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A wedge or a weight? Critically examining nuclear power's viability as a low carbon energy source from an intergenerational perspective

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ABSTRACT

Some integrated assessment studies of climate change have concluded that nuclear energy has a large potential impact on carbon abatement costs. However, these studies have often modeled the cost of nuclear waste management very simply or neglected it entirely. Common difficulties with existing studies include the use of simplistic nuclear waste management cost models and implicitly minimizing costs in the distant future by using discount rates that are arguably inappropriate for intergenerational cost-benefit analysis. These difficulties lead to results that may underestimate the cost of nuclear waste management – and therefore overestimate the value of nuclear energy as a low carbon energy technology. Here, we consider how a more realistic treatment of the nuclear waste disposal problem than has been used in previous studies could affect the viability of nuclear power in the context of integrated assessments of climate change. We construct a generic nuclear waste management cost model to develop cost estimates for nuclear waste management based on current policy, practice, and cost estimates for storage and disposal technologies. Our cost estimates are discounted using conventional constant exponential discounting as and a declining discount rate scheme. Results suggest that the optimism reflected in previous works is fragile: More realistic nuclear waste management cost models and uncertainty-appropriate intergenerational discount rates produce many more scenarios in which nuclear waste management costs are higher than previously assumed. As a consequence, nuclear energy's economic attractiveness as a low carbon energy option is appears to be lower than earlier works suggested.

1. Motivation

Integrated assessment analyzes large-scale human and Earth systems and is commonly used to evaluate the impacts of policy choices on climate outcomes [1]. Integrated assessment models link component models of, for example, climate, economics, and technology to evaluate these interconnected systems, and integrated assessment has played a prominent role in all five Intergovernmental Panel on Climate Change (IPCC) assessment reports [2–6].

1.1. The cost of nuclear drives the cost of carbon mitigation

Many studies have identified nuclear energy as a promising, low-cost, low-carbon alternative to fossil fuels. For example, Barron and McJeon [7] found that the cost of nuclear energy was the primary driver of carbon abatement costs under a range of socioeconomic and climate policy scenarios, and Hong et al. [8] found that if nuclear energy was unavailable, zero-carbon emissions pathways could require up to 50% greater capital investment than in high nuclear penetration scenarios. Bosettit et al. [9] report that climate policy costs were *"mostly sensitive to the possibility of very cheap or very costly nuclear options"*. McJeon [10] reports that nuclear energy (and CCS) was effective at limiting climate stabilization costs in *"worst-case technology scenarios"* – scenarios where new low-carbon technologies have little success. Kim and Edmonds [11] characterized the value of nuclear energy for addressing climate change as being *"denominated in the trillions of dollars"*. Hong et al. [12] reports that completely replacing nuclear energy with wind and solar was "*neither economically viable nor environmentally friendly"*, even when the impacts of non-dispatchability were mitigated by increased dispatchable backup and transmission capacities. Roth and Jaramillo [13] report that preserving the existing U.S. nuclear power plant fleet was a cost-effective carbon mitigation strategy. Bretschger and Zhang [14] report that for the Swiss economy the welfare loss due to carbon policy increased from 1.21% to 1.58% (a 30% increase in the cost of a carbon policy) if nuclear energy was phased out. Olaleye and Baker [15] examined the impact of technological advancement in energy technologies and determined that *"Nuclear and CCS have the most impact on abatement costs, with CCS mostly important at high levels of*

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abatement.”. Iyer [16] examined small modular reactors and model results suggested that they have significant potential to reduce carbon emissions and improve energy security. Brook [17] calculates that nuclear energy could supply more than half of global energy needs in a carbon-free world. Other studies have found that nuclear energy could reduce mitigation costs, but that its impact depends on other factors such as the carbon storage availability [18] or stakeholder preferences [19].

Other research has found little or no benefit from nuclear energy. Krey [20] evaluated a portfolio of low-carbon energy technologies and found that nuclear energy had a relatively small impact on carbon mitigation costs compared to carbon capture and bioenergy. Sovacool [21] noted many externalities surrounding nuclear energy, including issues of waste disposal, and found that nuclear power causes damages of $0.12[1] per kilowatt-hour of electricity (kWhe) produced. Wheatley et al. [22] estimated mean annual damages from nuclear power accidents to be $1.56 billion, assuming that the costliest possible accident is $270 billion (based on the cost of the Chernobyl disaster).

The wide range of projections about the costs and benefits of nuclear power can be at least partially attributed to differences among the models used for these analyses. Kim et al. [23] evaluated the role of nuclear energy in eighteen integrated assessment models and found that these models projected end-of-century (2100) market shares for nuclear energy ranging from 0 to 38%, depending on the model and carbon policy used.

Kim et al. [23] noted many substantial differences in the models' approach to nuclear energy and the level of detail of nuclear power technology representation. The approaches ranged from representing nuclear energy as a generic technology to detailed representations of the nuclear energy sector that include different reactor types and the nuclear fuel cycle. Of the eighteen integrated assessment models evaluated, only eight explicitly represented any part of the nuclear fuel cycle, and only five listed nuclear waste as a consideration. Kim et al. [23] reports that *“Greater clarification of nuclear fuel cycle issues and risk factors associated with nuclear energy use are necessary for understanding the nuclear deployment constraints imposed in models and for improving the assessment of the nuclear energy potential in addressing climate change.”*

1.2. The long tail of nuclear waste

In addition to significant disagreement about the best approach to modeling nuclear energy, there is also substantial disagreement about its intergenerational costs and benefits. In part, this reflects uncertainties in nuclear waste[2] storage and disposal time frames. For example, all waste disposal plans currently under consideration have project lifespans (the time from start of planning to final closure of the repository) on the order of a century or more. For example, the most recent U.S. Department of Energy estimate of the cost of the Yucca Mountain waste repository assumed a project lifespan of 149 years [24]. Delays in constructing disposal facilities extend the time frame and increase costs even further. According to the U.S. Government Accountability Office (GAO), delays in the Yucca Mountain repository project have led to lawsuits that are estimated to cost $13.7 billion through 2020, with continued delays beyond 2020 potentially costing and additional $500 million annually [25].

The longevity of nuclear waste and the intergenerational time horizon of waste disposal projects raise important issues of intergenerational distribution. This issue is further complicated when evaluating nuclear energy in the context of climate change, which also has intergenerational costs and benefits.

1.3. Ethics and intergenerational justice

A number of researchers have examined the implications of intergenerational justice considerations on choices about nuclear power. Kermisch [26] evaluated nuclear waste disposal options and concluded that irretrievable geologic disposal was the most favorable option from the perspective of remote future generations. On the other hand, Taebi and Kadak [27] examine the question of choosing a nuclear fuel cycle and conclude that, depending on the value criteria adopted by decision makers, permanent disposal in the current generation is not necessarily the best choice. Taebi et al. [28] argue that nuclear power should be framed as a social experiment and advocate for a debate that includes distributive justice alongside other evaluation criteria. They observed that *“Feelings of responsibility for our descendants seem to play an important role in the argumentation of both nuclear proponents and opponents.”* and also note that burning fossil fuels has many of the same intergenerational justice issues as nuclear power.

These intergenerational justice issues fuel debate about what discount rate to use in cost-benefit analyses. With time horizons of a century or more, nuclear waste disposal projects represent some of the longest-lived industrial projects. The unprecedented length of these projects raises serious issues for cost-benefit analysis because the discount rates commonly used to evaluate major industrial projects trivialize even large cashflows in the distant future.

This deep uncertainty[3] about critical aspects of nuclear energy and its waste, including the intergenerational time horizon of its impacts and its role in abating carbon emissions, call for an analysis of nuclear energy that considers the future generations that will inherit the consequences of our waste management strategies.

In this work, we begin to address this need by developing a nuclear waste disposal cost model that provides more detail of nuclear waste management costs than has commonly been used in integrated assessments. We then use this nuclear waste cost model to develop nuclear waste management scenarios based on existing U.S. policy and waste management options, and illustrate how these management strategies can impact policy analysis.

The balance of this paper is organized as follows: In the next section, we provide background information and a literature review of nuclear waste disposal and intergenerational discounting. The Methods section outlines our nuclear waste disposal cost model and nuclear waste disposal scenarios. The results section presents our model results, which are then discussed. Finally, we present our conclusions.

2. Background

This section provides background on nuclear waste management, discounting and intergenerational distribution, and the integrated assessment of Barron and McJeon [7] upon which this work is based.

2.1. Nuclear waste management

Under the right conditions, nuclear waste released into the environment can contaminate large areas of land to the point that it is unusable for generations [29,30]. A National Academies study [31] concluded that the risk of terrorist attacks on interim storage facilities

[1] All costs are deflated to 2016 US Dollars using the GDP implicit price deflators for gross domestic product published by the U.S. Bureau of Economic Analysis. If a source does not report the nominal year for their costs it is assumed to be the year of publication.

[2] The IAEA classifies nuclear waste into six categories ranging from exempt waste requiring no regulatory control to high level waste requiring deep geologic disposal [95]. In this paper we focus on spent nuclear fuel and any associated reprocessing by products, which fall into the category of high level waste, and which for simplicity we will refer to simply as “nuclear waste” in the balance of this paper.

[3] We use the term deep uncertainty as defined by [96] to mean a situation where there is fundamental disagreement among experts about the correct structure of the model.

cannot be dismissed and waste in interim storage is vulnerable to release due to accidents (as happened at Chernobyl) or natural disasters (as happened during the Fukushima Disaster). Because of its hazards and extreme longevity there is widespread consensus that nuclear waste should be disposed of in geologic repositories designed to isolate waste deep underground where it can remain isolated, undisturbed, and as secure as possible from accidental or deliberate release [32,33].

Nuclear waste management includes all the processes from initial generation of the waste to final disposal in such a repository. It is a years-long, multi-step process that is intended to provide adequate shielding and security to mitigate the waste's extreme and unique hazards. In this paper we distinguish between *storage*, an interim process that safeguards waste on a temporary basis and *disposal,* final emplacement in a geologic repository, after which waste is abandoned. The distinction between storage and disposal of importance in this work is that storage requires ongoing effort to maintain, while disposal does not.

2.1.1. Interim storage

Before waste can be disposed of in a repository it must undergo a period of cooling and preparation. This interim storage period allows radiation and decay heat to dissipate enough to allow safe transport of the waste. When spent nuclear fuel is removed from a reactor it is approximately one million times more radioactive than unused fuel and produces large amounts of decay heat [34]. Due to this extreme heat and radioactivity, spent fuel is generally stored submerged in pools at the reactor site for a minimum of three years after it is removed from a reactor [35,36].

After an initial cooling period of about five years waste could in theory be transported for disposal, but in practice waste has remained in interim storage due to lack of disposal facilities. Waste that remains in interim storage can continue to be stored in pools or be transferred into dry storage casks and moved to dry storage facilities for continued interim storage. As of 2014, 64 storage facilities were in operation at reactor sites in the U.S. [37]. There have also been proposals to build centralized storage facilities that would receive waste from multiple reactor sites. In 2006 the Nuclear Regulatory Commission granted a license for a proposed facility in Tooele County, Utah. That facility was never constructed and in 2012 the license was terminated. As of September 2017, the U.S. Nuclear Regulatory Commission was reviewing two applications for centralized facilities [38].

2.1.2. Geologic disposal

The goal of geologic disposal is to sequester the waste in an underground repository, where it can remain contained, isolated, and undisturbed for the geologic time span required for the radioactivity to dissipate, without the need for ongoing maintenance or monitoring. Repositories rely on multiple barriers – a combination of geologic and engineered barriers designed to provide multiple layers of containment [39,40]. Key design considerations for repositories include the type of host formation (e.g., salt, hard rock, clay), the presence or absence of water, and the engineered barriers.

Although there is widespread agreement that geologic disposal is necessary, efforts to build repositories have been largely unsuccessful and despite concerted effort, no repository is presently (as of 2018) available to dispose of commercial nuclear waste. Fears about the safety of nuclear waste have led many jurisdictions in the US to impose moratoria on new nuclear power plants until a permanent waste disposal facility is in place and operating [41]. The situation is similar elsewhere in the world: Of 24 waste disposal siting processes from around the world discussed in a report by the U.S. Nuclear Waste Technical Review Board, only four sites had reached a final site selection [32]. Of these only one had opened (the Waste Isolation Pilot Plant in New Mexico, USA), although it accepts only defense-related waste. The commercial-waste disposal facility currently closest to completion is the Onkalo repository in Finland. The Onkalo facility is under construction but has not yet been granted an operating license. According to Posiva (the operator of the Onkalo facility), the application license application will not be filed until 2020 [42].

2.1.3. Reprocessing

It is also possible to reprocess spent nuclear fuel to separate the uranium and plutonium from the rest of the waste. Unlike geologic disposal, reprocessing is not universally accepted as part of a nuclear waste management strategy. The economic competitiveness of reprocessing remains unresolved [43,44], and recent trends show a shift away from reprocessing [45]. Therefore, reprocessing is not considered in this work.

2.1.4. Where are we now?

In the absence of permanent repositories, spent fuel has continued to accumulate in interim storage. In 2016 spent fuel containing 78,590 metric tons of Uranium was being stored at reactor sites in the United States [46]. The International Panel on Fissile Materials estimates that worldwide approximately 290,000 Metric Tons of Heavy Metal (MTHM) were in storage at the end of 2009, with about 8500 MTHM being added to this figure annually [47].

This accumulation of waste has led to studies of interim storage as a long-term policy option. In 2014 the U.S. Nuclear Regulatory Commission removed the restriction against licensing (or relicensing) nuclear power plants based on an NRC analysis indicating that indefinite surface storage is acceptable if facilities are suitably sited and maintained, including repackaging approximately every century [37,48].

2.1.5. Estimating the cost

Estimates of the cost of nuclear waste management vary considerably. Many repository designs have been evaluated by different governments around the world. Segelod [49] noted that the estimated cost of waste disposal in the Swedish system is 40% more than the U.S. estimate. Nutt [50] surveyed international nuclear waste cost estimates and reported costs ranging from 148,000 to 1,041,000 $/MTHM. Hardin et al. [51] evaluated reference disposal concepts based on repositories in different host rock types and estimated disposal costs to be from 184,000 to 615,000 $/MTHM. The IAEA reviewed a number of repository cost estimates from around the world and calculated a range of 0.0008-0.01 $/kWh for repository disposal costs [52]. Although inter-study comparisons are difficulty due to differences baseline assumptions and methodologies, they all reflect a wide range of uncertainty in their estimates.

Even within a single project there is variability in cost estimates. The GAO conducted an in-depth analysis of the cost of Yucca Mountain using DOE's 2008 cost projections and determined that repository disposal of all of the spent fuel that will be generated if all currently operating reactors remain in operation for 60 years (153,000 MTHM) would have a Net Present Value (NPV) of $298,866 – 488,391/MTHM, plus an additional $109,341/MTHM in sunk costs [25].

Cost estimates for interim storage also vary. TRW Environmental Safety Systems Inc. estimated that construction of reactor-site storage facilities would cost $14 million per site for construction, and $1.05 million per year for pre-shutdown (of the associated power plant) monitoring. Post-shutdown monitoring costs were estimated at $5.6–12.7 million per year, depending on whether waste was in pools or dry storage [53]. These costs were reported on a per-site basis and were independent of the amount of fuel stored. The U.S. Government Accountability Office estimated the NPV of interim storage costs for 100 years to be $109,341 – 211,393/MTHM for centralized storage, and $94,762–318,651/MTHM for reactor-site storage [25].

Although only approximate comparisons can be made across these studies due to significant differences in methodology and assumptions, the wide range of approaches to the problem and significant variation across cost estimates for the same project highlight the deep uncertainty of the nuclear waste management problem. When normalized to a per-unit basis, cost ranges of several hundred percent are common, and the cost estimates for the repository designs evaluated in the aforementioned study by the IAEA [52] span an order of magnitude.

Cost estimates for nuclear waste projects have followed a pattern of increasing over time and are likely to continue to increase. The official DOE cost estimate of the Yucca Mountain program more than doubled between 1995 and 2007, from $50 to $110 billion [24,54]. Segelod [49] notes a similar increase of 102% in the cost estimate for Sweden's repository. Cost escalation is well documented in major engineering projects [55]. Moreover, cost estimates are nearly always underestimates: Flyvbjerg et al. [56] performed a statistical analysis of 258 transportation infrastructure projects and found that costs were underestimated in nearly 90 percent of projects.

2.2. Discounting and intergenerational distribution

Discounting is a central aspect of any cost-benefit analysis. Commonly, cost comparisons are based on net present values obtained using a constant exponential discount rate. For short-term projects on the scale of up to several decades, constant exponential discounting is an effective and widely accepted way to compare investment decisions. However, there is controversy surrounding the validity of discounting intergenerational phenomena and projects in this manner.

Much of the controversy about the appropriate method of intergenerational discounting is driven by uncertainty about future discount rates. One significant driver of interest rate uncertainty is differing viewpoints about the proper ethical framework in which to view the impacts of discounting on the future. This idea dates back at least to Ramsey's work in the 1929s [57]. Ramsey's opinion has been echoed by many others, including [58–62]. Parfit's paper *An Attack on the Social Discount Rate"* [63] describes the concept of a social discount rate as "indefensible". Cowen [64] examines intergenerational discounting from the perspective of making restitution for past injustices and concludes that *"Cost-benefit analysis does not provide a direct case for using market interest rates or measures of time preference to determine the rate of compounding across generations."*. Broome [65] concludes that market-based discounting is *"useless for projects aimed at mitigating global warming"*.

On the other hand, descriptive discounting takes the view that intergenerational costs and benefits should be discounted at the market rate of return because investments that benefit the distant future are done at the expense of other investment options. For example, Birdsall and Steer [66] argue that discounting at less than the market rate of return would result in suboptimal investments that reduced the stock of wealth bequeathed to future generations. This is based on the premise that by investing at the market rate of return in lieu of lower-return environmental projects, the current generation will leave the future better off, even after accounting for environmental damages, than they would have been had the environmental project been chosen. Cline [67] notes several problems with this approach, notably that there is no way to guarantee that investment returns will remain high, or that estimates of environmental damages are accurate. Lind [68] also notes that maintaining such a fund would require the sustained cooperation of future generations, which cannot be assured.

Ethical arguments about discounting are only one of many factors that create uncertainty about future discount rates. Other sources of uncertainty include future technological progress, future economic growth, environmental effects on consumption and welfare, and many other factors [69,70]. Weitzman [71] showed that uncertainty about the appropriate discount rate (as reflected by the difference of opinion among experts) increases as the time horizon extends into the future. Weitzman concluded on that basis that discount rates should decline over time because over the long-term, the scenario with the lowest discount rate will dominate all others, regardless of its likelihood of occurring. A number of papers have reiterated this point and advocated for declining discount rates in long-term cost-benefit analysis under uncertain discount rates [72–77].

Declining discount rates are beginning to gain a foothold in intergenerational cost-benefit analysis. The U.S. Government Accountability Office used a declining discount rate schedule in an evaluation of U.S. nuclear waste management alternatives [25]. The U.S. Environmental Protection Agency's *Guidelines for Preparing Economic Analyses* recommends incorporating declining discount rate schedules (along with other discounting methods) in long-term (> 50 years) cost-benefit analysis [70], and the UK Government's *Green Book* [78] specifies the use of a declining discount rate for cost-benefit analyses with time horizons greater than 30 years.

2.3. The integrated assessment of Barron and McJeon (2015)

In this work the potential influence of nuclear waste disposal costs are illustrated by estimating how our waste disposal scenarios would have affected the results of the integrated assessment conducted by Barron and McJeon [7]. Barron and McJeon evaluated the potential for low carbon energy technologies to reduce the cost of abating greenhouse gas emissions (abatement costs). They considered five technologies: solar photovoltaics, nuclear energy, liquid biofuels, biomass electricity, and carbon sequestration. They analyzed 1000 different energy sector outcomes, using the Global Change Assessment Model (GCAM) under a range of socioeconomic and climate policy assumptions.

Barron and McJeon developed two metrics of energy technology impact: the Critical Performance Level, and the Magnitude of Impact (MOI).[4] The Critical Performance Level is the lowest performance level at which an energy technology had a statistically significant impact on abatement cost; it can be thought of as the minimum level of performance that a given technology must achieve to be economically viable. The MOI is an effect size metric that measures the size of the impact that a technology could have on abatement costs. MOI ranges from 0 (no impact) to 1 (full elimination of abatement costs).

Barron and McJeon found that the critical performance level of the capital cost of nuclear energy was $4,937–5,148 per kw nameplate capacity and the associated MOI ranged from 22 to 37%, depending on the socioeconomic and climate policy assumptions used.

3. Methods

This section describes the nuclear waste management cost model and management scenarios, discounting schemes, socioeconomic scenarios, cost scenarios, and surrogate integrated assessment model used in this work.

3.1. The nuclear waste management cost model

The nuclear waste management cost model is a modular framework that supports high-level evaluation of waste management strategies in an integrated assessment context. It is a generic model of the waste management process; it is not intended to model any specific management infrastructure, or to provide cost estimates for any particular design. Instead, its purpose is to model the cost of waste management strategies in a generic way that can be used to parameterize integrated assessment models. Components of the model may be added or deleted as necessary to reflect changing technologies and policy decisions; for example, the model can be easily adapted to allow for different disposal options, such as repositories constructed in different types of rock, or alternative interim waste management techniques such as reprocessing. The model configuration used in this paper is illustrated in Fig. 1.

For consistency with Barron and McJeon [7] our calculations of

[4] A full explanation of these metrics is given in [7].

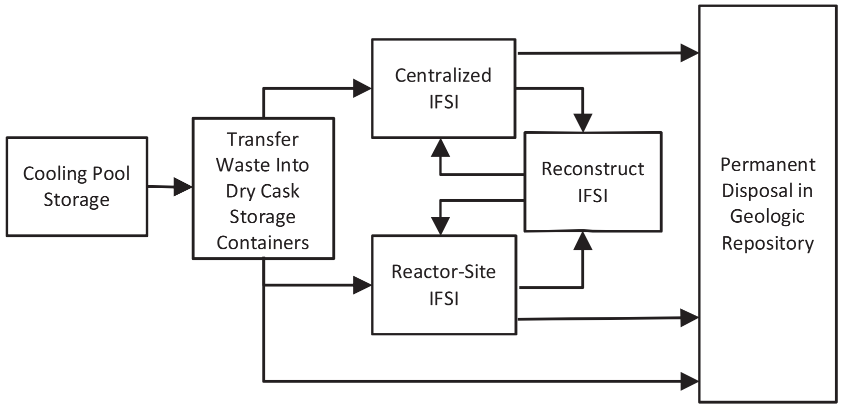

Fig. 1. Schematic showing the nuclear waste management cost model developed in this work. The process begins when waste is received from a reactor-site spent fuel pool. The waste is packaged and sent to one of three destinations: an reactor-site Interim Fuel Storage Installation (IFSI), an off-site centralized IFSI, or a repository. Waste in storage can be repackaged periodically to allow indefinite storage. The management process ends when waste is emplaced in a repository.

Table 1
Nuclear power plant performance parameters used in this study.

Parameter	Value	Source
Fuel Burnup	50 GWd/MTHM	[79]
Thermal Efficiency	33%	[79]
Capacity Factor	90%	[79]
Lifespan	60 Years	[80,81]

Table 2
Summary of Storage Costs Used in the Baseline Scenario, in millions of dollars. All are from [53].

Process	Cost	Source
Pre-Storage Preparation		
Packaging for Dry Storage	$99/MTHM	[53]
Reactor-Site Storage		
Capital Cost	$14/Site	[53]
Pre-Closure O&M	$1.05/Site/Year	
Post-Closure O&M	$6.3/Site/Year	
Centralized Storage		
Design, Engineering, & Licensing	$ 75.2/site	[53]
Capital Costs	$550.6/site/year [a]	
O&M (excluding labor) during loading and unloading	$107.6/site/year [a]	
Labor during loading/unloading	$9.47/site/year	
Labor during caretaker periods	$4.12/site/year	
Decommissioning	$250.9/site	

[a] Includes transportation costs.

waste production are based on the GCAM model's assumptions (Table 1). A 60 year power plant lifespan (based on a 40 year initial license and one 20 year renewal) is assumed throughout; this assumption reflects current policy in the U.S. [80,81]. It is possible that longer or shorter lifetimes may play out in practice, and the U.S. Nuclear Regulatory Commission has released guidance for subsequent (beyond 60 years) license renewals for nuclear plants [82], however we leave an analysis of this matter for future work. For waste management activities that require transportation of waste between sites those transportation costs are included in the respective cost estimates for each of these options.

waste management cost m

In the cost model, interim storage includes only waste storage after waste has been packaged into dry storage casks, it does not include the initial cooling off period when fuel is stored in pools. We do not consider the option of long-term pool storage.

Centralized storage is based on the generic interim storage facility described in a study by the Electric Power Research Institute [83]. The generic centralized facility has a design capacity of 40,000 MTHM, and a loading/unloading rate of 2000 MTHM per year. The facility's lifespan is up to 100 years, based on the time frames of the Nuclear Regulatory Commission's (NRC) *Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel* (NRC GEIS) [37].

Reactor-site storage is modeled as a dry storage facility co-located with a nuclear power plant. The storage facility is constructed at the plant site along with the rest of the facility and has sufficient capacity to hold the entire lifetime waste output of the plant. For consistency with the time frames of the NRC GEIS [37] we assume that reactor-site storage facilities have a useful life that extends to 60 years after reactor shutdown (120 years after plant opening), and that the storage facility must be rebuilt at that point and every 100 years thereafter as long as it remains in use.

Disposal is modeled as emplacement in a geologic repository, based on the planned operation of the Yucca mountain facility. Waste emplaced in the repository is abandoned and after final closure of the repository no further monitoring is done. The waste management cost model does not limit the amount of waste that can be stored, which implicitly assumes that there can be as many repositories as needed. Although in practice a repository could possibly be expanded beyond its original design capacity (or conversely, found to be unable to hold its full capacity), this model assumes that a repository, once designed, can hold its full design capacity of waste and that its capacity cannot be expanded at a later date.

3.2. Nuclear waste management scenarios

The waste management scenarios are based on current U.S. policy and practice. In all cases waste undergoes an initial period of pool cooling, followed by additional interim storage in an Interim Fuel Storage Installation (IFSI), before final disposal in a geologic repository. After the initial cooling period waste can be sent directly to a repository or stored at either a reactor-site or centralized storage facility. The waste management scenarios examined in this study are listed below:

3.2.1. Direct to disposal

In this scenario fuel is transported directly to a geologic repository with no intermediate storage. Fuel is stored in pools for five years before being sent to the repository.

3.2.2. Short-term storage

In the short-term storage scenario fuel is stored at an interim storage site before being sent to a repository. This scenario is based on the short-term timeframe scenario examined in the NRC GEIS [37]. This scenario assumes that waste is stored for a total of sixty years past the shutdown of the nuclear reactor (120 years after reactor startup), at which point the fuel is transported to a repository.

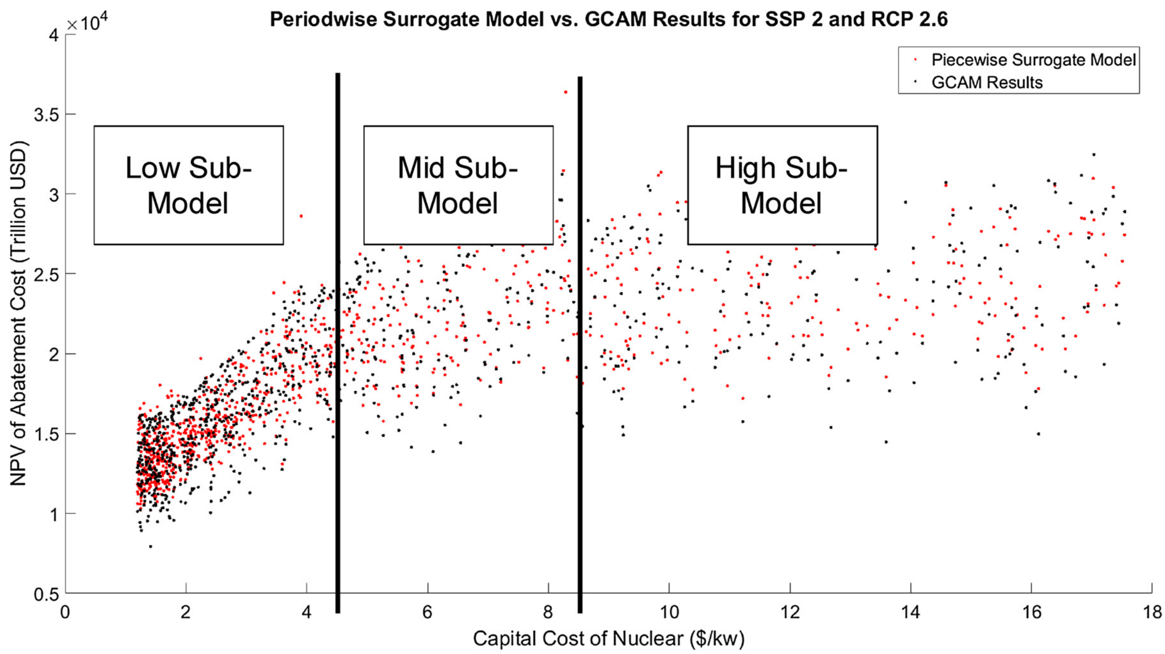

Fig. 2. Illustration of the surrogate model and comparison of original GCAM results with surrogate model results. The black dots are the original results from Barron and McJeon [7] and the red dots are the outputs from the surrogate model. The surrogate model is a composite of three linear sub-models that span the low, middle, and high range of nuclear energy costs respectively. The high sub-model (with high capital cost of nuclear) is the largest set of points for which nuclear does not have a statistically significant effect on abatement costs. The breakpoint between the low and mid sub-models is chosen to yield the error-minimizing composite model.

3.2.3. Long-term storage

The long-term storage scenario is based on the long-term storage timeframe discussed in the NRC GEIS [37]. This scenario is identical to the short-term scenario, except that storage is extended an additional 100 years, to 160 years post shutdown (220 years post-startup); this is modeled as a full reconstruction of the storage facility and replacement of the casks beginning in year 120, at the end of the short-term timeframe. Reconstruction costs are assumed to be the same as construction costs, and we assume that the facility is reconstructed on the same site as the original facility.

3.3. Discounting schemes

We consider two discounting schemes: constant exponential discounting, and gamma discounting as proposed by Weitzman [84]. Gamma discounting was proposed as a method for discounting long-term (> 100 years) projects, and was derived from an expert elicitation of over a thousand economists [85]. Expert elicitation is a well-supported and widely used technique for developing projections about future events [86], and has been widely applied to problems in fields as diverse as assessing nuclear accident risks [87], low-carbon energy [88], and valuing climate damages [89].

The discount rate for the constant discounting scheme is set to 5% for consistency with discounting in the GCAM model. The Gamma discounting scheme is modeled after Weitzman's [85], and we adopt Weitzman's formula for the effective discount rate:

$$R(t) = \frac{\mu}{1 + t\left(\frac{\sigma^2}{\mu}\right)}$$

Where t is the time in years, and μ and σ are the mean and standard deviation of the distribution of future discount rates. We set $\mu = 4.0\%$ and $\sigma = 3.0\%$ per Weitzman's results [85].

3.4. Socioeconomic scenarios

Barron and McJeon [7] considered six different scenarios of future socioeconomic development and climate policy (socioeconomic scenarios). These scenarios were based on the Shared Socioeconomic Pathways (SSPs) [90] and the Representative Concentration Pathways (RCPs) [91]. These scenarios are part of the so-called New Scenario Framework, a set of scenarios designed to provide an internally consistent set of plausible pathways of future development [92]. SSPs 1–3 span a range of possible socioeconomic futures from a world with high wealth and low population (SSP1), to one with higher population and lower per-capita wealth (SSP 3). RCP 2.6 is a scenario where greenhouse gas emissions are constrained to limit radiative forcing to 2.6 W per square meter (W/m^2) by 2100, similarly, under RCP 4.5 radiative forcing is constrained to 4.5 W/m^2 by 2100.

3.5. Cost scenarios

We evaluate three cost scenarios. Our baseline waste management cost scenario is based on the DOE cost estimate for Yucca Mountain [93] for repository storage, and the cost estimates in the above-referenced studies by TRW Environmental Safety Systems [53] and the Electric Power Research Institute [83] for reactor-site and centralized storage, respectively. These estimates were chosen for our analysis because they contained enough detail to construct annualized cashflow series, which allowed us to evaluate different discounting schemes and storage periods. We do not model transportation costs separately because the cost estimates for the options that require transporting waste (repository disposal and centralized interim storage) both include transportation costs.

Storage costs are summarized in Table 2. Waste packaging for dry storage is modeled as a variable O&M expense; packaging costs are $99/MTHM [53]. Costs for reactor-site storage are based on the costs in the TRW study [53]. They are $14 million per site for construction, and $1.05 million per year for pre-closure (of the associated power plant) and $6.3 million per year for post-closure monitoring of the reactor-site IFSI .These costs are given on a per-site basis, regardless of the amount of waste stored at a given site. Costs for the centralized storage facility are $75.2 million for design, engineering, and licensing, $550.6 million for construction and other capital costs, $107.6 million in annual

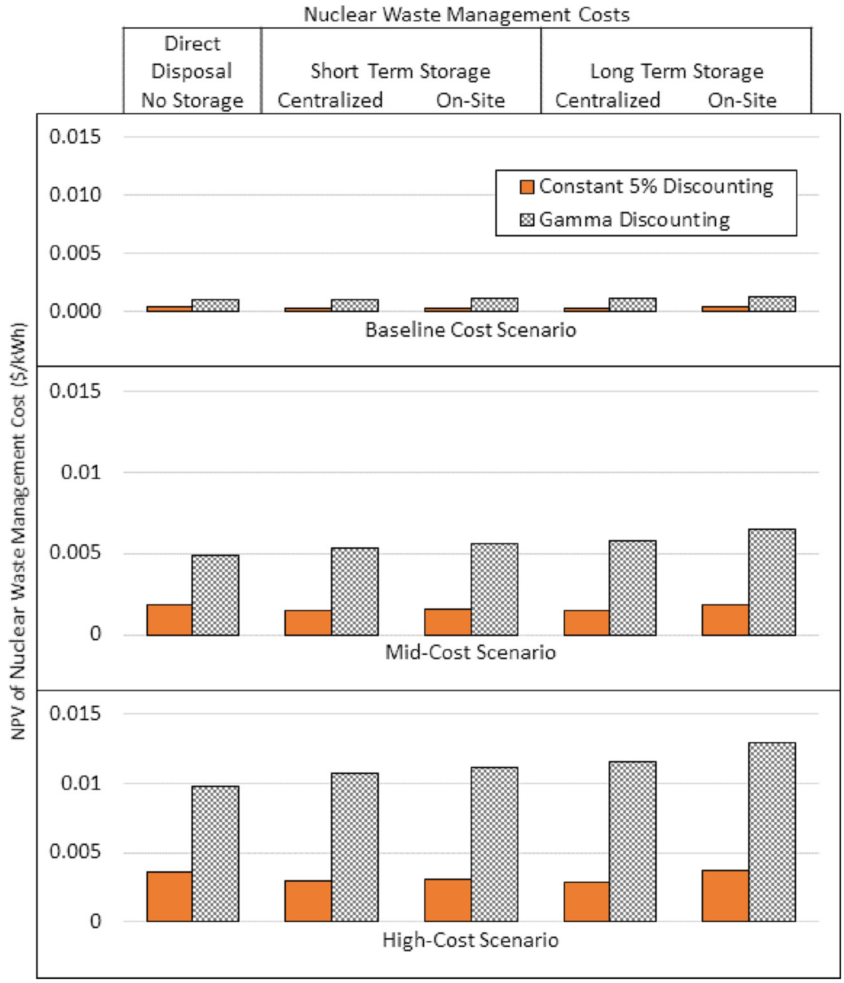

Fig. 3. Net Present Value (NPV) of nuclear waste management costs for three cost scenarios: the baseline: [from studies by the U.S. Deprtment of Energy (DOE) and the Electric Power Research Institute (EPRI)], mid cost (costs are five times higher than base), and high cost (costs are ten times higher). In the baseline cost scenario the NPV of waste management cost varies from 0.0003 $/kWhe for long-term onsite storage under exponential discounting to 0.0094 $/kWhe for direct disposal under gamma discounting.

operating costs during loading and unloading periods, $4.12 and $9.47 million annually for labor during caretaker and loading/unloading periods, respectively, and $250.9 million for decommissioning.

Repository costs are based on the analysis in the U.S. Department of Energy's *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program* [24]. Costs are assumed to be incurred according to the schedule of undiscounted cashflows in Appendix B of the report and are discounted according to the discounting schemes discussed in Section 3.3.

To consider the possible impact of cost increases two other cost scenarios are considered, a mid-cost scenario with costs five times higher than the baseline scenario and a high-cost scenario with costs ten times higher than the baseline cost scenario. The mid-cost scenario has repository costs in the middle of the range of the cost estimates reported by the IAEA [52]. The high-cost scenario represents an extreme but not impossible scenario; the costs are roughly the same as the highest estimated repository costs in the IAEA study [52].

3.6. The surrogate model of GCAM

The GCAM model requires considerable computation time. To provide an initial evaluation of the likely effect of an improved nuclear waste model, this work uses a surrogate model to approximate GCAM results quickly for a range of circumstances. The surrogate model of GCAM is based on the modeling results used by Barron and McJeon [7]. It is a composition of three multiple linear regression sub-models that span the low, middle, and high ranges of nuclear costs (Fig. 2). The three models together span the full range of nuclear cost values considered by Barron and McJeon [7]. In defining the breaks between the sub-models, we assume that when the cost of nuclear energy is high it will have no impact on the energy market, which implies that nuclear cost, when high, will not be a statistically significant predictor of abatement cost. Subject to this constraint, we select breakpoints between the sub-models to yield the error-minimizing composite model. A separate composite model is used for each of the socioeconomic/carbon policy scenarios considered. A comparison of our surrogate model results and Barron and McJeon's [7]'s model results is shown in Fig. 2.

We calculate the NPV of the waste management schemes by constructing undiscounted cashflow series based on the cost and timing of each step in the management process, then discounting that cashflow according to the relevant discounting scheme. To estimate the potential impact of these cost variations on the economic viability of nuclear energy the surrogate model is used to repeat Barron and McJeon's analysis under each of our waste management scenarios. This analysis used the same energy system outcomes as Barron and McJeon's original analysis but adjusted the cost of nuclear technology according to the waste management scenario and discounting scheme. Waste management costs are treated as a variable O&M expense, which is consistent with the per-kWh fee that the U.S. and Sweden intend to use to pay for waste management. An adjustment of $0.001 was applied to all waste

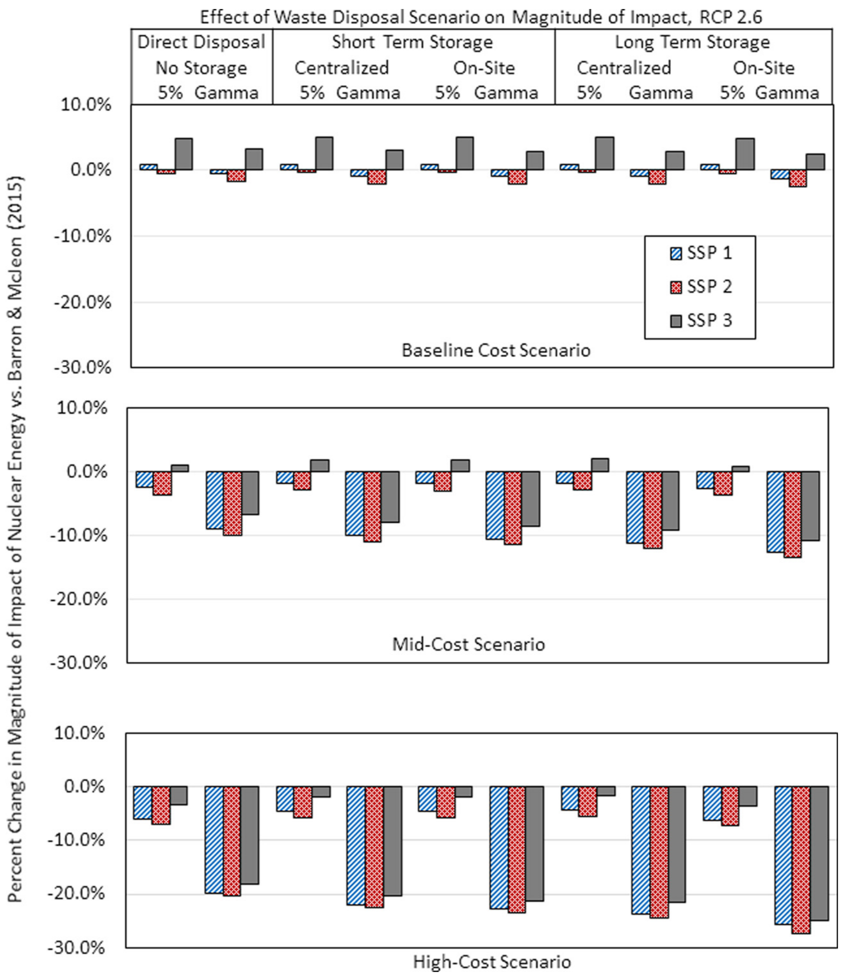

Fig. 4. Change in the magnitude of impact of nuclear energy under different waste management scenarios, relative to Barron and McJeon's results [7]. Values are in terms of percent change from the Barron and McJeon results. Bars above the axis indicate an improvement (increase) in the magnitude of impact, and bars below the axis represent reductions in the magnitude of impact. Improvements in the magnitude of impact are favorable to nuclear energy, reductions are unfavorable to nuclear energy. The choice of discounting scheme (bar groups) has the largest effect on nuclear energy's impact compared to the socioeconomic scenario (vertical bars within groups).

management cost scenarios to rremove the GCAM model's default treatment of nuclear waste [94].

4. Results and discussion

Fig. 3 illustrates the waste management cost results graphically. The NPV of waste management costs in the baseline waste management cost scenario are approximately 2.5–4 times higher under gamma discounting ($0.00097-0.00129 $/kWhe) than under constant exponential discounting (0.00029–0.00037 $/kWhe). The two discounting appro—aches have similar impacts on the mid- and high-cost scenarios.

The time horizon of waste management increases from left to right in Figure 3, from direct disposal to disposal following long-term storage (see Section 3.2 for additional information). The NPV of the waste management options changes significantly under the constant exponential and gamma discounting schemes and short- and long- term time horizons. Under exponential discounting long-term reactor-site storage is the highest cost option, and is 28% more costly than the lowest cost option, long-term consolidated storage. Under gamma discounting long-term reactor-site storage is the highest cost option by a margin of 32%, and the lowest cost option is direct disposal.

While the discounting approach has the greatest impact on the NPV of waste management costs, the time horizon of management options also has an impact. In the short-term storage scenarios the difference in cost between reactor-site and centralized storage is small, about 2% under exponential discounting and 4% under gamma discounting, while in the long-term scenarios reactor-site storage is 12 and 28% more costly, respectively.

The results above illustrate how different waste management strategies and discounting schemes can lead to very different costs for nuclear waste disposal. Now, we discuss how these differences in cost could affect the results of integrated assessments.

Figs. 4 and 5 summarize the impact of the waste disposal scenarios on the results reported by Barron and McJeon [7]. In order to emphasize the difference that nuclear waste management costs can make, we present our results in terms of the change in Barron and McJeon's [7]'s effect size metric, the Magnitude of Impact (MOI), under our waste management scenarios, relative to their results. Increases in the MOI indicate outcomes more favorable to nuclear energy than the assumptions used by Barron and McJeon [7], while reductions indicate less favorable outcomes.

Fig. 4 summarizes the results under the RCP 2.6 carbon constraint. In the baseline case waste disposal scenarios have only a small effect on Barron and McJeon's [7]'s results. Shifts in the MOI are in a range of approximately −2.5 to 5%. The largest effect is seen under SSP3, where MOI improves 2.5–5%. The discounting scheme has only a small effect on the results, although under gamma discounting the results are less favorable to nuclear energy.

Under the mid cost scenario nuclear waste costs reduce the MOI in all scenarios except SSP 3 and exponential discounting. Impact magnitudes reductions are greater under gamma discounting, with impact magnitudes reduced by approximately 7–13%, compared to a maximum reduction of 3.7% under exponential discounting. Under the high cost scenario, MOI is reduced across the board, but reductions are still relatively modest under exponential discounting, ranging from 3 to 10%, while compared to reductions of 17–39% under gamma discounting.

A similar pattern is evident under the RCP 4.5 carbon constraint

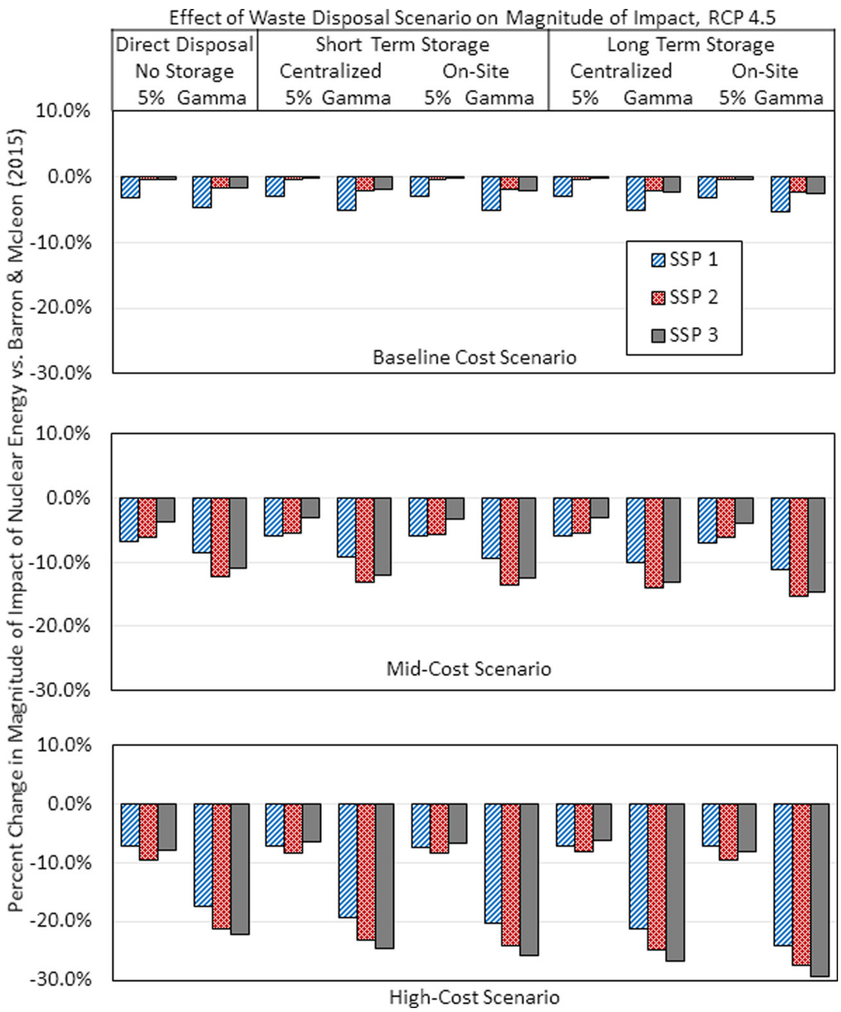

Fig. 5. Change in the magnitude of impact of nuclear energy under different waste management scenarios, relative to Barron and McJeon's results [7]. Values are in terms of percent change from the Barron and McJeon results. Bars above the axis indicate an improvement (increase) in the magnitude of impact, and bars below the axis represent reductions in the magnitude of impact. Improvements in the magnitude of impact are favorable to nuclear energy, reductions are unfavorable to nuclear energy. The choice of discounting scheme (bar groups) has the largest effect on nuclear energy's impact compared to the socioeconomic scenario (vertical bars within groups).

(Fig. 5), although waste management costs are generally more unfavorable to nuclear than in the more stringent RCP 2.6 carbon constraint. For example, nuclear energy's impact magnitude is reduced in all scenarios, even at the baseline cost level. As under RCP 2.6, gamma discounting leads to less favorable results than exponential discounting, however the difference between the effects of gamma and exponential discounting is smaller.

5. Conclusions and policy implications

This work analyzes the impact of using detailed nuclear waste management scenarios and alternative discounting scheme based on ones that are currently being suggested for use with long-term cost-benefit analysis. Results suggest that using this approach in place of the simplistic nuclear waste management assumptions and constant discount rates used in previous integrated assessment studies leads to higher nuclear waste management costs and reduced economic attractiveness of nuclear energy as a low carbon energy option. Our results indicate that using these higher waste management costs reduces the value of Barron and McJeon's [7] effect size metric (the Magnitude of Impact) by up to 29% compared to results under the GCAM model's default waste disposal assumptions used in their original analysis. Given the substantial role that integrated assessment plays in shaping climate policy discussions, such changes could have significant impacts on policy choices, especially as they relate to energy system transformations and energy technology R&D investments.

The analysis presented here shows that nuclear waste management costs depend on both the waste management strategy and the discounting scheme but the discounting scheme is more dominant. Although the dominant effect of discounting on the results of cost-benefit analysis is well known, a recent and growing body of literature argues that as time horizons increase, uncertainty about future discount rates also increases, and therefore discount rates should decline. Declining discount rates have already been used in at least one U.S. Government analysis of nuclear waste management costs [25], yet analysis of the impacts of such declining discount rates on long-term energy system planning has been lacking and this work addresses this need.

Using declining discount rates significantly increases the NPV of waste management costs, and our analysis suggests that these increased costs diminish the attractiveness of nuclear energy as a low-carbon energy option. These results imply that past integrated assessment studies that used exponential discounting and made simplifying assumptions about nuclear waste management costs may have overestimated the value of nuclear energy as a low carbon energy option, especially in cases where those models' assumptions about waste management costs were based on cost estimates for the U.S. waste management strategy, which tend to be lower (on a normalized basis) than other nations' estimates for their own nuclear waste management programs.

Although these results indicate that nuclear waste management costs may have a significant impact on the economic viability of nuclear energy as a low carbon energy option, this work has limitations. Firstly, we do not use GCAM, but rather a surrogate model derived from GCAM outputs. This limits our ability to explore scenarios to those in Barron and McJeon [7]. Secondly, our assumptions about nuclear energy, and especially about the burnup rate of nuclear fuel, were made for consistency with GCAM defaults and the assumptions used by Barron and McJeon [7], and may not accurately reflect current or future technology. Our assumption of a burnup of 50 MW d/MTHM is somewhat higher than the actual burnup rate that generated existing waste. Consequently, our estimates of waste generation are low, and this would tend to make our normalized waste management costs low. Although our results show that nuclear waste management costs would likely impact integrated assessments, further modeling exercises would be needed to fully quantify these effects.

Future integrated assessments should take discount rate uncertainty and specific waste management technologies into account. Our nuclear waste management cost model provides a framework for accomplishing this, with provisions for separate analysis of discounting schemes and waste management strategies. Future work should focus on better quantifying uncertainty with respect to (1) future discount rates, (2) the cost of waste management technologies, and (3) the timing of waste management efforts. One aspect of this problem which deserves particular attention is the impact of social and political controversies on these uncertainties, and possible methods for mitigating the cost, delays, and uncertainty those controversies impose on nuclear waste management. Better information about these critical parameters will yield better estimates of the true cost of nuclear waste management; this will in turn facilitate better integrated assessments and better estimates of nuclear energy's potential role in a low-carbon energy sector.

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