# Energy Storage Investment and Operation in Efficient Electric Power Systems

*Cristian Junge,[a] Dharik Mallapragada,[b] and Richard Schmalensee[c]*

This essay grew out of our work on the MIT Energy Initiative's ongoing *Future of Storage* project, which is concerned with the roles of different energy storage technologies in future decarbonized electric power systems. Our work has focused on simulating optimal investment in and operation of regional electric power systems with tight limits on carbon emissions circa 2050.

In this essay we explore the general properties of cost-efficient electric power systems in which storage performs energy arbitrage to balance supply and demand. We start from an investment planning model descended from the work of Boiteux and Turvey. We assume constant returns to scale in storage as well as in generation, and neglect startup costs of thermal generators. We assume perfect foresight but do not restrict the evolution of demand or of renewable generation. Time periods are linked by use of storage and of ramping constraints on thermal generators.

Using Karush-Kuhn-Tucker analysis we are able to obtain a number of general results regarding investment in and operation of storage facilities under perfect competition and that serve to unify and extend the prior literature. First, we show explicitly that the problem of maximizing overall social welfare in that model can be decomposed into the problems faced by profit-maximizing, perfectly competitive suppliers of each available technology. Second, we show that classic merit-order dispatch for thermal generators is not generally optimal when ramping constraints are binding. Third, our analysis reveals the greater complexity of efficient investment in and operation of storage facilities than for generation. In general, even under constant returns to scale, storage technologies are described by the values of seven parameters. We show that all deployed storage technologies break even at equilibrium under constant returns to scale.

We show analytically that if it is optimal to employ multiple storage technologies, the ones with the lowest capital cost of energy storage capacity are generally the best suited to providing long-term storage. Finally, we employ a numerical case study to illustrate the complexity of operating patterns of storage in systems with multiple storage technologies. Storage technologies optimally play multiple roles, providing charge-discharge cycles of various durations. This exercise supports the insights developed analytically, shows that general analytical results of the "merit-order" variety are not available for storage, and demonstrates the value of frequency domain analysis to characterize the cost-efficient operating regimes of multiple storage technologies.

We see three important directions for future work. First, if the market price of energy is capped below the value of lost load, as is often the case in practice, there will likely be under-investment in storage. It seems plausible, but unproven, that the second-best response involves subsidies to investment in storage. Moreover, even if such subsidies are second-best optimal, they surely vary with the characteristics of storage technologies in ways that are not yet understood.

Second, our use of frequency domain analysis here to describe the optimal operation of storage systems seems to us likely to have merely scratched the surface of what that approach

---

[a] MIT Energy Initiative, Massachusetts Institute of Technology

[b] MIT Energy Initiative, Massachusetts Institute of Technology

[c] Corresponding author: MIT Sloan School of Management and Department of Economics, Massachusetts Institute of Technology. Cambridge, MA 02139. USA. Email: rschmal@mit.edu

*The Energy Journal*, Vol. 43, No. 6

can contribute. Examining how the power spectra of alternative storage technologies respond to changes in cost parameters and system conditions may yield broadly useful insights.

Finally, there is clearly a need for efficient computational models that can be used to optimize the operation of real storage systems under realistic stochastic processes of demand and intermittent generation, with realistically imperfect foresight.