If cheaper fusion reactors were developed, such as from compact toroids
If fusion–fission hybrids were developed
If carbon emissions were taxed
If public opposition made it difficult to build new fission reactors or coal power plants

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Books and Reviews

Nuclear Power, Economics of
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Glossary

c Onetime costs [$]
Eₖ Cost of electricity [$]
FV Future value [$]
HM Heavy metal, refers to the uranium and or transuranic component of fuel
kg Kilogram
kW Kilowatt
kWh Kilowatt hour
kWh(e) Kilowatt hour electric
mill $0.001
n Number of years
MOX Mixed oxide fuel
MWh(e) Megawatt hour electric
p(t) Distributed costs [$/year]
Pu Plutonium
PV Present value [$]
r Yearly rate of return in discrete discounting
r(xᵢ, xⱼ) Correlation coefficient
SD Standard deviation
SF Spent fuel
SW Separative work
t Time [year]
U Uranium
UOX Uranium dioxide fuel
VHLW Vitrified high-level waste
xᵢ Denotes a cost component
α Linear cost escalation rate [$/year²]
β Linear cost escalation intercept [$/year]
δ Delta function
ρ Discount or interest rate [1/year]

Definition of the Subject

Financial viability is an important consideration when deciding whether to proceed with any large-scale engineering project. Many studies of nuclear power economics have been undertaken in an attempt to predict its overall costs or competitiveness (e.g., [1–4]). While these studies tend to differ in their assumptions about construction and operating expenses, they all use similar frameworks for the analysis. In essence, the idea is to predict the total cost of producing electric power over the lifetime of a facility and compare that to the market value of the electricity produced. All other things being equal, the larger the ratio of revenue to cost the better the project.

Introduction

Economic assessments of nuclear power tend to be complicated, and not just because of the number of components that have to be factored in, Fig. 1. The costs of any large project also depend on how it is financed, and whether this is done through the issuing of bonds by the entity undertaking the project, borrowed money, allocation of liquid assets, and/or the use of complex financial instruments such as derivatives. Tax rates, both federal and local, can also play an important role. The revenue stream from a nuclear power facility itself depends on whether the markets into which the electricity is fed are regulated or unregulated and whether arrangements exist that involve the sale of electricity at fixed rates to municipalities where the facilities reside. The effect of hard to predict market forces can affect the price of electricity itself.

In addition, nuclear power has some peculiarities that are unique to the industry. Among these is the need to safely store the radioactive waste products that are contained in spent nuclear fuel, for extended periods of time. At present, only the US Waste Isolation Pilot Plant, in Carlsbad NM, is actively used for this purpose, and then only for transuranics (a very specific class of high-level waste) from the US nuclear weapons program. Because of this, interim storage facilities exist at civilian nuclear power facilities to handle spent nuclear fuel, but the final disposal costs remain uncertain (e.g., [2]). In addition, most modern reactors run on a uranium fuel that has been enriched to contain more of the uranium 235 isotope than is present in natural uranium (natural uranium is made up of two isotopes: ²³⁸U and ²³⁵U. The ²³⁸U isotopes comprises
99.3% of the uranium atoms and $^{235}\text{U}$ 0.7%. It is the $^{235}\text{U}$ isotope that readily undergoes fission in the thermal reactors that dominate the civilian nuclear power industry. Because this isotope can also be used in the manufacture of nuclear weapons, concerted efforts have been undertaken to limit the development of enrichment facilities outside of a few highly industrialized countries (e.g., [5, 6]). This of course has the effect of forcing nuclear power facilities in less industrialized countries to buy fuel from external sources. Consequently, a common concern is that the fuel supply could be restricted for political reasons (e.g., [7]).

Uncertainties in fuel availability and spent fuel disposal introduce an element of financial risk that is difficult to quantify. Another potential complication comes from uncertainty in whether construction of a nuclear power plant will actually lead to an operational facility. It has in fact happened that facilities have been undertaken whose construction has been halted, or which have been completed but closed before becoming commercially operational. The Shoreham Nuclear Power Plant in Long Island, NY, is an example of this. The facility was completed in the mid-1980s, but public protest resulted in its closure before it produced commercial power.

**Nuclear Power, Economics of. Figure 1**

*Components of a nuclear power facility.* Construction of a nuclear power facility begins with site selection and approval. Facility construction (reactor and related facilities) comes next, with final startup typically coming 6–12 years after the start of construction activities. The process of producing uranium fuel typically starts 2 years prior to fuel placement in a reactor with uranium mining, milling, conversion enrichment, and fuel fabrication. Finally, fuel is transported to the reactor site. The fuel pipeline will function continuously as the reactor operates. Interim on-site storage is common until permanent storage facilities are established (Figure courtesy of Robert Bell, The University of Texas at Austin).
Because of the above factors, and others, it is difficult to make blanket statements about the economics of nuclear power, and facilities need to be evaluated on an individual basis. However, several recent studies have taken a look at nuclear power relative to competing technologies, see Table 1, with somewhat mixed results that reflect the different assumptions that went into the analyses. In the current article, the focus is largely on a discussion of how the cost of a nuclear power facility would be computed when taking into consideration factors such as its construction, operation, maintenance, and decommissioning.

Many of the elements that contribute to the life-cycle cost of a nuclear power plant are common to other types of facilities as well. These include:

**Capital costs** – The costs associated with building the plant and its components.

**O&M** – The cost to operate and maintain facilities.

**Depreciation** – This is a charge recorded against earnings that takes into consideration the lifetime of capital components and the fact that they must be replaced as a part of operating expenses. Depreciation of capital components is typically added to the yearly operations and maintenance costs.

**Interest** – The money paid for the use of borrowed capital or for bonds that have been issued.

**Taxes** – Both federal and local may apply.

**Interest rate** – The annual amount of money paid to a lender or bond holder for the use of capital as a percentage of the amount to be repaid.

**Discount rate** – Effectively the same as the interest rate, see section on discount rates.

Several other factors that affect the cost of nuclear power are particular to the industry. These include:

**Fuel costs** – A peculiarity of nuclear power facilities is that they do not always buy the fuel that is used to run them. Instead, they will often lease it, sometimes from a company that was created explicitly for the purpose of doing this. The reason has to do with accounting practices, and it is sometimes cost effective for a utility to acquire its fuel in this way [8].

**Nuclear waste fund fee** – This is a fee levied in the United States to cover the Federal Government’s obligation to take possession of spent nuclear fuel and dispose of it [8]. The current rate is $0.001/kWh of electricity produced, which is paid into the Nuclear Waste Fund (The Nuclear Waste Fund was established under US Code Title 42, Chapter 108, Subchapter III, 10222 – i.e., The Nuclear Waste Policy Act of 1983). This monetary unit is so common within the utility industry that it is often given a special unit called a “mill,” where 1 mill = $0.001 [8].

**On site spent fuel storage cost** – The cost to store spent nuclear fuel on site.

**Decommissioning costs** – The costs associated with removing the power plant and its components along with returning the site to an unrestricted use.

By far the dominant cost for a typical nuclear power plant is that of constructing the facility itself [4]. From the perspective of the people who are building a facility, the cash flows that are required for construction depend not only on the facility cost, and the time required to build it, but also on how it is financed. For example, cash flows associated with a facility financed with cash will be different than those for one financed with a loan that is to be paid back over a fixed period of time, or a bond. Once a facility is built, there are operation and maintenance charges to keep it in working order, and these are spread out over the operating life of the facility. Taxes on property begin as soon as land is acquired, and those on the facility itself depend on the location and municipality, but are likely to be yearly as are taxes on income. Depreciation too is spread out over the operating life of a component (a discussion of common depreciation methods can be found in [4]), and decommissioning costs are
incurred at the end of a facility’s life. However, it is typical that money must be set aside for decommission costs well in advance of them.

**Present and Future Value of Money**

The variable nature of the cash inflows and outflows complicates the cost analysis for any industrial facility, but especially those with long lifetimes as is typical with nuclear power plants. When undertaking a life-cycle cost study, it is also important to recognize that not all money is equivalent. Specifically, a dollar paid or earned today has a different value than does one paid or earned a year from now. The reason for this stems from the fact that money can devalue due to inflation, but also because money held today can be invested and earn interest. Conversely, money received in the future has less value, both because it may have devalued but also because of the inability to invest it until it is received. These concepts are captured in what is often referred to as the “time value of money” [9]. For example, $100 invested today, at a yearly return of 5%, will yield $105 in 1 year. In the parlance of financial engineering, $100 invested this way has a **future value** of $105, and $105 received in 1 year has a **present value** of $100. From the perspective of an investor who expects a yearly return of 5%, both are equivalent.

The relationship between **future value** (FV) and **present value** (PV) is simple:

\[
FV = PV(1 + r)^n \tag{1}
\]

Here \( r \) is the yearly rate of return, and \( n \) is the number of years over which the investment takes place (not necessarily an integer), and PV is said to be **compounded** over \( n \) years. Conversely, the **present value** of FV (received in \( n \) years) is given by:

\[
PV = FV/(1 + r)^n \tag{2}
\]

An important point that is often overlooked is that PV = FV when the expected rate of return is zero. This situation can effectively arise in environments, where the rate of return is equal to the inflation rate. Equation 2 is an example of **discounting**. When the effects of inflation are taken into consideration Eqs 1, 2 become:

\[
FV = PV(1 + r - i)^n \tag{3}
\]

and

\[
PV = FV/(1 + r - i)^n \tag{4}
\]

Here \( i \) is the yearly inflation rate. Equations 3, 4 give the present and future values in constant, or inflation adjusted, dollars. The quantity \( \rho = r - i \) is referred to as the “real rate of return” as opposed to the “nominal rate of return” \( r \), and \( \rho, r, \) and \( i \) all range between 0 and 1. Most economic analyses are done assuming a real rate of return, and that convention is adopted here.

Equations 1–4 are discrete representations of simple compounding and discounting, and there are several very good descriptions of how they can be extended to more complex situations in general (e.g., [10]), and to the nuclear power industry in particular [1, 8]. However, as these references quickly show, applying discrete financial models becomes cumbersome when the system being analyzed is complex. An alternative is to use continuous approximations to Eqs 3, 4, which then become:

\[
FV = PVe^{\rho t} \tag{5}
\]

and

\[
PV = FVe^{-\rho t} \tag{6}
\]

Here \( \rho \) is again the rate of real rate of return per unit time \( t \).

**Levelized Costs**

Nuclear power facilities typically operate over extended time periods, and some in the United States are even in the process of receiving license extensions that will bring their operating life spans to 60 years (e.g., [11]). As a result, the present value of funds that are used to build, maintain, fuel, or decommission a nuclear facility will depend significantly on when the costs occur. Therefore, the only way to accurately estimate the total cost of a facility is to compute its total **present value** relative to a specific date (usually the date of startup of the facility). This process is called **levelizing**. In fact, in the United States, all large-scale government projects are required to perform this type of levelized cost analysis [12]. Expenses that take place before the reference date have what is called a **lead time** as they happen before the reference time. Expenses that take place after the reference time have a **lag time** as they happen after the reference time [1, 13]. A framework for how
to levelize the costs for nuclear power facilities in terms of lead and lag times was given in a study done by the Organization for Economic Cooperation and Development (OECD) in collaboration with the Nuclear Energy Agency (NEA) [1]. Continuous discounting can be used within this framework to level all costs, as well as the revenue from electricity production, to the date at which fresh fuel is loaded into a reactor. Continuous discounting is mathematically simpler than its discrete alternative and often introduces negligible error relative to the large variances for unit cost predictions.

With this approach, levelized costs are easily obtained by multiplying the time-dependent costs, \( p(t) \), by the discounting factor, \( e^{-\rho(t) t} \), and integrating the product:

\[
PV = \int_{t_1}^{t_2} p(t)e^{-\rho(t) t} dt
\]

(7)

where \( PV \) is again the present value of a cash outflow, \( p(t) \) [$/year], \( \rho(t) \) is the real interest or discount rate [1/year], and \( t \) is time [year]. It is common in many studies to assume that \( \rho(t) \) is constant, though this is not necessary. The total cost of a system over its life is given by the sum over the costs incurred from its construction to its decommissioning:

\[
E_c = \sum_i PV_i
\]

(8)

The life-cycle cost in $/kWh(e) is calculated by dividing \( E_c \) by the total kWh's of electricity produced. Some economists argue that the electricity production should itself be discounted using Eq. 7 to factor in the temporal nature of the revenue stream (e.g., [14]). It might seem counter intuitive that a unit of energy, being immutable, should be discounted. However, economists who advocate this approach argue that energy (like money) can be viewed as having greater value when it is available in the near term than if its availability is off in the distance. Another interpretation was given by Hannon [14] who suggested that the energy discount rate reflects a society’s desire to convert “a present surplus energy into an energy-transformation process so that a greater surplus of energy can be created in the future, rather than consuming the energy now.” While energy discounting is used (e.g., [4, 8]), the approach is not universal.

**Examples.** Figure 2 shows several distributions for \( p(t) \) that are relevant to nuclear power systems and out of which any cost or revenue distribution can be built. Equation 7 is easy to apply to each situation when it is done systematically.

(a) The present value of a onetime cost, \( c_0 \), that occurs at time, \( t_0 \), is easy to derive using Eq. 7. One starts by noting that:

\[
\begin{align*}
    p & = 0 \quad 0 \leq t < t_0 \\
    p & = c_0 \quad t = t_0 \\
    p & = 0 \quad t > t_0
\end{align*}
\]

(9)

Assuming a constant discount rate, Eq. 7 becomes:

\[
PV = \int_{0}^{t_0} c_0 \delta(t_0) e^{-\rho t} dt
\]

(10)

Nuclear Power, Economics of. Figure 2

*Common payment, cost, and revenue distributions.* Common distributions for \( p(t) \) applicable to Eq. 7 are shown. In the figure, \( c_0 \) stands for one time cost, and \( p(t) \) for distributed cost. The left-hand side of the time axis is assumed to represent \( t = 0 \).
where $\delta(t_0)$ is the delta function (zero everywhere but $t_0$). Equation 10 then just gives:

$$PV = ce^{-\rho t_0}$$

(11)

which is just Eq. 6 again.

(b) The present value of a uniformly distributed cost is only slightly more complicated to calculate. Here:

$$p = \begin{cases} 0 & 0 \leq t < t_0 \\ c_1 & t_0 \leq t \leq t_1 \\ 0 & t > t_1 \end{cases}$$

(12)

Equation 7 then becomes:

$$PV = \int_{t_0}^{t_1} c_1 e^{-\rho t} dt$$

(13)

which has the simple solution:

$$PV = \frac{c_1 [e^{-\rho t_0} - e^{-\rho t_1}]}{\rho}$$

(14)

(c) The present value of a distributed cost and a onetime cost is just the sum of the results given in Eqs. 11, 14:

$$PV = c_0 e^{-\rho t_0} + \frac{c_1 [e^{-\rho t_0} - e^{-\rho t_1}]}{\rho}$$

(15)

It is implicit in Eq. 15 that the discount rate is the same for both distributions; however, this is not always the case, and not a necessary restriction.

(d) The present value of two uniformly distributed costs is just obtained using the result in Eq. 14 twice:

$$PV = \frac{c_1 [e^{-\rho t_0} - e^{-\rho t_1}]}{\rho} + \frac{c_2 [e^{-\rho t_0} - e^{-\rho t_1}]}{\rho}$$

(16)

Here $c_1$ and $c_2$ are the uniform cost rates for the respective distributions. It is again implicit that the discount rate is the same for both distributions, though this is again not a necessary restriction.

(e) Linearly escalating costs are also easy to deal with. Here the cost function is given by:

$$p = \begin{cases} 0 & 0 \leq t < t_0 \\ \alpha t + \beta & t_0 \leq t \leq t_1 \\ 0 & t > t_1 \end{cases}$$

(17)

where $\alpha$ has units of [$/year^2$] and $\beta$ [$/year$]. In this case, Eq. 7 becomes:

$$ PV = \int_{t_0}^{t_1} (\alpha t + \beta) e^{-\rho t} dt$$

(18)

Equation 18 has the simple solution:

$$PV = \frac{\alpha (t_0 - \frac{1}{\rho})(e^{-\rho t_1} - e^{-\rho t_0}) + \beta e^{-\rho t_0}}{\rho}$$

(19)

In general, Eq. 7 is integrable as long as $p(t)$ is known. While the formulas above may seem at first glance to be complicated, they are far simpler and more compact than their discrete discounting alternatives.

Lead and Lag Times in Cost Calculations

A critical factor in using the above equations, and when performing economic analyses in general, is to know when costs occur relative to a specified date. As already pointed out, this is captured in what are referred to as “lead” and “lag” times, and the reference time is typically taken to be the date of the facilities’ first operation. Components that affect the cost of nuclear power are shown schematically in Fig. 1. In very general terms, the costs associated with nuclear power production can be broken into capital costs (which include the construction of physical infrastructure such as the reactor plant, spent fuel storage facilities, or facilities involved in producing nuclear fuel, etc.), operating costs (which include operations and maintenance costs, taxes, fuel costs, as well as spent nuclear fuel disposal costs), and decommission costs (which include dismantling of physical infrastructure and site remediation).

Power Facility Construction

Historically, this has been by far the dominant factor affecting the cost of nuclear power (e.g., [3, 4]). The lead time is highly variable, Fig. 3, but 8 years or more is typical for modern large-scale facilities. How this cost is distributed depends on how a facility is financed, Fig. 2f.
Power Facility O&M

Operations and maintenance costs for the facilities are usually computed on a yearly basis and can be approximated with a uniform distribution as in Fig. 1b. Large capital outlays for replacement of major components can often be assumed to be onetime costs as in Fig. 2a (e.g., [3, 4]).

Cooling Water

Availability of cooling water has become a potential constraint for nuclear power plants in some locations. A facility’s water use depends on its efficiency, as well as how it is cooled (open loop, closed loop, evaporation pond, etc.). A typical range of water withdrawals for modern Rankine cycle power plants is 2,000–4,000 l/MWh(e), for closed loop systems, and 100,000–220,000 l/MWh(e) for open-loop systems. Water consumption rates are considerably smaller. In this context, water consumption describes water that is taken from a source (ground or surface water), used, and not returned to that source. A cooling tower consumes water through evaporation for example. Water withdrawal describes water that is taken from a source, used, and then returned to that source. Cost estimates for water vary widely, but $25 per 1,000 m³ has been reported and can be based on consumption, or withdrawal, rates and will depend on local water markets and regulatory structures (e.g., [15]).

Uranium Mining

The extraction of uranium ore typically occurs 2 years prior to its use as fuel in a reactor. Uranium is mined as U₃O₈ and is typically sold in this form. Modeled as a onetime cost that would recur with the refueling schedule of a reactor.

Uranium Conversion

The U₃O₈ requires conversion into UF₆ if the uranium is to be enriched to a higher ²³⁵U content that occurs in natural uranium. Uranium must be enriched for use as fuel in most commercial light water reactors worldwide [16]. The lead time for conversion is typically 1.5 years. Modeled as a onetime cost that would recur with the refueling schedule of the reactor.

Enrichment

Enrichment typically occurs 1 year before fuel placement in the reactor. Modeled as a onetime cost that would recur with the refueling schedule of the reactor.

Fuel Fabrication

Most reactors worldwide use uranium dioxide fuel that is surrounded by a protective “cladding” and configured in assemblies that can be placed into a reactor. Fabrication usually takes place 0.5 years before fuel emplacement. Modeled as a onetime cost that would recur with the refueling schedule of the reactor.

Leasing or Buying Nuclear Fuel

Not all nuclear utilities buy their fuel. Instead, many lease it, and sometimes from a company or trust that has been created specifically for the purpose of doing this. The lease company covers all expenses for the fuel (mining, conversion, enrichment, fuel manufacture transportation and storage) until it is onsite to be loaded into the core. During this time, the utility pays nothing. Once the fuel begins producing power, the utility will pay the lease company a prorated amount that covers the lease company’s expenses plus some degree of profit. In some situations, this arrangement is financially advantageous, though this depends on the accounting practices of the utility and possible constraints from regulatory agencies. Typically, the total
cost obligation is met when the fuel has been used to completion. The cost function for the leased fuel can be linearly decreasing, Fig. 2e, or of some other shape [8].

**Interim Spent Fuel Storage**

When the fuel reaches the end of its useful life, it is discharged from the core and is stored on site either under water or in air-cooled vaults until it is removed for final disposal or reprocessing. The residence time in interim storage is highly variable, and the spent fuel from some US reactors has remained in this type of onsite storage for decades. Spent fuel storage is typically calculated per unit time and per unit mass, and it is therefore a linearly increasing cost, Fig. 2e, at most reactor facilities, (e.g., [3, 4]).

**Spent Fuel Recycle**

Some countries, notably France, reprocess spent nuclear fuel and use the plutonium that it contains to manufacture what is called mixed oxide fuel (MOX – a mixture of plutonium oxide and uranium oxide) that can be used in addition to standard enriched uranium fuel, Fig. 4. In countries where this is done, spent fuel will cool in storage pools for 6–12 years before being sent to reprocessing. The distribution of this cost depends on whether funds are continuously set aside to meet this obligation or whether it is considered to be a series of onetime costs that occur as spent fuel is sent to recycle.

**Spent Fuel Disposal**

Most countries with domestic nuclear power assume that long-lived nuclear waste products will go into some form of geological storage. At present, only the US Waste Isolation Pilot Plant, in Carlsbad NM, is actively used for this purpose, and then only on a scale sufficient to handle transuranic waste from past US nuclear weapons efforts. As a result, the actual time at which spent fuel will leave interim storage for final disposal is unclear at most power plants (the final disposal of high-level waste from reprocessing is similarly unclear in countries where this is undertaken). Many reactor facilities whose spent fuel pools are nearing capacity have begun to transition fuel assemblies to onsite dry storage. In the United States, the Nuclear Waste Policy Act of 1987 gives responsibility for the disposal of spent nuclear fuel to the Federal government [17]. In order to cover the associated expenses, US nuclear power facilities pay 1 mill/kWh(e) into the Nuclear Waste Fund for the purpose of covering the final disposal costs [17, 18]. The cost is incurred quarterly and, as a result, constitutes a series of recurrent onetime costs for nuclear utilities in the United States, i.e., Fig. 2a.

**Estimating Uncertainties**

Equation 8 has the convenient feature of being linear with respect to the total cost of each fuel-cycle component. As a result, $E_c$ can be scaled to account for changes in unit cost, provided that time points for the integral
in Eq. 7 remain fixed. Uncertainty in unit costs causes a corresponding uncertainty in the prediction of $E_c$. These effects can be accounted for by using the well-known formula for error propagation, where the variance of $E_c(x_i)$ is given by:

$$\text{var}(E_c) = \sum_i \left( \frac{\partial E_c}{\partial x_i} \right)^2 \text{var}(x_i) + 2 \sum_i \sum_{j \neq i} \left( \frac{\partial E_c}{\partial x_i} \right) \left( \frac{\partial E_c}{\partial x_j} \right) \sqrt{\text{var}(x_i) \text{var}(x_j)} r(x_i, x_j)$$

(20)

Here the inputs, $x_p$, represent the PV in Eq. 8 with respective variances $\text{var}(x_i)$. The term $r(x_i, x_j)$ is the correlation coefficient, 1 for fully correlated, –1 for anticorrelated and 0 for uncorrelated. The maximum and minimum variances are given by assuming that $r = 1, –1$ respectively with uncorrelated, $r = 0$, typically giving a variance that falls into the midrange. Equation 20 is much simplified in the case of $r = 0$.

The electricity cost is assumed to have a Gaussian distribution which can be justified by the Central Limit Theorem [19], with the standard deviation of $E_c$ being the square root of the variance. It should also be pointed out that Eq. 20 can be used for cost-sensitivity studies.

**Costs and Their Uncertainties**

Numerous studies have investigated the economics of nuclear power, notably the series of reports produced between 1987 and 2002 by the Organization for Economic Cooperation and Development and the Nuclear Energy Agency (OECD/NEA) [1, 13, 20–22] along with recent reports from groups at MIT and the University of Chicago. The 1994 OECD/NEA study [1], in particular, developed a framework for assessing the economics of nuclear fuel cycles. The study derived the expected levelized cost of a fuel cycle over the lifetime of a reactor, including transients (at startup and shutdown). The fuel cycle was divided into front-end components (uranium ore requirements, conversion to UF$_6$, enrichment, fuel fabrication and transport) and back-end components (spent fuel transport, reprocessing, direct disposal, or high-level waste (HLW) vitrification and disposal). Cash outflows to meet these obligations were discounted to a reference date using a discrete model as was revenue from electricity, and the subsequent expected cost in $/kWh (e) was calculated.

The 1994 study [1] gave the most comprehensive cost estimates available at the time. Data were obtained from the literature and through survey of OECD member states and gave reliable results where industries were well established. Because no actual disposal facility existed for SF or vitrified HLW, these estimates were considered to be particularly uncertain [1]. The cost data were updated in the 2002 OECD/NEA study and estimated standard deviations were added [13]. Because no permanent repository is in operation, it is difficult to estimate what it would cost. However, the experience and cost studies at Yucca Mountain in the United States provides some indication. Here the cost estimates for the repository rose in constant dollars from $32.2 billion to $57.5 billion between 1989 and 2001, Fig. 5 [18, 23–26], for a repository that was designed to
hold 86,000 metric tons of spent nuclear fuel. Representative costs, lead/lag times, and standard deviations for nuclear power systems are given in Table 2.

Discount and Interest Rates

The values of $\rho$ that are used in discounting will have a significant effect on an economic analysis. As a result, discount rates have been widely discussed in the context of decision theory, and in cost-benefit analyses of things that can have intergenerational effects such as environmental damage, resource allocation, or nuclear waste disposal. For economic comparisons, or cost studies, discounting accounts for the fact that payments made could instead have been invested and earned a rate of return. Alternately, future payments could be met by setting aside a smaller amount of money today and letting compound interest make up

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### Nuclear Power, Economics of. Table 2

<table>
<thead>
<tr>
<th>Fuel cycle component</th>
<th>Basis</th>
<th>$</th>
<th>SD (%)</th>
<th>% loss</th>
<th>lead/lag (years)</th>
<th>References</th>
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<td>Reactor facility construction</td>
<td>$/kW(e) installed</td>
<td>3,560</td>
<td>15</td>
<td>-12 &gt; -8</td>
<td>[11], [13], NA, see text</td>
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<tr>
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<td>-1.5</td>
<td>[13], same as capital costs, NA, NA</td>
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<td>Uranium mining and milling</td>
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<td>33</td>
<td>-2.0</td>
<td>[13], [13], NA, [1]</td>
<td></td>
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<td>$\text{U}_2\text{O}_8$ to $\text{UF}_6$ conversion</td>
<td>$/kgU</td>
<td>5</td>
<td>40</td>
<td>0.5</td>
<td>-1.0</td>
<td>[13], [13], [29], [1]</td>
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<td>37.5</td>
<td>0.5</td>
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<td>UOX fabrication</td>
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<td>20</td>
<td>0.5</td>
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<td>[13], [13], [29], [1]</td>
</tr>
<tr>
<td>Onsite interim SF$_{\text{UOX}}$ storage</td>
<td>$/kgHM/year</td>
<td>30</td>
<td>5</td>
<td>+5</td>
<td>[13], [13], NA, NA</td>
<td></td>
</tr>
<tr>
<td>SF$_{\text{UOX}}$ conditioning and disposal</td>
<td>$/kgHM</td>
<td>668</td>
<td>24</td>
<td>+10.5</td>
<td>[13], [13], NA, see caption</td>
<td></td>
</tr>
<tr>
<td>Spent fuel recycle</td>
<td>SF$_{\text{UOX}}$ transport to reprocessing</td>
<td>$/kgHM</td>
<td>50</td>
<td>20</td>
<td>+11</td>
<td>[13], [13], see caption</td>
</tr>
<tr>
<td>SF$_{\text{UOX}}$ reprocessing</td>
<td>$/kgHM</td>
<td>800</td>
<td>12.5</td>
<td>2.0</td>
<td>+11</td>
<td>[13], [13], [13], see caption</td>
</tr>
<tr>
<td>MOX Fabrication</td>
<td>$/kgHM</td>
<td>1,100</td>
<td>18</td>
<td>1.0</td>
<td>+22.5</td>
<td>[13], [13], see caption</td>
</tr>
<tr>
<td>Onsite interim SF$_{\text{MOX}}$ storage</td>
<td>$/kgHM/year</td>
<td>30</td>
<td>5</td>
<td>+17.5</td>
<td>[13], [13], NA, NA</td>
<td></td>
</tr>
<tr>
<td>SF$_{\text{MOX}}$ transport to disposal site</td>
<td>$/kgHM/year</td>
<td>50</td>
<td>20</td>
<td>+22.5</td>
<td>[13], [13], see caption</td>
<td></td>
</tr>
<tr>
<td>SF$_{\text{MOX}}$ conditioning and disposal</td>
<td>$/kgHM</td>
<td>668</td>
<td>24</td>
<td>+57.5</td>
<td>Same as UOX, [13], NA, see caption</td>
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</tr>
<tr>
<td>VHLW conditioning and disposal</td>
<td>$/kgHM</td>
<td>288</td>
<td>12.5</td>
<td>+56</td>
<td>[13], [13], NA, see caption</td>
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</table>
the difference. In both cases, the appropriate discount rate would be one that reflects what one could obtain by investing the funds in bonds, stocks, or other investments, and receiving the market rate of return.

There is no single discount rate that is accepted for near-term analysis of utilities, nuclear power included, but values between 5% and 10% (in real terms) are common and reflect the historical range of return by the US utility sector (e.g., [4]). However, there are problems in using this discount rate for projects that run on intergeneration time scales. The dominant concerns are well summarized in several different studies (e.g., [27, 28]), but the main point is that a discount rate that is this high would suggest that money so invested would eventually grow to be larger than the domestic product of any country where the investment was made. As a result, some economists suggest that discount rates appropriate for intergenerational projects would have to tend toward a country’s real rate of GDP growth and can be assumed to be around 1–2% (e.g., [27, 28]).

The question of which discount rate to use in evaluating nuclear power facilities is far from academic. Cost studies are often used to compare different systems or management strategies. A high discount rate can make the present value of far-off costs appear negligible. In other words, using a high discount rate in a costs-benefit study of a politically divisive issue, such as spent fuel disposal, can have the perverse effect of suggesting that it would always be cheaper to delay action. In fact, this type of argument has been advanced in the United States to advocate for pushing off the development of reprocessing or permanent geologic disposal.

Cost Comparisons and External Costs

Using Eq. 8, or similar, one can calculate the cost associated with the generating electricity by various means. Results of such studies are shown in Tables 1 and 2. However, making true comparisons for the “cost” of generating electricity between different types of power systems can be complicated by the effect of externalities that are often difficult to capture in an economic analysis. Factoring in the true cost of carbon dioxide emissions would be an example. Carbon dioxide emissions from fossil-fueled plants are obvious. They are not so obvious for nuclear, wind, or solar power facilities. While nuclear power facilities have no direct emissions, there are carbon signatures associated with the materials out of which they are made,
the processes involved in facility construction, as well as for operations, maintenance, and decommissioning. The same is true for wind and solar power systems. Where one draws the boundary for an analysis (i.e., does one include the carbon dioxide needed to produce, say, the machinery for the processing of facility materials) can have a significant effect on the total carbon signature that is associated with a specific power source, and through this, its total potential cost. Because of the complexity of handling externalities (and the cost of carbon emissions is only one example), how best to do this remains an area of active research and debate.

**Future Directions**

Electricity demand varies with location, time of day, and time of year. The minimum demand at any point within a year is referred to as **base load**. The utility industry typically gauges demand requirements with what are called **load demand** and **load duration curves**, Figs. 6 and 7. Commercial nuclear power plants have historically been designed to operate at their maximum licensed power. The fraction of time that these facilities are in operation has also increased steadily over the years to an industry average of around 90%. As a result, commercial nuclear power is used to meet base-load requirements, along with coal, hydroelectric, and to a smaller extent wind. Additional load requirements are met with smaller-scale facilities (called **peaking power plants**) that typically run on oil or gas.

Because of perceived economies of scale, nuclear power plants have been built on an increasingly large scale. Recently though, this idea has begun to be revisited, and there are calls for the development of smaller-scale facilities with peak power outputs of as little as a few tens of megawatts. Such plants, known as **Small Modular Reactors**, could be used to meet local base-load requirements or as peaking plants. A shift in the industry to include smaller-scale facilities could have dramatic effects on the economics of nuclear power. Smaller facilities would likely have shorter build times and far lower capital costs. Many utilities also charge different rates, depending on when electricity is used, and this too would affect the economics of nuclear package plants that might be used to meet peak load requirements. (The first-generation light water reactors were designed for power outputs of 300–600 MWE. In the United States, today most nuclear power facilities are rated for 800–1,000 MWe, but it expected that the next generation of reactor will produce between 1,100 and 1,400 MWe.)

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**Bibliography**


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**Nuclear Reactor Materials and Fuels**

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**Nuclear Clad Materials**

**Nuclear Moderator Materials**

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**Glossary**

**Austenitic stainless steel** Austenitic steels contain alloys of chromium and nickel (sometimes manganese and nitrogen), structured around the Type 302 stainless steel composition of iron, 18% chromium, and 8% nickel. Austenitic steels are not hardenable by heat treatment. The most common austenitic stainless steel is type 304.

**Burnup** A measurement of the energy generated by fuel atoms that undergo fission. It is normally quoted in megawatt–days per metric ton of uranium metal or its equivalent (MWd/MTU).

**Core plate** In a reactor the upper and lower core plates supports the fuel, channels the cooling water into the fuel bundle, and assures each fuel bundle is maintained equidistant from each other.

**Fertile fuel** A material capable of creating a fissile fuel upon capture of a neutron. Examples are U$^{238}$ and Th$^{232}$, which create Pu$^{239}$ and U$^{233}$ respectively.

**Fissile fuel** Capable of undergoing fission by thermal neutrons. The four primary nuclides are U$^{233}$, U$^{235}$, Pu$^{239}$, and Pu$^{241}$.

**Fissionable fuel** A material capable of undergoing fission, via the absorption of a neutron with kinetic energy.