ANNEX XXV.

ANALYSIS OF ADVANCED EUROPEAN SCENARIOS INCLUDING TRANSMUTATION AND ECONOMICAL ESTIMATES

XXV-1. INTRODUCTION

The objective of this contribution is to analyze long-term scenarios for closed fuel cycle in a European context, including economical estimates as additional reference results.

The analysis of long-term sustainability of nuclear energy should consider transition scenarios from the current open fuel cycle or partially closed to fully closed cycles based on advanced technologies. This kind of study must provide answers to different aspects of transition scenarios, such as the period of time needed to reach material flow equilibrium, the recommended number and date of introduction of facilities in the fuel cycle, the amount of stored material, the nuclear waste, etc. Moreover, there is an interest to improve these studies with economics analyses, as a necessary input to evaluate the realistic viability of new strategies.

This Annex analyses the transition from the existing light water reactor (LWR) fleet to advanced fast spectrum reactors, taking also into account an intermediate stage of Generation III+ LWR deployment. It assumes that a representative number of European Union countries is involved, as in the exercise PATEROS [XXV-1]. The analysis of these fuel cycle scenarios has been performed according to guidelines specified in the EU CP-ESFR [XXV-2] and ARCAS projects [XXV-3].

The nuclear fuel cycle scenarios have been evaluated using TR_EVOL [XXV-4], a module developed by CIEMAT in order to improve the capabilities of the in-house burn-up simulation system, EVOLCODE 2.0 [XXV-5]. TR_EVOL has been designed to study short, medium and long-term options for the introduction of various types of nuclear reactors and for the usage of associated nuclear material, giving due consideration to the isotopic composition of the material in any stage of the fuel cycle, essentially uranium, plutonium, minor actinides and fission products. Moreover, the application of an economic module provides additional and relevant information to study the fuel cycle in a global context.

XXV-2. OBJECTIVES

The main objective of this work was to analyze in terms of available resources and economic implications the impact of the implementation of different reference scenarios for a European nuclear fleet under the assumption of constant nuclear electricity demand. This general objective requires the estimation of:

- Natural uranium and plutonium needs.
- Units of fast reactors (FR) and accelerator-driven subcritical systems (ADS) facilities to achieve an equilibrium content of minor actinides (MA) in the fleet.
- The MA evolution for transmutation scenarios.
- The levelized cost of electricity (LCOE) for each scenario and by reactor type.
- Impact in the LCOE of main components.

XXV-3. MAIN ASSUMPTIONS AND INPUT DATA

XXV-3.1. Assumptions concerning power plants and fuel cycle facilities

The scenarios consider five reactor types, named following the technology and loaded fuel type:

- LWR_UOX: Light Water Reactors (LWR Gen II, Pressurized Water Reactor -PWR- or Boiling Water Reactor -BWR- type) with UO_2 fuel.
- LWR_MOX: Light Water Reactor (Gen II, PWR or BWR) with MOX fuel.
- LWR_GENIII: Light Water Reactor (Gen III+) with 100% of UO_2.
- SFR: Sodium-cooled Fast Reactor with MOX fuel, Pu average content close to 15% (however, this is a dynamic parameter depending on the available isotopic composition of streams used for fuel fabrication). T-SFR stands for SFR technology working for MA transmutation purposes in addition to Pu breeding and electricity production. In this case, the assumed reference concept is a 2.5%w MA loading, homogeneously distributed in the reactor core, replacing the same original U content.
- ADS: Accelerator Driven System, with inert matrix fuel (45 %weight of heavy metal is Pu/ 55% is MA).

It should be added that the assumed MA homogeneous loading in the T-SFR is a relatively simple strategy for MA destruction, which is coherent with a large reactor design allowing a moderate deterioration of safety parameters (Doppler, void worth, beta effective), in the range of 10%. Different configurations of MA loading, especially in heterogeneous axial or radial blankets are still possible, see [XXV-6], and they may lead to low deterioration of reactivity coefficients while achieving low to moderate transmutation values. Heterogeneous loading is out of the scope in our analysis, although it was recognized that must deserve attention in future studies.

The assumed reactor operation characteristics are summarized in Table XXV-1, obtained from [XXV-2 and XXV-3].

TABLE XXV-1. GENERAL PARAMETERS FOR EACH REACTOR TYPE

Reactor	LWR_UOX	LWR_MOX	LWR_GENIII	SFR	ADS
Unit thermal power, GW(th)	2.965	2.965	4.4	3.6	0.4
Thermal efficiency, %	34	34	34	40	32
Electric power, GW(e)	1.008	1.008	1.496	1.44	0.128
Capacity factor, %	80	80	85	80	75
Unloaded fuel burn-up, GWday/tHM	50	45	55	99	150
Unit lifetime, years	40	40	60	60	60
Pu conversion ratio	0.42	0.66	0.48	1.08	1.00

In this table, it should be noted that ADS Pu conversion ratio accounts for Pu occurrence after Am capture and Cm decay.

The composition of the initial legacy of spent fuel (SF) in the fleet comes from 7 EU nuclear countries, assumed associated for back-end fuel management purposes. The accumulated actinide mass up to 2010 is taken from EU CP-ESFR project specification, in turns based on the previous PATEROS project. The total Pu mass estimation by year 2010 is 386.6 t. In addition, 126.7 t are released from a specific country in year 2022 (after a phase out assumption in such a country) and added to the initial legacy.

Regarding the UO_2 fuel enrichment, no maximum limit in the SWUs plants capacity was considered. The tails assay for ^{235}U enrichment is 0.25% until 2020 and 0.20% after this year. Time required for fuel fabrication is 1 year for any type of fuel. No restriction in fabrication capacity has been considered in this work.

Three reprocessing plants are considered in these scenarios depending on the fuel types (LWR fuel, SFR fuel and ADS fuel). The minimum cooling time for the irradiated fuels before reprocessing is 5 years. Reprocessing period takes 1 year. A reprocessing loss of 0.1% w is considered for Pu, U and MA. For the fabrication stage, no loss is taken into account in this exercise, in coherence with CP-ESFR reference scenario.

It is interesting to provide here the total amount of uranium resource at world level of 16.8 Mt, according to [XXV-7] and ignoring phosphates and seawater. This value is not directly used in this study, however.

XXV-3.2. Assumptions concerning fuel cycle costs

The LCOE is defined as a sum of four components, further averaged in a period of time:

- Investment cost: It includes the overnight cost and financial costs. Financial costs are additionally split in interest during construction (where a large disbursement takes place), and interest for the financing.
- Fuel cost: In this study, this contribution represented the front-end cost, including structural fuel assembly and required reprocessing in case of MOX and advanced fuel fabrication.
- Operation and maintenance (O&M): Annual cost for running the plant, which depends on the installed capacity.
- Decommissioning, dismantling and waste disposal (DDD): In addition to reactor plant dismantling, the fuel waste final management associated to the back-end fuel costs is included here; i.e., repository costs.

All costs, excluding those for DDD, are summarized in Table XXV-2 where the Best Case (BC) unit costs for each item are shown, taken from the ARCAS project. Plant and reprocessing technologies have different readiness levels; therefore a cost uncertainty band with low and upper values was provided around the Best Case values. Uncertainties are taken from [XXV-8], adjusted for inflation and currency conversion. Base year for costs was 2010.

Concerning MOX and advanced fuel costs, there are two contributions: (i) the assembly costs (simply named ‘fabrication’ in the table) and (ii) a mixed reprocessed material compound cost in terms of new fabricated fuel. This compound cost is obtained after assumptions of fixed unitary cost of spent fuel reprocessing, which implicitly include the investment, O&M and decommissioning costs of fabrication and reprocessing facilities. It also depends on the evolution of scenarios. Values are obtained after application of reprocessing unitary input costs per technology and they are dependent on strategies assumed for combination of available masses. For instance, some 3 kg of LWR-MOX of spent fuel (SF) are necessary to be reprocessed at beginning of Scenario 2 to obtain 1 kg of SFR

fabricated fuel (FF), which means (3 kg-SF/1 kg-FF)*1000 €/kg-SF = 3000 €/kg-FF. As the scenario proceeds, a new source appears from SFR spent fuel. Therefore, as SFR BR~1, at advanced scenario stages one has (1 kg-SF/1 kg-FF)*1000 €/kg-SF = 1000 €/kg-FF. Note that the value shown in Table XXV-2 is an average over the whole scenario period (2000 €/kg-FF, in this case), which in addition has been rounded off to be used as input for the economic module.

In Table XXV-2, assembly, unitary reprocessing and compound costs are shown but not the total final cost (it may be obtained just adding assembly and compound fabricated fuel costs).

Current LWR_UOX and LWR_MOX plants operate since the 70's and 80's, while our analysis starts in year 2010. Hence, they were assumed to be paid off at the beginning of the scenarios and therefore it was considered that generation costs for this type of plants will only include fuel, O&M and DDD costs, while excluding all their investment cost. Note that this was a common assumption for all scenarios; therefore, results will be easily compared.

TABLE XXV-2. COST INFORMATION PER REACTOR TYPE

Reactor technology	LWR-UOX			LWR-MOX			LWR-GENIII		
	Lower bound	Best Case	Upper bound	Lower bound	Best Case	Upper bound	Lower bound	Best Case	Upper Bound
Investment costs									
Overnight ,€/kW(e)	1875	2500	2970	1875	2500	2970	2251	3002	3565
Interest (financial)	8%	8%	8%	8%	8%	8%	8%	8%	8%
Construction time, years	4	6	8	4	6	8	4	6	8
Interest (construction)	8%	8%	8%	8%	8%	8%	8%	8%	8%
O&M costs									
M€/GW(e)/years	56	75	94	56	75	94	56	75	94
Fuel costs									
Natural U, €/kgU_3O_8	40	100	160	-	-	-	40	100	160
Conversion 1, €/kgU	5	8	13	-	-	-	5	8	13
Enrichment, €/SWU	80	100	120	-	-	-	80	100	120
Conversion 2, €/kgU	5	8	13	-	-	-	5	8	13
Fabrication cost, assembly contribution, €/kgHM-fabricated fuel	200	250	300	800	1000	1200	200	250	300

TABLE XXV-2. COST INFORMATION PER REACTOR TYPE (cont.)

Reactor technology	LWR-UOX			LWR-MOX			LWR-GENIII		
Unitary reprocessing cost (€/kgHM-spent fuel)	875	1000	1125	875	1000	1250	875	1000	1125
Compound cost of fuel, mixed reprocessing contribution (€/kgHM-fabricated fuel)	-	-	-	5400	6100	6900	-	-	-
Reactor technology	SFR			T-SFR			ADS		
	Lower bound	Best Case	Upper bound	Lower bound	Best Case	Upper bound	Lower bound	Best Case	Upper Bound
Investment costs									
Facility, €/kW(e)	2465	3902	4724	2465	3902	4724	11500	14760	18000
Interest (financial)	8%	8%	8%	8%	8%	8%	8%	8%	8%
Construction time, years	4	6	8	4	6	8	4	6	8
Interest (construction)	8%	8%	8%	8%	8%	8%	8%	8%	8%
O&M costs									
M€/GW(e)/year	65	86	108	65	86	108	168	223	279
Fuel costs									
Fabrication cost, assembly contribution , €/kgHM-fabricated fuel	1000	1500	2000	5000	10000	15000	9100	20000	27300
Unitary reprocessing cost ,€/kgHM-spent fuel	455	1000	1364	4550	10000	13640	14300	20000	34300
Compound cost of fuel, mixed reprocessing contribution, €/kgHM-fabricated fuel	1400	2000	2400	4000	8300	11200	10800	15700	28100

For DDD cost, the first contribution is decommissioning and dismantling, for which an average value of 15% of the reactor overnight cost has been assumed. The second contribution is disposal, for which two phases are considered according to nowadays policies in many countries: Interim Disposal (ID) and Final Disposal (FD), with corresponding costs each one. They are estimated following the TR_EVOL model consisting in dividing their cost into a fixed cost plus and a variable cost. For the ID, the variable cost depends mainly on the mass to store. For the FD, the variable cost represents the galleries length cost in an underground geological repository. Both variable costs include canisters fabrication and operation.

Concerning FD storage, the main approach is to be limited by thermal and mass constraints in the packages to be placed in the repository. As an example, in RED-IMPACT project [XXV-11] it was assumed that 4 LWR-UOX spent fuel assemblies were loaded in a waste package, and only one LWR-MOX spent fuel per package. In case of HLW obtained in advanced closed cycles, standard vitrified packages are considered to be produced, then assuming a certain quantification of actinide and FP masses based in the same reference [XXV-11]. These amounts have been directly correlated to final gallery dimensions in this study.

Definitive figures used for ID estimates are shown in Table XXV-3, while Table XXV-4 shows figures for FD. It must be emphasized that such figures have been obtained from specific own studies and additional consultations; they should be considered generic values with relative usefulness, mostly for comparison of results among scenarios.

TABLE XXV-3. COST RELATED TO INTERIM DISPOSAL

	Cost, M€
Investment cost	424
Decommissioning cost	65
Total fixed cost	489
O&M unit cost (M€/t)	0.155
O&M unit cost (M€/canister PWR)	0.290
O&M unit cost (M€/canister BWR)	0.335

TABLE XXV-4. ASSUMED DATA RELATED TO FINAL DISPOSAL

	Cost, M€
Fixed cost (including encapsulating plant & decommissioning)	2130
Gallery length cost per km	19.7
Encapsulation cost per canister	0.203
Management and conditioning cost (HM and HLW)	0.042
Mass per assembly	465
HLW mass per UC-V	60
Canister length and separation	6.6
UC-V length and separation (without encapsulation)	1.8

XXV-4. DESCRIPTION OF SCENARIOS

Scenarios start at year 2010 with 91.2 GW(e) jointly generated, 112.9 GW(e) installed, by seven EU associated countries, based on LWR_UOX and LWR_MOX reactors, i.e., Gen II technology. Scenarios finalize in year 2210 with the same value of total generated power.

Four fuel cycle scenarios were analyzed. All of them consider an initial period of LWR Gen II decommissioning since year 2020 to 2025 for LWR_MOX and from 2020 to 2050 for LWR_UOX.

- Scenario 1 (SCN-1) is the open cycle reference. At the assumed end of life of the LWR plants, they are replaced by a LWR_GENIII fleet operating until the end of the analysis period, year 2210.
- Scenario 2 (SCN-2) assumes that LWR plants are replaced by LWR_GENIII after year 2021, and SFR after year 2040, until contributions to the total electricity respectively are 2/3 and 1/3 of the total by year 2050. Later, GENIII

reactors are also substituted after end of life, and 100% of the electricity is obtained in SFR at the end of the century, which means around 79 reactors.

- Scenario 3 (SCN-3) is similar to Scenario 2, except 56% of the SFR plants are loaded with MA fuel for net transmutation (T-SFR technology), meaning around 44 reactors at the end of cycle. The balance of 44% SFR (or 35 units) burn only Pu.
- Scenario 4 (SCN-4) assumes that MA transmutation is exclusively done in ADS units, while SFR are dedicated to Pu burning and breeding. Concerning LWR, this scenario has no changes compared to SCN-2. The amount of electricity generated by the ADS depends on its transmutation potential and the Pu and MA availability. A maximum amount of 51 ADS units was considered to be necessary to deploy at some period of the scenario, while 37 units are required at the end of scenario, leading to an average of electric contribution of 3% along the cycle.

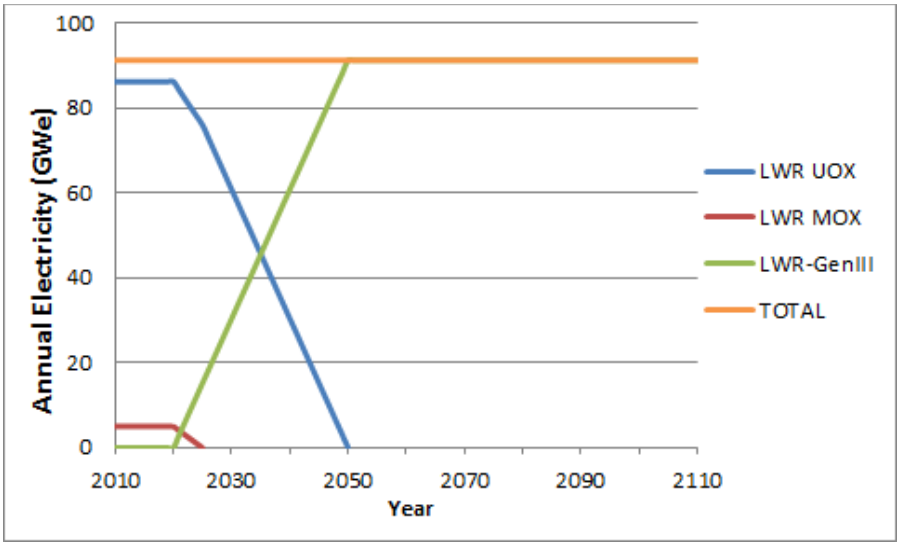

FIG. XXV-1. SCN-1 power generation (open cycle).

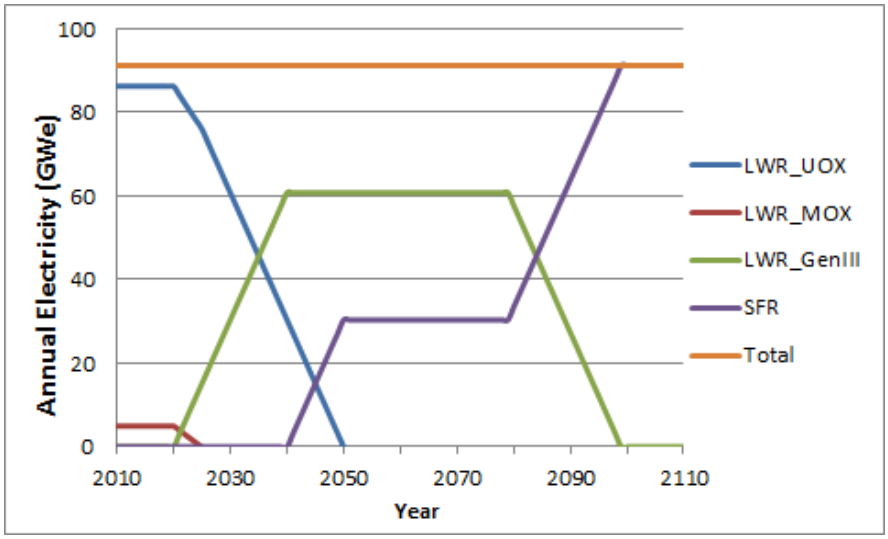

FIG. XXV-2. SCN-2 power generation.

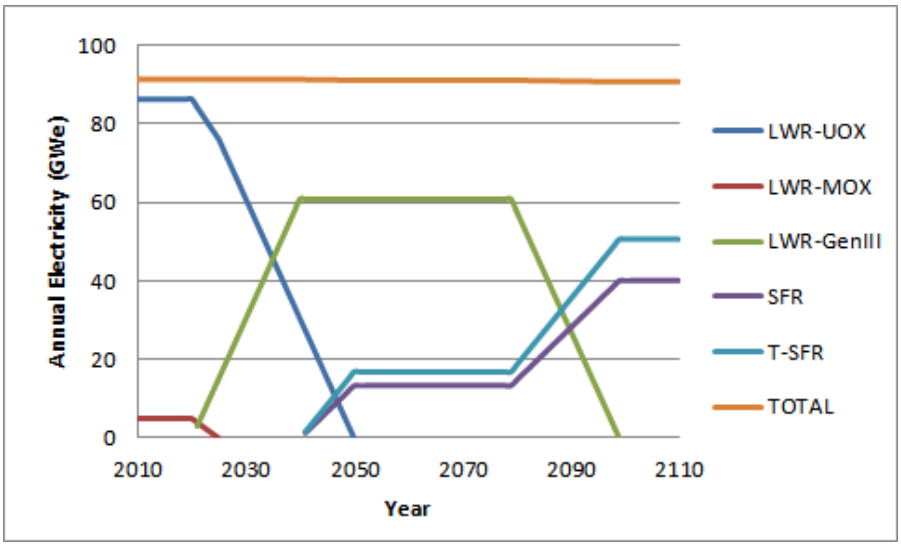

FIG. XXV-3. SCN-3 power generation.

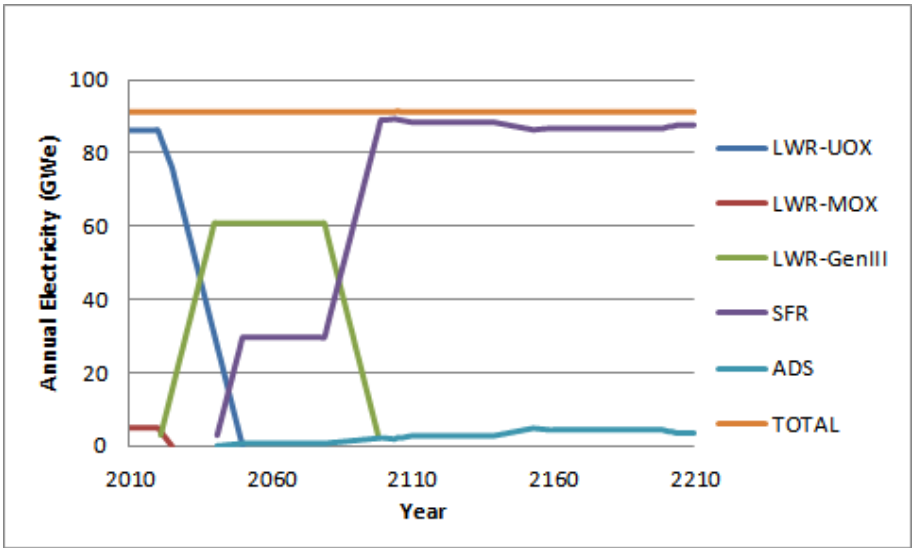

FIG. XXV-4. SCN-4 power generation.

Figures XXV-1 to XXV-4 show the contribution to the energy per reactor type in GW(e). Beyond year 2110, installed capacity of the scenario remains unchanged until 2210 except in SCN-4 which undergoes small changes due to variations in the required number of ADS for MA equilibrium achievement. Each reactor is assumed to operate 60 years.

XXV-5. THE SIMULATION TOOL: DESCRIPTION OF THE TR_EVOL MODULE

The TR_EVOL module [XXV-4] has been designed to evaluate different options for the fuel cycle scenario, enhancing the capabilities of the burn-up simulation system EVOLCODE [XXV-5]. In particular, diverse nuclear power plants (PWR, SFR, ADS, etc.), having possibly different types of fuels (UO_2, MOX, etc.), and the associated fuel cycle facilities (enrichment, fuel fabrication, reprocessing, interim storage, waste storage, geological disposal) can be assessed. The module is intended to simulate each reactor fleet as a single averaged macro-reactor, although it can also simulate individually each reactor of the fleet if required (requiring however large computer resources). Due to this purpose and assuming that the

nuclear fleet is large enough (usually tens of reactors), every magnitude is provided per year. Hence, large fluctuations of operational parameters on individual cycle facilities are averaged over the year.

Each fuel cycle storage facility is represented in TR_EVOL by one or several different buffers. For instance, a nuclear fleet might consist of a series of PWR with N different ^{235}U enrichments fuels. Hence, data concerning fresh fuels with different enrichments would be stored in N different buffers containing the isotopic vector and the total amount of material present in that storage. Storage facilities taken into account in a general fuel cycle (other could be included when necessary for particular cycles) are fresh fuel for nuclear reactors, spent fuel in cooling storage, separated material from reprocessing and nuclear waste.

Connections between buffers represent mass flows. They can link one buffer to another, but can also join more than two buffers or divide different buffers. The parameters of the cycle facilities and the time-dependent interconnections are described in TR_EVOL using a series of basic operational instructions or rules. Each rule specifies a particular action that is applicable to a particular buffer (decay of stored material) or to a particular interconnection (fuel irradiation, fuel fabrication, reprocessing, etc.). The period of time for which that particular action is active is also specified (for instance, advanced reprocessing may be only applicable from a certain year on).

The evolution of fuel isotopic composition and nuclear materials during the lifetime of the nuclear fleet is performed in TR_EVOL by means of ORIGEN 2.2 (Isotope Generation and Depletion Code [XXV-9]) specifically in the decay and irradiation processes. In case of irradiation, the ORIGEN reference cross section libraries or libraries specifically calculated with EVOLCODE 2.0 can be used. In this work, EVOLCODE-made libraries were used for all the fast neutron systems while ORIGEN reference libraries were used for thermal reactors.

The TR_EVOL module for economic assessments provides the levelized cost of electricity making use of the TR_EVOL mass balance output and four main sources of economic information: Investment cost, Fuel cost, Operation and Maintenance (O&M) cost and Waste Management cost. Investment costs take into account the overnight cost of the plant, interest rates, payback periods and construction periods. Fuel cost is calculated using parameters such as raw materials, enrichment, conversions and fabrication in case of UO_2 fuel, or a fixed cost by kg in case of MOX fuel for LWR, FR or ADS. O&M can be explained as a cost by GW(e) installed. Waste Management cost is the sum of interim and final disposal cost, including fixed and variable costs like shaft, galleries, canisters and glasses (which are limited by heat production), and the decommissioning cost as a percentage of the overnight cost.

Although the TR_EVOL economic module usually provides the LCOE as a best estimate value, the LCOE uncertainties can be additionally assessed via probabilistic distributions for the unit costs. The best estimate case can be executed many times; for each run or history, a simultaneous random sampling of the probability density functions of the unit costs (described as uniform or triangular distributions) has to be carried out to obtain the results. Finally, a statistical analysis of the outputs provides the assessments of the LCOE uncertainties.

To improve the methodology, the possibility of setting correlations between unit costs has been implemented in the code for those costs that are strongly dependent between them. For instance, the overnight cost for LWR_UO2 and LWR_MOX, or the cost of natural uranium for different LWR, can be considered correlated, meaning that the same random number is used for each of them in the same history. No partial correlations have been implemented in this study; the unit cost can be correlated at 100% or 0%.

XXV-6. MAIN RESULTS

XXV-6.1. Fuel cycle scenario analysis

Concerning resource availability, Fig. XXV-5 shows the natural uranium (NatU) needs for all scenarios. The reference scenario (SCN-1) requires ~3.3 million tons of U by 2210. Considering that the current global energy demand is approximately four times larger than the scenarios energy demand, and that the total amount of uranium worldwide that is available economically is five times the U requirements, these U requirements do not seem to be a significant constraint. Advanced scenarios require less than one third of the uranium needed in the reference cycle at the end of the scenario. The NatU curves for these scenarios have two changes in the slope, the first one at year ~2040 when the LWR_GENIII commissioning is completed, demanding less NatU, and the second one at year ~2100 when they finish their operation and the scenarios continue just with SFR or ADS fuel.

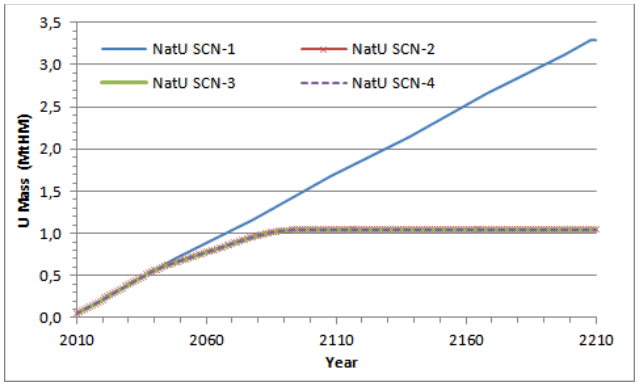

FIG. XXV-5. Natural uranium required by scenario.

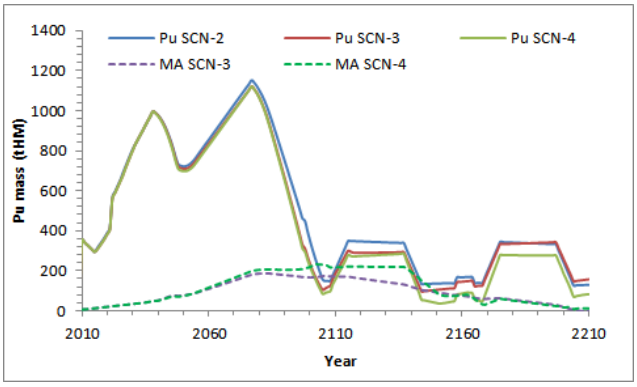

FIG. XXV-6. Availability of Pu and MA separated or ready for reprocessing.

Regarding Pu availability, i.e., Pu separated or in SF ready for reprocessing, Fig. XXV-6 shows that every advanced scenario has the same tendency, due to the SFR (or T-SFR and ADS) Pu consumption. A initial peak of ~1000 t at year 2038 is formed when the first 10 year stage of advanced reactors commissioning begins, demanding Pu for the fabrication of new MOX cores. After this period, Pu is accumulated due to the Pu generation in LWR_GENIII and the SFR breeding. The beginning of the second stage of 20 years of advanced reactors commissioning is marked by the second peak of ~1100 t around year 2077 reducing the Pu availability for a period of 20 years. The reduction in Pu availability continues for 10 more years due to the replacement of the advanced reactors from the first stage commissioning. It has to be taken into account that the reactor decommissioning along the cycle leads to

unloading significant mass as spent cores; they are also considered in the Pu availability curve.

Additionally, Fig. XXV-6 shows that it is not necessary to design reactors with high breeding ratios beyond 2110 since equilibrium can be achieved with a smaller breeding ratio. Thus, breeding ratios around 1.01-1.03 (see Fig. XXV-7) were utilized to keep a reasonable Pu stock to maintain the cycle, avoiding separated Pu accumulation in storage with no use.

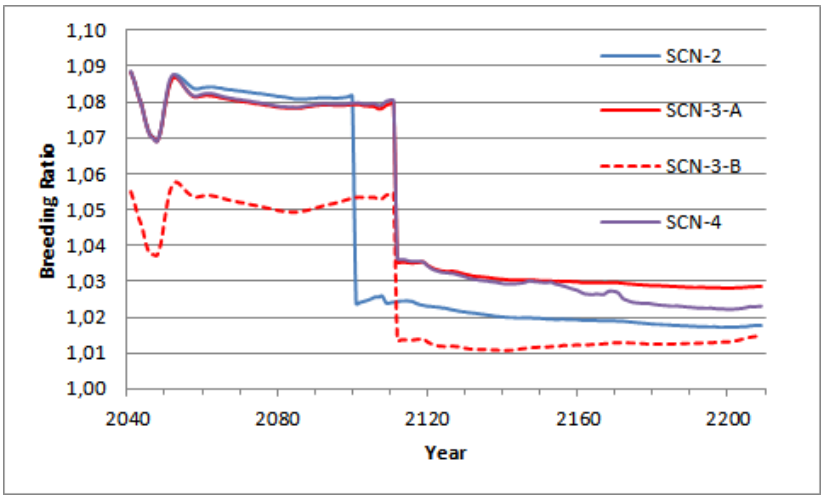

FIG. XXV-7. Breeding ratio for SFR by scenario. SCN-3-A and SCN-3-B represent the SFR and T-SFR breeding ratios respectively.

In scenarios SCN-2, SCN-3 and SCN-4, depleted uranium (DepU) is used for FR fuel fabrication. Figure XXV-8 shows that DepU for SFR fuel fabrication is not a constraint as there is sufficient quantity to fabricate fuels for at least 1,000 years. Additionally, Fig. XXV-9 shows the evolution of the RepU stock by scenario. Although this material can also be used for the FR fuel or for its re-enrichment in UO_2 fuel fabrication, these options have not been taken into account because their use lead to other implications (generation of different waste streams, for instance) that are beyond the scope of this analysis.

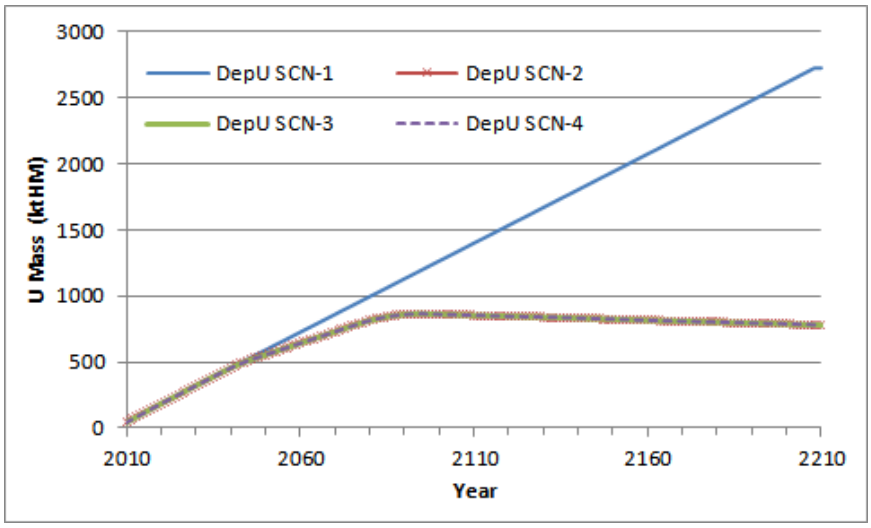

FIG. XXV-8. Depleted uranium needs by scenario.

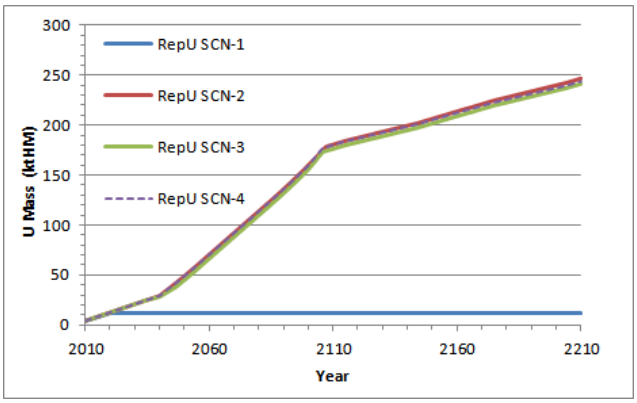

FIG. XXV-9. Reprocessed uranium stock by scenario.

Regarding the transmutation performance, the figure shows larger amounts of transmuted mass than in the estimations at equilibrium. ARCAS project estimates a transmuted mass of ~6.03 kg/TW(e)h for the T-SFR simulated in SCN-3, and 112.5 kg/TW(e)h for the ADS in SCN-4. However, these estimations have been calculated in equilibrium stages and they do not consider the isotopic evolution of their Pu or MA pool streams for fuel fabrication. Considering this fact, the transmuted mass amount experiences continuous changes along the cycle giving averaged values of 8.2 kg/TW(e)h for T-SFR and 131 kg/TW(e)h for ADS. Table XXV-5 shows the Pu and MA inventories stored in the interim and final disposal at year 2210 for the different scenarios. This table shows that scenarios involving fast reactors reduce significantly the Pu inventory to dispose of, although the MA inventory is not considerably modified unless scenarios with dedicated MA transmutation are performed. In these cases, a reduction factor of ~500 in the MA inventory can be achieved.

TABLE XXV-5. PU AND MA INVENTORIES IN THE INTERIM AND FINAL DISPOSAL AT YEAR 2210 FOR THE DIFFERENT FUEL CYCLE SCENARIOS (T)

	SCN-1	SCN-2	SCN-3	SCN-4
Pu	4697	50.68	20.86	21.79
MA	1134	985.5	2.25	2.03

The number of reactors dedicated to transmutation at the end of the scenarios is 44 T-SFR units for SCN-3 (out of 79 SFR in total) and 37 ADS for SCN-4. These unit numbers have been chosen to reasonably fulfill the hypothesis of having equilibrium between the amount of MA transmuted and generated at the end of the scenario. In order to reach this equilibrium in SCN-4, a larger number of transmuters is needed in an intermediate period. An arbitrary number of 51 ADS units has been chosen.

Finally, Table XXV-6 shows the High Level Waste (HLW) inventories (including reprocessing losses, non-reprocessed actinides and fission products, and SF assemblies for SCN-1), stored in interim or final disposal for each scenario at year 2210.

TABLE XXV-6. HLW INVENTORIES AT THE END OF THE SCENARIO IN INTERIM & FINAL DISPOSAL (T)

	LWR-UOX SFA	LWR-MOX SFA	Rep. UOX	Rep. MOX	Rep. SFR	Rep. ADS
SCN-1	397296	4280	69.6	0	0	0
SCN-2	0	0	6721	320	9116	0
SCN-3	0	0	6183	277	9232	0
SCN-4	0	0	6183	277	9008	410

XXV-6.2. Economic Analysis

XXV-6.2.1. Best Case cost

Concerning the costs of electricity generation, the LCOE was obtained applying the Base Case (BC) unit costs shown in Table XXV-2. Results are shown in Table XXV-7, where the contribution per component or sub-cost (Investment, Fuel, O&M and DDD) to the total is also shown. It can be found that all scenarios have a large dependence on the investment cost, responsible of 60% to 69% of the energy cost. Results show that the investment cost can be subdivided as financing of the overnight cost in ~79% and interest during construction in ~21%, a really important contribution.

TABLE XXV-7. SUMMARISED ECONOMIC RESULTS PER SCENARIO

	SCN-1	SCN-2	SCN-3	SCN-4
LCOE, cent €/kW(e)h	4.65	5.58	6.20	6.09
Investment cost, %	61.3	68.8	60.4	68.1
Fuel cost, %	10.9	6.4	18.0	8.8
O&M, %	22.2	21.6	19.0	20.3
DDD cost, %	5.6	3.2	2.6	2.8

It should be added that the LCOE is an integral parameter calculated for the whole scenario length (duly averaged by technology and energy share) and every scenario considers an initial period where the investment costs of LWR_UOX and LWR_MOX are not considered, as explained above. Thus, the LCOE should not be considered as an absolute value but a relative one between fuel cycle scenarios with different technologies.

Regarding other costs also calculated in detail, the HLW storage costs are shown in Fig. XXV-10, which includes the costs of the ID and the FD per scenario for the HLW inventory displayed in Table XXV-6. According to current policies in a number of countries, the HLW mass (formed by fission products, non-recovered actinides and reprocessing losses, or SF in case of SCN-1) has been assumed to be temporarily stored in interim facilities and finally

disposed of in a deep geological repository or final disposal. As shown in the figure there is a notorious difference between the Once-Through scenario (SCN-1) and the reprocessing strategies. The storage costs are reduced three times for SCN-2 and 3.6 times for transmutation scenarios (SCN-3 and SCN-4) while the gallery length for FD is reduced to 42% and 29% respectively. These costs are part of the DDD costs and represent ~3.5% of the LCOE for SCN-1, ~1% for SCN-2 and ~0.7% for SCN-3 and SCN-4.

On the other hand, there are two additional contributions not included in Fig. XXV-10: RepU storage and final disposal of long-lived intermediate level wastes resulting from fuel reprocessing (they should be addressed in a future studies for completion).

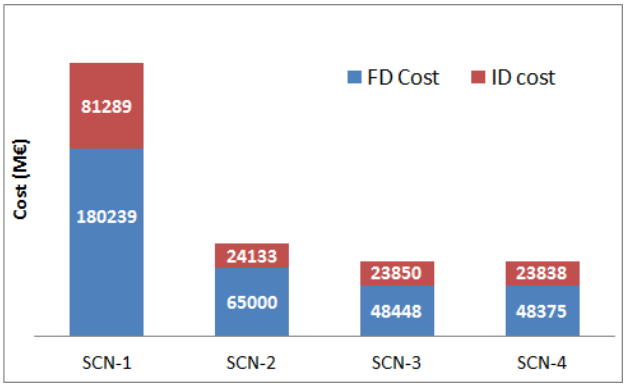

FIG. XXV-10. SF/HLW storage costs per scenario for interim and final disposal.

In order to analyze the influence of each technology to the scenario, the generation cost per reactor type was additionally calculated. The result is shown in Fig. XXV-11, where all scenarios are plotted together. It can clearly be seen that the energy cost per reactor type increases with the reactor technology complexity. Here, it has been assumed that each technology unit must pay back the investment during its lifetime, presented in Table XXV-1.

Differences between scenarios for LWR_UOX and LWR_MOX technologies (Gen II) are explained solely by the DDD costs. Note that none of these technologies include the investment cost; obviously, this could increase the generation costs, reducing the differences between Gen-II and Gen-III technologies.

For LWR_GENIII, differences between scenarios are due to investment costs, mainly in SCN-1, because there is a fraction of LWR_GENIII in SCN-1 commissioned but with a lifetime beyond the end of the scenario (so a fraction of its generated energy is not accounted for). SFR group remains almost unchanged because its cost is very similar between scenarios. Moreover, for T-SFR, the difference regarding SFR is caused by the expensive cost of its fuel type. It is notorious the large cost obtained for the ADS in scenario SCN-4 (divided by 10 in the figure), more than 3 times more expensive than T-SFR in SCN-3. However, the impact of this technology to the LCOE of SCN-4 is very similar to T-SFR in SCN-3 due to the small contribution to the energy production of this specific technology (~3% on average).

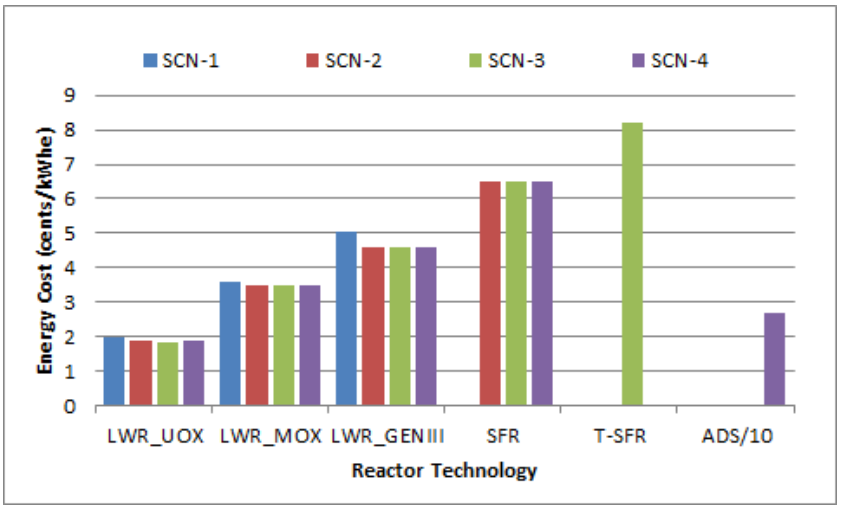

FIG. XXV-11. Energy cost by technology for the different scenarios. Conventions: (i) ADS cost is divided by 10; (ii) as explained in the text, LWR_UOX and LWR_MOX are considered legacy technologies with capital expenses not included.

XXV-6.2.2. Additional cases

As seen from Table XXV-1, calculations shown in the previous section were made assuming 40% SFR thermodynamic efficiency. In order to illustrate the effect of increasing such an efficiency after vigorous R&D plans for high temperature materials availability, the exercise was done again assuming 47% efficiency. Therefore, a reduction of SFR units needed to produce 91.26 GW(e) is obtained, and concerning SCN-2 (maybe the most representative scenario to underline the role of the SFR technology) the new LCOE result is close to 14% lower for the SFR technology and 13% when the whole fuel cycle is accounted (in other words, this result means that the effect of efficiency in LCOE is slightly lower than linear, due to the influence of the fuel cycle back-end part).

Two aspects concerning the Final Disposal issue have been also addressed: the impact of additional canister protection in HLW capsules and the impact of different Final Disposal gallery length (i.e., total number of geological repositories). Estimations shown in the base case of previous section assumed a realistic situation where HLW and SF are placed in seven FD repositories, one per associated country. Also in the base case, an additional assumption concerns the capsules that house the vitrified HLW, in that no additional canister is considered but just a fabricated steel liner (it can be added here that maximum values of 60 kg of fission products and 400 W per glass package are additional assumptions in the capsules). This design guideline is a relaxing one based on the much lower period of time for vitrified HLW to decay, compared to Spent Fuel, in order to equal the radiotoxicity of equivalent mined uranium at long term.

In our additional case, it was firstly explored the possibility for the seven repositories FD to provide an additional canister protection of the HLW packages, i.e., a surrounding new canister housing 3 vitrified HLW capsules (see Spanish/ENRESA concept, REDIMPACT project). In this case, it was obtained that costs associated with the new canister plant construction and processing are responsible for a significant FD costs increase around 45% in advanced scenarios (SCN-2, SCN-3 and SCN-4), with no virtual impact in SCN-1.

Calculations concerning the size of the FD take into account a maximum amount of 70000 tHM per repository (and as in the base case, no additional canister). This assumption means that SF material in SCN-1 still would need several repositories, but 5 instead of 7.

However, concerning HLW disposal, only one would be necessary instead of 7. Therefore, this fact impacts on cost saving associated with avoidance of vertical shafts, decommissioning and encapsulation plants. Compared with the base case, there is a reduction of FD costs presented in Fig. XXV-10, as for 17% in SCN-2 and 23% in SCN-3 and SCN-4, while only 3% in SCN-1. It can be added that the impact on LCOE is much lower in all cases (less than 0.5%) as the contribution of DDD to LCOE is small.

XXV-6.3. Uncertainty analysis

Uncertainties in the LCOE have been estimated via a Monte Carlo 'brute force' methodology using 50 000 different histories. In this work, triangular distributions have been used for each unit cost. These distributions are commonly utilized when there is limited information but lower limit, upper limit and best-estimate values are available for the unit costs.

In this analysis the lower and upper limits have been taken from NEA 2006 [XXV-8] resized to the values appearing in the ARCAS project [XXV-3], which have been taken as the modes of the triangular distributions. These values are shown in Table XXV-2 above.

Figure XXV-12 shows the result of the statistical analysis of the cost assessment. It has to be noted that the Best Case values do not match the average values of the uncertainty distributions. This is a consequence of the distributions taken from the bibliography for the unit costs, where the Best Case value (mode of the distribution) does not usually match the median.

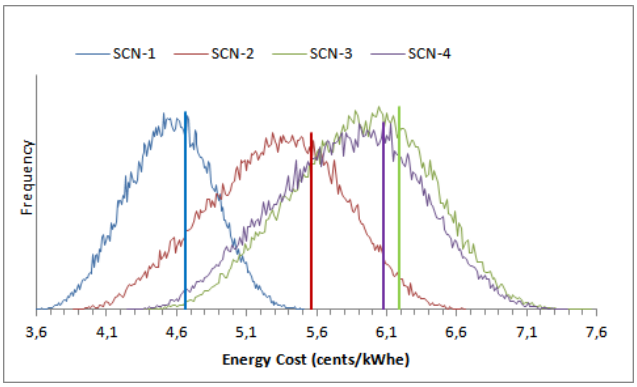

FIG. XXV-12. Histograms of LCOE statistical analysis and the Best Case results.

It can be observed that, although the Best Case of the LCOE of scenario SCN-2 was around 37% larger than the value for SCN-1, there is a significant overlapping between the two distributions. This means that the probability that SCN-2 is more expensive than SCN-1 is significant, but giving an exact value for the relative increment in the energy cost for these scenarios may be senseless. A similar rationale can be made for the scenarios with dedicated transmutation. Although the LCOE of these scenarios is around 10% larger than the LCOE of scenario SCN-2, the overlapping between the distributions is even more significant. This figure also shows that there are no meaningful differences between the two transmutation strategies SCN-3 and SCN-4.

The influence of each technology on the generation cost by reactor type is shown in Fig. XXV-13, where the green lines represent the Best Case values of the LCOE and the red lines show a 2σ interval (95% of the values) around the mean of the statistical analysis of the cost assessment. As mentioned above, the energy cost by reactor type clearly increases with the

reactor technology complexity, although it can be seen that some distributions slightly overlap. Note that the ADS cost is again displayed after divided by 10, and that investment costs have not been included for LWR-GENII technologies.

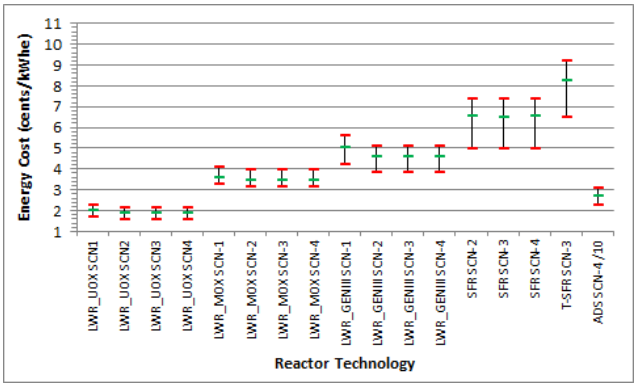

FIG. XXV-13. LCOE range and the Best Case.

The contribution to the uncertainties by cost type can be seen in Fig. XXV-14. The investment cost is the most important source to the uncertainties shown in Fig. XXV-12, with over 80% for all scenarios. The second source come from the O&M cost followed by those one caused by the fuel cost. Note that this fuel cost, the uncertainties are significant smaller in SCN-2 and SCN-4. This is caused by its lower contribution to the energy cost (6.4% and 8.8% respectively) and the lower range of cost for fabrication and reprocessing cost for FR fuel (without MA), which is uppermost in both scenarios. For every scenario, the DDD cost represents the smallest contribution to the uncertainty.

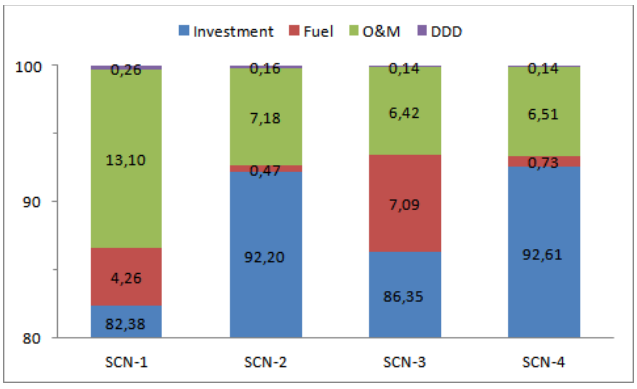

FIG. XXV-14. Contribution to the uncertainties by cost type. The vertical axis shows the uncertainty ranging from 80% to 100%.

XXV-7. CONCLUSIONS

In this work four fuel cycle scenarios involving transmutation options have been simulated by means of TR_EVOL code in order to analyze, in economic and resource terms, the impact of the implementation of advanced technologies including Gen-III+ and Gen-IV reactors and advanced partitioning and transmutation techniques.

The feasibility of all these fuel cycle scenarios was confirmed concerning resources availability. There is no constraint in terms of natural uranium, depleted uranium, and Pu & MA availability.

Concerning the transmutation performance, it was found that, without a transmutation strategy for MA, fast reactors reduce significantly the amount of Pu in the final repository (to a 1% of the total). Additionally, a MA transmutation strategy is needed to reduce the amount of MA in the final disposal. This objective can be achieved (to less than 1% of the total MA amount) with a strategy including SFR for both electricity generation and MA transmutation, and also in a strategy where SFR is responsible for energy generation and ADS is essentially dedicated to MA burning.

Regarding the economic analysis, compared to the reference scenario, the estimates show an average increase of LCOE of 20% for SFR strategy (SCN-2) over the whole period, and ~35% for transmutation scenarios. This result is considered fully valid in spite of some special hypotheses included in this work, common to all scenarios, as it is that the current fleet of LWR had been paid off at the beginning of the scenario. It was also found that the main contributor to the cost of electricity is the investment cost, responsible for 60% to 69% of the total cost.

Results show that the cost of the HLW disposal can be reduced by approximately a factor 4 in a strategy using fast reactors, and a factor 5 in a transmutation strategy. This cost represents a relatively small value for LCOE compared to other contributions (it is 3.7% for SCN-1 and less than 1% for advanced cycles). Additional assumptions concerning disposal with significant impact in DDD costs (though not on LCOE) have been identified, as canister fabrication and total number of repositories.

It has also been found that investment costs are the most important parameters that have to be carefully considered to assure a proper estimation of the energy cost in the standpoint of uncertainties reduction. Also, results show that a vigorous policy of capital costs reduction for future technologies deserves much attention (higher efficiencies, standardization, etc.).

Investment outcomes are significantly dependent on the input data and the range of the uncertainties. Unfortunately, published unit cost uncertainties are too large to find optimal answers to any parameter by means of an economic criterion.

Concerning the TR_EVOL computational tool, it has been proved to be powerful enough to simulate different types of fuel cycle scenarios including their economic implications.

XXV-8. ACKNOWLEDGEMENTS

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