**Award Information** - ER64947
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**Principal Investigator**: Mort D Webster
**Institution**: Massachusetts Institute of Technology
**Title**: RECOVERY ACT - Methods for Decision under Technological Change Uncertainty and Risk Assessment for Integrated Assessment of Climate Change
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**Program Manager**: Robert W. Vallario
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## FINAL REPORT

This report presents the final outcomes and products of the project as performed at the Massachusetts Institute of Technology.

## SECTION 1. RESEARCH RESULTS

The research project can be divided into three main components: methodology development for decision-making under uncertainty, improving the resolution of the electricity sector to improve integrated assessment, and application of these methods to integrated assessment. Results in each area is summarized below.

### *A. Methods for Decision under Uncertainty*

There has been substantial progress on developing alternative algorithms for multi-stage decision-making under uncertainty with learning. Most of this work has been to develop methods for approximate dynamic programming that could be applied to integrated assessment models and related analysis tools.

In one study, we developed and demonstrated a method for coupling time-scales (fast and slow) when there is stochasticity on both time scales (Parpas and Webster, 2014). The key idea of this approach is to use the theory of Markov processes and show that the fast time-scale can be approximated by using its steady-state distribution, and embedding that within the slow time-scale. We applied this method to capacity planning for electricity generation, but the method could be applied to many other problems.

Another method developed and applied to two different problems (Parpas and Webster, 2013; Webster et al., 2012) performs approximate dynamic programming using a mesh-free approach to approximating the value function. Rather than try to develop a reduced-form function that globally fits everywhere, this approach relies on piecewise linear fits in each region around the samples that have been observed. We have shown in these two applications to electricity and to integrated assessment of climate change that the model converges to a solution in several orders of magnitude less computation time than traditional solution methods.

Finally in another study currently in review (Parpas et al., 2014), we have developed an innovative method for multi-stage (more than two) stochastic programming using importance sampling. This method uses Markov Chain Monte Carlo to sample from the optimal importance sampling distribution to generate samples for the stochastic programming algorithm. We have tested this method on a variety of problems, and this method demonstrates advantages over the alternative method (Quasi-Monte Carlo sampling) for problems with high variance or other non-standard distribution shapes.

*B. Improving resolution of Electric Sector*

Much work has progressed in developing models of the electricity sector, which can eventually be coupled with economy-wide integrated assessment models. In one set of studies (Palmintier and Webster, 2014a; 2014b), we developed an innovative method for incorporating hourly dynamics and constraints of electric power systems into long-term energy planning models. This approach, based on converting from binary variables and constraints to far fewer integer variables and constraints, allows the solution of long-term models in orders of magnitude less computation time. Using this method, we have shown that the mix of technologies for generating electricity would be significantly different with a carbon constraint and renewable standard when accounting for the hourly dynamics than when neglecting them. Current long-term models without the hourly dynamics are likely to have significant errors in their estimates of emissions, costs, and technology mix.

In another high-impact study (Webster et al., 2013), we have coupled the carbon emissions problem with considerations of water impacts, specifically the withdrawals of water for cooling of thermal generation plants. Within a power sector planning model, we have demonstrated that the least-cost mix of technologies that would reduce carbon emissions would likely have greater water usage, and that the mix of technologies required to reduce both carbon emissions and water withdrawals is qualitatively different from that to reduce only carbon.

Two other analyses have used electric sector models to address questions key integrated assessment questions that require greater resolution of the power sector. In one study currently in review (Eide et al., 2014), we explored the implications of carbon emissions standards within a stochastic planning model to see if this mechanism would provide incentive for investment into carbon capture and sequestration (CCS). This study demonstrated that emissions standards could deter investment into CCS depending on emissions limit set. In another study to be submitted shortly for publication (Santen et al., 2014), an electric sector planning model was used to explore the impacts of R&D into various technologies, and the interactions of the R&D portfolio with long-run emissions reductions.

*C. Applications for Integrated Assessment*

Several studies have applied the methods of uncertainty and decision to integrated assessment. In one set of studies (Felgenhauer and Webster 2013; 2014), we have demonstrated the importance of distinguishing among adaptation activities when assessing the balance of mitigation and adaptation under uncertainty. Rather than treat adaptation investments as homogenous in integrated assessment studies, we propose three distinct categories: flow adaptation, stock adaptation, and option stock adaptation.

In two other studies to be submitted shortly (Morris and Webster, 2014; Seelhof et al., 2014), we have applied the dynamic programming methods developed (see above) to two different models to explore the mix of electricity sector technologies that should be invested in in the near-term when long-term emissions reductions targets are uncertain, as well as future technology costs and future fuel prices. In both of these studies, the methods developed allow us to demonstrate within a variety of models the importance of a robust near-term investment strategy within the energy sector.

Most recent products delivered:

**SECTION 2. PUBLICATIONS AND PAPERS IN PRESS**

de Sisternes, F.J., Webster, M.D., and Perez-Arriaga, J.I. (2015). The Impact of Bidding Rules on Electricity Markets with Intermittent Renewables. *IEEE Transactions on Power Systems* (in press).

Eide, J., de Sisternes, F., Herzog, H. and Webster, M. (2014). $CO_2$ emissions standards and investment in carbon capture. *Energy Economics* **45** (2014) 53–65.

Felgenhauer, T. and Webster, M. (2014). Modeling Adaptation as a Flow and Stock Decision with Mitigation. *Climatic Change* **122**: 665-679.

Felgenhauer, T. and Webster, M. (2013) Multiple Adaptation Types with Mitigation: A Framework for Policy Analysis. *Global Environmental Change* **23** (6): 1556-1565.

Palmintier, B. and Webster, M. (2014). Heterogeneous Unit Clustering for Efficient Operational Flexibility Modeling. *IEEE Transactions on Power Systems* 29 (3): 1089-1098.

Parpas, P., Ustun, B., Webster, M., and Tran, Quang Kha (2015). Importance Sampling in Stochastic Programming: A Markov Chain Monte Carlo Approach. *INFORMS Journal on Computing*. (in press).

Parpas, P. and Webster, M. (2013). A stochastic minimum principle and a meshfree method for stochastic optimal control. *Automatica* **49** (6): 1663-1671.

Parpas, P. and Webster, M. (2014). A stochastic multiscale model for electricity generation capacity expansion. *European Journal of Operational Research* **232** (2): 359-374.

Webster, M., Donohoo, P., and Palmintier, B. (2013). Water-$CO_2$ Tradeoffs in Electricity Generation Planning. *Nature Climate Change* **3** (27 October 2013): 1029-1032. DOI: 10.1038/nclimate2032.

Webster, M.D., Santen, N.R. and Parpas, P. (2012). An approximate dynamic programming framework for modeling global climate policy under decision-dependent uncertainty. *Computational Management Science* **9**: 339–362.

**Section 3. Papers in Review and Working Papers**

Morris, J., Webster, M., and Reilly, J. (2014). Hedging Strategies: Electricity Investment Decisions under Policy Uncertainty. *Energy Journal*. (Revise-and-Resubmit).

Palmintier, B. and Webster, M. (2015). Impact of Operational Flexibility on Generation Planning. *IEEE Transactions on Sustainable Energy*. (In Review).

Santen, N.R., Webster, M.D., Popp, D. and Perez-Arriaga, I. (2014). Inter-temporal R&D and capital investment portfolios for the electricity industry's low carbon future. *Energy Journal*. (Revise and Resubmit).

Seelhof, M., Ustun, B., and Webster, M. (2014). Long-term Planning for the Electric Sector under Regulatory and Market Uncertainty. Working Paper.

**Section 4. Selected Other Publications (Student Theses and Conference Abstracts)**

Palmintier, B.P., 2012: Incorporating Operational Flexibility into Electric Generation Planning: Impacts and Methods for System Design and Policy Analysis. Ph.D. Thesis, Engineering Systems Division, MIT, June.

Santen, N.R., 2012: Technology Investment Decisions under Uncertainty: A New Modeling Framework for the Electric Power Sector. Ph.D. Thesis, Engineering Systems Division, MIT, June.

Morris, J., 2013: Electricity Generation and Emissions Reduction Decisions under Uncertainty: A General Equilibrium Analysis. Ph.D. Thesis, Engineering Systems Division, MIT, June.

Seelhof, M., 2014: Long Term Infrastructure Investments Under Uncertainty in the Electric Power Sector Using Approximate Dynamic Programming Techniques. Ph.D. Thesis, Systems Design and Management, MIT, January.

**Most recent notes concerning the project:**
None

**Other Project Information Sources:**

**Project URL:**
None

**Related URL at institution:**
None