

# **Economic Analysis of Complex Nuclear Fuel Cycles with NE-COST**

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**Abstract** – The purpose of this work is to present a new methodology, and associated computational tools, developed within the U.S. Department of Energy (U.S. DOE) Fuel Cycle Option Campaign to quantify the economic performance of complex nuclear fuel cycles. The levelized electricity cost at the busbar is generally chosen to quantify and compare the economic performance of different baseload generating technologies, including of nuclear: it is the cost of electricity which renders the risk-adjusted discounted net present value of the investment cash flow equal to zero. The work presented here is focused on the calculation of the levelized cost of electricity of fuel cycles at mass balance equilibrium, which is termed LCAE (Levelized Cost of Electricity at Equilibrium). To alleviate the computational issues associated with the calculation of the LCAE for complex fuel cycles, a novel approach has been developed, which has been called the “island approach” because of its logical structure: a generic complex fuel cycle is subdivided into subsets of fuel cycle facilities, called islands, each containing one and only one type of reactor or blanket and an arbitrary number of fuel cycle facilities. A nuclear economic software tool, NE-COST, written in the commercial programming software MATLAB®, has been developed to calculate the LCAE of complex fuel cycles with the “island” computational approach. NE-COST has also been developed with the capability to handle uncertainty: the input parameters (both unit costs and fuel cycle characteristics) can have uncertainty distributions associated with them, and the output can be computed in terms of probability density functions of the LCAE. In this paper NE-COST will be used to quantify, as examples, the economic performance of (1) current Light Water Reactors (LWR) once-through systems; (2) continuous plutonium recycling in Fast Reactors (FR) with driver and blanket; (3) Recycling of plutonium bred in FR into LWR. For each fuel cycle, the contributions to the total LCAE of the main cost components will be identified.

**Keywords:** Nuclear Economics, Fuel Cycles;

## **I. INTRODUCTION**

The purpose of this paper is to present a new methodology, and associated computational tools, developed within the U.S. Department of Energy (U.S. DOE) Fuel Cycle Options Campaign (FCO) to quantify the economic performance of complex nuclear fuel cycles. The methodology will be applied, as examples, to the quantification of the economic performance of (1) current Light Water Reactors (LWR) once-through systems; (2) continuous plutonium recycling in Fast Reactors (FR); (5) Recycling of plutonium bred in FR into LWR. The levelized electricity cost at the busbar is generally chosen to quantify and compare the economic performance of different base-load generating technologies, including of nuclear energy [1, 2, 3, 4, 5, 6]: it is the cost of electricity which renders the risk-adjusted discounted Net Present Value (NPV) of the project cash flow equal to zero. The work presented here is focused on the calculation of the levelized cost of electricity of fuel cycles at mass balance equilibrium, which is termed LCAE (Levelized Cost of Electricity at Equilibrium). Mass balance equilibrium implies that all the mass streams in a given fuel cycle do not change with time, or from one fuel residence cycle in the reactor to the next. This condition is an assumption that allows the evaluation of performance of fuel cycles independently of the transients required to reach equilibrium situations. The same methodological approach can be applied to the economic analysis of fuel cycles in non-equilibrium conditions.

## **II. METHODOLOGY**

For the calculation of the LCAE, each expense and revenue streams is discounted to an arbitrary point in time, typically the beginning of reactor construction or the first reactor criticality, using a discount rate that reflects the financial risk of the project.

The revenue generated by the sale of the product (e.g., electricity) needs to cover both the fixed and variable expenses incurred during normal operations, such as, for example fuel purchases and Operations & Maintenance (O&M) for a nuclear reactor; to repay the capital employed during the construction and decommissioning phases, including both overnight and financing charges; and to compensate the owners of that capital (both debt and equity investors) for the risk taken with the project. The constant electricity price that, in real dollars, covers all these charges is the LCAE. In more formal terms, the LCAE is the net present value of a continuous stream of revenue charged against the sale of electricity, equalized to the sum of the net present value of all the expenditures incurred by the plant owner throughout the physical life of the plant for a system in equilibrium, according to Equation (1),

$$\int_0^{T_{\text{plant}}} C_{\text{lev}} E(t) e^{-rt} dt = \int_0^{T_{\text{plant}}} K(t) e^{-rt} dt \quad (1)$$

where  $C_{\text{lev}}$  is the levelized cost of electricity at equilibrium (LCAE);  $E(t)$  represent the time profile of the electricity generated over the life of the plant and  $K(t)$  is the dollar value of the expenditures sustained at time  $t$ .

The discounting is expressed here as continuously compounded, rather than the perhaps more familiar annual compounding, since the revenue from selling electricity is collected continuously. Because, by definition,  $C_{\text{lev}}$  is a constant, an explicit solution for  $C_{\text{lev}}$  can be found under the assumption that  $E(t)$  is also constant, “E”, under the “base-load” assumption.

$$C_{\text{lev}} = \frac{1}{E} \frac{r}{1 - e^{-rT_{\text{plant}}}} \int_0^{T_{\text{plant}}} K(t) e^{-rt} dt \quad (2)$$

In Equation (2), it is noted that the resulting LCAE is simply the integral of the net present value of the expenditures sustained by the plant operator, multiplied by a term called “capital recovery factor”, which is a function of the discount rate ( $r$ ) and of the financial life of the plant ( $T_{\text{plant}}$ ).

### **III. THE “ISLAND” COMPUTATIONAL APPROACH AND NE-COST**

The practical calculation of the cost of electricity for any fuel cycle is, in principle, a straightforward application of Equation (1). This involves the identification of the amount and timing of all the expenses sustained during the entire life of the system, and the calculation of the amount of electricity and/or heat available for sale from the system during that time. However, as the complexity of the fuel cycle increases, the computations get more complex: involving a large number of material processing facilities and more than one reactor. Each reactor will generally have a different reloading schedule and operational life, and the proper computation of the LCAE for the entire fuel cycle requires the inclusion of the amount and timing of all the expenditures for every facility and reactor in the fuel cycle. Additionally, the facilities that supply materials and services to the reactors are generally interconnected in a manner unique to each particular fuel cycle.

To alleviate these computational issues, a novel approach has been developed, which has been called the “island approach” because of its logical structure. Additionally, a new economic analysis code (NE-COST) was developed specifically for the calculation of the LCAE metric for complex fuel cycles, using the “island approach”.

### **III.A. The “island” computational approach**

In the island approach, a generic complex fuel cycle is subdivided into subsets of fuel cycle facilities, called islands, each containing one and only one reactor or blanket type and an arbitrary number of fuel cycle facilities.

(Fig 1 here)

As an example Figure 1 shows a complex, three stage fuel cycle scheme, involving three reactor

types:

1. A fleet of standard Pressurized Water Reactors (PWR) using mined and enriched uranium;
2. A fleet of PWR Mixed Oxide Fuel (MOX) utilizing as primary fissile material the plutonium recovered from spent fuel from the fleet of standard PWR;
3. A fleet of fast reactors with a conversion ratio lower than 1, recycling their own fuel through electrochemical processing and utilizing as makeup fissile Transuranic (TRU) recovered from the MOX spent fuel and Minor Actinides (MA) recovered from the spent Uranium Dioxide (UOX) PWR fuel.

The calculation of the LCAE for this system can be simplified, as will be shown in the remainder of this section, by splitting the fuel cycle into the three subsections (islands), each containing only one of the three reactor types and a number of related non-electricity-producing fuel cycle facilities, as shown in Figure 2.

(Fig 2 here)

It is noted that each fuel cycle facility can belong to only one island, although it is possible to subdivide a facility “logically” into two or more sub-facilities that could be located on different islands, with the caution that economies of scale have to be accounted properly for the size of the single facility before the split-up. Between islands, material is allowed to flow, but there is no cash transfer. Therefore, the cash flow of each sub-section of the system will be evaluated separately and the LCAE computed, based on the calculated cash flow, separately for each island. The system-wide cost of electricity will then be calculated as the weighted average of the

cash flow of each individual subsection. The weights are the fractional energy generated by each system subsection.

The island approach presents the following advantages: (1) it allows substantial savings in the complexity of the set-up, thus reducing the time and effort necessary in setting up the input and increasing the robustness and the reliability of the calculated output; (2) It minimizes new model developments, by avoiding the need to set up a new code or a new spreadsheet for each different fuel cycle (the code is never changed, even for very complex fuel cycles, only the inputs of each island); and (3) It simplifies debugging: it is far easier to identify errors in the relatively simple input of each island as opposed to the case of a very complex fuel cycle.

The methodological framework of the island approach produces a close approximation of the theoretically exact LCAE for complex fuel cycle systems. To understand the conditions under which the approximate solution provided by the island methodology is exact, the methodology to incorporate the time-offsets of reactor startups in different islands is first identified. The equations are developed for a two-islands case as an example, but can easily be extended to situations involving more than two islands.

In the island approach the LCAE of each island is estimated independently. The cost of electricity  $C_{lev1}$  for island 1 is calculated with Equation (3).

$$C_{lev1} = \frac{1}{E_1} \frac{r}{1 - e^{-rT_{plant1}}} \int_0^{T_{plant1}} K_1(t) e^{-rt} dt \quad (3)$$

For simplicity of notation, the integral of the expenditures  $K(t)$  over the life of the plant is indicated as the “net present value of expenditures 1”, or  $NPV_1$ , as in Equation (4).

$$\int_0^{T_{plant1}} K_1(t) e^{-rt} dt = NPV_1 \quad (4)$$

Equations analogous to (3) and (4) can be written for island 2.

Expressing  $E_2$  as a multiple of  $E_1$  as in Equation (5), the overall weighted average of the cost of

electricity for the system composed of the two islands is shown in Equation (6), where the weights are the fractional electricity produced by each reactor on each island.

$$E_2 = \alpha E_1 \quad (5)$$

$$C_{\text{average}} = C_{\text{lev1}} \frac{E_1}{E_1 + E_2} + C_{\text{lev2}} \frac{E_2}{E_1 + E_2} = C_{\text{lev1}} \frac{1}{1 + \alpha} + C_{\text{lev2}} \frac{\alpha}{1 + \alpha} \quad (6)$$

When substituting Equations (3) for  $C_{\text{lev1}}$  (and its analogous for  $C_{\text{lev2}}$ ) in Equation (6), Equation (7) is obtained.

$$C_{\text{average}} = \frac{r}{E_1(1 + \alpha)} \left( \frac{NPV_1}{1 - e^{-rT_{\text{plant1}}}} + \frac{NPV_2}{1 - e^{-rT_{\text{plant2}}}} \right) \quad (7)$$

However, if one of the two reactors feature a start-up time offset  $T_0$  (as shown in Figure 3), evaluating the levelized cost for the combined system  $C_{\text{combined}}$  yields Equation (8) (in discrete annual compounding).

$$NPV_1 + \frac{NPV_2}{(1+r)^{T_0}} = C_{\text{combined}} E_1 \left[ \sum_{i=0}^{T_0} \frac{1}{(1+r)^i} + (1 + \alpha) \sum_{i=T_0}^{T_{\text{plant1}}} \frac{1}{(1+r)^i} + \alpha \sum_{i=T_{\text{plant1}}}^{T_0 + T_{\text{plant2}}} \frac{1}{(1+r)^i} \right] \quad (8)$$

Equation (8) can be easily translated into the equivalent Equation (10) using continuous compounding  $r_{\text{continuous}}$ , which simplifies the calculation. In turn,  $r_{\text{continuous}}$  can be easily obtained from  $r_{\text{annual}}$  by using Equation (9).

$$r_{\text{continuous}} = \ln(1 + r_{\text{annual}}) \quad (9)$$

(Fig 3 here)

$$NPV_1 + NPV_2 e^{-rT_0} = C_{\text{combined}} E_1 \left[ \int_0^{T_0} e^{-rt} dt + (1 + \alpha) \int_{T_0}^{T_{\text{plant1}}} e^{-rt} dt + \alpha \int_{T_{\text{plant1}}}^{T_0 + T_{\text{plant2}}} e^{-rt} dt \right] \quad (10)$$

Equation (10) can be solved to yield an explicit expression for  $C_{\text{combined}}$ , as shown in Equation (11).

$$C_{\text{combined}} = \frac{r}{E_1} \left[ \frac{NPV_1 + NPV_2 e^{-rT_0}}{(1 - e^{-rT_{\text{plant1}}}) + \alpha e^{-rT_0} (1 - e^{-rT_{\text{plant2}}})} \right] \quad (11)$$

By comparing Equations (11) and (7), it is possible to understand under which conditions the island approach approximate solution of Equation (7) ( $C_{\text{average}}$ ) is exact: Equation (11) is identical to Equation (7) if  $T_0=0$  (i.e., there is no time offset in the startup of the two islands) and if  $T_{\text{plant1}}=T_{\text{plant2}}$ . Because of the typically long reactor's lifetimes, the "error" incurred because of possibly slightly different lifetimes is usually, at most, a small percentage of the electricity costs.

### III.B. The NE-COST economic analysis code

A nuclear economic software tool, NE-COST, has been developed to calculate the probability density function of the LCAE of complex fuel cycles within the "island approach" computational framework.

Other available tools to calculate the levelized cost of electricity, such as G4-ECONS [7], for example, had been developed for fuel cycles containing only one reactor, and of generally limited complexity. For this reason, they are not adequate to calculate the LCAE for complex, multi-reactor fuel cycles, in a simplified, systematic, and robust way.

NE-COST is a set of 4 sub-programs, each written in the commercial programming software MATLAB®, that perform the following logically separated tasks (listed here in order of execution):

- *Monte Carlo Sampler.* It generates a set of sampled inputs according to prescribed rules and available cost data, both specified by the user.
- *NE-COST levelized electricity cost (LCAE) calculator.* It generates the cost of electricity (essentially solving Equation (1) for each of the Monte Carlo generated input) for each of the system's islands, each composed of one and only one nuclear reactor and/or blanket type, and a number of fuel cycle facilities, that do not produce electricity, associated with that reactor

or blanket. It is possible to model drivers and blankets on 2 separate islands or on the same island: please see sections IV.B and IV.C for examples of both approaches. The levelized cost per unit of product of each of the non-reactor facilities is calculated separately, by solving Equation (1) for the “levelized cost at equilibrium per unit of product” (e.g. \$/kgHM). NE-COST accepts as input the “levelized cost at equilibrium per unit of product” (e.g., \$/kgHM) and an associated uncertainty distribution for each fuel cycle costs.

- *Multi-island system combiner/data plotter.* In a multi-island calculation, this sub-program generates the LCAE for the overall system, starting from the LCAE of each island. Additionally, it calculates the statistical properties of each LCAE distribution, both of the entire system and of each of the islands.
- *Plotting/Comparison tool.* It compares the LCAE probability distribution of any given system to that of any chosen reference system, while accounting for the correlation information between uncertain input cost variables, when available.

An important design objective for NE-COST is to allow the calculation of the cost of electricity of arbitrarily complex nuclear systems by just changing the input, without the need to alter the model’s programming. For this purpose, the general structure of the LCAE calculator sub-program has been developed, as shown in Figure 4, with several alternative fuel cycle front-end and back-end paths.

(Fig 4 here)

The front end possible paths in each island are based on the source of the main fissile material:

- *Mined natural uranium (Front-end path 1, highlighted in Figure 5).* The extracted uranium

needs to be converted, enriched, and fabricated before the reactor irradiation. The depleted uranium that is not used as makeup fuel in another island is de-converted and disposed. If needed, thorium can also be added to the fresh fuel in front-end path 1, with or without uranium.

- *Reprocessed fuel received from the previous island (Front-end path 2, highlighted in Figure 6).* The user has the choice of which fissile material drives the amount of separation services required, between plutonium, TRU, MA and Recovered Uranium (RU). The amount of separation services (in \$/kgHM of feed material) is determined by the ratio of the mass of the main fissile material required in the output fuel to the mass of the main fissile material present in the feed fuel. All the output streams of the separation plants can be stored, disposed of, or re-used. The code allows the re-enrichment of recovered uranium, with a different SWU cost as compared to that of natural uranium.
- *Reprocessed/re-fabricated fuel from the reactor on the island (Front-end path 3, or Back-end path 5, highlighted in Figure 7).* This is a material feed-back loop within the island.

(Fig 5, 6 and 7 here)

The back end possible paths in each island are:

- *Wet Storage + do nothing (Back-end path 1).* Fuel is passed to the next island after irradiation and wet storage, at no cost.
- *Wet Storage + geologic disposal (Back-end path 2).*
- *Wet Storage + dry storage + geologic disposal (Back-end path 3).*
- *Wet Storage + dry storage + 1 mills/kWh (i.e. \$0.001/kWh) (Back-end path 4).* The disposal

fee is “per energy produced”, and can be changed by the user to a value different than 1 mill/kWh, if desired.

- *Reprocessed/re-fabricated fuel from the reactor on the island (Back-end path 5 or Front-end path 3, highlighted in Figure 7).* This is a material feed-back loop within the island.

A set of switches in the input allows the user to choose the desired fuel cycle path, and/or combination of paths: all paths can be used simultaneously and in fractional amounts set by the user. For example, it is possible to model a PWR operating with a mixed UOX/MOX core, or a fast reactor receiving TRUs both (1) from reprocessed fuel irradiated in a previous island and (2) from its own reprocessed fuel.

For each path, the user can eliminate the cost associated with any fuel cycle step by simply “zeroing” its cost in the NE-COST input.

All the masses and the unit costs are normalized to 1 kg of initial heavy metal (kgiHM) and subsequently scaled up by the batch requirement including processing losses, and discounted using lead/lag times for purchase/disposal at each refueling interval.

NE-COST has been developed with the capability to handle uncertainty as a required functionality, through the capability (1) to estimate the magnitude and the functional form of the uncertainty in the calculated LCAE; and (2) to identify the biggest uncertainty drivers and their individual impact. To this end, the NE-COST structure has been developed specifically to handle uncertainty distribution information.

NE-COST has been benchmarked against the well-established nuclear economic code G4-ECONS [7] for a single reactor case, as well as against results obtained during the Global Nuclear Energy Partnership (GNEP) program [8] for a complex, 3-stages system. In both cases, the NE-COST results are in good agreement with the previously-obtained results: Table 1

compares the results of the two codes for a once-through fuel cycle.

(Table I here)

#### **IV. EXAMPLE RESULTS**

As a practical example of implementation of the island methodology with NE-COST, the calculation of the LCAE is presented in this section for the following three fuel cycles:

1. Commercial PWR Once Through (OT-U);
2. Continuous plutonium recycle in sodium fast reactors (FR-Pu);
3. Breed plutonium in sodium fast reactors and burn extra plutonium in PWR (FR-PWR-Pu).

For the sake of simplicity and clarity, the NE-COST calculations have been performed in deterministic mode, using the averages of the input cost distributions for the various fuel cycle services unit costs presented in Section V1.A to V1.C. These costs are obtained from Ref [9], and are augmented with additional data that became available since the 2009 release of Ref [9]. While the calculations can easily be performed using uncertainty distributions for the cost and other data, using deterministic values allows a compact presentation of the input parameters and of the results, and facilitates the presentation of the cost breakdown for each of the fuel cycles. This in turn allows a more insightful and informative understanding of the economic performance of each of the fuel cycles analyzed.

In the examples presented here, no legacy material (such as depleted uranium) is included: i.e. all the make-up material for fast reactors is assumed to be natural uranium that has to be purchased: this allows the simulation of a truly “equilibrium” situation that can be sustained for a very long period of time. The cost of make-up natural uranium is not a significant factor in the economic performance of fuel cycles analyzed that could alternatively use depleted uranium.

Following is a description of each of the fuel cycles with the assumptions relevant for the economic analysis and the average cost data used for the analysis.

Additionally, Table II lists the assumptions common to all three example cases.

(Table II here)

#### **VI.A. Commercial PWR Once Through (OT-U): description of the fuel cycles and list of the input parameters relevant for the economic analysis**

OT-U, “Commercial PWR Once Through”, features a PWR operating on enriched uranium in a once-through fuel cycle with final disposal of spent fuel after reactor discharge.

The main relevant assumptions for the economic analysis of this fuel cycle are the following:

- UO<sub>2</sub> fueled PWR with a core thermal power of 3000 MW;
- Thermal efficiency: 33%
- Capacity factor 90%;
- Specific power density: 33.7 MW/MTiHM;
- Average discharge burnup: 50 GWD/MTiHM;
- Uranium enrichment: 4.2%, tails enrichment 0.25%.

Having a single reactor, a single NE-COST island is used to model this fuel cycle. The purchase of make-up Natural Uranium (NU) is modeled through the use of the front-end path that is described in Section III.B as “Front End Path 1”, or “Mined natural uranium”.

The input cost parameters for the economic analysis, from Ref [9], are the following:

- Overnight reactor capital cost: 4000 \$/kW<sub>e</sub>;
- Reactor operation and maintenance fixed cost: 71 \$/kW<sub>e</sub>-y;
- Reactor operation and maintenance variable cost: 1.8 mills/kWh;
- Cost of UO<sub>2</sub> fuel fabrication: 350 \$/kg of enriched uranium;

- Cost of spent nuclear fuel conditioning before shipment: 93 \$/kg
- Cost of direct spent nuclear fuel geologic disposal: 540 \$/kg

## **VI.B. Continuous plutonium recycle in sodium fast reactors (FR-Pu): description of the fuel cycles and list of the input parameters relevant for the economic analysis**

Fuel cycle FR-Pu, “Continuous plutonium recycle in sodium fast reactors”, is a single stage continuous recycle of all plutonium and uranium in a sodium-cooled metal-fueled breeder fast reactor, with a driver and a blanket. The Sodium Fast Reactors (SFR) core concept was designed to achieve a break-even Plutonium (Pu) conversion ratio (i.e., slightly higher than 1.0 to account for losses in the fuel separation and fabrication) in the equilibrium cycle. Both the driver and the blanket’ spent fuel is sent to separation processes after irradiation. The separated U/Pu is used to fabricate a new driver fuel, while the separated MA and FP are sent to disposal. The blanket fuel accumulates a burnup of 23.5 GWD/T and is sent to a separation process. The remaining uranium along with newly-purchased makeup natural uranium is used to make a new blanket fuel. All the minor actinides, fission products and losses from separations are disposed as High Level Wastes (HLW), all the Pu and RU minus losses are recycled.

The relevant assumptions for the economic analysis of this fuel cycle are the following:

- The reactor is a sodium fast reactor (SFR) with a core thermal power of 1000 MW;
- Thermal efficiency: 40%
- Capacity factor 90%;
- Specific power density: 52 MW/MTiHM;
- Average discharge burnup: 81.5 GWD/MTiHM for the driver; 23.5 GWD/MTiHM for the blanket;
- Fuel residence time: 3.6 Evaluated Full Power Years (EFPY) for the driver, 5.4 EFPY for the

blanket;

- Pu content in fresh fuel: 15.3% Pu in the driver; natural and reprocessed uranium in the blanket;
- Fraction of Natural Uranium (NU) to be purchased as make-up material: 8.8% of the whole reloading mass, which includes driver and blanket;
- Average fraction of (FP+MA+reprocessing losses) in discharged fuel, to be disposed of as High Level Wastes (HLW): 8.5%.

This fuel cycle is modeled in NE-COST as a 2 islands system:

- Island 1 contains the SFR driver;
- Island 2 contains the SFR blanket.

The reprocessing facilities are included in each island using the front-end path that is described in Section III.B as “Front End Path 2”, or “Reprocessed fuel received from the previous island”.

The LCAE of the system is the weighted average of the LCAE of the two individual islands, with the fractional energy generated by each island as weights. The fractional energy generated by the driver in island 1 is 95.4%, while the remaining 4.6% is generated by the blanket of island 2. The fractional energy is calculated from the average power density of the driver and blanket (i.e. burnup divided by fuel residence time) and core average power density, specified above, by determining the fractional HM mass in each (resulting in 80% driver / 20% blanket) and the corresponding average power distribution (954 MW<sub>t</sub> driver / 46 MW<sub>t</sub> blanket).

The input cost parameters for the economic analysis from Ref [9], are the following:

- Overnight reactor capital cost: 4300 \$/kW<sub>e</sub>;
- Operation and maintenance fixed cost: 72 \$/kW<sub>e</sub>-y;
- Operation and maintenance variable cost: 1.9 mills/kWh;

- Cost of driver fuel fabrication: 3750 \$/kg;
- Cost of blanket fuel fabrication: 440 \$/kg;
- Cost of spent nuclear fuel conditioning before shipment to the reprocessing plant: 93 \$/kg;
- Cost of reprocessing: 925 \$/kgHM;
- Cost of fission product conditioning before disposal: 4600 \$/kgFP ;
- Cost of fission product geologic disposal: 4580 \$/kgFP.

**VI.C. Breed plutonium in sodium fast reactors and burn extra plutonium in PWR (FR-PWR-Pu): description of the fuel cycles and list of the input parameters relevant for the economic analysis**

Fuel cycle FR-PWR-Pu, “Breed plutonium in sodium fast reactors and burn extra plutonium in PWR”, is a two stages system in which excess Pu generated in an SFR with a conversion ratio of 1.5 (stage 1) is utilized in a single-pass PWR MOX reactor (stage 2). Makeup natural uranium is required in stage 1 only. All the FP, MA and reprocessing losses from both the SFR and the PWR MOX are geologically disposed-of as HLW.

This option is modeled in NE-cost as a 2-islands system:

- Island 1 contains the SFR, with both driver and blanket, and the reprocessing and re-fabrication facility for both the seed and blanket. The purchase of make-up NU is modeled through the use of the front-end path that is described in section III.B as “Mined natural uranium”; the reprocessing of the SFR driver and blanket is modeled through the back-end path that is described in section III.B as “Reprocessed/re-fabricated fuel from the reactor on the island”. The burnup is the weighted average of the seed and the blanket. The specific reprocessing costs (in \$/kg of reprocessed material) in island 1 are the same for driver and blanket, but the cost of re-fabrication is not, since the new driver fuel contains plutonium and

the blanket only depleted uranium. The cost of reprocessing and re-fabrication is computed as the weighted average of the fabrication costs of the driver and blanket.

- In Island 2 the PWR MOX fuel is fabricated using Pu and RU from the reprocessing of the spent MOX PWR fuel of island 2, as well as with excess Pu from the blanket of the SFR in island 1. No NU is necessary since the 40%Pu/60%RU mixture from Stage 1 brings enough RU. The front-end path that is described in Section III.B as “Reprocessed fuel received from the previous island” is used to model the fabrication of MOX fuel.

The relevant assumptions for the economic analysis of this fuel cycle are the following:

- The reactor in island 1 is a sodium fast reactor (SFR) with a core thermal power of 1000 MW;
- The reactor in island 2 is a MOX fueled PWR with a core thermal power of 3000 MW;
- Thermal efficiency: 40% for the SFR, 33% for the PWR;
- Capacity factor 90% for both reactors;
- Specific power density: 16 MW/MTiHM for the SFR, 35.4 MW/MTiHM for the PWR;
- Average discharge burnup: 96.8 GWD/MTiHM for the SFR driver; 20.7 GWD/MTiHM for the SFR blanket, 50 GWD/MTiHM for the MOX PWR;
- Fuel residence time: 4.75 EFPY for the SFR driver, 9.5 EFPY for the SFR blanket, 3.9 EFPY for the MOX PWR;
- HM content in fresh fuel: 21.4% Pu in the driver; natural and reprocessed uranium in the blanket; 9.1 % Pu in the MOX PWR fuel;
- Fraction of NU to be purchased as make-up material: 11.1% of the whole SFR reloading mass, which includes driver and blanket; no make-up material is required for stage 2;
- Average fraction of (FP+MA+reprocessing losses) in discharged fuel, to be disposed of as

HLW: 5.8% in SFR used fuel; 6.9% in MOX PWR used fuel;

The LCAE of the system is the weighted average of the LCAE of the two individual islands, with the fractional energy generated by each island as weights. The fractional energy generated by the SFR type reactors on island 1 is 61.1%, while the remaining 38.9% is generated by the MOX PWRs of island 2.

The input cost parameters for the economic analysis, from Ref [9], are the following:

- Overnight reactor capital cost: 4300 \$/kW<sub>e</sub> for the SFR, 4000 \$/kW<sub>e</sub> for the PWR;
- Operation and maintenance fixed cost: 72 \$/kW<sub>e</sub>-y for the SFR, 70 \$/kW<sub>e</sub>-y for the PWR;
- Operation and maintenance variable cost: 1.9 mills/kWh for the SFR, 1.8 mills/kWh for the PWR;
- Cost of SFR driver fuel fabrication: 3750 \$/kg;
- Cost of blanket fuel fabrication: 440 \$/kg;
- Cost of MOX PWR fuel fabrication: 3750 \$/kg;
- Cost of conditioning before shipment to the reprocessing plant for both the SFR and MOX spent fuel: 93 \$/kg;
- Cost of reprocessing for both SFR and MOX spent fuel: 925 \$/kgHM;
- Cost of fission product conditioning before disposal: 4600 \$/kgFP;
- Cost of fission product geologic disposal: 4580 \$/kgFP.

#### **VI.D. Results and comparison of the breakdown of the cost of electricity for the 3 fuel cycles described in Sections IV.A, IV.B and IV.C.**

Table I and Figure 8 show a direct comparison<sup>1</sup> of the calculated LCAE for the 3 fuel cycles described in Sections IV.A, IV.B and IV.C, broken down in the three main components of the

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<sup>1</sup> Please note that the comparison here is based exclusively on the average (or expected) values, and neglects the large uncertainties associated with these values. More on this topic in Section IV.E.

LCAE (in mills/kWh): (1) reactor capital cost, (2) reactor (O&M) cost and (3) fuel cycle cost. While the reactor O&M is about the same for the 3 systems, the reactor capital cost is, as expected, higher for the 2 fuel cycles that involve fast reactors. Fuel cycle “FR-PWR-Pu” shows a reactor capital cost that is in between the other two systems, since it involves both FR and PWR. It is also observed that the fuel cycle cost is similar for the LWR and for the FR systems, while it is higher for fuel cycle “FR-PWR-Pu”, causing the overall economic performance of this fuel cycle to be slightly worse than the other two.

(Table III and Figure 8 here)

In order to understand the reasons for the observed fuel cycle cost performances, the various contributions to the total fuel cycle costs for each of the fuel cycles is shown in Table II and in Figure 9.

(Table IV and Figure 9 here)

It is noted that, albeit similar, the contributions to the total fuel cycle costs for fuel cycles “OT-U” and “FR-Pu” are due to very different processes. In particular, while in the OT-U fuel cycles the dominant costs are the purchases of new uranium and of enrichment services, in the case of the FR-Pu fuel cycle the cost is dominated by the re-fabrication of the driver fuel, which, because of the presence of plutonium, requires glove box handling. Reprocessing, albeit expensive, gives a smaller cost contribution than reprocessed fuel fabrication. The cost of conditioning and disposal of HLW combined is about the same as the cost of SNF conditioning and disposal. The

reason for the higher fuel cycle cost of fuel cycle “FR-PWR-Pu”, is that both reprocessing and fuel re-fabrication are more expensive: this is due mainly to the comparatively short burnup of the MOX-PWR, which requires more frequent reprocessing and fuel re-fabrication. The unit costs of reprocessing in island 1 (SFR) is 2.4 mills/kWh, and that of fuel fabrication, for both the driver and the blanket, is 4.1 mills/kWh.

The costs of reprocessing and re-fabrication in island 2 (MOX PWR) are 2.7 mills/kWh and 10.8 mills/kWh respectively. When weighted by the fractional energy generated by the two islands, the overall system costs yield the values shown in Table II and Figure 9.

### **VI.E. Uncertainty analysis and future developments**

The NE-COST code has been developed with the capability to handle uncertainty in the input cost and, if desired, also in other input parameters. Large uncertainty ranges in the input parameters can cause the calculated probability density functions of the LCAE to overlap, possibly making it difficult to draw clear conclusions as to the relative economic performance of alternative fuel cycles. However, NE-COST is designed to account for correlations between uncertainty cost distributions, making it possible to obtain more informative comparisons of the cost of electricity of various fuel cycle alternatives, since the probability density functions of the cost differences will be narrower when the correlation between costs is accounted for. The development of defensible correlation coefficients between uncertainty cost distributions is an area where work is currently in progress. Another area where work is currently in progress is the extension of the NE-COST capabilities to perform the economic analysis of fuel cycles during transitions.

### **V. CONCLUSIONS**

A novel methodology and associated computational tools (NE-COST) to quantify the economic

performance of complex nuclear fuel cycles were presented in this paper, followed by implementation examples.

The work is focused on the calculation of the levelized cost of electricity of fuel cycles at mass balance equilibrium, or LCAE (Levelized Cost of Electricity at Equilibrium).

The practical calculation of the cost of electricity for any fuel cycle is, in principle, straightforward: it involves the identification of the amount and timing of all the expenses sustained during the entire life of the system, and the calculation of the amount of electricity and/or heat available for sale from the system during that time frame. However, as the complexity of the fuel cycle increases, the computations get more complex, possibly involving a large number of fuel cycle facilities and more than one reactor. Each reactor will generally have a different reloading schedule and operational life, and the proper computation of the LCAE for the entire fuel cycle requires the inclusion of the amount and timing of all the expenditures for each facility and reactor. Additionally, the facilities that supply materials and services to the reactors are generally interconnected in a manner unique to each particular fuel cycle.

To alleviate these computational issues, the “island approach” has been developed, so-called because of its logical structure: a generic complex fuel cycle is subdivided into subsets of fuel cycle facilities, called islands, each containing one and only one reactor and/or blanket and an arbitrary number of fuel cycle facilities. Between islands, material is allowed to flow, but there is no cash transfer. Therefore, the cash flow of each sub-section of the system can be evaluated separately and the LCAE computed, based on the calculated cash flow, separately for each island. The system-wide cost of electricity can then be calculated as the weighted average of the cash flow of each individual subsection. The weights are the fractional energy generated by each island.

The island approach presents the following advantages: (1) it allows substantial savings in the complexity of the set-up, thus reducing the time and effort necessary in preparing the input and increasing the robustness and the reliability of the calculated output; (2) It minimizes new model developments; and (3) It simplifies debugging.

The methodological framework of the island approach allows the calculation the LCAE for complex fuel cycle systems exactly, if (1) there is no time offset in the startup of the different islands within a system and (2) the financial lives are the same for all the power plants on the system's islands. Typically those conditions are satisfied or closely approximated. Alternatively, because of the typically long reactor's lifetimes, the "error" incurred because of different reactor's lifetimes is in the low-single percent digits.

A nuclear economic software tool, NE-COST, written in the commercial programming software MATLAB®, has been developed to calculate the LCAE of complex fuel cycles with the "island" computational approach. Other available tools to calculate the levelized cost of electricity, such as G4-ECONS, for example, had been developed for fuel cycles containing only one reactor, and of generally limited complexity.

An important design objective for NE-COST is to allow the calculation of the cost of electricity of arbitrarily complex nuclear systems by just changing the input, without the need to alter the model's programming. For this purpose, the general structure of the program has been developed with several alternative fuel cycle front-end and back-end paths, which the user can select through switches in the input.

NE-COST has also been developed with the capability to handle uncertainty: the input parameters (both unit costs and fuel cycle characteristics) can have uncertainty distributions associated with them, and the output can be computed in terms of probability density functions

of the LCAE. To improve the capability of the code to inform on nuclear fuel cycle economics, the results can be broken down into the several sub-components of the levelized cost of electricity. If correlation coefficients are available between uncertainty cost distributions, it is possible to incorporate those in the NE-COST calculations to obtain more informative comparisons of the cost of various fuel cycle alternatives, since the probability density functions of the cost differences will be narrower. The development of correlation coefficients between cost distributions is an area of current work.

In this paper the island methodology and NE-COST have been used to quantify, as examples, the economic performance of (1) current LWR once-through systems; (2) continuous Pu recycling in fast reactors with driver and blanket (FR); (3) Recycling of Pu bred in FR into LWR.

For each fuel cycle, the contributions to the total LCAE of the main cost components have been identified.

### **Acknowledgments**

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## Figures

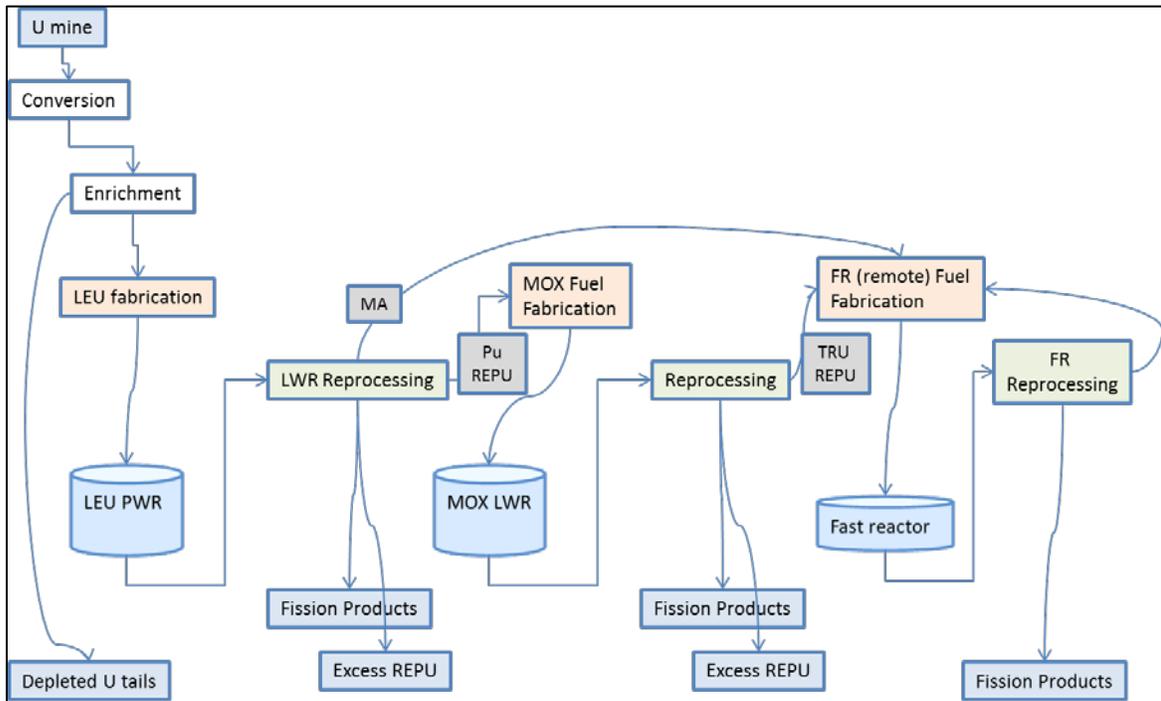


Fig. 1. Schematic of a 3-stage fuel cycle.

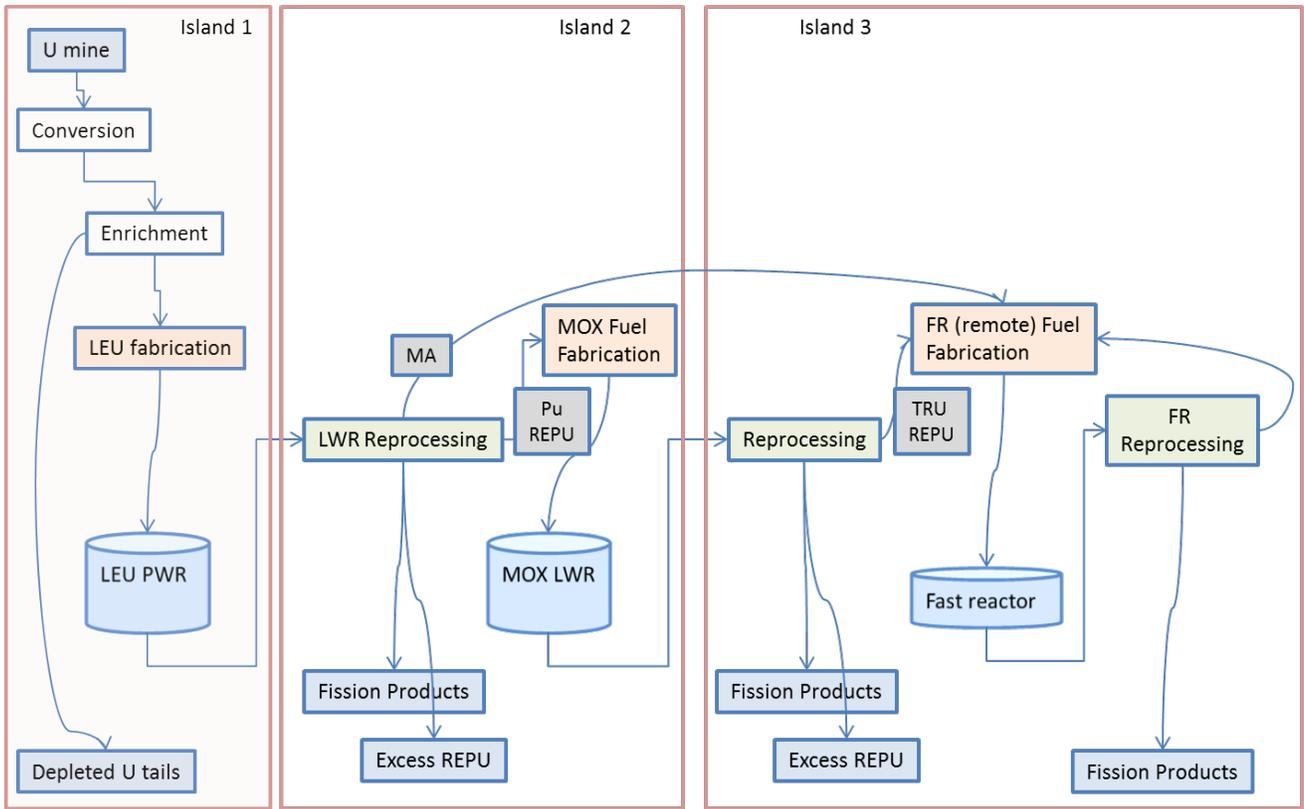
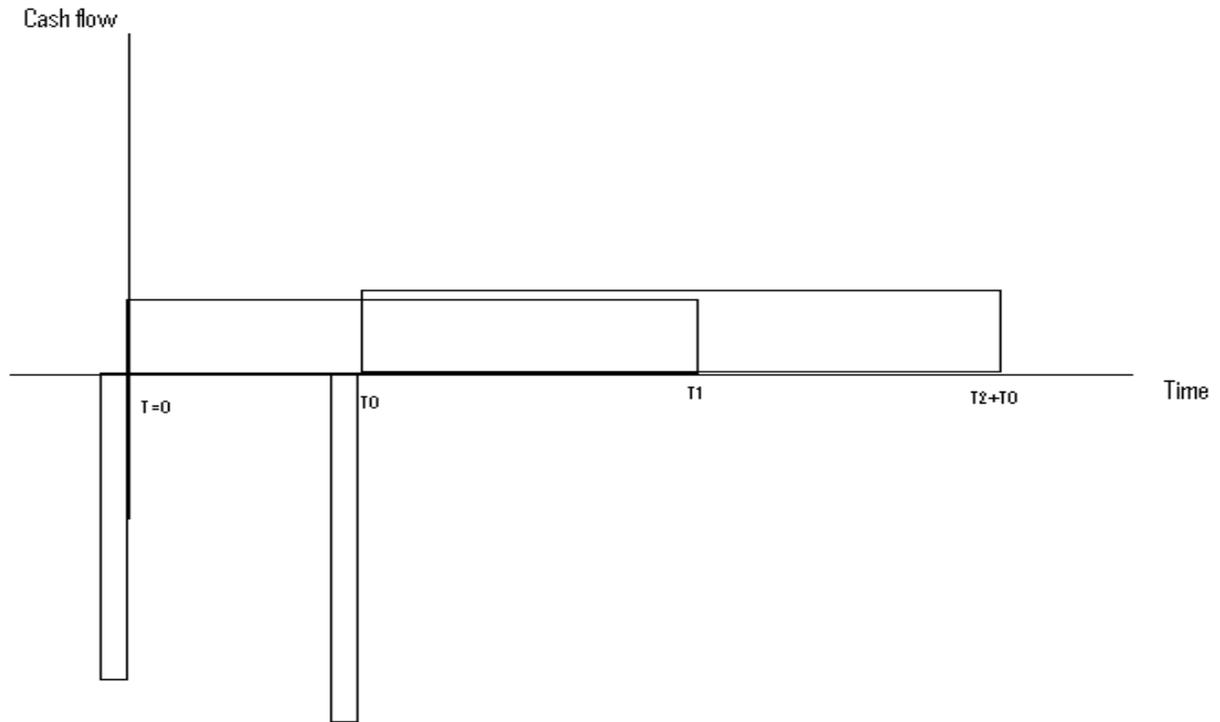


Fig. 2. Schematic of the 3-stage fuel cycle of Fig. 1 sub-divided into 3 islands.



*Fig. 3. Qualitative representation of the cash flow for two reactors on different islands, within the same fuel cycle, with a start-up time offset ( $T_0$ ).*

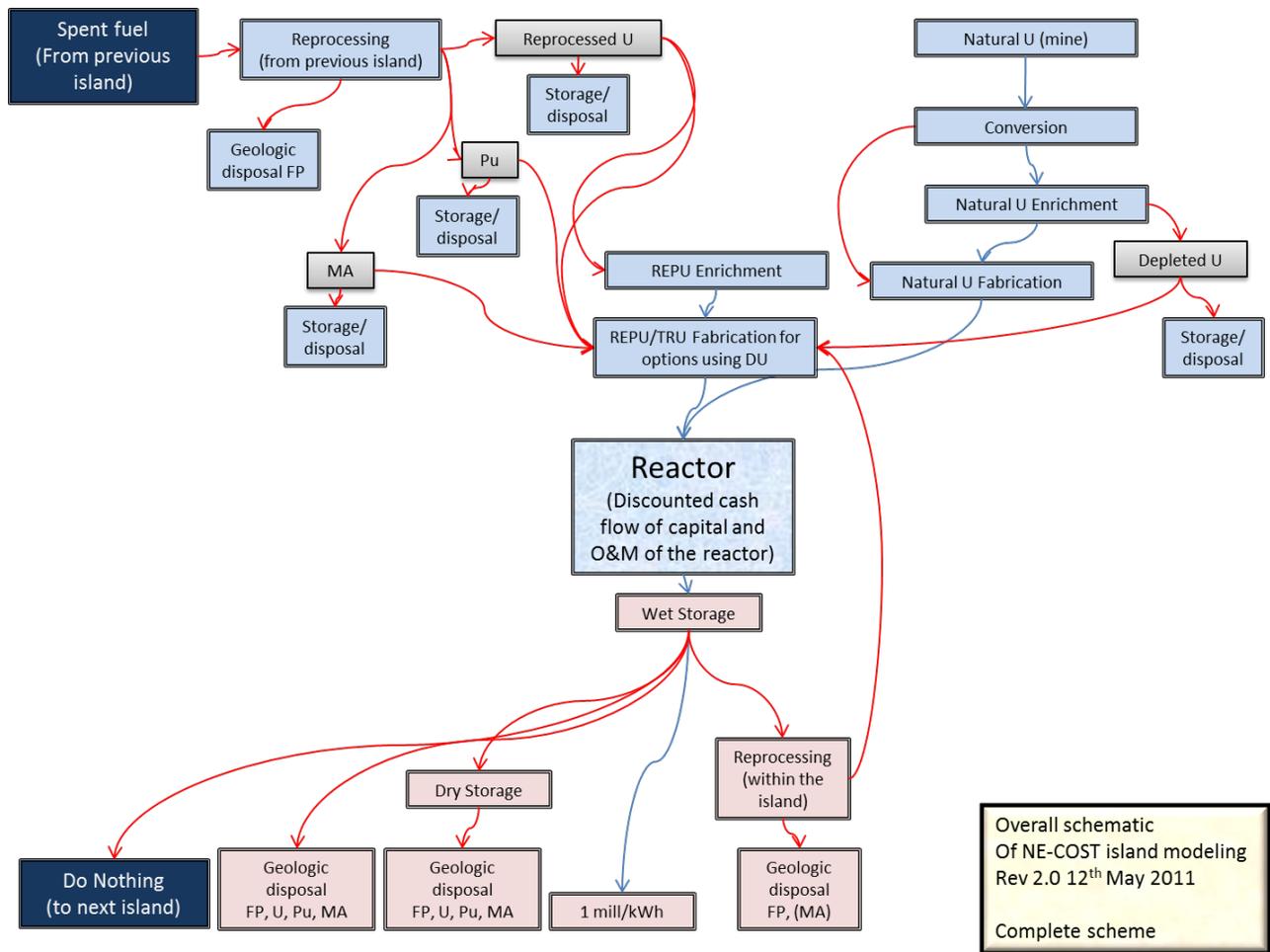


Fig. 4. Schematic representation of the NE-COST structure.

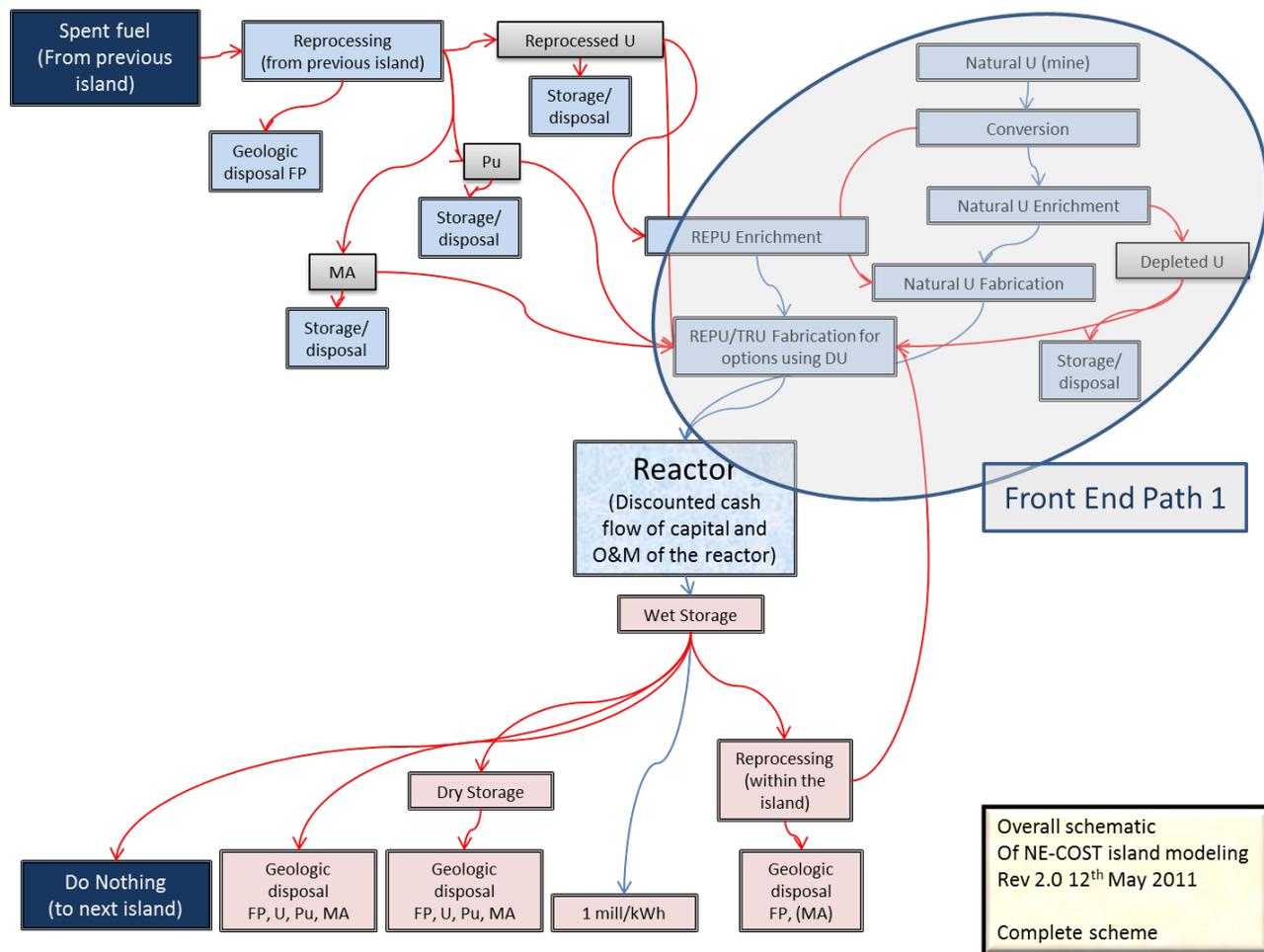


Fig. 5. Schematic representation of the NE-COST structure with front-end path 1 highlighted.

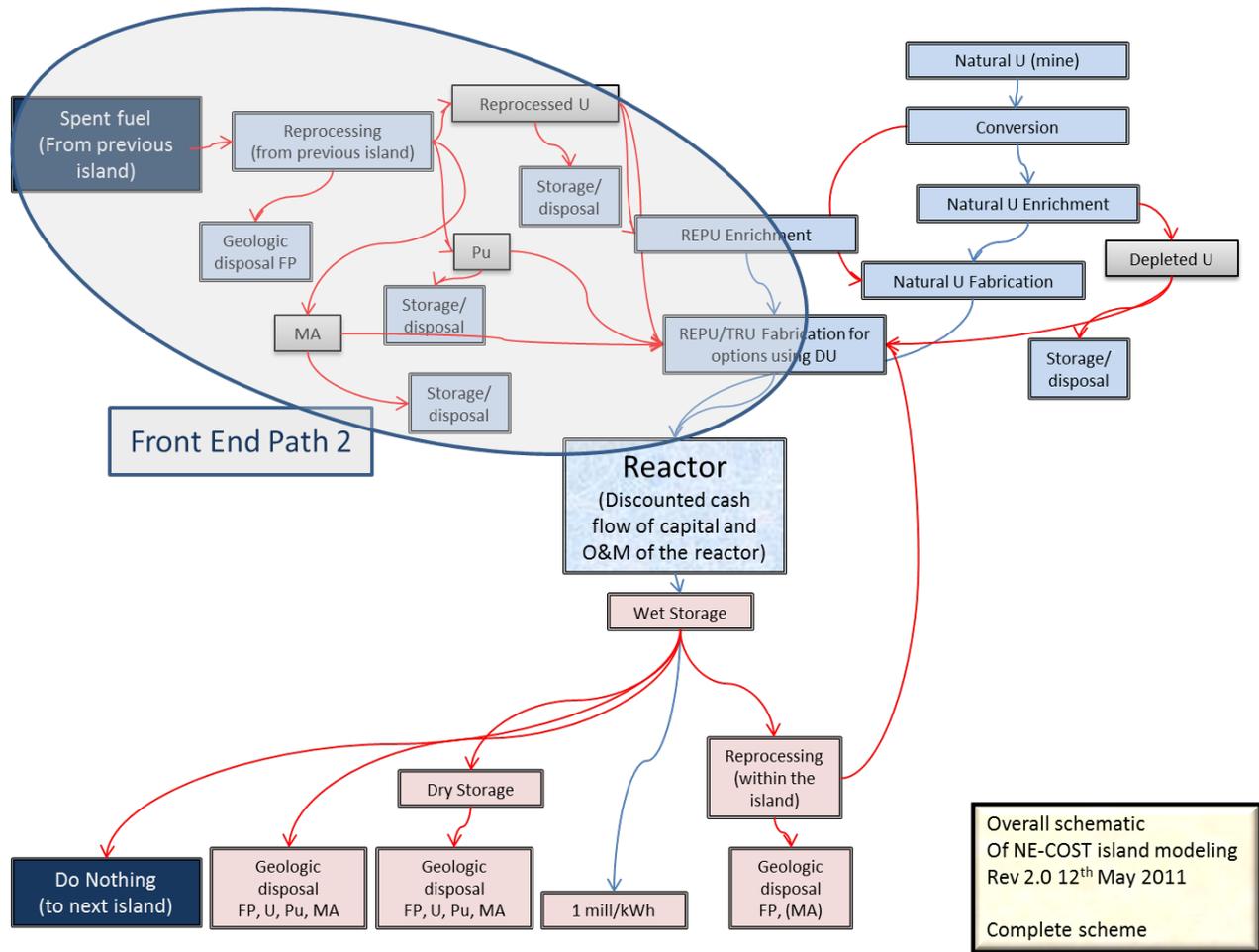


Fig. 6. Schematic representation of the NE-COST structure with front-end path 2 highlighted

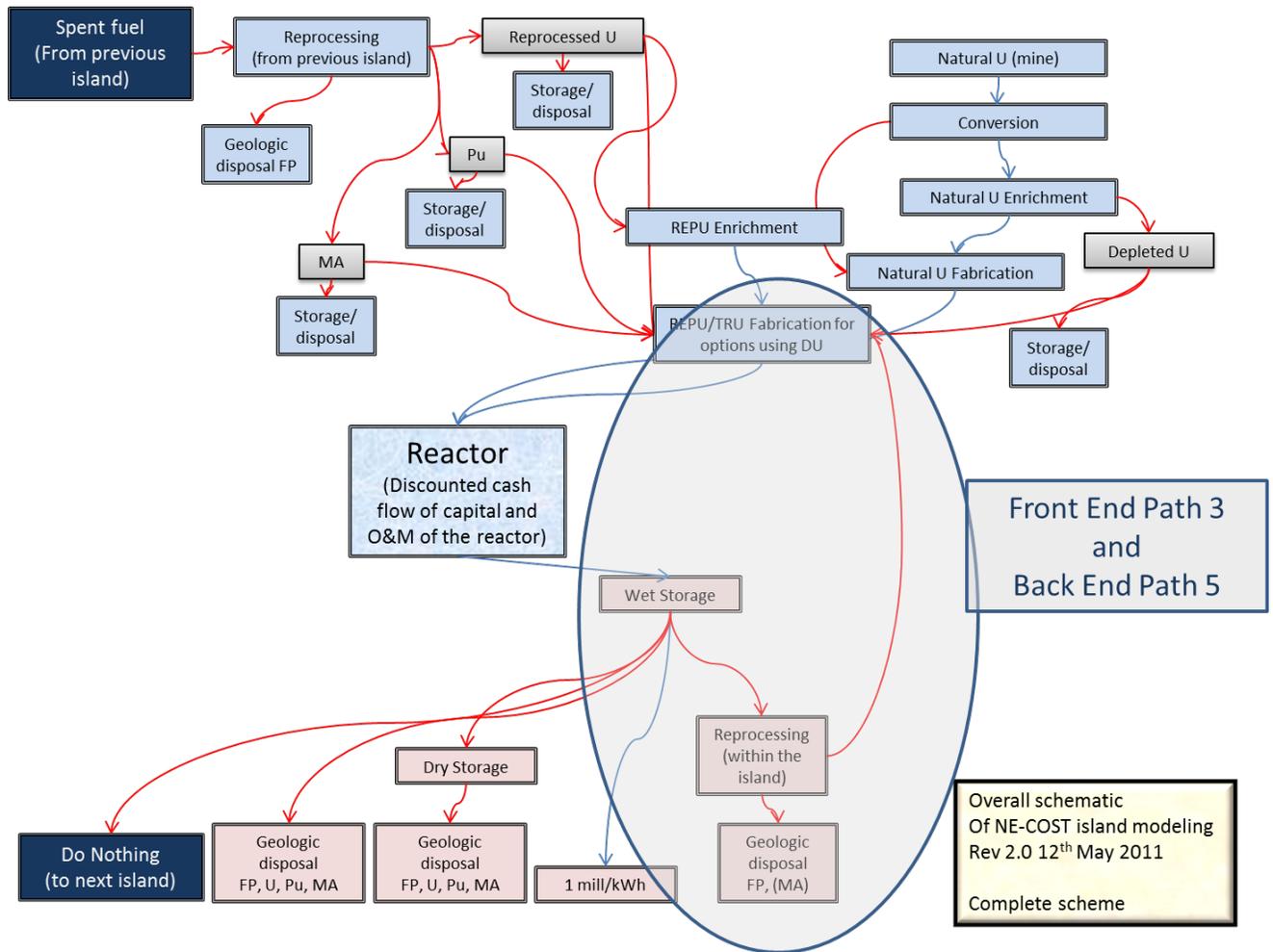
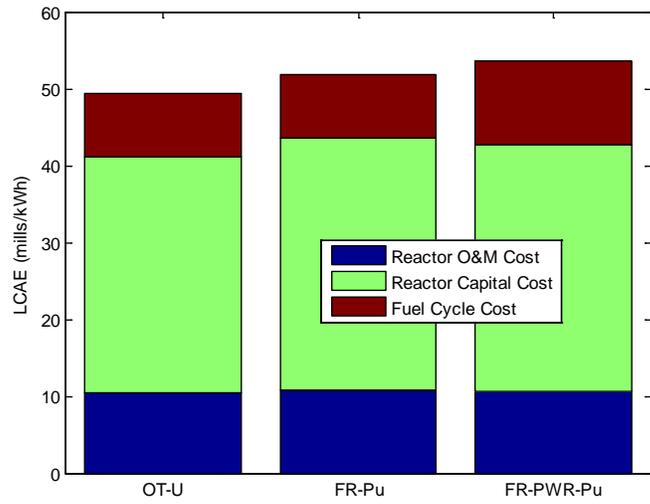
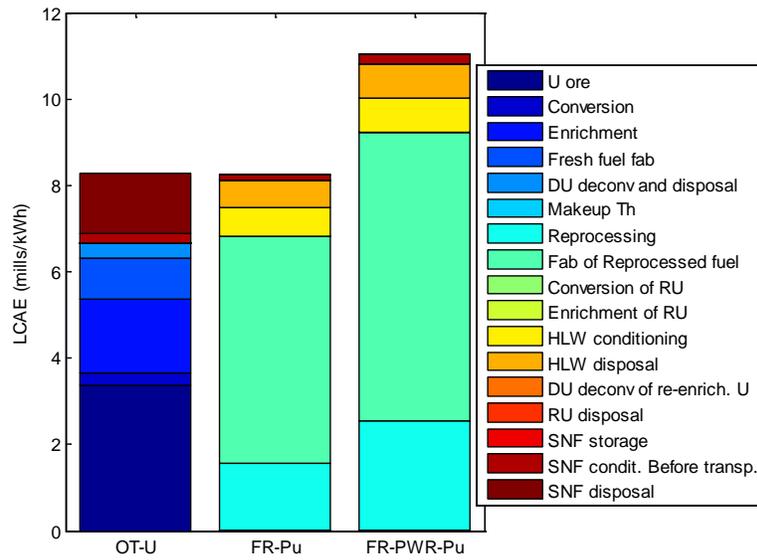


Fig. 7. Schematic representation of the NE-COST structure with front-end path 3 (which is also back-end path 5) highlighted.



*Fig 8. Comparison of the electricity cost breakdown for the 3 analyzed fuel cycles. Averages of the calculated values.*



*Fig 9. Comparison of the fuel cycle cost breakdown for the 3 analyzed fuel cycles. Averages of the calculated values.*

## Tables

*Table I*  
*Results of the benchmark for a once-through LWR between G4-ECONS and NE-COST.*

	G4-ECONS	NE-COST
Total Cost of Electricity	43.42	43.40
Cost of Capital (Including Financing)	26.68	26.48
Cost of reactor operation (O&M)	10.56	10.72
Fuel Cycle cost	6.14	6.19

*Table II*  
*Assumptions common to all three example cases.*

Discount rate	5%
Escalation rates for front-end, back-end and O&M costs	0%
Reactor construction time	5 years
Cost of capital during construction	5%
Lead times for uranium purchase, conversion, enrichment, fuel fabrication, uranium de-conversion, fuel reprocessing and re-fabrication	2 years before irradiation
Cost of uranium	135 \$/kg
Cost of SWU	95 \$/kgSWU (Dollars per kg of Separating Working Units)
Cost of uranium conversion	12 \$/kgU
Cost of depleted uranium de-conversion	6 \$/kgDU
Cost of de-converted DU disposal	9 \$/kgDU

*TABLE III*

*Comparison of the electricity cost breakdown for the 3 analyzed fuel cycles. Averages of the calculated values.*

<b>Costs (all in mills/kWh)</b>	OT-U	FR-Pu	FR-PWR-Pu
Reactor O&M Cost	10.5	10.8	10.7
Reactor Capital Cost	30.6	32.9	32.0
Fuel Cycle Cost	8.3	8.2	11.0
<b>Total</b>	<b>49.4</b>	<b>51.9</b>	<b>53.7</b>

**TABLE IV**

*Comparison of the fuel cycle cost breakdown for the 3 analyzed fuel cycles. Averages of the calculated values.*

<b>Costs (all in mills/kWh)</b>	<b>OT-U</b>	<b>FR-Pu</b>	<b>FR-PWR-Pu</b>
U ore	3.36	0.019	0.024
U Conversion	0.30	0	0
U Enrichment	1.72	0	0
Fresh fuel fabrication	0.94	0	0
DU deconversion	0.34	0	0
Makeup Th	0	0	0
Reprocessing	0	1.53	2.53
Fab of Reprocessed fuel	0	5.28	6.69
Conversion of RU	0	0	0
Enrichment of RU	0	0	0
HLW conditioning	0	0.64	0.78
HLW disposal	0	0.64	0.78
DU deconv of re-enrich. U	0	0	0
RU disposal	0	0	0
SNF storage	0	0	0
SNF condit. Before transp.	0.23	0.13	0.21
SNF disposal	1.41	0	0
<b>Total</b>	<b>8.3</b>	<b>8.2</b>	<b>11.0</b>