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The role of electricity storage and hydrogen technologies in enabling global low-carbon energy transitions

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HIGHLIGHTS

- Without climate policy, small storage/H_2 costs enable smaller power sector emissions.
- With climate policy, small storage/H_2 costs reduce long-term mitigation costs.
- Large-scale deployment of electricity storage only occurs when costs are small.
- With large storage/H_2 costs, large wind and solar PV shares can still be supported.

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ABSTRACT

Previous studies have noted the importance of electricity storage and hydrogen technologies for enabling large-scale variable renewable energy (VRE) deployment in long-term climate change mitigation scenarios. However, global studies, which typically use integrated assessment models, assume a fixed cost trajectory for storage and hydrogen technologies; thereby ignoring the sensitivity of VRE deployment and/or mitigation costs to uncertainties in future storage and hydrogen technology costs. Yet there is vast uncertainty in the future costs of these technologies, as reflected in the range of projected costs in the literature. This study uses the integrated assessment model, MESSAGE, to explore the implications of future storage and hydrogen technology costs for low-carbon energy transitions across the reported range of projected technology costs. Techno-economic representations of electricity storage and hydrogen technologies, including utility-scale batteries, pumped hydro storage (PHS), compressed air energy storage (CAES), and hydrogen electrolysis, are introduced to MESSAGE and scenarios are used to assess the sensitivity of long-term VRE deployment and mitigation costs across the range of projected technology costs. The results demonstrate that large-scale deployment of electricity storage technologies only occurs when techno-economic assumptions are optimistic. Although pessimistic storage and hydrogen costs reduce the deployment of these technologies, large VRE shares are supported in carbon-constrained futures by the deployment of other low-carbon flexible technologies, such as hydrogen combustion turbines and concentrating solar power with thermal storage. However, the cost of the required energy transition is larger. In the absence of carbon policy, pessimistic hydrogen and storage costs significantly decrease VRE deployment while increasing coal-based electricity generation. Thus, R&D investments that lower the costs of storage and hydrogen technologies are important for reducing emissions in the absence of climate policy and for reducing mitigation costs in the presence of climate policy.

1. Introduction

During the period from 1990 to 2010, variable renewable energy (VRE) deployment increased rapidly, with average annual global primary energy growth rates of 44% and 25% for solar and wind, respectively [1,2]. This largescale deployment has been motivated by a number of drivers, including government subsidies, rapidly declining investment costs, energy security concerns, and growing global consensus around climate change risks [3,4]. Future scenarios of the global energy system suggest an even larger role for renewable energy over the

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Acronyms: VRE, variable renewable energy; PHS, pumped hydro storage; CAES, compressed air energy storage; IAM, integrated assessment model; MESSAGE, model for energy supply strategy alternatives and their general environmental impact; RLDC, residual load duration curve; H2, hydrogen; CT, combustion turbine; GHG, greenhouse gas

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next century, particularly if climate policy is introduced. Six global integrated assessment models (IAMs) indicate that solar and wind energy is projected to comprise 35–63% of total electricity generation in 2050 and 47–86% in 2100 if policies that limit warming in 2100 to 2 degrees Celsius above pre-industrial levels are introduced [5]. However, integration of renewable electricity sources, with their inherently variable nature, introduces novel challenges, both in terms of real-world deployment and model implementation.

VRE temporal variability, forecast uncertainty, and location-dependence prompt accompanying integration costs in terms of short-term balancing services, firm reserve capacity, thermal plant operational flexibility, VRE curtailment, and transmission expansion [6]. The increased flexibility required to maintain grid balance with large-scale VRE deployment can be achieved through a number of strategies or technologies such as flexible generation, VRE curtailment, electricity storage, hydrogen technologies, and demandside management [7]. The role of storage technologies for integrating large shares of renewables are typically assessed using temporally-resolved electricity dispatch models, with the intention of quantifying storage requirements [8,9], assessing storage profitability in power markets [10–12], or forecasting storage deployment in capacity expansion models [13–15]. However, it is also important to account for these challenges and their associated costs when assessing the long-term global energy system transitions needed to mitigate climate change.

The models typically used to assess these transitions are global IAMs, which endogenously consider cost and performance trade-offs among energy supply and end-use technologies to provide insights into the future development of energy systems and the associated investments required to meet long-term climate targets [16]. Given their technological detail and broad spatial and temporal scope, IAMs have been effective tools for assessing long-term global energy and emission scenarios and have been widely used to identify mitigation challenges, emission trajectories, and the implications of policy for meeting climate change targets [16]. However, for computational reasons, the broad scope has necessitated compromises in spatial and temporal resolution, which poses a challenge for representing renewable energy resources, which typically exhibit large spatial and temporal heterogeneity. Consequently, the variability of renewable generation and its associated integration challenges must be parameterized indirectly in IAMs. Although several global IAMs have recently addressed this concern by improving their representation of the technologies and investments required to integrate large VRE shares [5,17], no previous study has used a global IAM to assess the sensitivity of future VRE deployment to uncertainties in the future costs of storage and hydrogen technologies, which previous studies suggest will be important technologies for integrating VRE [13].

In this study, we assess the role of electricity storage and hydrogen technologies in enabling global low-carbon energy transitions using the global IAM, MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), which is a partial-equilibrium optimization model with a detailed bottom-up representation of energy transformation technologies (see supplementary material for more information) [18,19]. In previous research, the representation of system adaptations for integrating VRE was improved through the introduction of two constraints to ensure sufficient capacity reserves and system flexibility [20] and through the parameterization of VRE curtailment, non-VRE flexibility requirements, and wind and solar PV capacity values based on region-specific residual load duration curves (RLDC) [21]. Using this updated representation, Johnson et al. [21] highlight the importance of electricity storage and hydrogen technologies in enabling high-VRE penetration scenarios, particularly in carbon-constrained scenarios. However, previous studies assumed a single 'generic' storage technology with a relatively small cost ranging from \$800/kW in 2010 to \$600/kW in 2100 for 12 h of storage. Yet, there are several technologies that can provide bulk electricity storage and grid services, including hydrogen technologies, and there is uncertainty regarding their future costs and deployment potentials [22]. Thus, future VRE deployment and/or the costs of climate change mitigation may depend on how storage and hydrogen technologies develop.

This paper contributes modeling methods and policy insights regarding the roles of electricity storage and hydrogen technologies for integrating large shares of renewable energy. We improve upon the representation of electricity storage in the MESSAGE model by implementing several storage technology profiles to replace the single existing 'generic' technology profile. The approach and parameterization described herein could inform improved storage technology representations in other long-term energy-economic models. With these updated technologies, we conduct a scenario-based assessment of how VRE deployment rates are impacted across a range of plausible storage technology cost trajectories. Given the substantial role of VRE resources in low-carbon energy scenarios as well as the importance of electricity storage and hydrogen technologies for enabling VRE deployment, this analysis contributes important insights regarding the techno-economic conditions that may facilitate or impede low-carbon futures. While previous reports have published near-term storage technology assessments [23–25], to our knowledge no previous analysis has assessed the impact of storage and hydrogen cost trajectories on long-term global low-carbon energy transitions. More specifically, storage forecasting assessments generally extract historical trends or perform expert surveys, and are often limited to a short (< 25 year) forecasting horizon and small geographic area. Further, the techno-economic assessments of hydrogen and storage technologies provide valuable information on the state-of-the-art, but do not provide insight into the system-level impacts of cost uncertainties. In contrast, the use of an integrated assessment model enables an exploration of how these cost uncertainties may impact future energy investment decisions and the consequences for long-term climate change mitigation strategies and costs. Each storage technology profile is parameterized through a literature review, focusing on the grid services that they provide (Section 2), as well as the reported ranges for their future costs and deployment potentials (Section 3). These ranges are represented in the integrated assessment model MESSAGE using ten distinct scenarios (Section 4). Using these scenarios, we assess the sensitivities of VRE deployment and climate change mitigation costs across the range of projected electricity storage and hydrogen technology costs (Sections 5). Finally, the limitations associated with this analysis (Section 6) and key conclusions (Section 7) are discussed.

2. Storage technology services

The electricity system services provided by storage technologies are represented by a series of constraints in MESSAGE that account for hourly-daily and seasonal curtailment and ensure sufficient firm capacity and flexible generation as VRE deployment increases [20,21]. Hydrogen and storage technologies with distinct technical characteristics are included in the model that can mitigate curtailment and/or provide firm capacity and system flexibility.

VRE curtailment in MESSAGE has been parameterized using regional residual load duration curves (RLDC) for distinct wind/solar PV mixes, which represent net load after VRE generation has been subtracted from the total load [21,26]. The average total curtailment is split into short-term curtailment (< 24 h) and seasonal curtailment [21]. Pumped hydro, compressed air energy storage, utility-scale batteries, and hydrogen electrolysis enable load-following and ramping services that can mitigate curtailment at the hourly-daily timescale.

Seasonal variations in electricity demand have historically been accommodated by gas, oil, and coal fuel storage. At high VRE penetrations, the seasonal variations in renewable resources combined with smaller shares of conventional generators may require additional seasonal electricity storage to balance the grid. As such, at high VRE penetration levels, VRE curtailment is observed, even with an entirely