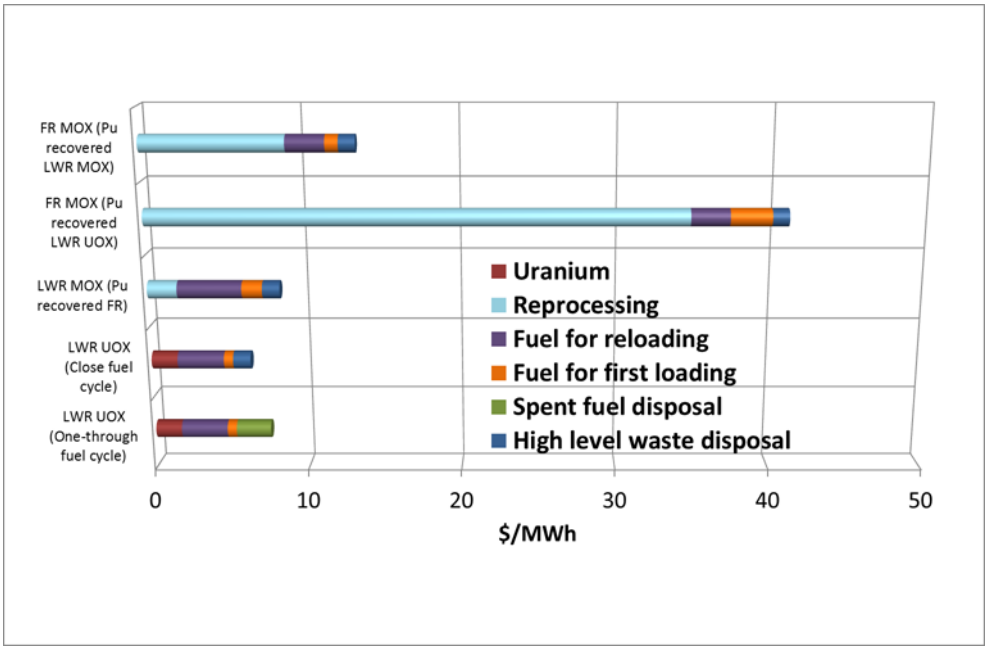

FIG. VIII-17. Levelized fuel cycle unit costs (reference approach (R)).

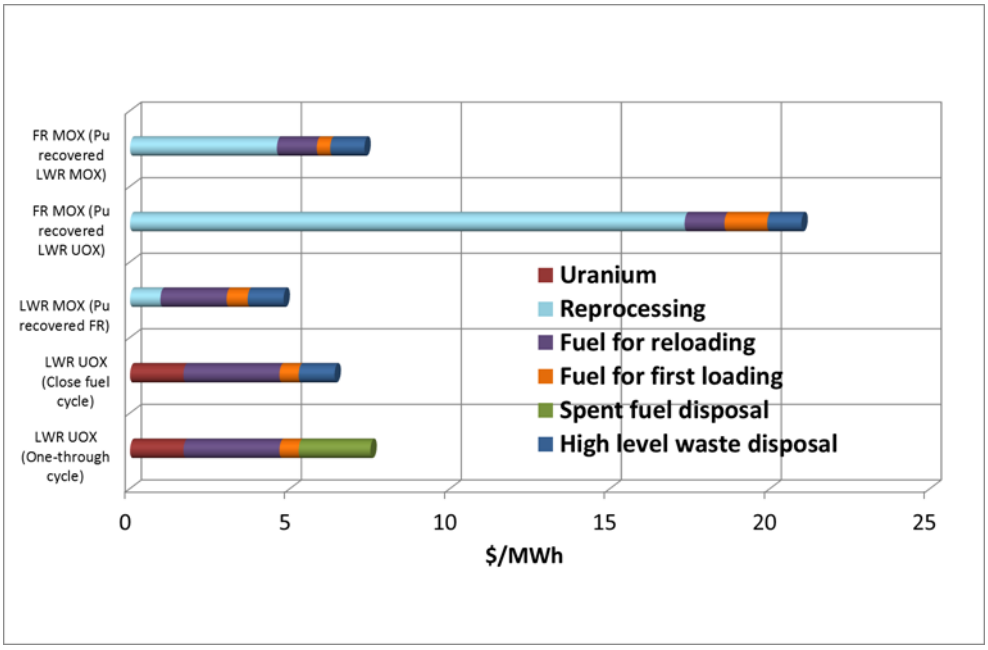

FIG. VIII-18. Levelized fuel cycle unit costs (international approach (I)).

VIII-5. CONCLUSIONS

The current study employs nominal grouping of global nuclear power structure based on NFC strategies adopted by the countries as developed in GAINS framework and called as NG groups. According to this division, the synergistic collaboration takes place between counties such that NG1 countries pursue fast reactor programme and recycle SNF, NG2 countries either directly dispose SNF or send it to the NG1 for reprocessing and NG3 countries send their SNF to NG1 or NG2 countries for recycling or disposal.

The present study focused on impact of uncertainties in nuclear energy demand growth and scale of nuclear power structure on transition scenarios to globally sustainable nuclear energy system. The analysis was performed using the GAINS framework for low energy growth scenario and for delayed moderate and high energy demand growth. The low demand scenario analysis shows that SNF accumulation problem can be resolved by using existing LWRs and FRs with MOX-fuel in the near term. The plutonium extracted from SNF of MOX-fuel based FRs can be recycled as MOX-fuel for 1/3 core loading in existing advanced LWRs and then multi-recycled in existing FRs.
Back end synergistic cooperation can be formed in which NG1 country group can take back SNF from NG3 countries for reprocessing and fabrication of MOX-fuel for its fast reactors. Addition of few FRs would be required at NG1 for utilizing plutonium coming in SNF of NG3. Additional facilities for supply of MOX-fuel for LWRs of NG3 would also be needed. Further increase in nuclear energy demand in medium and long term could be met by adding MOX-fuel based FR1 type fast reactors (BR=1.16). The startup fuel for FR1 type fast reactors can utilize plutonium extracted from spent fuel of MOX-fuelled FR type reactors along with recycling of their own fuel in a close fuel cycle subsequently.

It is pertinent to mention that all fast reactors with BR of 1.0 and 1.16 considered in transition scenario analyses in the current study are based on nearer term fast reactor technologies such as sodium cooled fast reactors. Such reactors are either in construction phase or at advanced stages of project development in several technology holder countries.

Some intermediate results of study were presented at Proceedings of ICAPP 2014. [VIII-10]

REFERENCES TO ANNEX VIII

[VIII-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)

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[VIII-8] SHROPSHIRE, D., WILLIAMS, K., ET AL, Advanced Fuel Cycle Economic Analysis of Symbiotic Light-Water Reactor and Fast Burner Reactor Systems, INL/EXT-09-15254, USA (2009).

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