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# Investigating the value of fusion energy using the Global Change Assessment Model

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ABSTRACT

The availability of fusion energy could prove valuable in meeting carbon mitigation targets over the course of the century. We use recent cost estimates for future fusion power plants in order to incorporate fusion into the Global Change Assessment Model (GCAM), a long-term energy and environment model used to study the interaction between technology, climate, and public policy. Results show that fusion's growth will depend on: the chosen carbon mitigation target (if any); the availability of competing carbon-neutral options for the provision of baseload electrical power, in particular nuclear fission as well as carbon capture and storage; the chosen discount rate; the initial year of availability; and the assumed costs of fusion electricity. We quantify the present value of the fusion option while varying the assumptions about these other parameters, and we find that it is, in general for our range of assumptions, significantly larger than the estimated cost of a comprehensive R&D plan to develop fusion energy. The results emphasize the wisdom in hedging against uncertainty in future technology availability by pursuing the development of multiple options that could feasibly play a major role in the latter half of the century.

## 1. Introduction

Integrated assessment models are used to explore the complex relationships between economic activity, energy and industrial systems, ecosystems, and the earth climate. Researchers examine different future trajectories in energy and environmental systems by varying the assumptions that are built into the models. GCAM (Global Change Assessment Model) is one such model. It is produced and maintained by the Joint Global Change Research Institute and it is most often used to examine technology options and their interaction with climate impacts and policy (Kim et al., 2006). The main result of the work described here was to incorporate fusion energy into GCAM so as to estimate the present value of fusion under different technological and climate policy scenarios.

GCAM currently yields projections out to 2095, and therefore the nature of the model necessitates making a wide range of assumptions and predictions about technological changes over time. The inherent uncertainty implies that its utility is not in making absolute predictions but rather in examining the relative changes in parameters between scenarios with differing assumptions. As a tool for examining climate policy, technological projections are particularly challenging under advanced carbon mitigation scenarios, in which there will necessarily be dramatic shifts in global energy production. The results from long-term energy and environment modeling are often used to make near-term policy prescriptions, so it is important to project advanced future technology options as accurately as possible.

We add a generic fusion option by mimicking GCAM's treatment of "Gen III" nuclear fission, which has similar features in terms of size, capacity factor, the provision of baseload electrical power, and linkages to other energy technologies. The base case uses recent best estimates for fusion power plant costs, assuming that: 1) first-of-a-kind plants are available by 2035; 2) costs fall to the 10th-of-a-kind level by 2050; 3) 100th-of-a-kind costs are attainable by 2065; and 4) costs continue to fall with a progress ratio of .9 (or a learning rate of 10%). In all

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model runs, the assumed cost reductions are justified *a posteriori* by ensuring that the rate of deployment is in fact consistent with that which is required to achieve these costs. In addition to the base case, we examine the sensitivity to the initial year available by uniformly delaying fusion's timetable by 15 years, and also the sensitivity to absolute costs with a ± 30% change in the inputs.

Fusion is a complex technology, although steady progress and sustained political will to support projects like ITER (for magnetic fusion) and NIF (for inertial fusion) lend credibility to the notion that fusion energy could be a contributor to meeting future energy demand in this century. However, most assessments suggest it is unlikely to replace fossil fuels unless external costs are taken into account (Han and Ward, 2009) (Ward et al., 2005). Indeed, we find that fusion grows slowly in GCAM scenarios with no carbon mitigation policy. The value of fusion becomes evident in carbon-constrained scenarios, where a tax on carbon makes carbon-neutral sources much more competitive. In such scenarios, the "value" of fusion emerges as the difference between the costs of meeting a mitigation target with and without the availability of fusion technology. Fusion, if commercialized and proven cost-competitive, could act as an alternative non-carbon-emitting technology for the provision of baseload power. GCAM does have several other technologies – namely nuclear fission, carbon capture and storage (combined with either coal, gas, or biomass), and renewables combined with energy storage – that can fulfill this role. Therefore the assumptions that are made about the availability of each of these technologies have a major impact on each other's deployment, and in turn the value of these technologies. In light of this fact, we will consider the nonmarket impediments that may constrain future growth of nuclear fission, and briefly comment on carbon capture and storage (CCS).

This analysis is similar in scope and procedures to an earlier effort to evaluate the value of advanced nuclear *fission* technology (Kim and Edmonds, Program on Technology Innovation: Nuclear Energy in a Carbon-Constrained World, 2005), but here we consider nuclear fusion. Its goals are also in line with those of an earlier study on fusion energy that used the EFDA/TIMES integrated assessment model (Han and Ward, 2009), but the authors of that work stressed that the model was in a very early stage of development whereas GCAM is much better established in the modeling community. Others have previously examined the impact of a technology they identified as "fusion", but they sought the requisite breakeven prices for fusion to penetrate the market rather than use projected costs based on engineering assessments (Kim and Edmonds, 1996) (Tokimatsu, et al., 2002).

## 2. Methods

### 2.1. GCAM

The Global Change Assessment Model is used to examine carbon-constrained scenarios – stabilizing $CO_2$ (not $CO_2$-e) concentrations at 450 ppm or 550 ppm by 2095 – under a range of technology options including the new addition of fusion energy. In general, the focus is on the interaction between GCAM's climate and energy models. In GCAM, certain parameters are prescribed exogenously, such as global population, labor productivity, and carbon emissions in scenarios with climate policy. Others are calculated endogenously, for example electricity prices, carbon prices, and electricity demand. It is a partial equilibrium model operating in 5-year time steps, so in every period the energy market is cleared by balancing supply and demand. Unlike some other models in common practice, it is not an optimization model, meaning the policy cost associated with meeting a particular carbon target is not necessarily the minimum cost of all possible trajectories that reach that target.

In the energy sector, new builds to meet growing demand for electricity are allocated using a "logit choice methodology" (Kim et al., 2006). This means that, because costs are only prescribed as average values, market shares are determined using a probabilistic model of the relative prices based on the assumption that every market includes a range of suppliers, purchasers, and circumstances unique to a particular environment. Therefore not all purchasers will choose the technology with the lowest average price, which is argued to be consistent with both economic principles and real observations. Furthermore, the age of the existing stock is stored in the model, and the plants have prescribed lifetimes (although they can be shut down prematurely if operating costs alone exceed the total cost of alternatives). Together, this treatment tends to prevent rapid shifts in the energy sector and also tends to preclude convergence toward a single "winning" technology. Nevertheless, we will see that with strong mitigation targets, carbon-neutral baseload technologies become extremely important.

### 2.2. Assessing fusion costs

Creating a new option for electricity generation in GCAM requires that the costs of that technology be specified in the model in every time period. Recent cost estimates were made for hypothetical magnetic fusion power plants (Han and Ward, 2009) and inertial fusion power plants (Anklam et al., 2011). Since estimates are comparable and it is too early to say which technology (if any) will ultimately be commercialized, we use the former more well-developed estimates but assume that the technology specifications are not rigid.

Han and Ward's approach was to update *The European Power Plant Conceptual Study* (PPCS) (Maisonnier, et al., 2005), which assessed the likely economic performance of fusion power plants concepts under a range of technical assumptions. The estimates from the PPCS bracketed those of another study that analyzed the ARIES-AT design (Najmabadi, et al., 2005), which increases confidence in the assessment methodology. Han and Ward argued that recent advances called for modifications to several assumptions and warranted an update for the cost estimates. They focused on two PPCS concepts that might be deployed, labeled them the "basic" and "advanced" reactors and, using the same methodology as the original study, derived estimates for "10th of a kind" and "100th of a kind" plants. Although the "advanced" plant would be less expensive, we use their estimates for the "basic" plant (in an attempt to be more conservative) in the base case, assume that 10th of a kind costs will be realized by 2050, 100th of a kind by 2065, and subsequently multiply capital costs and variable operations and maintenance by .9 in both 2080 and 2095. As mentioned, alternative cases are also considered—namely one in which fusion is delayed by 15 years, and another in which costs are varied by ± 30%.

The factor of 0.9 was chosen to account for learning, which has not yet been included in GCAM as an endogenous parameter. Taking that to be the progress ratio implies a doubling of fusion deployment from 2065 to 2080 and 2080 to 2095. This progress ratio is roughly consistent with the 0.89 that Han and Ward originally used to calculate the 100th of a kind cost. It is fairly conservative compared to the widely used ratio of 0.8 (or "80 percent rule") that stems from an extensive review of learning rates in diverse industries (Dutton and Thomas, 1984), or even compared to the estimate of 0.83–0.84 emerging from a specific review of energy technologies (McDonald and Schrattenholzer, 2001). We do note, however, that learning for nuclear fission has been much less pronounced and, in fact, sometimes has been characterized as negative, even in the case of France (Grubler, 2010). The final assumption we make is that the first year that fusion power plants will be available is 2035 in the base case (2050 in the delayed case), at costs that are 20% higher than 10th of a kind plants. Note that the rate of cost reductions from this first of a kind plant to the prescribed 10th of a kind plant is not consistent with the progress ratio of .9, but we assume that the first batch of power plants would receive national assistance to facilitate fusion's entry into the market. While out of the scope of this work, it would be valuable to benchmark the costs used here with those projected for ITER—a magnetic fusion project current under construction in France that is expected to precede a demonstration power plant. ITER is considerably more expensive (despite having neither a breeding blanket for fuel production nor equipment for electricity