ANNEX XVII.

# COMPARATIVE ECONOMIC ANALYSIS OF SELECTED SYNERGISTIC AND NON-SYNERGISTIC GAINS SCENARIOS

## XVII-1. COMPARISON OF SYNERGISTIC AND NON-SYNERGISTIC GAINS SCENARIOS

The implementation of nuclear programmes can be a significant economic challenge for NG3 newcomer countries and countries with small nuclear programmes [XVII-1 and XVII-2]. The total investment required to install a NES should be compatible with the ability of potential investor (government or private company) to raise the necessary capital in the country at the time of committing to construction of the nuclear power plants and nuclear facilities [XVII-3].

Low nuclear fuel cycle (NFC) cost is one of the advantages of nuclear power, and keeping the costs of the fuel cycle low is important to the economic viability of nuclear power. However, installing new fuel cycle capacities requires significant, additional capital investments. Investments for a uranium enrichment facility [XVII-4] are estimated to be in the range of $2-4 billion. Conversion and UOX fuel fabrication plants are not very capital intensive, but they could raise the issue of economy of scale at the country level. Investments in back end facilities are even more challenging. An OECD study [XVII-2] estimates overnight investments in interim storage facility to be $1-1.5 billion (capacity 8000 tHM). The overnight investment costs of the integrated facility at La Hague reprocessing plant and Melox MOX fuel fabrication plant in France was approximately $20 billion [XVII-2 and XVII-5]. The capital cost of the THORP facility of 1200 tHM/year nominal capacity in the United Kingdom was estimated at about $5.32 billion [XVII-2], and capital cost of the Mixed Oxide Fuel Fabrication Facility that was estimated at $7.7 billion. Geological repository investments cost [XVII-2] varies in range $5-10 billion depending on facility capacity in the range 20 000-60 000 tHM. The data on the Yucca Mountain DGR (120 000 tHM) were about $35 billion. Thus, NFC investment is an important component in assessment of benefits and disadvantages of the various collaborative architectures.

The study is based on scenario approach developed in GAINS project. It assumed global electricity generation as 1500 GW$*$year in 2050, 5000 GW$*$year in 2100, then flat to the end of modelled period. The heterogeneous model for NG1, NG2 and NG3 groups of countries is the basis for assessment of benefits and issues of the cooperation between groups (Synergistic) and separate group development (Non-synergistic) cases. NG1, NG2 and NG3 shares keep a nominal fraction as 40%, 40% and 20% in 2100, see Fig. XVII-1. More details on GAINS approach are provided in the GAINS final report [XVII-6] and in Appendix III to this report. Calculation of investment in fuel cycle and reactors for Non-synergistic and Synergistic cases was performed with MESSAGE tool using method described in Appendix II to this report. The investments in particular NFC facility are calculated as sum of capital investment uniformly distributed over construction time (5 year for all facilities). Life times are assumed to be practically unlimited except of reprocessing facilities limited by 60 year of life time. The load factor of NFC facilities is assumed to be 1. The total investments in fuel cycle scheme are the sum of investments corresponding to each fuel cycle stage.

The objective is not to give an accurate cost calculation, but to show the relative difference between two cases. Investments in NFC based on costs provided in Appendix II to the report. The investments in fuel cycle are calculated first for Separate (Non-synergistic)

nominal case in NG1 and NG3 groups and then for Synergistic nominal case in the NG1 which provided fuel cycle (FC) services for NG3. The study examines reference (R), national (N) and international cost approaches (I). Reference fuel cycle facilities correspond to reference size facilities for moderate national nuclear power programme and reference costs (Appendix II to the report). Small nuclear power programme with a few GW(e) reference facilities and their costs are scaled to national size (N). Then, cooperation among groups in term of economies of scale is explored for Synergistic case. The most expensive fuel cycle facilities, including reprocessing and recycling, are scaled to international centre size (I).

Some other features such as time value of money and discount rate (discounted investment costs) and first-of-a-kind (FOAK) costs of first facilities in a country are also discussed in the study.

In the Separate (Non-synergistic) case, there is no movement of nuclear materials among NGs. All NGs have equal access to natural uranium. NG3 has its own fuel cycle front end and back end requirements. In the Synergistic case movement of nuclear material between the NGs is allowed. In the present study NG1 is assumes to provide 100% of the fresh fuel to NG3 and take back 100% of its spent nuclear fuel for Synergistic case.

Cooperation between NG1 and NG3 impacts on the structure of electric energy generation growth in NG1, since more material would be available for FRs in NG1. In Separate case, the reprocessing capacity of LWR spent fuel is assumed to be limited up to rate 850 t/year to process available spent fuel till 2050, and reprocessing capacity of LWR spent fuel is assumed to be limited up to rate 850 t/year to process available spent fuel till 2050 and up to 3000t/year after 2050. In Synergistic case the constraint on the reprocessing capacity was increased up to 3000 t/year of spent nuclear fuel after 2030 associated with international centre introduction. Figures XVII-2 and XVII-3 show reprocessing requirements for Separate and Synergistic cases respectively.

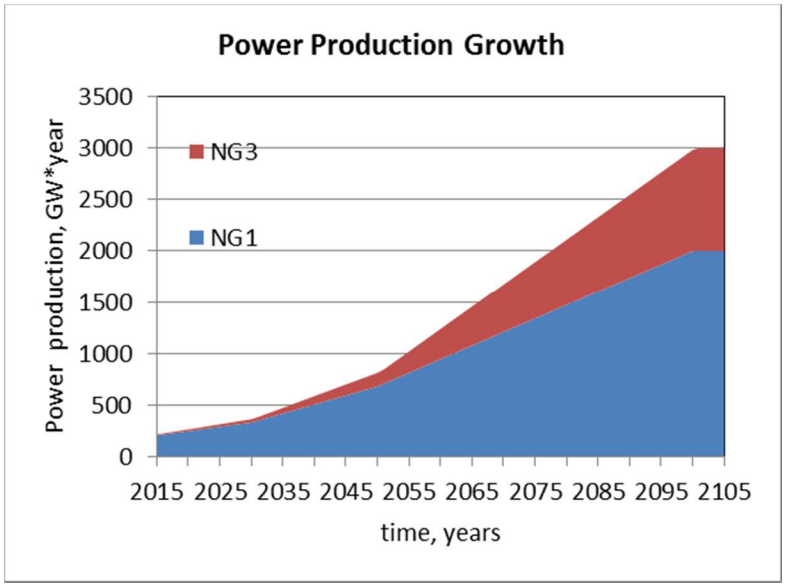


*FIG. XVII- 1. Per annum electric energy generation growth, NG1, NG3.*

Figures XVII-4 and XVII-5 compare the electric energy production from FRs and FR commissioning in NG1 for Separate and Synergistic cases. The percentage of FR commissioning in Synergistic case increases in average by 30 % compared to the Separate case in the medium term (2030-2050). In long term first it keeps at the same level (2050-2065) and then increases by 40% (2065-2100) in comparison with the separate case. The difference in medium term occurs mainly due to LWR SF scale reprocessing (3000 kt/year

versus 850 kt/year), in long term it increases mainly because more LWR fuel from NG3 are available for reprocessing in NG1. The change in the NG1 electric energy production structure leads to the change in fuel cycle structure from conversion mining to reprocessing. Investments are also changed even under the same reference cost for Separate and Synergistic cases.

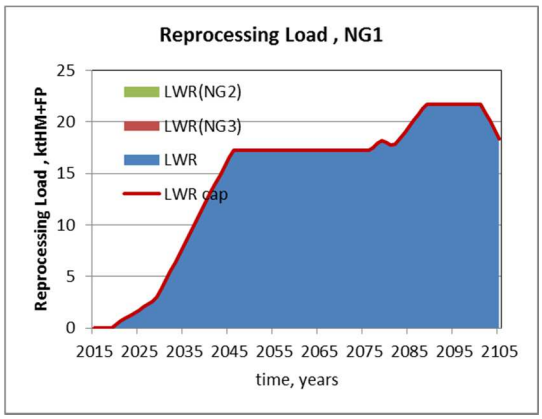


*FIG. XVII-2a. LWR SF reprocessing requirements (Separate case).*

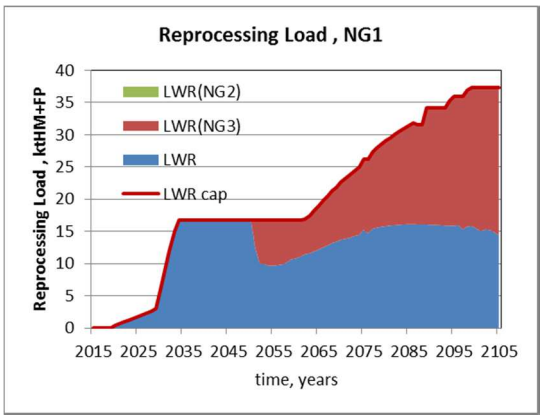


*FIG. XVII-2b. 3LWR SF reprocessing requirements (Synergistic case).*

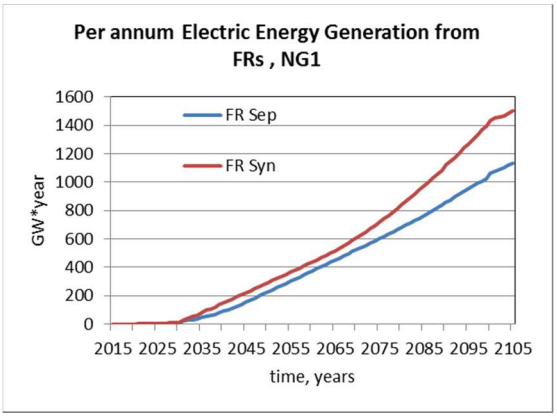


*FIG. XVII-4. FR per annum electric energy generation growth in NG1.*

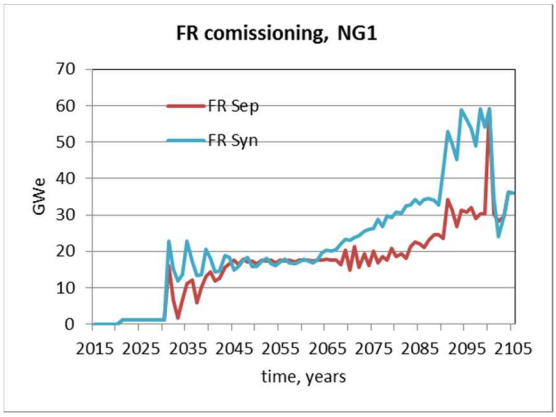


*FIG. XVII-5. FR commissioning, NG1.*

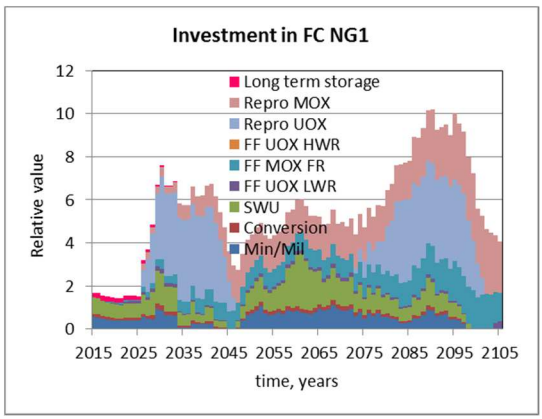


*FIG. XVII-6. NFC investments in NG1, Separate (R) case.*

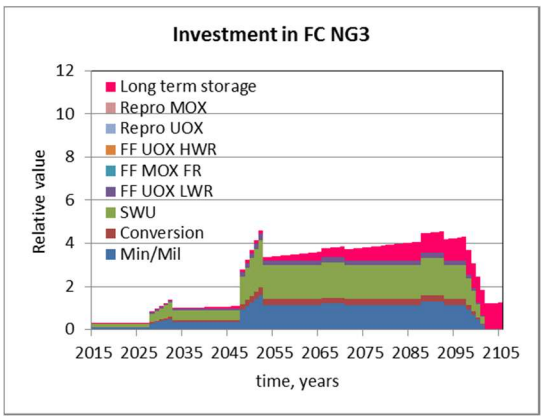


*FIG. XVII-7. NFC investments in NG3, Separate (R) case.*

Figure XVII-6 summarizes investments to all fuel cycle stages including mining and milling, conversion, enrichment, uranium oxide (UOX) fuel fabrication, mixed oxide (MOX) fuel fabrication, UOX reprocessing, MOX reprocessing, and long term spent fuel storage for NG1 for Separate case. Investments in LWR SF reprocessing is the major contributor to the total FC investments in 2025-2045; they can be a serious barrier on the way to the innovative NES in medium term. Investment in NFC is represented as relative values in no dimensional form with non-dimensionalization parameter billion $ as described in Appendix II to the report.

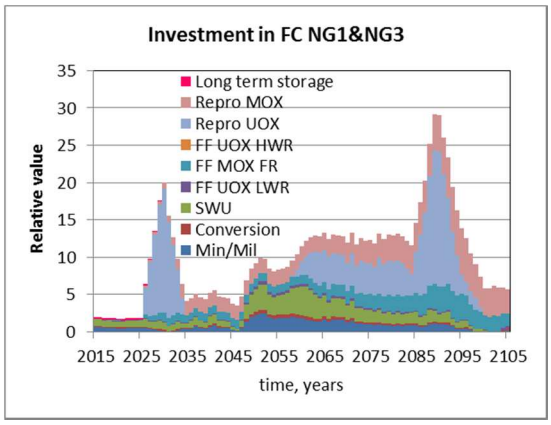


*FIG. XVII-8. NFC investments for Synergistic (R) case.*

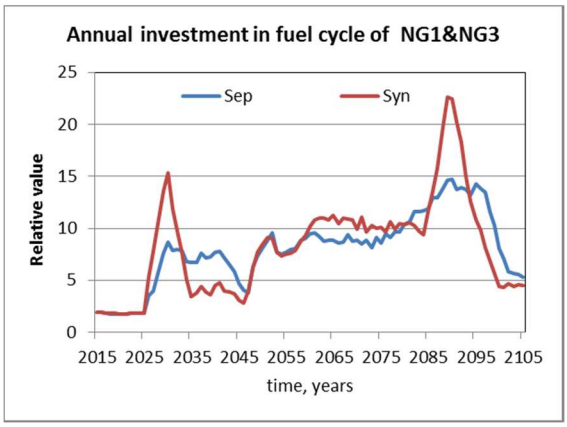


*FIG. XVII-9. NFC investments for Separate (R) versus Synergistic (R) case.*

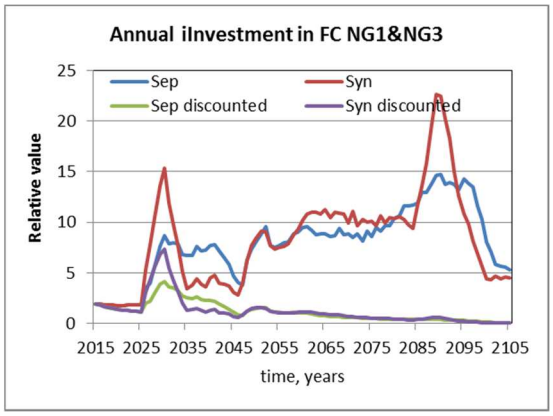


*FIG. XVII-10. NFC annual discounted investments for Separate (R) versus Synergistic (R) case.*

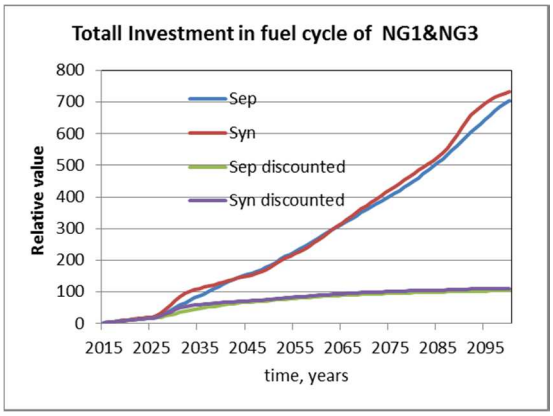


*FIG. XVII-11. NFC total discounted investments for Separate (R) versus Synergistic (R) case.*

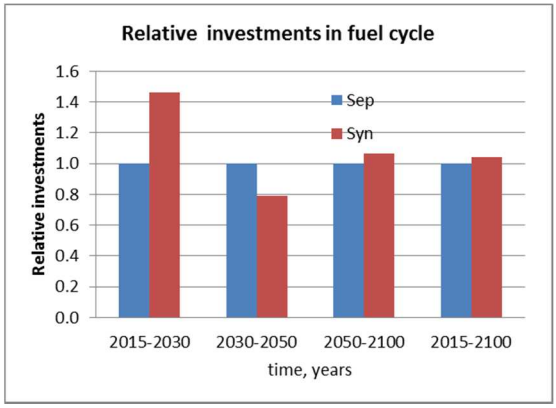


*FIG. XVII- 12. Relative investments in fuel cycle for Separate (R) and Synergistic (R) cases.*

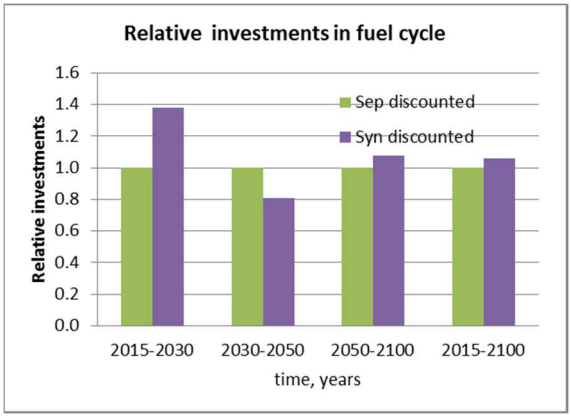


*FIG. XVII- 13. Relative discounted investments in fuel cycle for Separate (R) and Synergistic (R) cases.*

Figure XVII-7 shows total investments in all fuel cycle stages in NG3 fuel cycle for Separate case. The result was obtained using the same approach as for NG1. Investment structure differs from those of NG1. Investment in enrichment facilities is the major contributor to NG3 fuel cycle. Moreover construction of long term SF storage in NG3 requires a significant investment after 2050 while SF storage in NG1 fully depletes around 2075.

Figure XVII-8 summarises investments in all fuel cycle stages (mining and milling, conversion, enrichment, UOX fuel fabrication, MOX fuel fabrication, UOX reprocessing, MOX reprocessing, and long term spent fuel storages) in the NG1 fuel cycle for Synergistic case. The results are obtained using the reference cost approach (R) as for Separate case. Investments in LWR SF reprocessing remain the major contributor to the total investments in fuel cycle.

Comparison of annual investment in fuel cycle is shown in Figs XVII-9 and XVII-12 for reference Separate and Synergistic cases. Figure XVII-12 provides comparison of investments in the fuel cycle for Separate and Synergistic cases, in relative form with Synergistic divided by Separate.

Difference in the figures is due to LWR SF scale reprocessing assumption and movement of fresh and spent fuel among regions. Both cases are assumed to have the same reference costs. Under these conditions the main issue related to the high investment in LWR reprocessing facilities in period 2025-2035 becomes even more drastic for the Synergistic case. Therefore, investment in the Synergistic case is 47% higher than for the Separate case in the short term period 2015-2030. In the period 2030-2050, the Synergistic case investments are 21% less than investments for the Separate case because of continuing commissioning of LWR SF reprocessing facilities in the Separate case. Total investments during 2050-2100 are 7% higher than for the separate case. Investments for the whole modelling period 2015- 2100 are become comparable for both cases having 4% higher for Synergistic case, see Fig. XVII-12.

Accounting discount doesn't change the conclusion qualitatively. Figures XVII-10 and XVII-11 give the discounted annual and total investment cost for discount rate as 5%. Discounting is more sensitive to the near term rather than off term investments; it evens differences between Separate and Synergistic cases in short (2030) and medium term (2050) and slight impact in long term (2100), see Fig. XVII-13.

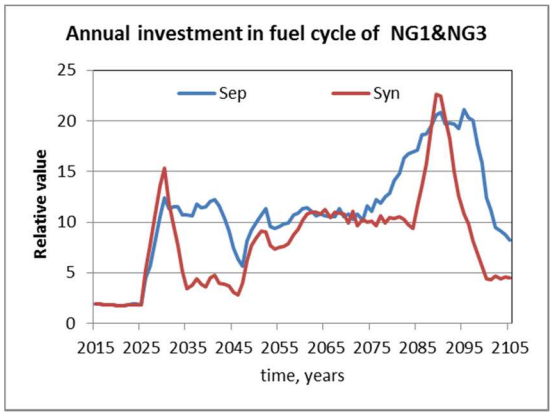


*FIG. XVII-14. NFC investments Separate (N) versus Synergistic (R) case.*

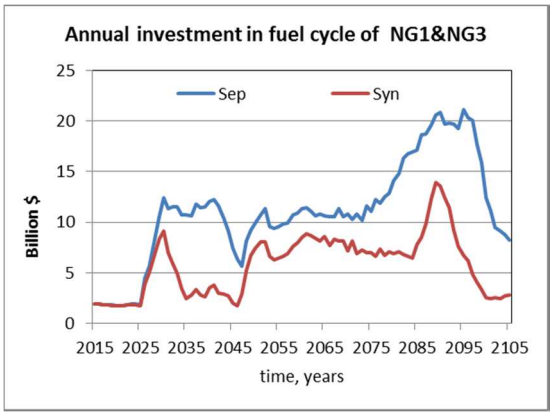


*FIG. XVII-15. NFC investments Separate (N) versus Synergistic (I) case.*

Since investment in reprocessing and recycling facilities is one of the most important issues, we took into consideration economies of scale impact on fuel cycle investments for Separate and Synergistic cases. First, we applied the national cost approach to the Separate case remaining reference cost approach for the Synergistic case. The result is given in Figures XVII-14 and XVII-16. Scaling to the national facility sizes and corresponding costs for the Separate case leads to increasing its fuel cycle investments. In the period 2030–2050 the Separate case investments are still more than investments for Synergistic case, but the difference between cases decreases noteworthy to about 20%.

In the period 2030–2050 the Synergistic case investments are 47% less than investments for the Separate case. Total investments during whole modelling period 2015–2100 become 24% less for the Synergistic case.

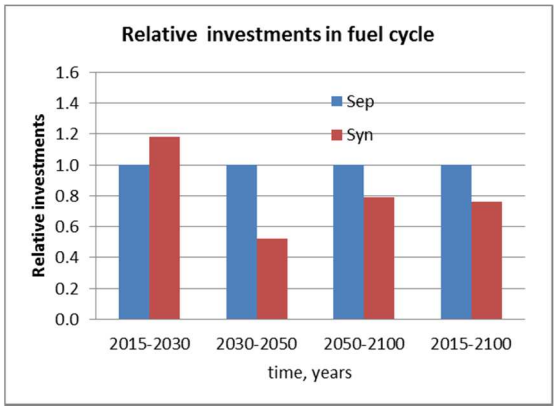


*FIG. XVII- 16. Relative investments in fuel cycle for Separate (N) and Synergistic (R) cases.*

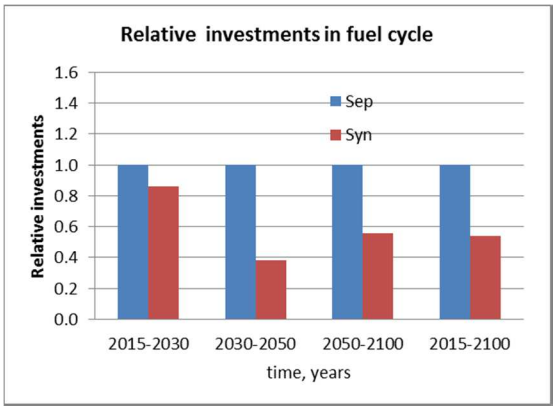


*FIG. XVII- 17. Relative investments in fuel cycle for Separate (N) and Synergistic (I) cases.*

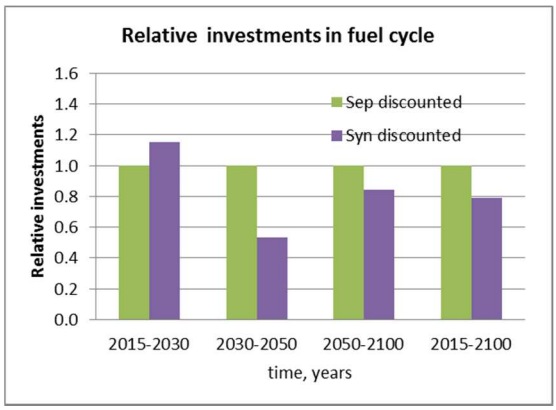


*FIG. XVII- 18. Relative discounted investments in fuel cycle for Separate (N) and Synergistic (R) cases.*

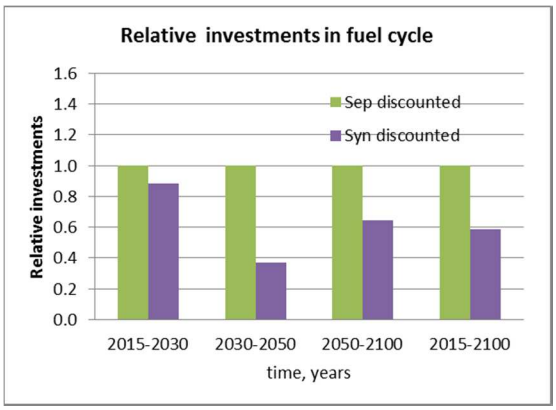


*FIG. XVII- 19. Relative discounted investments in fuel cycle for Separate (N) and Synergistic (I) cases.*

An international approach for the Synergistic case can lead to further reduction of investment in the fuel cycle. Figures XVII-15 and XVII-17 show that the International centres for reprocessing and recycling based on the economies of scale can enhance the transition to an innovative fuel cycle through investment barriers associated with reprocessing/recycling facilities. The economies of scale for large International centres lead to decreasing fuel cycle investments for the Synergistic case in the short term up to 14 %, in medium term up to 62% and in long term up to 44%, in comparison with the Separate case. Total investments during whole modelling period 2015–2100 become 46% less for Synergistic case. Discounting doesn't' change general results although slightly decreases the effect of investment saving for Synergistic case due to economies of scale, see Fig. XVII-18 and XVII-19.

The comparison of cases is based on a simplified approach, assuming only use of $n^{th}$-of-a-kind (NOAK) for fuel cycle facilities. According to reported experience, the FOAK plants are 15-55% more expensive than the subsequent serial units. In the period till approximately 2035 fuel cycle facilities can be available as FOAK plants, so investments can be increased for both cases (Separate and Synergistic).

Another benefit of international cooperation in short term is related to benefits in sharing of long term storages.

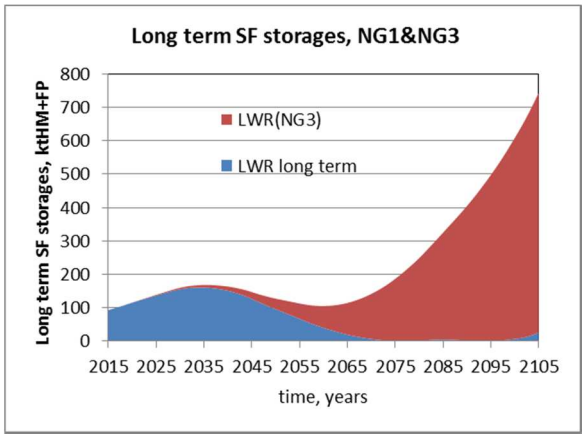


*FIG. XVII-20. Long term SF storages, Separate case NG1+NG3.*

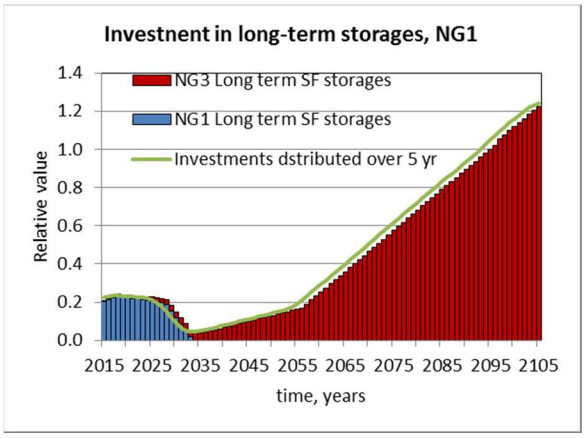


*FIG. XVII-21. Investments in long-term storages, Separate case NG1+NG3.*

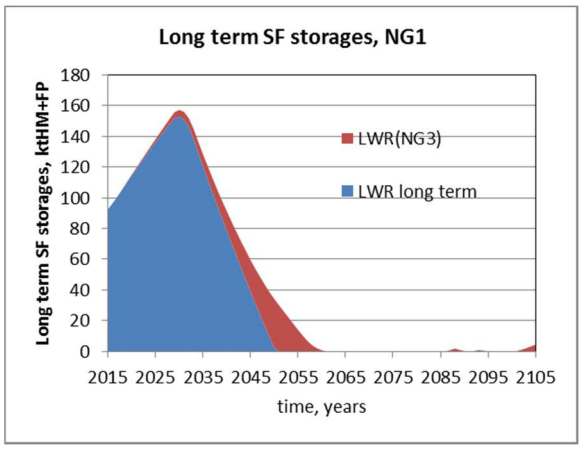


*FIG. XVII- 22. Long term SF storages, Synergistic case.*

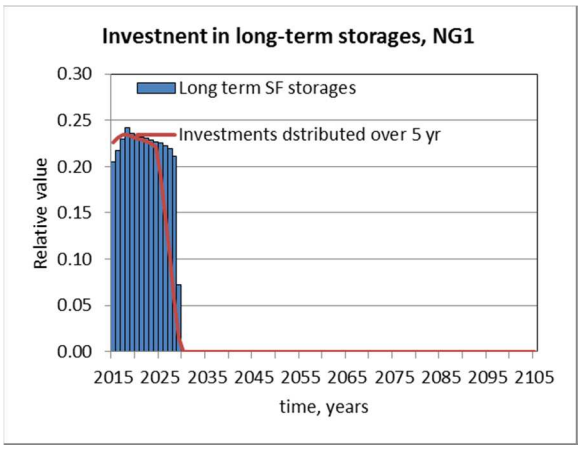


*FIG. XVII- 23. Investments in long-term storages, Synergistic case.*

Accumulation of UOX spent fuel in long term storage and associated relative investments in storage facilities for Separate case in NG1 and NG3 are shown in Figures XVII-20 and XVII-21. NG1 solves its issue of spent fuel accumulation by 2075 by investment only in the short term (2015-2025). NG3 steadily increases spent fuel accumulation, achieving more than 500 ktHM by the end of century, while spent fuel storage in NG1 archives maximum capacity of 160 ktHM by 2035. Investment in SF storage for NG3 has a notable contribution to the total fuel cycle, especially after 2050.

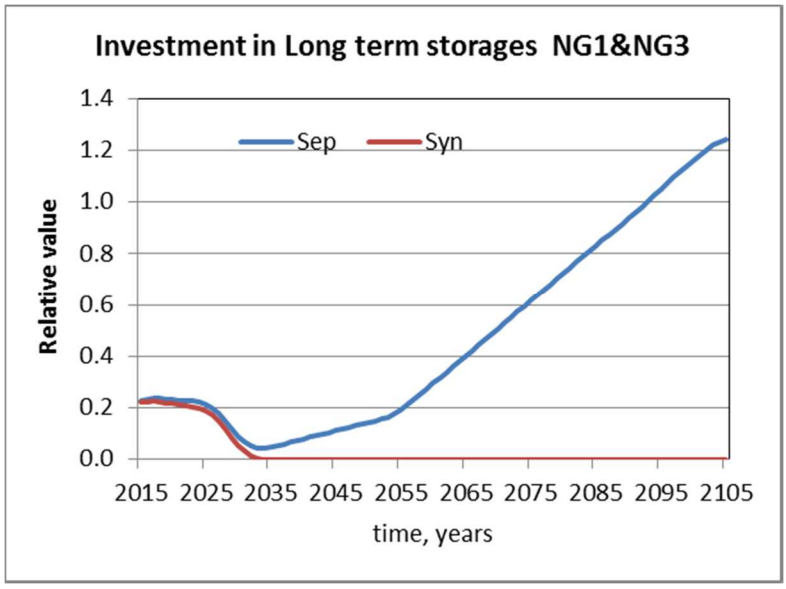


*FIG. XVII- 24. Investments in long term storages, Separate versus Synergistic cases.*

In the Synergistic case the accumulation and relative investment pattern has much in common with the Separate case in NG1 as shown in Fig. XVII-22 and XVII-23. The spent fuel storage reaches its maximum capacity of 160 ktHM by 2035, then it decreases and fully depletes around 2060 for the Synergistic case. By then, all LWR SF available for reprocessing is reprocessed without accumulation in long term storage. The required investments in the short term are practically the same as for separate NG1. Figure XVII-24 compares relative long term storage investments for the Separate case versus the Synergistic case for reference (R) cost approach. Nearly identical storage capacities are needed for storing NG1 SF in the Separate case and NG1&NG3 SF in the Synergistic case, even in the R approach without taking into consideration economies of scale.

## XVII-2. COMPARISON OF LEVELIZED UNIT FUEL CYCLE COSTS (LUFC) FOR LWR AND FR FOR REFERENCE AND INTERNATIONAL COST APPROACH

The above Separate and Synergistic scenarios include LWR operating in once through fuel cycle, FR in closed fuel cycle fueled by its own reprocessed plutonium, and FR fueled by plutonium recycled from LWR spent fuel during its first three years in operation.

Figure XVII-25 shows levelized fuel cycle unit cost at discount rate 5% for LWRs and FRs considered in this study, calculated using the reference service cost (Appendix II to the report) for all fuel cycle steps. The NFC component encompasses uranium cost, reprocessing, fuel fabrication and waste management, as well as fuel for first load of both reactor types. Fuel cost of FRs fueled by their own reprocessed plutonium is comparable with fuel cost of LWRs, while FR fueled by plutonium recycled from LWR spent fuel for first load and first three operating years is about 50% higher. This is caused by the much higher amount of spent fuel reprocessing needed to produce fuel for FR from LWR spent fuel in comparison of reprocessing FR spent fuel with much higher plutonium content. Therefore the development of a fast reactor programme can face additional financial barriers at first stage, as all new FRs must pass through a stage of rather expensive fuel fabricated from LWR plutonium. The same issue was indicated in investment analysis for the Synergistic and Separate cases. The reprocessing and recycling of LWR SF can be a barrier to the implementation of a closed fuel cycle based on LWRs and FRs.

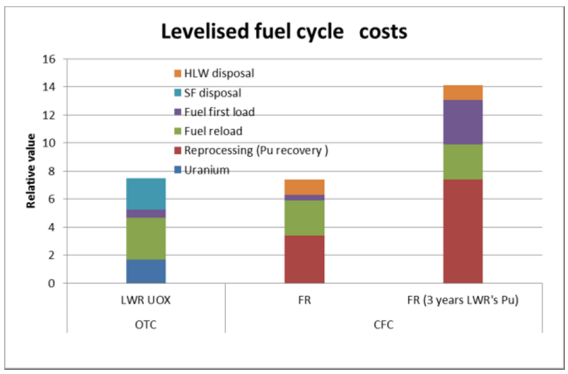


*FIG. XVII-25. Levelized fuel cycle unit cost, Reference approach for service cost.*

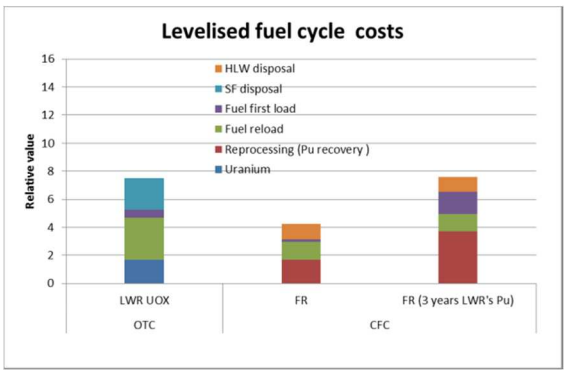


*FIG. XVII- 26. Levelized fuel cycle unit cost, International approach for service cost.*

The capital costs (LUAC) and the operation and maintenance costs (LUOM) are much higher, while the fuel cycle part of levelized cost normally presents an insignificant part of the total levelised cost. Assuming stability of total levelized cost in the long term, fuel is essentially the biggest advantage of nuclear power. Without low fuel cycle costs nuclear energy is not economically competitive with other energy sources, thus, it is essential to find a way to keep costs low.

An international centre for LWR spent fuel reprocessing – potentially including FR spent fuel reprocessing and MOX fuel fabrication – is one of possible way to reduce reprocessing costs. Figure XVII-26 shows levelized fuel cycle unit cost at discount rate 5% for LWRs and FRs calculated using the International approach service cost with 50% reduction of reprocessing/recycling costs (see Appendix II to the report). In this case the LUFC of FR fueled by plutonium recycled from LWR spent fuel for the first load and the first three operating years becomes comparable with fuel cost of LWRs. Another factor that can change the situation in favor of FRs would be an increase of natural uranium costs. In turn the LWR fuel component increases as uranium cost increases, whereas FR fuel cost does not depend on natural uranium cost. An international centre for reprocessing/fabrication can facilitate transitions to a NES based on FRs; coupled with uranium cost increase, it can enhance economic attractiveness of NES coming to FRs.

## XVII-3. CONCLUSIONS

Investment in the NFC is an important component in assessment of benefits and disadvantages of the various collaborative architectures, as low fuel cycle cost is one of the main advantages of nuclear power and keeping the costs low is key to its economic viability. This study is based on the scenario approach developed in GAINS project. The heterogeneous model for NG1, NG2 and NG3 country group is the basis for assessment of benefits and issues of the cooperation between groups (Synergistic) and Separate group development (non-synergistic) cases. In the present study NG1 is assumed to provide 100% of the fresh fuel to NG3 and to take back 100% of its spent nuclear fuel.

Cooperation between NG1 and NG3 impacts the structure of electric energy generation growth and fuel cycle structure in NG1. The change in the NG1 electric energy production structure leads to a change in NFC structure, from mining through reprocessing. Investments are also impacted even under the same reference cost for Separate and Synergistic cases.

The major contributors to the total NFC investment are SF reprocessing and recycling in the short and long term and enrichment in medium term. Under the same reference cost for Separate and Synergistic cases, the issue related to the high investment in LWR reprocessing facilities in the period 2025–2035 becomes even more drastic for the synergistic case.

Therefore, investment in the Synergistic case is 47% higher than for the Separate case in the short term period 2015–2030. In the period 2030–2050 the Synergistic case investments are 21% less than investments for the Separate case due to continuing commissioning of LWR SF reprocessing facilities in the Separate case. Total investments during 2050–2100 are 7% higher than in the Separate case. Investments for the entire modelling period (2015–2100) are comparable for both cases, with the Synergistic case being 4% higher. Accounting for the discount does not change this conclusion qualitatively; it evens differences between the Separate and Synergistic cases in the short (2030) and medium term (2050) and has a slight impact in the long term (2100). Therefore, the development of a FR programme can face significant financial barriers at the first stage, as all new FRs must pass through a stage of rather expensive fuel fabricated from LWR plutonium in the short or medium term.

Since the investment in reprocessing and recycling facilities is one of the most important issues, we took into consideration the impact of economies of scale on fuel cycle investments for the Separate and Synergistic cases. First, we applied a national cost approach to the Separate case and a remaining reference cost approach for the Synergistic case. Scaling to the national facility sizes and corresponding costs for Separate case leads to increasing fuel cycle investments. In the period 2030–2050 the Separate case investments are still more than investments for the Synergistic case, but the difference between cases decreases significantly to 20%. In the period 2030–2050 the Synergistic case investments are 47% less than investments for the Separate case. Total investments during the entire modelling period (2015– 2100) become 24% less in the Synergistic case.

An international approach for the Synergistic case can lead to a further reduction of investment in the NFC. The economies of scale for large International Centres lead to decreasing fuel cycle investments for the Synergistic case, up to 14% in the short term, up to 62% in medium term, and up to 44% in long term in comparison with the Separate case. Total investments during the entire modelling period 2015–2100 become 46% less in the Synergistic case. Discounting does not change the overall results, although it slightly decreases the effect of investment savings for the Synergistic case due to economies of scale. International centres for reprocessing and recycling – together with the economies of scale – lead to decreasing investments in the NFC in comparison with the Separate case, and enhance the transition to an innovative NFC through the investment barrier associated with reprocessing/recycling facilities.

Another benefit of international cooperation in the short term is related to the benefits of sharing long term storage facilities. Accumulation of UOX spent fuel in the long term storage of NG3 steadily increases, achieving more than 500 ktHM by the end of century in the non-Synergistic case. NG3 investment in SF storage would have notable contributions to the total fuel cycle cost, especially after 2050. Cooperation between NG1 and NG3 resolves the issue of SF accumulation in both regions by around 2060. Practically the same storage capacities and investments are needed for storing NG1 SF in Separate case and NG1 and NG3 SF in the Synergistic case, even in the reference approach without taking into account economies of scale.

Calculation of the NFC part of levelized cost confirms the findings that an international centre for reprocessing /fabrication can facilitate transition to an innovative NES based on FRs. Coupled with uranium cost increase, it can enhance the economic attractiveness of transitioning to FRs.

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