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A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling ☆,☆☆

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ABSTRACT

In this paper we show how the traditional definition of the levelized cost of electricity (LCOE) can be extended to alternative nuclear fuel cycles in which elements of the fuel are recycled. In particular, we define the LCOE for a cycle with full actinide recycling in fast reactors in which elements of the fuel are reused an indefinite number of times. To our knowledge, ours is the first LCOE formula for this cycle. Others have approached the task of evaluating this cycle using an 'equilibrium cost' concept that is different from a levelized cost. We also show how the LCOE implies a unique price for the recycled elements. This price reflects the ultimate cost of waste disposal postponed through the recycling, as well as other costs in the cycle. We demonstrate the methodology by estimating the LCOE for three classic nuclear fuel cycles: (i) the traditional Once-Through Cycle, (ii) a Twice-Through Cycle, and (iii) a Fast Reactor Recycle. Given our chosen input parameters, we show that the 'equilibrium cost' is typically larger than the levelized cost, and we explain why.

1. Introduction

In this paper we show how the traditional definition of the levelized cost of electricity (LCOE) can be extended to alternative nuclear fuel cycles in which elements of the fuel are recycled. In particular, we define the LCOE for a cycle with full actinide recycling in fast reactors in which elements of the fuel are reused an indefinite number of times. To our knowledge, ours is the first LCOE formula for this cycle. Others have approached the task of evaluating this cycle using an 'equilibrium cost' concept that is different from a levelized cost.

We demonstrate the methodology by estimating the LCOE for three classic nuclear fuel cycles:

- the traditional, Once-Through Cycle, in which the spent fuel is not recycled, but sent for disposal in a geologic repository,
- a Twice-Through Cycle, in which the plutonium and part of the uranium extracted from the spent fuel from the first pass in a light water reactor are used in a second pass through a light water reactor, after which the spent fuel is sent for disposal in a geologic repository, and
- a Fast Reactor Recycle system, in which the spent fuel from the first pass in a light water reactor is followed by a repeated recycling of all of the transuranics — plutonium plus the minor actinides — through a fast reactor.

We then contrast our LCOE in the Fast Reactor Recycle with the 'equilibrium cost', a calculation often found in the literature. Given our chosen input parameters, we show that the 'equilibrium cost' is typically larger than the levelized cost.

The LCOE for the Once-Through Cycle is usually implemented by calculating the stream of costs associated with a single reactor. Attempts to extend this calculation to systems with recycling usually involve separate calculations of the LCOE for the reactor burning fresh fuel and the LCOE for the reactor burning recycled fuel. Difficulty arises because each of the separate LCOEs requires as an input the price attributed to the recycled elements. How should that price be determined? In studies of the Twice-Through Cycle it is typically assumed that the price for the recycled plutonium is set by competition between reactors burning the fuel with recycled elements and reactors burning fresh fuel. Extending this solution to a Fast Reactor Recycle system is troublesome since the reactor burning the recycled fuel in turn sends its spent fuel for recycling, creating an infinite regression that appears to eliminate any firm foundation for determining the price of the recycled elements. To our knowledge,

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there are no studies of a fast reactor recycling system that confront the problem head-on and determines a price for the recycled elements. Instead, the problem is finessed by turning to the 'equilibrium cost' concept, which does not require determination of a price for the recycled elements. This equilibrium cost is different from a levelized cost, as we will show.

Our solution to the problem is to postpone discussion of separate LCOEs for the reactors in a cycle burning fuel fabricated exclusively from freshly mined uranium and reactors burning some recycled fuel. Instead, we start with a definition of the LCOE for the cycle as a whole, reflecting the full time profile of costs incurred as the fuel is originally used and repeatedly recycled. This definition is independent of any price one might determine for the recycled elements. Once the total LCOE is defined, one can decompose the profile of costs into separate costs for reactors using fresh fuel and reactors using recycled fuel by attributing a price to the recycled elements. There is a unique price for which the decomposed LCOEs match the LCOE for the cycle as a whole. Although we ultimately derive an LCOE for each reactor burning the fuel, this is a result and not the starting point. The unique price determined for the recycled elements is a property of the full LCOE for the cycle, and not something derived antecedent to calculating the LCOE.

Our contribution is a general methodological one that can be extended to many different nuclear fuel cycles involving recycling of some of the spent fuel elements. However, we develop the results through the analysis of three classic cycles which are similar to the cycles discussed in the MIT (2003) *Future of Nuclear Power* study with the labels "option 1", "option 2" and "option 3", respectively. To keep our focus on the economic methodology, we suppress some of the essential details about each cycle, including a comprehensive mass balance accounting. However, a complete description of each cycle can be found in Guerin and Kazimi (2009).

The Once-Through Cycle is similar to what is practiced in the US nuclear industry today. Fig. 1 shows a schematic of the cycle and its main components. However, the US has postponed implementing its geologic disposal plans in the face of political and technical disputes, leaving some uncertainty about what will eventually be done. In contrast, we model a definite cycle.

The Twice-Through Cycle we model is similar to the system used in France, up to the disposition of the spent fuel from the second pass. Fig. 2 shows a schematic of the two steps in the cycle and its main components. We assume that at the end of the first pass through a light water reactor, the PUREX process is used to separate the spent uranium oxide (UOX) fuel into three streams: uranium, plutonium and a waste stream containing the fission products, minor actinides and impurities. After a period of storage, the waste stream is sent for disposal in a geologic repository. The recovered uranium is used for fabrication of fresh UOX fuel, including reconversion and reenrichment. The recovered plutonium is used, together with depleted uranium, for fabrication of mixed oxide fuel (MOX) for reuse in a light water reactor. In France, the MOX fuel, once spent, is kept in interim storage pending future resolution of its disposition which may include further recycling. In the Twice-Through Cycle that we evaluate the spent MOX fuel is not recycled, but sent for disposal in a geologic repository.

The Fast Reactor Recycle system begins with a first pass of UOX fuel through the traditional light water reactor. At the end of this first pass, the TRUEX process is used to separate the spent UOX fuel into three streams: uranium, the transuranics, and a waste stream made up of the fission products together with impurities. After a period of storage, the waste stream is sent for disposal in a geologic repository. The uranium can be re-enriched and used for fabrication of fresh UOX fuel for reuse in a light water reactor. The transuranics are blended with depleted uranium to produce a metallic fuel for a fast reactor. The fast reactor can be designed to produce new fissile transuranics at a rate that exceeds or falls short of its rate of consumption by the neutron chain reaction, i.e. the fast reactors can operate as either a breeder or a burner, respectively. At the end of each pass through a fast reactor, pyroprocessing is used to separate the spent fuel into two streams: a mixture of uranium and transuranics, and a waste stream containing the fission products and impurities. After a period of storage, the waste stream is sent for disposal in a geologic repository. The mixture of uranium and transuranics can be refabricated into fresh fuel for another fast reactor. This process can then be repeated indefinitely. This cycle is not currently practiced at an industrial scale anywhere on the globe, although it is widely studied as a potentially valuable option for the future. Fig. 3 shows a schematic of the cycle with fuel first passing through a light water reactor and then beginning the repeated passes through fast reactors.

Our selected recycling systems are only two out of many, many possible systems for recycling portions of the fuel used in nuclear reactors. Our aim in this paper is to develop a general methodology that can be applied to any system with recycling. The two selected differ from one another in a key dimension so that it is useful to the exposition to examine them separately. The Twice-Through Cycle can be modeled with a finite time horizon, since we assume that the spent fuel from the second pass is treated as a waste and sent for geologic disposal. In contrast, the Fast Reactor Recycle must be modeled with an infinite time horizon since we assume that the spent fuel is continually reprocessed and some components are recycled. While the principle behind the levelized cost calculation will be the same in both cases, implementing it for the two different recycle cases is instructive. The formulas derived here will be easily adapted across any of the many systems within each category.

The problem of allocating costs in a complex production system is an old one, and the issues are addressed in general microeconomic texts, as well as in specialized volumes dedicated to cost allocation—see, for example, Young (1985) and Weil and Maher (2005). Electricity generation is replete with examples of the joint production of electricity and some other product. Cogeneration of electricity and steam is an obvious example. The production of electricity by incinerating waste is another example. If one wants to calculate a levelized cost of electricity, it is necessary to attribute some portion of the total production costs to the different products. In the case of cogeneration, some portion of the costs needs to be attributed to the steam and some to the electricity—see IEA/NEA (2010) and Verbruggen (1983). In the case of nuclear fuel recycling, the problem is one of assigning total system costs to electricity produced at various points in the fuel cycle. Some of the electricity is produced by burning fresh

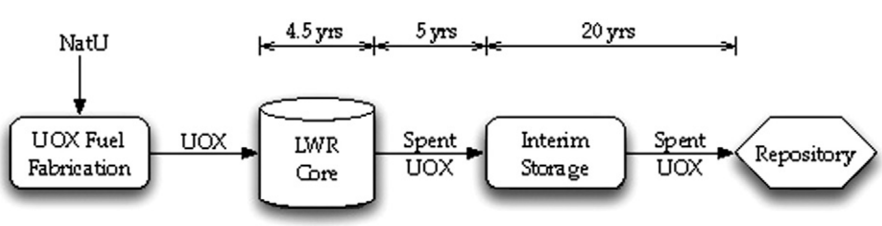

Fig. 1. The Once-Through Cycle. The cycle begins on the left with the production of natural uranium. Uranium oxide fuel (UOX) is fabricated. It is then burned in a light water reactor (LWR) core. The spent UOX is removed from the reactor and initially stored in a reactor pool. It is then removed for additional storage time above-ground in casks. Finally, the spent fuel is sent for disposal in a repository. Not shown is the depleted uranium produced as a byproduct/waste of the fabrication process.

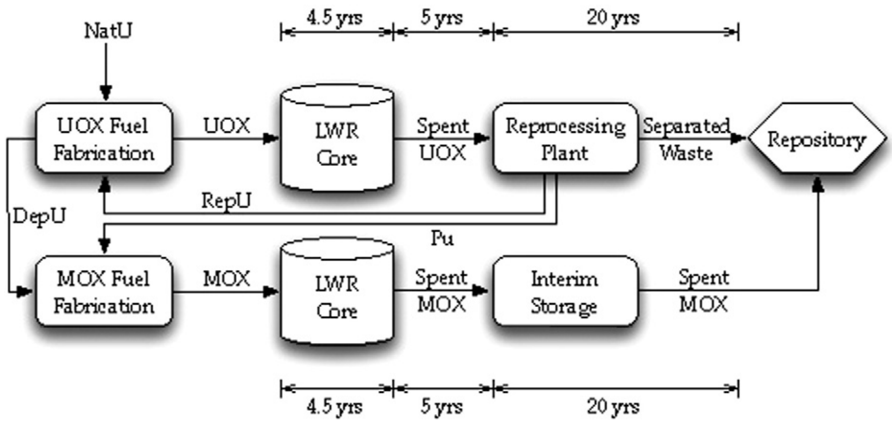

Fig. 2. The Twice-Through Cycle. The top portion of the figure shows the first cycle of fuel through a light water reactor (LWR). As in the Once-Through Cycle, it begins on the left with the production of natural uranium. Uranium oxide fuel (UOX) is fabricated. It is then burned in a light water reactor (LWR) core. The spent UOX is removed from the reactor and initially stored in a reactor pool. In this cycle, the spent fuel is sent to a reprocessing plant so that it can be separated into three streams: (i) reprocessed uranium, which can potentially be used to fabricate UOX fuel, (ii) plutonium, and (iii) the separated waste which consists of fission products and minor actinides. These wastes are sent for disposal in a repository. The bottom portion of the figure shows the second cycle of fuel through a light water reactor (LWR). This uses plutonium separated from the original spent fuel, as well as depleted uranium, to produce mixed oxide fuel (MOX). It is then burned in a light water reactor (LWR) core. The spent MOX is removed from the reactor and initially stored in a reactor pool. It is then removed for additional storage time aboveground in casks. Finally, the spent fuel is sent for disposal in a repository.

fuel, while some of the electricity is produced by burning recycled fuel. But the total costs incurred at each stage are determined by the decision to recycle fuel at all, and by the chosen recycling system. Therefore the total system costs must be allocated across electricity produced burning fresh and recycled fuel.

The next section develops the general methodology. In Section 3 we show how to implement the methodology given specific input values. The choice of input values is open to significant debate. Even for the Once-Through Cycle, which has, in part, been in operation in many countries for several decades, the correct parameter estimates are hotly contested. All the more uncertain and open to dispute will be the inputs for a prospective technology like the Fast Reactor Recycle. Our objective in executing the calculations is threefold. First, implementation often helps to clarify certain steps in a theoretical methodology. Second, we show that our proposed methodology is relatively easy to implement. Third, we use this implementation to help clarify the differences between the LCOE and the equilibrium cost. In this paper we are not concerned with defending the choice of input parameters, and we are not executing the calculation in order to advocate one cycle or another. A proper policy evaluation of the different cycles will need to consider the LCOE, but will also need to consider many other factors about each cycle that are omitted in this paper. By making possible an LCOE calculation for systems with recycling, we hope to contribute to future comprehensive policy analyses.

2. Defining levelized cost in a system with recycling

2.1. The levelized cost of electricity in the once-through fuel cycle

To calculate the LCOE, one first selects some appropriate scale of operations, which is most commonly a single nuclear reactor. The window of time, [*A*,*B*], encompasses the useful life of the reactor as well as the initial construction period and any time at the end of the

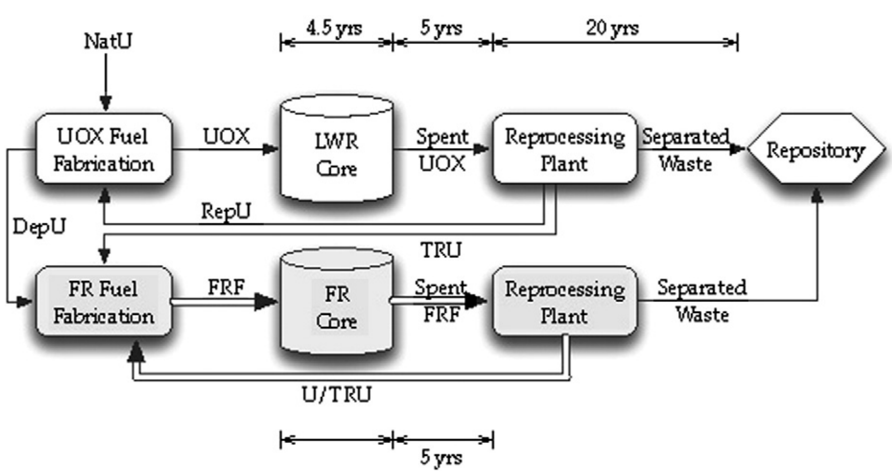

Fig. 3. The Fast Reactor Recycle. The top portion of the figure shows the first cycle of fuel through a light water reactor (LWR). As in the Once-Through Cycle, it begins on the left with the production of natural uranium. Uranium oxide fuel (UOX) is fabricated. It is then burned in a light water reactor (LWR) core. The spent UOX is removed from the reactor and initially stored in a reactor pool. In this cycle, the spent fuel is sent to a reprocessing plant so that it can be separated into three streams: (i) reprocessed uranium, which can potentially be used to fabricate UOX fuel, (ii) the transuranics (TRU), and (iii) the separated waste which consists of fission products. These wastes are sent for disposal in a repository. The bottom portion of the figure shows the second cycle of fuel through a fast reactor (FR). This uses the transuranics separated from the original spent fuel, as well as depleted uranium, to produce fast reactor fuel (FRF). It is then burned in a fast reactor core. The spent FRF is removed from the reactor and sent to another reprocessing plant so that it can be separated into two streams: (i) a mixture of the transuranics and uranium (U/TRU), and (ii) the separated waste which consists of fission products. These wastes are sent for disposal in a repository. The mixture of transuranics and uranium can be recycled again, fabricated once again into FRF with the addition of some depleted uranium, and sent to be burned in a FR core. This last portion of the cycle continues indefinitely, according to whether the Fast Reactor is a burner, sustaining or a breeder.

life necessary for dismantling operations. Let C_t denote the full set of realized costs at each date $t \in [A,B]$. The costs include all costs from the purchase of the raw ore, the fabrication of the fuel, construction and operation of the nuclear reactor, and the interim storage and final disposal of the spent fuel.[1] Let Q_t denote the time profile of electricity produced at each date $t \in [A,B]$. Finally, let R denote the continuously compounded discount rate. Then the levelized cost of electricity (LCOE) for the traditional, Once-Through Cycle is the usual formula:

$$\ell_1 = \frac{\int_A^B C_t e^{-Rt}\, dt}{\int_A^B Q_t e^{-Rt}\, dt}. \tag{1}$$

One thing to note about Eq. (1) is that the LCOE is defined independently of the costs of any other technology for producing electricity. Although easily overlooked, this proves to be an important feature to which we return later.

2.2. The levelized cost of electricity formula in the Twice-Through Cycle

The LCOE for the Twice-Through Cycle is similar to Eq. (1), except that we have to represent the costs incurred and electricity produced for both the first pass of fresh UOX fuel through a reactor (referred to as the "first" reactor) and the second pass of the recycled, MOX fuel through a reactor (referred to as the "second" reactor). So the numerator of the traditional formula will show two profiles of costs, and the denominator will show two profiles of electricity production. The subscript 1 denotes the first pass with fresh UOX fuel, while the subscript 2 denotes the second pass with recycled, MOX fuel. The window of time $[A_1,B_1]$ encompasses the electricity produced in the first reactor using the fresh UOX fuel, while the window of time $[A_2,B_2]$ encompasses the electricity produced in the second reactor using the recycled, MOX fuel. Correspondingly, C_{1t} denotes the full set of realized costs related to the electricity produced in the first reactor, C_{2t} denotes the full set of realized costs related to the electricity produced in the second reactor, and Q_{1t} denotes the time profile of electricity produced in the first reactor, while Q_{2t} denotes the time profile of electricity produced in the second reactor. Then the LCOE for the Twice-Through Cycle is given by:

$$\ell_2 = \frac{\int_{A_1}^{B_1} C_{1t}\ e^{-Rt}\ dt + \int_{A_2}^{B_2} C_{2t}\ e^{-Rt}\ dt}{\int_{A_1}^{B_1} Q_{1t}\ e^{-Rt}\ dt + \int_{A_2}^{B_2} Q_{2t}\ e^{-Rt}\ dt}. \tag{2}$$

The full set of realized costs will include the costs of reprocessing the fuel at the end of the first pass, including any storage costs, the costs of disposing of any separated waste stream that will not be passed along to the second reactor, the costs of fabricating the MOX fuel from the plutonium that is passed along from the first reactor to the second, and the cost of interim storage and final disposal of the spent MOX at the conclusion of the second pass. It is arbitrary whether the costs of reprocessing and MOX fuel fabrication are assigned to the first or to the second reactor, since the definition of the LCOE depends only upon the total costs for the complete pair of passes. We choose to assign these costs to the first reactor, but this does not impact any of the results, only the form in which they are presented.

There are two important things to note about Eq. (2). First, the LCOE is defined for the cycle as a whole. There are not two separate LCOEs, one for reactors using fresh UOX fuel and one for reactors using the recycled, MOX fuel. A fuel cycle with recycling is a single integrated technology. Costs incurred at any point in the cycle, must be levelized across the electricity produced throughout the full cycle. For example, the Twice-Through Cycle incurs a cost for geologic disposal of the spent MOX fuel at the end of the second cycle. As we shall see when it comes to parameterizing our formulas, this cost is very high. From the point of view of a levelized cost calculation, it makes no sense to allocate this cost only to the electricity produced by the reactor burning the recycled, MOX fuel. The need to incur the cost of disposing of spent MOX is determined by the decision to avoid disposing of the spent UOX from the first pass of the fuel and to instead recycle the fuel, and so this cost must be shared by the electricity produced in the first pass. This is equally true of the costs of reprocessing the spent fuel from the first pass and fabricating the recycled, MOX fuel. These are costs that must be shared across the electricity produced by both passes of the fuel.

Second, the equation does not include any explicit assessment of the value or price of the recovered plutonium passed from one reactor to another, since the cost to one reactor would be exactly cancelled out in the equation as a credit to the other reactor. The LCOE is defined independently of whatever price one might assign to the recovered plutonium.

2.2.1. The price of the recycled elements — plutonium

There is, however, one price that can be attributed to the plutonium such that we can calculate separate LCOEs for each pass of the fuel through a reactor which are equal to the LCOE for the cycle as a whole. This proves to be a convenient tool for discussing the LCOE and for thinking about the economics of the cycle.

Writing p as an arbitrary price for the plutonium and q for the quantity of plutonium separated out from the spent UOX fuel, Eq. (2) can be rewritten as:

$$\ell_2 = \frac{\int_{A_1}^{B_1} C_{1t}\ e^{-Rt}\ dt - qpe^{-RB_1} + qpe^{-RB_1} + \int_{A_2}^{B_2} C_{2t}\ e^{-Rt}\ dt}{\int_{A_1}^{B_1} Q_{1t}\ e^{-Rt}\ dt + \int_{A_2}^{B_2} Q_{2t}\ e^{-Rt}\ dt}. \tag{3}$$

We can use this price to decompose the levelized cost calculation for the cycle as a whole into separate levelized costs for each pass through a reactor:

$$\ell_{2,1}(p) = \frac{\left(\int_{A_1}^{B_1} C_{1t} e^{-Rt}\ dt - qp\ e^{-RB_1}\right)}{\int_{A_1}^{B_1} Q_{1t} e^{-Rt}\ dt}, \tag{4}$$

and,

$$\ell_{2,2}(p) = \frac{\left(qp\ e^{-RB_1} + \int_{A_2}^{B_2} C_{2t} e^{-Rt}\ dt\right)}{\int_{A_2}^{B_2} Q_{2t} e^{-Rt}\ dt}. \tag{5}$$

Of course, an arbitrary attributed value for the plutonium produces an arbitrary pair of LCOEs. Changing the value attributed to the plutonium leaves Eq. (3) unchanged, but changes Eqs. (4) and (5), and

[1] Throughout this paper we assume that all costs and prices are constant. This can be either in nominal terms, which then requires use of a nominal discount rate, or in real terms, which then requires use of a real discount rate. The formulas can be modified to account for real costs that evolve arbitrarily, but deterministically, although we do not show that here.

in general for an arbitrary price, p, we can expect that $\ell_{2,1}(p) \neq \ell_{2,2}(p)$ with either $\ell_{2,1}(p) > \ell_2 > \ell_{2,2}(p)$ or $\ell_{2,1}(p) < \ell_2 < \ell_{2,2}(p)$. We define by p^* the unique attributed value of plutonium such that the LCOE for each pass is the same as the LCOE calculated for the entire cycle:

$$\ell_2 = \ell_{2,1}(p^*) = \ell_{2,2}(p^*). \tag{6}$$

Studies of the Twice-Through Cycle have adopted a variant of this approach that avoids the simultaneous solution of the LCOE and the value of the recycled resource. This is done by valuing the separated plutonium as a substitute for fresh UOX fuel, and attempting to define the price in this fashion. In our notation, they begin by finding a $\hat{p}$ that solves $\ell_{2,2}(\hat{p}) = \ell_1$. They then define the LCOE of the Twice-Through Cycle as $\ell_2 \equiv \ell_{2,1}(\hat{p})$. This methodology is used in NEA (1985) and (1994), where $\hat{p}$ is called "the indifference value," and in Bunn et al. (2003) and (2005).[2] Note that in this methodology it will generally be the case that $\ell_{2,1}(\hat{p}) \neq \ell_{2,2}(\hat{p})$, which also implies that their derived LCOE for recycling will not match the LCOE definition provided in our Eq. (3). Moreover, using this methodology, it is impossible to define the LCOE of the recycling system independently of the LCOE for the Once-Through Cycle. This is odd. In every other mundane application of the LCOE methodology, the LCOE for a given technology is defined independently of the LCOE of any other technology, not on some relative basis.

2.3. The levelized cost of electricity formula for fast reactor recycling

2.3.1. A general formula

In recycling of spent fuel through fast reactors, the process of passing along a portion of the original fuel to the next reactor is repeated ad infinitum. A truly complete LCOE calculation requires a full accounting of the infinite chain of costs incurred as the packet of fuel moves from one reactor to the next. So the numerator of our formula will now show an infinite chain of profiles of costs, and the denominator will show an infinite chain of profiles of electricity production. Let subscript j index the passes through a reactor, with $j = 1$ referring to the initial pass through the light water reactor with fresh UOX fuel, and $j = 2,3,4\ldots$ referring to the subsequent passes through fast reactors using fast reactor fuel fabricated using recycled transuranics. The window of time $[A_j, B_j]$ encompasses the electricity produced in the jth pass through a reactor, C_{jt} denotes the full set of realized costs in pass j at date t, and Q_{jt} denotes the time profile of electricity produced in pass j at date t. Then the LCOE for the Fast Reactor Recycle is given by:

$$\ell_3 = \frac{\sum_{j=1}^{\infty} \left[\int_{A_j}^{B_j} C_{jt} e^{-Rt} \, dt \right]}{\sum_{j=1}^{\infty} \left[\int_{A_j}^{B_j} Q_{jt} e^{-Rt} \, dt \right]}. \tag{7}$$

A proper representation of the chain of costs in a full actinide recycling system is actually very complex. Each pass through a reactor changes the isotopic composition of the fuel. In particular, the vector of uranium and transuranic elements is changing with each pass, only gradually approaching an equilibrium vector. The isotopic composition determines the neutronic behavior which must be taken into account in fabricating the new fuel at each stage, changing the costs at each pass. A proper calculation of the levelized cost for the cycle as a whole must account for the complete profile of these changing costs through time, requiring a unique assessment of C_{jt} for each j.

[2] All of these sources assume away the differential cost of disposing of spent MOX fuel as compared to the cost of disposing of spent UOX fuel.

2.3.2. The price of the recycled elements — the transuranics

Once again, we note the two important features Eq. (7). First, the LCOE is defined for the cycle as a whole. There are not two separate LCOEs, one for light water reactors using fresh UOX fuel and one for fast reactors using the recycled fuel containing the transuranics. Second, the LCOE is defined independently of whatever value one might assign to the recovered transuranics.

Paralleling our earlier solution for an attributed price of plutonium, we now derive an attributed value for the transuranics passed from one cycle to another.[3] Remembering that in the more general version of the problem, the vector of transuranics passed along at each pass is varying, we write p_j as an arbitrary attributed price for the vector of transuranics separated out from pass j, and q_j for the corresponding quantity of transuranics. Then Eq. (7) which defines the LCOE, becomes:

$$\ell_3 = \frac{\int_{A_1}^{B_1} C_{1t} e^{-Rt} \, dt - q_1 p_1 \; e^{-RB_1} + \sum_{j=2}^{\infty} \left[q_{j-1} p_{j-1} \; e^{-RB_{j-1}} + \int_{A_j}^{B_j} C_{jt} e^{-Rt} \, dt - q_j p_j \; e^{-RB_j} \right]}{\sum_{j=1}^{\infty} \left[\int_{A_j}^{B_j} Q_{jt} e^{-Rt} \, dt \right]}. \tag{8}$$

Using this series of attributed prices for each vector of transuranics to decompose the levelized cost calculation into a sequence of individual levelized cost of electricity calculations for each component pass in the full cycle, we have:

$$\ell_{3,1}(p_1) = \frac{\left(\int_{A_1}^{B_1} C_{1t} e^{-Rt} \, dt - q_1 p_1 \; e^{-RB_1} \right)}{\int_{A_1}^{B_1} Q_{1t} e^{-Rt} \, dt}, \tag{9}$$

and,

$$\ell_{3,j}\left(p_{j-1}, p_j\right) = \frac{\left(q_{j-1} p_{j-1} \; e^{-RB_{j-1}} + \int_{A_j}^{B_j} C_{jt} e^{-Rt} \, dt - q_j p_j \; e^{-RB_j} \right)}{\int_{A_j}^{B_j} Q_{jt} e^{-Rt} \, dt}, \text{for } j = 2, 3, \ldots. \tag{10}$$

In general, for an arbitrary set of prices, p_j, we cannot expect that $\ell_3 = \ell_{3,1}(p_1) = \ell_{3,j}(p_{j-1}, p_j)$, for $j = 2,3,\ldots$ We define by $(p_1^*, p_2^*, \ldots, p_j^* \ldots)$ the unique vector of attributed prices of transuranics at each pass such that the LCOE for each pass is the same as the LCOE calculated for the entire cycle:

$$\ell_3 = \ell_{3,1}\left(p_1^*\right) = \ell_{3,j}\left(p_{j-1}^*, p_j^*\right), \text{for } j = 2, 3, \ldots. \tag{11}$$

The decomposition shown in Eqs. (9) and (10) and satisfying Eq. (11) is feasible under a minimal set of conditions. For example, let us assume that the mix of uranium and transuranics reaches its equilibrium after a finite number of steps, i, and that $\frac{q_{i+1}}{q_i} e^{-R(B_{i+1} - B_i)} < 1$.[4] Then, for $j > i$, the

[3] In fact, it is not really the transuranics that are exchanged from one step of the cycle to another, but more generally, a mix of transuranics and depleted uranium. Hence we should consider a price for the mix. But since at each step, the new fuel can be obtained by addition of depleted uranium or transuranics to the mix, we can show that the value of the mix is equal to the value of its separated elements. In our calculations, the price of depleted uranium is given as an input parameter. Therefore, we can extract and reason with a price for the transuranics alone.

[4] For example, a reactor with a fuel cycle length of 10 years and a discount rate of 7%, $\alpha < 1$ implies a transuranics mass ratio approximately less than 2, MR < 2.01. In practice, the highest conversion ratios and the corresponding mass ratios do not exceed 1.5.

vector of elements making up the right-hand-side of Eq. (9), $\left[\int_{A_j}^{B_j} Q_{jt}e^{-Rt}dt, -q_{j-1}e^{-RB_{j-1}}+q_je^{-RB_j}, \int_{A_j}^{B_j} C_{jt}e^{-Rt}dt\right]$, is proportional to the vector of elements making up the right-hand-side for the equilibrium cycle, i, $\left[\int_{A_{i+1}}^{B_{i+1}} Q_{i+1,t}e^{-Rt}dt, -q_ie^{-RB_i}+q_{i+1}e^{-RB_{i+1}}, \int_{A_{i+1}}^{B_{i+1}} C_{i+1,t}e^{-Rt}dt\right]$, which means that Eq. (10) requires $p_i^*=p_j^*$, for $j>i$. For $j\le i$, solving for transuranics prices can be represented as the solution to the following set of equations shown in matrix form:

$$\begin{bmatrix} \int_{A_1}^{B_1} Q_{1t}e^{-Rt}\,dt & q_1e^{-RB_1} & 0 & 0 \\ \vdots & \ddots & \ddots & 0 \\ \int_{A_i}^{B_i} Q_{it}e^{-Rt}\,dt & 0 & -q_{i-1}e^{-RB_{i-1}} & q_ie^{-RB_i} \\ \int_{A_{i+1}}^{B_{i+1}} Q_{i+1t}e^{-Rt}\,dt & 0 & 0 & -q_ie^{-RB_i}+q_{i+1}e^{-RB_{i+1}} \end{bmatrix} \begin{bmatrix} \ell_3 \\ p_1^* \\ \vdots \\ p_i^* \end{bmatrix} = \begin{bmatrix} \int_{A_1}^{B_1} C_{1t}e^{-Rt}\,dt \\ \vdots \\ \int_{A_i}^{B_i} C_{it}e^{-Rt}\,dt \\ \int_{A_{i+1}}^{B_{i+1}} C_{i+1t}e^{-Rt}\,dt \end{bmatrix}. \tag{12}$$

Since all quantities, costs and production are strictly positive, the matrix is invertible and there exists one unique solution for the set of prices attributable to the set of transuranic vectors passed at each cycle.

2.3.3. A simplified set of formulas

The levelized cost formula in Eq. (7) can be greatly simplified if we assume that the vector of transuranics is constant through all of the fast reactor cycles, as if the equilibrium vector were reached at the extraction of the transuranics from the light water reactor. We can then assume that all of the various costs at each fast reactor cycle scale according to the transuranics mass ratio, q_2/q_1, which measures the quantity of the transuranics exiting the cycle relative to the quantity entering the cycle. This ratio is linked to but different from the conversion ratio by which fast reactors are usually labeled.[5] Under this constant transuranics vector assumption, the present value of the costs at each successive pass through a fast reactor is a simple scaling of the costs at the previous pass in a fast reactor, with the scaling factor being $\alpha=\frac{q_2}{q_1}e^{-R(B_2-B_1)}$. Consequently, the infinite chain of distinct cost calculations can be reduced to one involving only two cycles with different cost elements:

$$\ell_3=\frac{\int_{A_1}^{B_1} C_{1t}e^{-Rt}\,dt+\sum_{j=2}^{\infty}\alpha^{j-2}\left(\int_{A_2}^{B_2} C_{2t}e^{-Rt}\,dt\right)}{\int_{A_1}^{B_1} Q_{1t}e^{-Rt}\,dt+\sum_{j=2}^{\infty}\alpha^{j-2}\left(\int_{A_2}^{B_2} Q_{2t}e^{-Rt}\,dt\right)}.$$

[5] The conversion ratio is the ratio of the rate of production of new fissile transuranics to the rate of fissile transuranics consumption by the neutron chain reaction. At equilibrium, if the transuranics mass ratio is equal to one, then the conversion ratio is also equal to one. Around this point, the two ratios move together, with the conversion ratio having greater amplitude than the transuranics mass ratio.

For most cycles under consideration today one will have $\alpha<1$.[6] In that case, the sums in the numerator and denominator are finite and this equation collapses to,

$$\ell_3=\frac{\int_{A_1}^{B_1} C_{1t}e^{-Rt}\,dt+\frac{1}{1-\alpha}\int_{A_2}^{B_2} C_{2t}e^{-Rt}\,dt}{\int_{A_1}^{B_1} Q_{1t}e^{-Rt}\,dt+\frac{1}{1-\alpha}\int_{A_2}^{B_2} Q_{2t}e^{-Rt}\,dt}. \tag{13}$$

Given the smaller impact of variations in isotopes on the neutronic spectrum at high energy, and the large uncertainties involved in estimating major elements of the total cost for the recycle technology, the approximation of a stable transuranics vector seems reasonable.

Attributing a value to the separated transuranics through the decomposition of the LCOE can then also be done in this simpler case. Rewriting Eq. (13) with our arbitrary price attributed to the single vector of transuranics, p, passed from one cycle to the next, we have:

$$\ell_3=\frac{\left[\int_{A_1}^{B_1} C_{1t}e^{-Rt}\,dt-q_1p\;e^{-RB_1}+\frac{1}{1-\alpha}\left(q_1pe^{-RB_1}+\int_{A_2}^{B_2} C_{2t}e^{-Rt}\,dt-\alpha q_1pe^{-RB_1}\right)\right]}{\left[\int_{A_1}^{B_1} Q_{1t}e^{-Rt}\,dt+\frac{1}{1-\alpha}\int_{A_2}^{B_2} Q_{2t}e^{-Rt}\,dt\right]}. \tag{14}$$

This is decomposed into a LCOE for the initial pass—through a light water reactor—and a LCOE for the succeeding passes—through a fast reactor:

$$\ell_{3,L}(p)=\frac{\left(\int_{A_1}^{B_1} C_{1t}e^{-Rt}\,dt-q_1p\;e^{-RB_1}\right)}{\int_{A_1}^{B_1} Q_{1t}e^{-Rt}\,dt}, \tag{15}$$

$$\ell_{3,F}(p)=\frac{\left(q_1p\;e^{-RB_1}+\int_{A_2}^{B_2} C_{2t}e^{-Rt}\,dt-\alpha\;q_1pe^{-RB_1}\right)}{\int_{A_2}^{B_2} Q_{2t}e^{-Rt}\,dt}. \tag{16}$$

Define by p^* the unique attributed value of the transuranics such that the LCOE for each pass is the same as the LCOE calculated for the entire cycle:

$$\ell_3=\ell_{3,L}(p^*)=\ell_{3,F}(p^*). \tag{17}$$

3. Implementation

We now implement these calculations starting from a set of assumptions on the relevant input parameters necessary for each fuel cycle. The purpose here is to illustrate how to use the general formulas, rather than defending specific input values or recommending one cycle over another. As noted in the introduction, there is enormous uncertainty surrounding many of the key inputs.

The main parameter assumptions we make are displayed in Table 1. All figures are denominated in 2007 dollars. The complete details for the calculations can be found in De Roo and Parsons

[6] We understand that there are cycles that have been proposed with a fast reactor fuel cycle length as long as 5 years. With a discount rate of 7%, the requirement that $\alpha<1$ would imply MR<1.42, and this constraint would begin to be restrictive.

Table 1
Input parameter assumptions.

Front-end Fuel Costs			
[1]	Natural uranium	\$/kgHM	80
[2]	Depleted uranium	\$/kgHM	10
[3]	Conversion of natural U	\$/kgHM	10
[4]	Enrichment of natural U	\$/SWU	160
[5]	Fabrication of UOX from natural U	\$/kgHM	250
[6]	Conversion of repr. U, (prem. to natural)		200%
[7]	Enrichment of repr. U, (prem. to natural)		10%
[8]	Fabrication of UOX from repr U, (prem. to natural)		7%
[9]	Fabrication of MOX	\$/kgHM	2,400
[10]	Fabrication of FR fuel	\$/kgHM	2,400
Reactor Costs			
[11]	LWR capital cost (overnight)	\$/kWe	4,000
[12]	LWR capacity Factor		85%
[13]	FR capital cost (premium to LWR)		20%
[14]	FR O&M cost (premium to LWR)		20%
[15]	FR capacity Factor		85%
Reprocessing cost			
[16]	UOX, PUREX	\$/kgHM	4,000
[17]	UOX, UREX+ or TRUEX	\$/kgHM	1
[18]	FR fuel, pyroprocessing	\$/kgHM	0
			0.2
Waste Costs			0.85
[19]	Interim storage of UOX	\$/kgiHM	200
[20]	Interim storage of MOX	\$/kgiHM	200
[21]	Disposal of spent UOX	\$/kgiHM	470
[22]	Disposal of spent MOX	\$/kgiHM	3,130
[23]	Disposal of HLW from UOX (PUREX)	\$/kgiHM	190
		d. factor	2.5
		\$/kgFP	3,650
[24]	Disposal of HLW from UOX (TRUEX)	\$/kgiHM	190
[25]	Disposal of HLW from FR	\$/kgiHM	280
[26]	Discount Rate (real)		7.6%

Notes:
Figures are in 2007 dollars.
[16]–[18] Reprocessing costs are inclusive of storage, transportation and vitrification.
[21]–[25] Disposal costs are inclusive of transportation and packaging and are quoted as paid at time of unloading, which is five years before being sent to interim storage.
[21] Equal to the 1 mill/kWh statutory fee given our burn-up assumptions. Approximately equal to the 1 mill/kWh statutory fee given our burn-up assumptions and our discount rate.
[22] = [21]/0.15. The 0.15 densification factor applied is based on BCG (2006) figures; approx. equal to [C − 21]/[C − 22]. Discrepancy arises due to addition of transportation costs after accounting for the densification factor.
[23] = [24].
[24] = [21]/2.5. The 2.5 densification factor applied is based on Shropshire et al. (2006) and (2009).
[25] = ([24]/5.146%)*7.8%. I.e., cost is based on the cost of disposal of the HLW from TRUEX measured per kg fission products, multiplied times the quantity of fission products in the fast reactor spent fuel.
[26] 7.6% is the annually compounded rate, r. The equivalent continuously compounded rate, R, is R = LN(1 + r) = 7.3%.

(2009).[7] We report here the portions that are most valuable in clarifying the meaning of our LCOE definitions and in comparing the LCOEs across fuel cycles.

3.1. The Once-Through Cycle

We write the levelized cost of electricity in Eq. (1) as the sum of four components:

$$\ell_1 = f_1 + k_1 + m_1 + d_1, \tag{18}$$

where f_1 is the levelized cost (per kWh) associated with the front-end of the fuel cycle, including the raw ore, conversion, enrichment and fabrication, k_1 is the levelized capital charge for the light water reactor, m_1 is the levelized operating and maintenance charge for the light water reactor, and d_1 is the levelized cost associated with the back-end of the fuel cycle, i.e., disposal, including any above-ground storage and final geologic sequestration. Each charge is calculated to be sufficient, in present value terms, to cover the actual respective cash flows for each activity at the time the cash flow is incurred. For later comparison purposes, it will be useful to write the front-end cost as the sum of the cost of raw uranium, u_1, and the sum of the enrichment, conversion, and fabrication costs, b_1, with

$$f_1 = u_1 + b_1. \tag{19}$$

Given the inputs we have selected and our technological assumptions, we find that the cost of the raw uranium is $u_1 = 2.76$ mill/kWh, and the sum of the enrichment, conversion, and fabrication costs is $b_1 = 4.35$ mill/kWh, so that $f_1 = u_1 + b_1 = 7.11$ mill/kWh. Following Du and Parsons (2009) for the overnight capital cost, the capital charge per unit of electricity is given by $k_1 = 67.68$ mill/kWh. Our operating and maintenance cost schedule gives us $m_1 = 7.72$ mill/kWh. Our LCOE is a busbar cost and so does not include the costs of transmission and distribution required to bring the electricity to the customer. We assume that the spent UOX fuel is stored first in a cooling pond for 5 years, but the cost for this storage is generally included in the reactor capital and operating cost figures, and so this charge is not separately itemized here. We assume a system will include some period of above-ground storage in dry casks and ultimate disposal in a geologic repository similar in cost to Yucca Mountain as currently designed. This gives us $d_1 = 1.30$ mill/kWh.

Pulling together these results into one equation, we have that the LCOE for the Once-Through Cycle is:

$$\begin{aligned}\ell_1 &= f_1 + k_1 + m_1 + d_1\\ &= 7.11 + 67.68 + 7.72 + 1.30\\ &= 83.81\,\text{mill / kWh}.\end{aligned}$$

Table 2 lists these results. Fig. 4 graphs the LCOE with a breakdown into four categories, (i) capital cost, k_1, (ii) operating and maintenance costs, m_1, (iii) front-end fuel cycle cost, and (iv) back-end fuel cycle cost. The largest component is the capital cost which accounts for 81% of the total LCOE. O&M costs account for 9%. The total fuel cycle cost contribution is 10%, made up of 8% from the front-end and 2% from the back-end.

3.2. The Twice-Through Cycle

We write the two levelized costs in Eq. (4) and (5) as the sum of the same four components used in the Once-Through Cycle:

$$\ell_{2,1}(p) = f_{2,1} + k_{2,1} + m_{2,1} + d_{2,1}(p), \tag{20}$$

$$\ell_{2,2}(p) = f_{2,2}(p) + k_{2,2} + m_{2,2} + d_{2,2}, \tag{21}$$

where, by definition, $f_{2,1} = f_1$, $k_{2,1} = k_1$ and $m_{2,1} = m_1$. We also assume that $k_{2,2} = k_{2,1}$ and $m_{2,2} = m_{2,1}$, although in general this need not be the case. The cost of disposal for the first reactor in the Twice-Through Cycle is, in turn, composed of four elements:

$$d_{2,1}(p) = s_{2,1} + w_{2,1} - u_{2,1B} - z_{2,1}(p), \tag{22}$$

where $s_{2,1}$ is the levelized reprocessing cost, $w_{2,1}$ is the levelized cost of disposal of the separated high level waste stream, $u_{2,1B}$ is the levelized credit for the recovered reprocessed uranium, and $z_{2,1}$ is the levelized attributed value of the separated plutonium. Similarly, the front-end fuel costs for the second reactor is composed of three elements, the cost of purchasing the plutonium, the cost of purchasing

[7] A spreadsheet containing the detailed calculations is available on the web for download at http://web.mit.edu/ceepr/www/publications/workingpapers/DeRooParsons_spreadsheet.xls.

Table 2
LCOE for alternative fuel cycles, by components, and the implied price of plutonium or the implied price of transuranics.

		Once-Through Cycle (mill/kWh) [A]			Twice-Through Cycle (mill/kWh) [B]			Fast Reactor Recycle (mill/kWh) [C]		
[1]	Raw uranium	u_1	2.76		$u_{2,1A}$	2.76		$u_{3,LA}$	2.76	
[2]	Fabrication	b_1	4.35		$b_{2,1}$	4.35		$b_{3,L}$	4.35	
[3]	Front-end fuel cycle	f_1		7.11	$f_{2,1}$		7.11	$f_{3,L}$		7.11
[4]	Capital charge	k_1		67.68	$k_{2,1}$		67.68	$k_{3,L}$		67.68
[5]	O&M costs (non-fuel)	m_1		7.72	$m_{2,1}$		7.72	$m_{3,L}$		7.72
[6]	Reprocessing				$s_{2,1}$	2.36		$s_{3,L}$	2.36	
[7]	HLW disposal				$w_{2,1}$	0.40		$w_{3,L}$	0.40	
[8]	Reprocessed uranium				$-u_{2,1B}$	−0.14		$-u_{3,LB}$	−0.14	
[9]	Plutonium/TRUs				$-z_{2,1}$	0.25		$-z_{3,L}$	1.43	
[10]	Disposal cost	d_1		1.30	$d_{2,1}$		2.87	$d_{3,L}$		4.06
[11]	LCOE total	ℓ_1		83.81	$\ell_{2,1}$		85.38	$\ell_{3,L}$		86.57
[12]	Depleted uranium				$u_{2,2}$	0.03		$u_{3,FA}$	0.02	
[13]	Plutonium/TRUs				$z_{2,2}$	−4.39		$z_{3,F}$	−19.72	
[14]	Fabrication				$b_{2,2}$	7.38		$b_{3,F}$	4.05	
[15]	Front-end fuel cycle				$f_{2,2}$		3.02	$f_{3,F}$		−15.66
[16]	Capital charge				$k_{2,2}$		67.68	$k_{3,F}$		81.22
[17]	O&M costs (non-fuel)				$m_{2,2}$		7.72	$m_{3,F}$		9.26
[18]	Reprocessing							$s_{3,F}$	2.66	
[19]	HLW disposal							$w_{3,F}$	0.34	
[20]	Depleted uranium							$u_{3,FB}$	−0.01	
[21]	TRUs							$-\alpha\, z_{3,F}$	8.75	
[22]	Disposal cost				$d_{2,2}$		6.96	$d_{3,F}$		11.74
[23]	LCOE total				$\ell_{2,2}$		85.38	$\ell_{3,F}$		86.57
[24]	Price of plutonium, $/kgHM				p^*	−15,734				
[25]	Price of TRU, $/kgHM							p^*	−80,974	

Notes:
[A].
[3] = [1] + [2].
[11] = [3] + [4] + [5] + [10].
[B].
[3] = [1] + [2].
[10] = [6] + [7] + [8] + [9].
[11] = [3] + [4] + [5] + [10].
[14] = [12] + [13].
[23] = [15] + [16] + [17] + [22].
[24] chosen to set [23] = [11].
[C] The conversion ratio = 1.
[3] = [1] + [2].
[10] = [6] + [7] + [8] + [9].
[11] = [3] + [4] + [5] + [10].
[14] = [12] + [13].
[22] = [18] + [19] + [20] + [21].
[23] = [15] + [16] + [17] + [22].
[25] chosen to set [23] = [11].

the depleted uranium and the cost of fabricating the MOX fuel, respectively:

$$f_{2,2}(p) = u_{2,2} + z_{2,2}(p) + b_{2,2}. \tag{23}$$

The back-end cost of the second reactor, $d_{2,2}$, does not depend on the value of separated plutonium, but is equal to the levelized interim storage and the disposal costs for spent MOX fuel.

We now turn to inputting the respective values for the variables. For the first reactor we have the following. The cost of reprocessing is $s_{2,1} = 2.36$ mill/kWh. Our cost for the waste stream from reprocessed light water reactor spent fuel is $w_{2,1} = 0.40$ mill/kWh. The value of the reprocessed uranium recovered is $u_{2,1B} = 0.14$ mill/kWh. Finally, 1 kg of spent UOX leads to the separation of 0.011 kg of plutonium, so that $z_{2,1}(p) = 1.57 \times 10^{-5}\, p$ mill/kWh, where the price of plutonium, p, is denominated in $/kgHM. So Eq. (19) becomes:

$$\ell_{2,1}(p) = 7.11 + 67.68 + 7.72 + \left(2.36 + 0.40 - 0.14 - 1.57 \times 10^{-5} p\right).$$

For the second reactor we have the following. The cost of purchasing depleted uranium is $u_{2,2} = 0.03$ mill/kWh. The cost of purchasing the plutonium (from the first pass), is $z_{2,2}(p) = 2.79 \times 10^{-4}\, p$ mill/kWh. The cost of MOX fabrication is $b_{2,2} = 7.38$ mill/kWh. The back-end cost reflects the cost of storage and geologic disposal of the MOX which are $d_{2,2} = 6.96$ mill/kWh.[8] So Eq. (21) becomes:

$$\ell_{2,2}(p) = \left(0.03 + 2.79 \times 10^{-4} p + 7.38\right) + 67.68 + 7.72 + 6.96.$$

[8] Note that the value of the recovered plutonium from the first reactor must equal the value of the plutonium input to the second reactor, when measured in absolute dollars. However, in Eqs. (22) and (23) the terms $z_{2,1}(p)$ and $z_{2,2}(p)$ report these respective values measured per unit of electricity produced during the fuel's occupation of the respective cores, and so $z_{2,1}(p) \neq z_{2,2}(p)$. Instead, we have:

$$z_{2,2}(p) \,/\, z_{2,1}(p) = \int_{A_1}^{B_1} Q_{1t}\, e^{-Rt}\, dt \,/\, \int_{A_2}^{B_2} Q_{2t}\, e^{-Rt}\, dt.$$

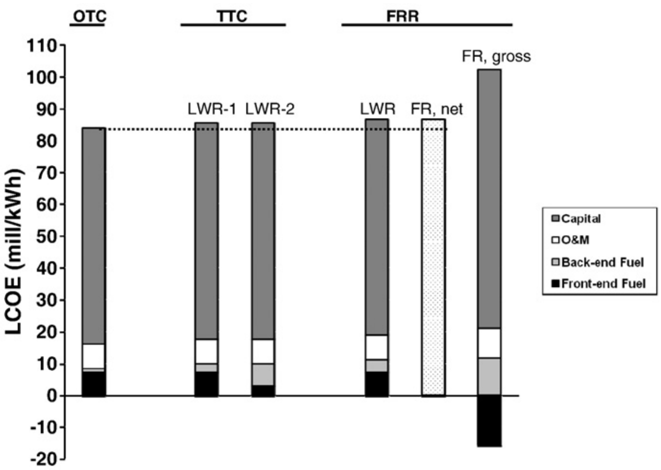

Fig. 4. LCOEs for alternative cycles, by component. The graph displays the LCOE figures from Table 2. The first bar shows the LCOE, by component, for the Once-Through Cycle. The second and third bars show the two LCOEs for the Twice-Through Cycle: the left-hand bar is the LCOE for the first pass reactor, while the right-hand bar is the LCOE for the second pass reactor. The fourth, fifth and sixth bars show the LCOEs for the Fast Reactor Recycle: the left-hand bar is the LCOE for the light water reactor, while the center and right-hand bar show the LCOE for a fast reactor. The total fuel cycle cost for the fast reactor is negative, so that the total LCOE is less than the sum of the reactor capital and O&M costs. The center bar shows the total or net cost. The right-hand bar shows each cost component, with the capital, O&M and back-end fuel cycle costs being positive and the front-end fuel cycle cost being negative.

Now, using the condition expressed in Eq. (6) which defines the unique attributed value of the plutonium, p^*, as the value for which these two LCOEs are equal to one another, we obtain that $p^* = -15{,}734$ \$/kgHM. Substituting this into our earlier expressions gives us $z_{2,1}(p^*) = -0.25$ mill/kWh, $d_{2,1}(p^*) = 2.87$ mill/kWh, $z_{2,2}(p^*) = -4.39$ mill/kWh, and, $f_{2,2}(p^*) = 3.02$ mill/kWh. Then, Eqs. (20) and (21) give,

$$\ell_2 = \ell_{2,1}(p^*) = \ell_{2,2}(p^*) = 85.38\,\text{mill / kWh}.$$

Table 2 lists these results. Fig. 4 shows the LCOE for this Twice-Through Cycle with a breakdown into the four categories. The figure shows two separate bars for the cycle. The first bar in the pair is the breakdown of costs for the first reactor in the cycle, and the second bar is the breakdown for the second reactor in the cycle. For the first reactor, the capital cost accounts for 79% of the total LCOE, while O&M costs account for 9%. The total fuel cycle cost contribution is 12%, made up of 8% from the front-end and 3% from the back-end. For the second reactor, the fraction accounted for by the capital and O&M costs is the same as for the first reactor. The total fuel cycle cost contribution is 12%, made up of 4% from the front-end and 8% from the back-end.

There is no a priori constraint on the sign of the price of the recovered plutonium. It may be positive or negative. If it is positive, then the recovered plutonium is an asset for which the second reactor is willing to pay money. If it is negative, then the recovered plutonium is a liability and the second reactor has to be compensated for accepting it. The payment made to the second reactor is the first reactor's contribution to the ultimate disposal cost. For example, increasing the cost of MOX disposal drives down the plutonium price, increasing the amount the first reactor must pay. Although the second reactor is the point of payment for the cost of disposing of the spent MOX, the cost of disposal should be understood to be borne by both reactors.[9]

3.3. The Fast Reactor Recycle

We write the two levelized costs in Eqs. (15) and (16) as the sum of the same four components:

$$\ell_{3,L}(p) = f_{3,L} + k_{3,L} + m_{3,L} + d_{3,L}(p), \tag{24}$$

$$\ell_{3,F}(p) = f_{3,F}(p) + k_{3,F} + m_{3,F} + d_{3,F}(p). \tag{25}$$

In our Fast Reactor Recycle, the initial pass through the light water reactor is the same as in the Once-Through Cycle, up to disposal. Therefore, $f_{3,L} = f_1$, $k_{3,L} = k_1$ and $m_{3,L} = m_1$. In the Fast Reactor Recycle, $d_{3,L}$ has four components:

$$d_{3,L}(p) = s_{3,L} + w_{3,L} - u_{3,L} - z_{3,L}(p), \tag{26}$$

where $s_{3,L}$ is the levelized cost of reprocessing, $w_{3,L}$ is the levelized cost of disposing of the high level wastes, $u_{3,L}$ is the levelized value of the reprocessed uranium recovered from the light water reactor spent fuel, and $z_{3,L}(p)$ is the levelized value of the separated transuranics. In the Fast Reactor Recycle, the front-end fuel costs for the fast reactor is the sum of the cost of the depleted uranium required, the cost of the transuranics, and the cost of fabrication:

$$f_{3,F}(p) = u_{3,FA} + z_{3,F}(p) + b_{3,F}. \tag{27}$$

where $u_{3,FA}$ is the levelized value of the depleted uranium contained in the fast reactor fuel, $z_{3,F}(p)$ is the levelized value of the transuranics contained in the fast reactor fuel, and $b_{3,F}$ is the cost of fabricating the fast reactor fuel. The cost of disposing of the spent fuel from the fast reactor is:

$$d_{3,F}(p) = s_{3,F} + w_{3,F} - u_{3,FB} - \alpha z_{3,F}(p), \tag{28}$$

[9] BCG (2006) evaluate the Twice-Through Cycle by comparing exclusively the disposal costs of the first reactor in the Twice-Through Cycle against the disposal cost for the reactor in the Once-Through Cycle: $d_{2,1}(p)$ vs. d_1. Since $f_{2,1} = f_1$, $k_{2,1} = k_1$, and $m_{2,1} = m_1$, it follows that $\ell_{21}(p) - \ell_1 = d_{2,1}(p) - d_1$, i.e. the difference in levelized costs equals the difference in disposal costs so that their focus is locally similar to ours. The uncommon step in their methodology is to avoid making a definitive decision about the ultimate disposition of the spent MOX fuel, and the corresponding cost. They argue that the spent MOX fuel will not be sent to a geologic repository since that cost is too high, and they suggest several recycling strategies. However, they never cost any of these strategies fully. Therefore, they never directly define an expected cost for the contingent disposition of the spent MOX fuel. This would seem to pose an insurmountable hurdle in arriving at a definite LCOE for the cycle, leaving a key parameter input, $d_{2,2}$, undefined. Their solution is to assign a cost of managing the spent MOX fuel that is equal to the cost of managing the spent UOX fuel, i.e., $d_{2,2}(p) = d_{2,1}(p)$. There is little foundation for setting the cost of managing the spent MOX fuel this way. It does not account for the disposal of the ultimate streams of waste coming from spent MOX recycling. Absent more detailed investigation of the possible scenarios, setting $d_{2,2}(p) = d_{2,1}(p)$ is just a bald assumption. De Roo (2009) provides a rigorous option-theoretic analysis of the contingent value of the spent MOX held in storage, and finds savings compared to traditional deterministic valuations, albeit not enough to make MOX more attractive than interim storage.

Table 3
LCOEs for the fast reactor recycle with different conversion ratios.

			CR = 0.5 (mill/kWh) [A]		CR = 1 (mill/kWh) [B]		CR = 1.2 (mill/kWh) [C]	
[1]	Raw uranium	$u_{3,LA}$	2.76		2.76		2.76	
[2]	Fabrication	$b_{3,L}$	4.35		4.35		4.35	
[3]	Front-end fuel cycle	$f_{3,L}$		7.11		7.11		7.11
[4]	Capital charge	$k_{3,L}$		67.68		67.68		67.68
[5]	O&M costs (non-fuel)	$m_{3,L}$		7.72		7.72		7.72
[6]	Reprocessing	$s_{3,L}$	2.36		2.36		2.36	
[7]	HLW Disposal	$w_{3,L}$	0.40		0.40		0.40	
[8]	Reprocessed Uranium	$-u_{3,LB}$	0.14		0.14		0.14	
[9]	TRUs	$-z_{3,L}$	−0.73		−1.43		−1.78	
[10]	Disposal cost	$d_{3,L}$		3.35		4.06		4.40
[11]	LCOE total	$\ell_{3,L}$		85.86		86.57		86.91
[12]	Depleted Uranium	$u_{3,FA}$	0.01		0.02		0.02	
[13]	TRUs	$z_{3,F}$	−13.32		−19.72		−22.60	
[14]	Fabrication	$b_{3,F}$	2.25		4.05		5.83	
[15]	Front-end fuel cycle	$f_{3,F}$		−11.07		−15.66		−16.74
[16]	Capital charge	$k_{3,F}$		81.22		81.22		81.22
[17]	O&M costs (non-fuel)	$m_{3,F}$		9.26		9.26		9.26
[18]	Reprocessing	$s_{3,F}$	1.45		2.66		3.20	
[19]	HLW Disposal	$w_{3,F}$	0.34		0.34		0.29	
[20]	Depleted Uranium	$u_{3,FB}$	0.00		0.01		0.01	
[21]	TRUs	$-\alpha\, z_{3,F}$	−4.67		−8.75		−9.69	
[22]	Disposal cost	$d_{3,F}$		6.45		11.74		13.17
[23]	LCOE total	$\ell_{3,F}$		85.86		86.57		86.91
[24]	Price of TRU, $/kgHM	p^*	−41,100		−80,974		−100,534	

Notes:
All input parameters for column [B] are as shown in Table 1. The notes below discuss the adjustments that must be accounted for as the conversion ratio is changed, moving from column [B] to either column [A] or column [C].
As the CR increases, the burnup per kgHM decreases. We have 132, 73 and 55 MWd/kgHM for CR = 0.5, 1 and 1.23, respectively. We keep the cost of fabrication and reprocessing, measured in $/kgHM, constant. Consequently, the cost measured in $/kWh will increase as the CR increases. Arguably, the higher CR means a lower TRU concentration in the fuel and therefore a possibly lower fabrication cost measured in $/kgHM.
As the CR increases, the cycle length also increases. The average residence time in the reactor is 4.4, 4.2 and 6.7 for CR = 0.5, 1 and 1.23, respectively. One consequence of these residence times is that although the ratio of burnup to fission products is fairly constant, the timing of the realization of the disposal cost varies. This explains line [20] above.
We keep the cost of disposal of the separated waste from the fast reactor fuel constant in $/kgFP. This means a varying cost when measured in $/kgHM of initial heavy metal.

where $u_{3,FB}$ is the levelized price of depleted uranium recovered from the fast reactor spent fuel and $z_{3,F}(p)$ is the levelized value of the separated transuranics.

For the initial pass through the light water reactor, the total cost of disposal is composed of the cost of TRUEX reprocessing which produces the separated streams, the cost of disposal for the high level waste stream, and the value attributed to the stream of separated transuranics and uranium. The cost of reprocessing is, $s_{3,L} = 2.36$ mill/kWh. Our cost for disposing of the waste stream from reprocessed light water reactor spent fuel is $w_{3,L} = 0.40$ mill/kWh. The value of the reprocessed uranium recovered is $u_{3,LB} = 0.14$ mill/kWh. Finally, the value of the separated transuranics, as a function of the attributed price, is $z_{3,L}(p) = 1.77 \times 10^{-5}\ p$ mill/kWh, where the price of transuranics, p, is denominated in $/kgHM. So Eq. (24) becomes

$$\ell_{3,L}(p) = 7.11 + 67.68 + 7.72 + \left(2.36 + 0.40 - 0.14 - 1.77 \times 10^{-5} p\right).$$

For the subsequent passes through the fast reactors, the cost of purchasing the depleted uranium is $u_{3,FA} = 0.02$ mill/kWh. The cost of the transuranics is $z_{3,F}(p) = 2.44 \times 10^{-4}\ p$ mill/kWh, and the cost of fabricating the fast reactor fuel is $b_{3,F} = 4.05$ mill/kWh. We have $k_{3,F} = 81.22$ mill/kWh, and $m_{3,F} = 9.26$ mill/kWh. The cost of reprocessing spent fuel from the fast reactors using pyroprocessing is $s_{3,F} = 2.66$ mill/kWh. The cost of disposing of the waste from reprocessing spent fast reactor fuel based on the 7.8% fission products it contains, is $w_{3,F} = 0.34$ mill/kWh. The credit for the depleted uranium in the spent fast reactor fuel is $u_{3,FB} = 0.01$ mill/kWh. Finally, the credit for the recovered transuranics in the spent fast reactor fuel is $\alpha\ z_{3,F}(p) = 1.08 \times 10^{-4}\ p$ mill/kWh. So Eq. (25) becomes

$$\ell_{3,F}(p) = \left(0.02 + 2.44 \times 10^{-4} p^* + 4.05\right) + 81.22 + 9.26 + \left(2.66 + 0.34 - 0.01 - 1.08 \times 10^{-4} p\right).$$

The attributed price of the transuranics, p, is the free parameter that allows us to set the two LCOEs in Eqs. (24) and (25) equal to one another so as to satisfy equation (17).[10] We find that $p^* = -80{,}974$ $/kgHM, so that finally $z_{3,L}(p^*) = -1.43$ mill/kWh, $d_{3,L}(p^*) = 4.06$ mill/kWh, $z_{3,F}(p^*) = -19.72$ mill/kWh, $f_{3,F}(p^*) = -15.66$ mill/kWh, $\alpha z_{3,F}(p^*) = -8.75$ mill/kWh, and, $d_{3,F}(p^*) = 11.74$ mill/kWh.

Inserting these values back into Eqs. (24) and (25) gives,

$$\ell_3 = \ell_{3,L}(p^*) = \ell_{3,F}(p^*) = 86.57\ \text{mill/kWh}.$$

Table 2 lists these results. Fig. 4 shows the LCOE for this Fast Reactor Recycle with a breakdown into the four categories. The figure shows

[10] The price of reprocessed uranium is determined by the price of raw uranium, also assumed constant through time, and the relative cost of producing uranium-oxide fuel from raw or from reprocessed uranium. This enters into the calculation of the levelized cost, but is derived explicitly beforehand. It is independent of the levelized cost of either component of the cycle, and need not be solved for implicitly by equating the two levelized costs.

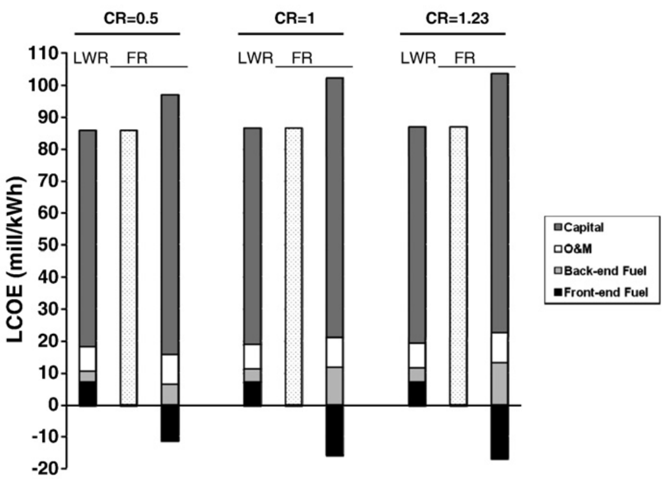

Fig. 5. LCOEs in a Fast Reactor Recycle for alternative conversion ratios. The displays 3 bars graph the LCOE figures from Table 3. In each set of three bars, the left-hand bar in each set of three is the LCOE for the light water reactor, while the center and right-hand bar show the LCOE for a fast reactor. The total fuel cycle cost for the fast reactor is negative, so that the total LCOE is less than the sum of the reactor capital and O&M costs. The center bar in each set of three shows the total or net cost. The right-hand bar in each set of three shows each cost component, with the capital, O&M and back-end fuel cycle costs being positive and the front-end fuel cycle cost being negative.

Table 4
Increase in LCOE relative to the Once-Through Cycle.

Twice-Through Cycle	
[1] mills/kWh, $\ell_2-\ell_1$	1.58
[2] % of total LCOE in OTC, ℓ_1	1.9%
[3] % of total fuel cycle costs in OTC, f_1+d_1	19%
[4] % of back-end fuel cycle costs in OTC, d_1	122%
Fast Reactor Recycle	
Burner, CR = 0.5	
[5] mills/kWh, $\ell_3-\ell_1$	2.06
[6] % of total LCOE in OTC, ℓ_1	2.5%
[7] % of total fuel cycle costs in OTC, f_1+d_1	24%
[8] % of back-end fuel cycle costs in OTC, d_1	159%
Self-sustaining, CR = 1	
[9] mills/kWh, $\ell_3-\ell_1$	2.76
[10] % of total LCOE in OTC, ℓ_1	3.3%
[11] % of total fuel cycle costs in OTC, f_1+d_1	33%
[12] % of back-end fuel cycle costs in OTC, d_1	213%
Breeder, CR = 1.23	
[13] mills/kWh, $\ell_3-\ell_1$	3.11
[14] % of total LCOE in OTC, ℓ_1	3.7%
[15] % of total fuel cycle costs in OTC, f_1+d_1	37%
[16] % of back-end fuel cycle costs in OTC, d_1	240%

three separate bars for the cycle. The first bar in the triple is the breakdown of costs for the light water reactor in the cycle. The second bar is the total cost for the fast reactor in the cycle. The third bar shows the breakdown of the fast reactor costs into the four categories. Note that the front-end fuel cycle costs are negative, so that the sum of the other three categories total more than the net cost of the cycle. For the light water reactor, the capital cost accounts for 78% of the total LCOE, while O&M costs account for 9%. The total fuel cycle cost contribution is 13%, made up of 8% from the front-end and 5% from the back-end. For a fast reactor, the capital cost accounts for 94% of the total LCOE, while O&M costs account for 11%. The total fuel cycle cost contribution is −5%, made up of −18% from the front-end and 14% from the back-end.

As with the previous cycle, there is no a priori constraint on the sign of the price of the recovered transuranics. If it is positive, then the separated transuranics are an asset for which the fast reactor is willing to pay money. If it is negative, then the separated transuranics are a liability and the fast reactor has to be compensated for accepting them.

To this point, the Fast Reactor Recycle system that we studied used a conversion ratio of 1. We repeated our calculations for a burner system with a conversion ratio of 0.5 and for a breeder system with a conversion ratio of 1.23. For each system some adjustments need to be made in some of the input parameters, especially those relating to the fabrication of the fuel and the cost of disposal of high level wastes, as well as changes to the cycle lengths. The LCOE's for all three Fast Reactor Recycle systems are shown together in Table 3. The results are also shown in Fig. 5. The notes to Table 3 discuss changes to the input parameters. The lower the conversion ratio, the lower the transuranics mass ratio, the lower the LCOE. The burner system with a conversion ratio of 0.5 has a LCOE of 85.86 mill/kWh, which is less than a 1 mill/kWh improvement over the 86.57 mill/kWh for the system with a conversion ratio of 1. The breeder system with a conversion ratio of 1.23 has a LCOE of 86.91 mill/kWh, which is less than a 1 mill/kWh more expensive than the 86.57 mill/kWh for the system with a conversion ratio of 1.

3.4. The relative LCOE across fuel cycles

Given our parameter selections, recycling increases the total LCOE, regardless of which form of recycling is used. Table 4 shows these results. The LCOE for the Twice-Through Cycle is 1.58 mill/kWh greater than the LCOE for the Once-Through Cycle, a 1.9% increase. Relative to just the fuel cycle costs in the Once-Through Cycle, which are 8.40 mill/kWh, this is a 19% increase. Relative to the cost of disposal, which is 1.30 mill/kWh, this is a 122% increase. The LCOE for the Fast Reactor Recycle is 2.76 mill/kWh greater than the LCOE for the Once-Through Cycle, a 3.3% increase. Relative to just the fuel cycle costs in the Once-Through Cycle, this is a 33% increase. Relative to the cost of disposal, this is a 213% increase.

What does recycling do to the portion of the LCOE that is the fuel cycle? This seems like a straightforward question, but on examination the issues are more troublesome than first supposed, and such a simple comparison is likely to be uninformative at best and misleading at worst. In the Once-Through Cycle, the sum of the front- and back-end fuel cycle costs is 8.40 mill/kWh. In the Twice-Through Cycle, this sum is 9.98 mill/kWh. In the Fast Reactor Recycle, this cost depends upon which reactor we are examining. For the light water reactor, the sum of the front- and back-end fuel cycle costs is 11.16 mill/kWh. For the fast reactor, the sum is −3.92 mill/kWh. The fast reactor apparently has a negative fuel cycle cost! This is due to the high value paid by the light water reactor to the fast reactor for taking its wastes, its transuranics. This upfront payment more than compensates the fast reactor for the high costs of fuel fabrication and the ultimate charge it must pay for passing along its own wastes, its own transuranics. But by focusing only on the cost components that are somewhat arbitrarily grouped together as the fuel-cycle components, we overlook a key cost of the fuel cycle which is the high capital and operating costs for the fast reactor itself. The fast reactor in this system is operating like a sort of "waste incinerator". Some of the high capital costs of the fast reactor are being charged back to the light water reactor as a price for disposing of the light water reactor's wastes. These capital costs are, in an economic sense, part of the fuel cycle costs. This highlights the caution with which a comparison of any subset of the cost components across fuel cycles should be made.

3.5. The negative value to transuranics

In the Twice-Through Cycle, the price of plutonium we derive is negative. In the Fast Reactor Recycle, the price of the transuranics is negative. This has implications for the feasible commercial organization of a system with recycling. What it means is that the next reactor in the system must be paid to take the separated plutonium or the separated transuranics.

In the Twice-Through Cycle, if the second reactor is not paid to take the separated plutonium, then its costs of producing electricity will be greater than the costs for the first reactor. Assuming that at any point in time there will be both types of reactors operating in the system—reactors burning UOX fuel and reactors burning MOX fuel, and assuming that the reactors are selling their electricity into a common marketplace with a single price for electricity, then it is not commercially viable for one type of reactor to have higher costs than the other type of reactor. Unless reactors are paid to take the separated plutonium, reactors will prefer to fabricate their fuel from uranium rather than from plutonium. A competitive market in fresh fuel, spent fuel and separated components would drive the price of the spent UOX fuel and the plutonium down below zero. Even if the prices are not set in a competitive market, a system in which one type of reactor is producing electricity at a higher cost than another type of reactor will come under pressure to somehow spread the burden beyond the customer base of the reactors with the higher cost. This could be done through subsidies of various sorts.

4. The LCOE vs. 'equilibrium cost'

The major point of departure between our analysis and other studies comes in the calculation of the LCOE for the Fast Reactor Recycle. Studies of a Fast Reactor Recycle system typically adopt an entirely different approach known as the 'equilibrium cost'. For example, this is employed in EPRI (2007) and Shropshire et al. (2009). Bunn et al. (2003) and (2005) calculate a 'Cost of Electricity' for fast reactors. Although they do not employ the term 'equilibrium cost', because of the special assumptions they make to analyze a system of recycling with fast reactors, their methodology reduces to the 'equilibrium cost' methodology.[11] The equilibrium cost is based on the condition that "all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium" (EPRI 20007, p. 4–1). Our LCOE definition requires no such condition, so clearly the two concepts are different. 'Equilibrium cost' does not correspond to a levelized cost.

One way to understand the difference between our definition of the LCOE and the equilibrium cost concept is with respect to the dimension of time. Eq. (13) constructs a profile of electricity production *through time*. It follows a unit of fuel as it passes through one reactor, is unloaded, reprocessed and then fed into a reactor again. As with all levelized cost calculations, Eq. (13) generates a kind of average cost. In the Fast Reactor Recycle, Eq. (13) generates an average of (i) the costs incurred in burning fresh UOX fuel in a first pass through a light water reactor, and (ii) the costs incurred in burning fast reactor fuel containing transuranics in an infinite sequence of succeeding fast reactors. The weights in the averaging calculation are determined by (i) the relative quantity of electricity produced by 1 kg of UOX in the first reactor as compared against the quantity of electricity produced by the transuranics extracted from that 1 kg of UOX when it is fabricated into fast reactor fuel and burned in the infinite sequence of fast reactors, and (ii) the present value weights that adjust the respective values of these two quantities of electricity and the associated cost expenditures.

Note that the relative weights in Eq. (13) are set once and for all by the technology. They are not dependent upon the share of electricity being produced by light water reactors versus the share being produced by fast reactors at a given point in time. Suppose, for example, that we are examining an economy with a constant demand for electricity through time being served by the Fast Reactor Recycle technology. There will be an initial moment of construction of light water reactors, followed by the gradual construction of fast reactors. The fraction of electricity generated by light water reactors will start high and gradually decline. Nevertheless, the LCOE will be constant through time. We could have constructed our illustrative example using an economy with a growing demand for electricity through time. The specifics of the time profile of the shares of light water and fast reactors would have been different. Nevertheless, the LCOE would still be constant through time, and would equal the LCOE of the economy with a constant demand for electricity. The LCOE is entirely independent of the economy's aggregate profile of electricity consumption and the fraction of the profile currently being generated by one or the other reactor type. This property of Eq. (13) holds for any profile of electricity demand, so long as that profile can be produced by the cycle. This is a question of the feasibility of matching the time pattern of net investment in the cycle so as to recreate the time profile of electricity demanded.[12]

In contrast, the equilibrium cost concept calculates the cost *at a single moment in time*. The concept requires that we find the equilibrium profile of reactors in the recycling system precisely because the instantaneous measured system-wide costs will vary as one selects different points in time along the historical trajectory defined by the recycling technology. The true LCOE is an average of all of these instantaneous system-wide costs. But the equilibrium cost concept does not calculate this average, and instead focuses on the cost at one single point in the historical trajectory.[13]

In general, for parameters like those used in Section 3 for which the LCOE of the Fast Reactor Recycle is greater than the LCOE of the Once-Through system, the Fast Reactor Recycle will have an equilibrium cost that is greater than the LCOE. This is because the Fast Reactor Recycle system involves a delayed realization of costs. A portion of the costs required to operate the light water reactor that begins the system are paid by the operators of the fast reactors as they manage the stream of transuranics inherited from the initial light water reactor. Our LCOE measure levelizes these costs across the full time profile of electricity generated by the system. The equilibrium cost measure does not. It charges these costs as they are realized, and a larger portion of these costs are realized in the profile of electricity produced in the equilibrium system. This leads to an equilibrium cost that is larger than the LCOE for the Fast Reactor Recycle system.

The equilibrium cost measure appears to be attractive because it avoids attributing any value to the recycled transuranics. But avoiding this attribution is exactly what causes the equilibrium cost measure to deviate from a proper levelized cost. It is the attributed value of the transuranics that serves, in our Eq. (15)–(17) to levelize the costs properly across the units of electricity produced by all of the reactors, both light water and fast reactors. The Fast Reactor Recycle system

[11] Bunn et al. (2003) analyze the cost of a fast reactor with a conversion ratio between 1 and 1.25, and assume the transuranics are supplied to the reactor at no cost. This gives the same result as an equilibrium cost measure since a conversion ratio greater than or equal to 1 implies that the limiting steady-state is one populated only by fast reactors. The equilibrium cost in this steady-state equals the realized costs on the fast reactors, without any accounting for the value of the transuranics passed from the light water reactor to the fast reactors. In the appendix (p. 103) they state that their calculation requires that the levelized cost of the transuranics entering and leaving the fast reactor are the same. In our notation this requires that $\alpha = 1$, which in turn implies $q_1/q_2 > 1$, so that the conversion ratio must be greater than 1.

[12] For a more thorough investigation into this property of the LCOE under different aggregate demand profiles, see De Roo and Parsons (2010). We abstract here from problems that follow from discreteness in the construction of individual reactor units. This is a second order problem that a systems analysis model is well suited to tackle. See for example, Busquim et al. (2008). We also abstract from the problem of a potentially declining demand profile and the depreciation of installed capital.

[13] For a system with breeder reactors, the concept of a steady-state or equilibrium profile is problematic.

Table 5
Equilibrium Cost for the fast reactor recycle with different conversion ratios.

			CR = 0.5 (mill/kWh) [A]		CR = 1 (mill/kWh) [B]		CR = 1.2 (mill/kWh) [C]	
[1]	Raw uranium	$u_{3,LA}$	2.76		2.76		2.76	
[2]	Fabrication	$b_{3,L}$	4.35		4.35		4.35	
[3]	Front-end fuel cycle	$f_{3,L}$		7.11		7.11		7.11
[4]	Capital charge	$k_{3,L}$		67.68		67.68		67.68
[5]	O&M costs (non-fuel)	$m_{3,L}$		7.72		7.72		7.72
[6]	Reprocessing	$s_{3,L}$	2.36		2.36		2.36	
[7]	HLW Disposal	$w_{3,L}$	0.40		0.40		0.40	
[8]	Reprocessed uranium	$-u_{3,LB}$	0.14		0.14		0.14	
[9]	TRUs	$-z_{3,L}$						
[10]	Disposal cost	$d_{3,L}$		2.90		2.90		2.90
[11]	LCOE total	$\ell_{3,L}$		85.41		85.41		85.41
[12]	Depleted uranium	$u_{3,FA}$	0.01		0.02		0.02	
[13]	TRUs	$z_{3,F}$						
[14]	Fabrication	$b_{3,F}$	2.25		4.05		5.83	
[15]	Front-end fuel cycle	$f_{3,F}$		2.25		4.06		5.85
[16]	Capital charge	$k_{3,F}$		81.22		81.22		81.22
[17]	O&M costs (non-fuel)	$m_{3,F}$		9.26		9.26		9.26
[18]	Reprocessing	$s_{3,F}$	1.45		2.66		3.20	
[19]	HLW disposal	$w_{3,F}$	0.34		0.34		0.29	
[20]	Depleted uranium	$u_{3,FB}$	0.00		0.01		0.01	
[21]	TRUs	$-\alpha\ z_{3,F}$						
[22]	Disposal cost	$d_{3,F}$		1.79		3.00		3.50
[23]	LCOE total	$\ell_{3,F}$		94.52		97.55		99.84
[24]	Equilibrium FR share			40.1%		100.0%		100.0%
[25]	Equilibrium cost			89.07		97.55		99.84
[26]	Equilibrium Cost − LCOE			3.20		10.98		12.92
[27]	as % of LCOE			4%		13%		15%

Notes:
[1]–[8] are as shown in Table 3.
[9] set equal to zero.
[12] is as shown in Table 3.
[13] set equal to zero.
[14] is as shown in Table 3.
[15] = [12] + [13] + [14].
[16]–[20] are as shown in Table 3.
[21] set equal to zero.
[22] = [18] + [19] + [20] + [21].
[23] = [15] + [16] + [17] + [22].
[24] Column A: A LWR generates 50*33% = 16.5 MWd of electricity and produces 13 g of transuranics. A FR generates 132*41% = 54.1 MWd of electricity and with CR = 0.5 burns (1 − 0.81)*33.3% = 63 g of transuranics. In equilibrium, and ignoring losses, the transuranics produced by the LWRs equals the transuranics burned in the FRs. Therefore, in equilibrium, burning 13 g of transurancis in the FR produces 11MWd of electricity, and the LWRs represent 16.5/(11 + 16.5) = 59.9% of the generation and the FRs represent 11/(11 + 16.5) = 40.1% of the generation.
[24] Column B: Ignoring losses, in equilibrium all production is from FRs, so equal to 100%.
[24] Column C: Set equal to 100%.
[25] = (1 − [24])*[11] + [24]*[23].
[26] = [25]-Table 3, line [21].
[27] = [26]/Table 3, line [21].

water reactor. The negative value of the transuranics is what allows this unrealized cost to be attributed back to the electricity produced by the light water reactor.

Table 5 shows the 'equilibrium cost' for our Fast Reactor Recycle using our input parameters. We calculated the 'equilibrium cost' for all three conversion ratios. For the conversion ratio of 0.5, the equilibrium distribution of reactors is 59.9% light water reactors and 40.1% fast reactors. For the conversion ratio of 1.0, the system reaches an equilibrium distribution in the limit as time approaches infinity, and that distribution is defined as 100% fast reactors. For any conversion ratio greater than 1, we treat the equilibrium distribution as 100% fast reactors. In calculating the costs for each type of reactor, we have zeroed out any credits or charges associated with the recycled transuranics. Therefore the sum of the costs for the light water reactor are slightly lower than the LCOE for the light water reactor as shown in Table 3—85.41 mill/kWh in Table 5 for all three conversion ratios as opposed to between 85.86 and 86.91 mill/kWh in the costs for the fast reactor as shown in Table 5—between 94.52 and 99.84 mill/kWh—are higher than the LCOE for the fast reactor as shown in Table 3—between 85.86 and 86.91 mill/kWh. Table 5 shows the calculation of the final 'equilibrium cost', which involves averaging the cost incurred by the light water reactor with the cost incurred by the fast reactor, weighting the calculation by the proportion of each in the equilibrium distribution. The 'equilibrium cost' is always higher than the LCOE. For the conversion ratio of 0.5, the 'equilibrium cost' exceeds the LCOE by 4%, while for the conversion ratio of 1.23 the 'equilibrium cost' exceeds the LCOE by 15%.

5. Conclusion

We analyzed the LCOE for three different fuel cycles: the traditional, Once-Through Cycle, in which the spent fuel is not recycled, but sent for disposal in a geologic repository; a Twice-Through Cycle, in which the plutonium and uranium extracted from the spent fuel from the first pass in a light water reactor are used in a second pass through a light water reactor, after which the spent fuel is sent for disposal in a geologic repository, and a Fast Reactor Recycle system, in which the spent fuel from the first pass in a light water reactor is followed by a repeated recycling of all of the transuranics through a fast reactor.

The main contribution of this paper is a methodology for calculating the LCOE for systems with nuclear fuel recycling. This has been missing in the literature on the economics of nuclear fuel recycling. Our definition of the LCOE is independent of any value ascribed to the recycled materials, whether plutonium or transuranics. Nevertheless, we showed that it is convenient to derive a value for these materials as one step in the calculation of the LCOE for a system with recycling.

One widely used definition of cost for fast reactor cycles is the 'equilibrium cost'. This concept requires the definition of a steady-state distribution of reactors – the ratio of fast reactors to light water reactors – and other activities. It totals all of the costs realized in the steady-state. We showed how this concept differs from a levelized cost concept. We show that for our chosen input parameters the equilibrium cost of a system with recycling is greater than the LCOE. This is because the fast reactor recycle system involves a delayed realization of costs. Therefore the steady-state distribution chosen for the analysis happens to capture many of the realized costs which a levelized cost would attribute back to units of electricity produced from the fresh fuel.

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