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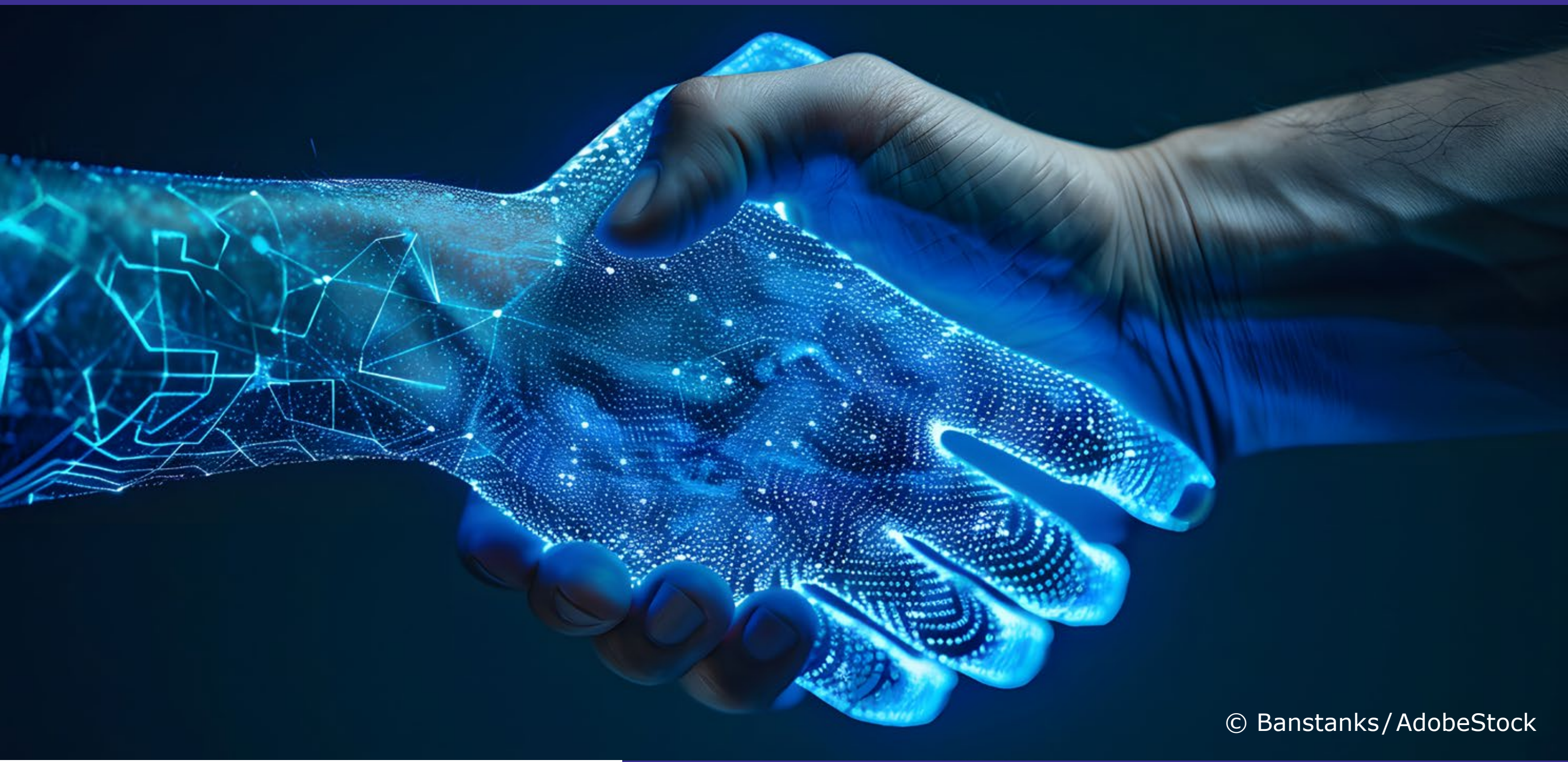

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LIGHTS - Technology

Beyond battery-only thinking: What dual storage means for renewable power decisions

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Abstract

This paper translates recent research on batteries, hydrogen, and renewable load shifting into managerial and policy terms. The core message is that storage choices should not be reduced to a search for a single winning technology. Batteries and hydrogen-like storage differ not only in cost and efficiency, but also in how they charge, how often they can be used, and how operating rules shape private investment. We show why a less efficient technology like hydrogen can still improve system-level outcomes in some settings, why hydrogen may become relevant for daily balancing earlier than it is often assumed, and why combining storage technologies can lower cost and even unlock higher renewable penetration than a single-technology strategy.

Keywords: energy storage, batteries, hydrogen, renewable integration, responsible decision-making

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Why this research matters now

Power systems are under pressure to do two things at once: decarbonize rapidly and remain reliable every hour of the day. Solar power has become cheap and abundant, but its output is null at night and maximum in the middle of the day, while electricity demand often peaks later. That mismatch is now one of the central operational challenges of the energy transition. Storage is the natural bridge, yet most discussions still treat storage as if one technology should dominate. Our research asks a different question: what happens when decision-makers consider two fundamentally different storage technologies together?

The paper studies a stylized but practically relevant setting in which developers can invest in two types of storage. One resembles batteries: efficient, fast, and storage-constrained – to store more energy, one needs to buy more batteries. The other resembles hydrogen or other long-duration, conversion-limited technologies: less efficient, but able to keep charging for long periods once power capacity is installed – and this type of storage is relatively cheap if the gas is stored in salt caverns. We then examine not only investment decisions, but also an operational question that matters more than it may first appear: when excess renewable electricity is scarce, which technology gets priority for charging and discharging?

Why operating rules matter as much as technology choice

Operating rules matter because the energy transition is not only about adding capacity. It is also about shaping incentives. Developers invest based on expected usage and profitability. Regulators and system operators, meanwhile, care about broader outcomes such as renewable penetration, system cost, and responsible use of public support. Here, a priority rule simply means a dispatch instruction deciding which storage asset gets scarce surplus electricity first; renewable penetration means demand served by renewables, including via energy stored and later released. The core contribution of the research is to show that these operational and investment choices interact in non-obvious ways. For managers and policymakers, the main takeaway is simple: storage decisions should not be reduced to an efficiency contest. The right answer depends on how technologies complement each other, how often they can be used, and what operating rules govern them. In some cases, a less efficient technology can still improve system-level outcomes because of how it changes investment incentives and how long it can stay active when renewable surplus is available.

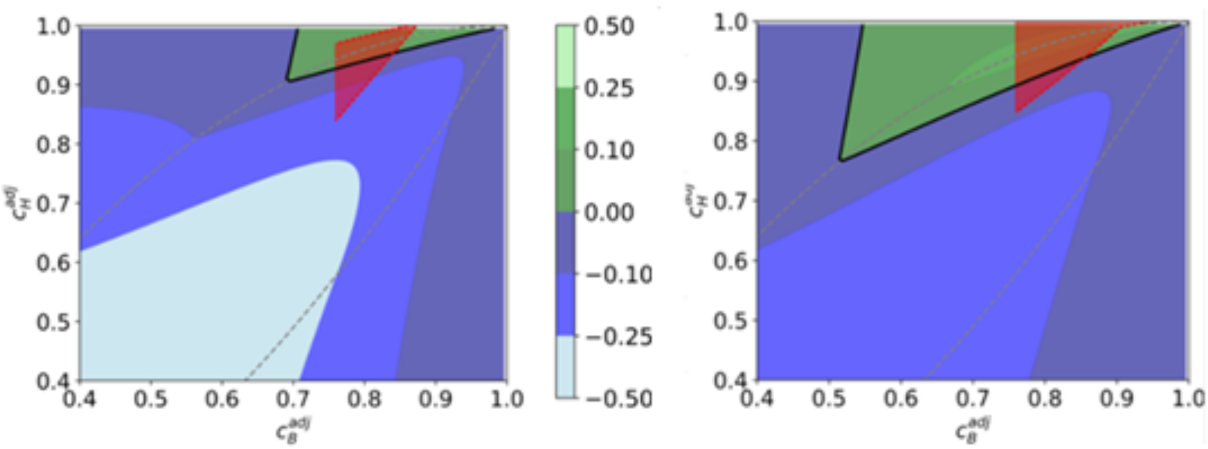
In a simple setting where installed capacities are already fixed and the system operator must simply decide how to run them, then the more efficient technology should be prioritized. In our setting, that means batteries should go first ex post, because they lose less energy in the charge-discharge cycle. That result is intuitive and robust.

The more interesting result appears when operational priority is chosen before developers invest, and hence affects investment decisions. In that case, the logic changes. Giving priority to hydrogen-like storage can, under identifiable market conditions, increase renewable penetration relative to battery-first rules. This is not because hydrogen becomes more efficient. It does not. The reason is that hydrogen-like technologies (when the gas is stored in salt caverns) are constrained mainly by power rather than by stored energy. Put simply, the costly part is the pipe, not the tank: Once built, a unit of capacity can keep charging for many hours whenever surplus renewable electricity is available, without operators worrying too much about whether there is enough space to store the energy. That can make early units of hydrogen capacity especially valuable on sunny days. If priority rules make those units more likely to be used, developers may invest in them when they otherwise would not. The result can be more renewable electricity shifted into the hours when demand needs it most.

This finding is important for responsible decision-making because it shows that operating rules are not neutral. They shape market outcomes. A regulator that wants to support a broader storage mix does not always need to rely only on subsidies. In some settings, it can influence investment through transparent, verifiable priority rules. That may reduce the need for more distortionary interventions. At the same time, the result does not justify a blanket hydrogen-first policy. The gain appears only in part of the parameter space, especially when hydrogen-like technologies are still relatively costly but close to being commercially viable. The policy lesson is therefore targeted rather than universal: where markets are near a tipping point, operational design can matter a great deal.

What the priority results look like in practice

Figure 1 summarizes this idea. It shows the range of technology cost combinations for which giving priority to hydrogen-like storage can increase renewable penetration (green area). The research estimates that, in the relevant part of the cost space, prioritizing hydrogen rather than batteries may raise the share of demand served through stored renewable electricity by up to 19%. The effect can be even larger for a more efficient conversion-limited technology such as compressed air. But the picture also shows why decision-makers should be cautious. The region where this effect appears is meaningful in practice today (the red cone in Figure 1 identifies likely cost evolutions for the coming years), yet it is far from being the whole cost space. As technology costs evolve, the best policy can change.



(a) Hydrogen (b) Compressed Air

Figure 1. The impact of prioritizing hydrogen-like storage on renewable penetration, as a function of technology costs

Hydrogen may matter earlier than the standard narrative suggests

A second message is that hydrogen should not be thought of only as a distant seasonal solution. Public debate often frames hydrogen storage as something for the distant future, mainly useful when energy must be shifted across weeks or months. Our results suggest a more nuanced view. Because hydrogen-like technologies and batteries differ in how they charge, hydrogen can become a profitable part of diurnal load shifting before seasonal storage becomes attractive. In calibrated examples for European markets, hydrogen can become commercially relevant for day-night balancing as early as 2027 or 2028.

That does not mean hydrogen will dominate batteries. It means managers should avoid a false dichotomy. Batteries remain highly attractive because of their efficiency and operational flexibility, but storing energy for more than several hours is still too costly. The evidence suggests that hydrogen-like storage may enter earlier than many decision-makers assume, particularly in systems with long periods of daytime surplus. This matters for strategic planning, supplier relationships, permitting, and infrastructure investment. Firms that wait for a single technology winner may miss the window to build capabilities in a mixed-storage world.

Look at duration, not only at peak surplus

A third message is that the timing and shape of renewable surplus matter as much as, or more than, its headline volume. One of the most useful managerial findings in the paper is that hydrogen-like technologies are likely to be adopted first in places where excess renewables are available for longer hours, not necessarily where the daily surplus peaks are highest. In the model, solar duration plays a decisive role in technology adoption, while solar peak does not drive adoption in the same way.

That insight matters because managers often look first at aggregate renewable build-out or at the maximum amount of excess generation. Our results suggest a more operational lens. What matters for some storage technologies is how long surplus energy persists, because that determines whether power-constrained assets, like hydrogen storage, can keep charging over an extended period. For market analysis, business development, and site selection, duration should therefore be treated as a first-order variable. A region with somewhat smaller solar peaks but long hours of surplus may be more attractive for hydrogen-like storage than a region where production peaks dramatically every day but only for a short time.

The same logic applies to seasonal storage. When renewable surplus occasionally exceeds unmet demand at night, the balance begins to tilt further toward hydrogen-like storage. We identify two tipping points. The first is the moment when hydrogen starts to be worth adding next to batteries. The second comes when batteries reach their practical discharge limit in seasonal conditions. After that point, further cost declines can shift more of the storage mix toward hydrogen-like assets. This helps explain why hydrogen is so often associated with seasonal balancing, while also clarifying that that role may become relevant much earlier, in shorter-duration applications.

The case for a portfolio of storage technologies

A fourth message is that the real value of storage may lie in portfolios rather than stand-alone technologies. Much of the market discussion compares battery-only and hydrogen-only strategies. Our results suggest that this framing is often too narrow. It is true that in some situations, combining the two technologies offers no real advantage over investing in one. But in other situations, dual investment leads to materially lower cost or to renewable penetration levels that cannot be reached with a single technology alone.

Figure 2 illustrates this portfolio logic. At current or near-current cost levels and moderate renewable surplus (scenario A), load shifting can remain expensive regardless of the technology used. But when technology costs fall and renewable surplus grows, the picture changes (scenarios B and C). In one set of scenarios calibrated to future market conditions, a dual-technology strategy can reduce cost by roughly 25% to 30% compared to a single-technology strategy. When oil price and solar surplus are very substantial, the outcome of a dual-technology strategy is even more important: very high renewable penetration becomes feasible when neither batteries alone nor hydrogen alone can achieve this.

Why does this happen? Each technology solves a different problem. Batteries are efficient but expensive when used to carry large quantities of energy for long periods. Hydrogen-like storage can accumulate charge across longer windows but loses more energy in the process. Used separately, each technology runs into its own limitation. Used together, they can offset each other's weaknesses. For managers, this is a classic portfolio insight: complementarities matter, and the best system design can involve a mix of assets with different strengths rather than a scaled-up version of one familiar technology.

Consider a solar-rich region in Southern Europe with long midday surplus but evening reliability problems. A battery-only plan may efficiently cover the first evening hours but become costly if the region wants to shift energy across a longer window. A hydrogen-only plan may absorb long surplus periods but will waste more energy in conversion. A mixed plan could let batteries handle scarce or short surplus and hydrogen-like storage absorb longer surplus periods, reducing fossil backup and curtailment.

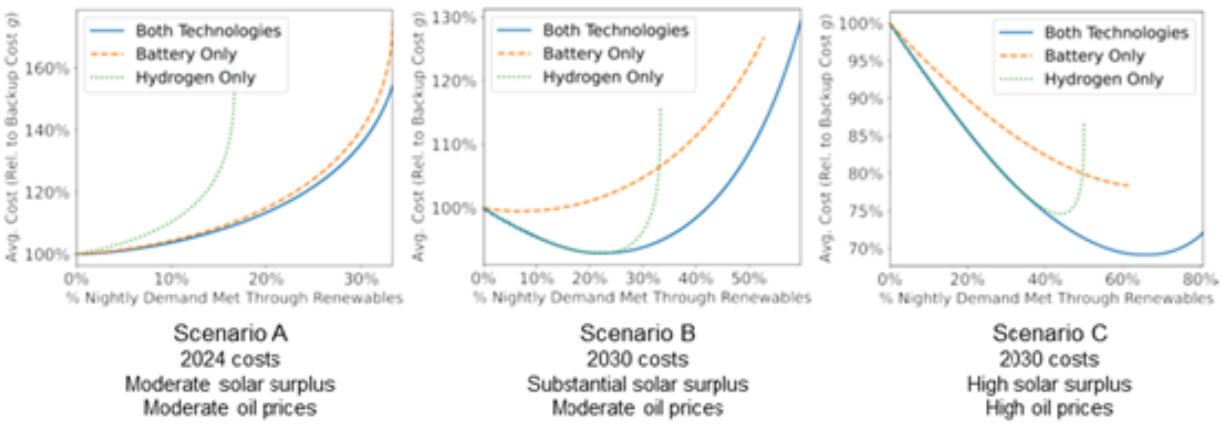


Figure 2. Cost implications of battery-only, hydrogen-only, and dual-technology strategies 32,

3,20at different renewable penetration levels.

A useful refinement: solar-adaptive priority

The research also explores a promising policy refinement: a solar-adaptive priority rule. Instead of always giving priority to one technology, the rule changes with solar conditions. Batteries receive priority when surplus is limited, because efficiency matters most then. Hydrogen-like storage receives priority when surplus is abundant, because long charging windows become more valuable. Under mild assumptions, this adaptive rule improves on a simple hydrogen-first policy by raising renewable penetration and developers' profit while preserving the same capacity choices.

For policy-makers, that result points toward a broader principle of responsible design. Static rules are easy to communicate, but state-contingent rules can better match physical realities if they exploit the right contingency. In practice, a market operator could implement such a rule through published surplus thresholds, dispatch protocols, and metering-based audits. The challenge, of course, is governance: rules must remain transparent, implementable, and resistant to manipulation. The hard parts would be choosing thresholds, updating them as costs change, and avoiding opaque rules. Still, the broader implication is encouraging. Better outcomes may not require choosing between market efficiency and environmental performance. Well-designed operating rules can improve both.

How the research is built, and why that matters

Behind these messages is a deliberately simple research design built to make trade-offs visible. The paper models two profit-seeking storage developers and a regulator that cares about the share of demand met through renewable energy. Excess solar generation varies from day to day, and any unmet demand can still be served by conventional backup generation. This framing is useful for practice because it mirrors the real tension that many energy systems face: private investors respond to project economics, while public authorities care about broader system outcomes. The research therefore does not ask only what an ideal planner would do. It asks how decentralized investment and operational rules interact.

That distinction matters. In many markets, storage will not be built by a single actor optimizing the whole system. Independent developers, utilities, technology firms, and regulators all influence the outcome, often with different objectives. A decision rule that looks sensible from a purely engineering perspective may create weak incentives for private investment. Conversely, a policy that stimulates one technology too aggressively may lock the system into a less balanced portfolio. By analyzing these interactions directly, the research addresses a common managerial challenge: how to align commercial viability with decarbonization goals.

The paper also calibrates the model using data from three European settings with different characteristics: France, Germany, and La Palma in the Canaries. That step is important because it grounds the analysis in markets with distinct mixes of demand, renewable output, and backup power cost. France combines high renewable ambitions with substantial nuclear baseload. Germany is scaling renewables without comparable firm low-carbon baseload. La Palma is a smaller island system with higher electricity costs and strong incentives to reduce reliance on fossil generation. The point is not that these three cases represent every market. The point is that the main mechanisms remain visible across quite different operating environments.

Implications for responsible management and policy

What should decision-makers do with these findings? First, evaluate storage projects as part of a system, not one asset at a time. A battery business case that looks strong in isolation may look different once hydrogen-like storage is available, and vice versa. The relevant question is not simply which technology has the lower unit cost, though cost matters. In our research, we develop adjusted cost metrics that capture operational features of a technology, such as usable hours and capacity limits. It is which mix of technologies best matches the pattern of surplus supply, the timing of demand, and the cost of backup generation. Executives should therefore ask: how many hours does surplus power last, and would a second storage technology reduce backup use or unlock higher renewable targets?

Second, use care when translating technology narratives into policy. A common narrative says that batteries are for the short term and hydrogen is for the long term. That is directionally useful, but too crude for actual decision-making. The research shows overlap, interaction, and sequencing effects. Hydrogen-like storage may play a role in daily balancing earlier than expected. Batteries may remain essential even in systems that eventually rely on seasonal hydrogen. Responsible management requires resisting simple labels when the economics are system-dependent.

Third, operational priority is an important lever that needs to be understood and regulated when combining multiple storage technologies. Letting the most efficient technology go first is not always the best choice once developers' response is taken into account. And policy-makers should consider state-contingent policies, which under the appropriate design can improve outcomes for everyone.

Limitations

The paper is intentionally stylized, and its limits should be kept in mind. It studies two technologies rather than many, abstracts from variable electricity prices and ancillary service revenues, and simplifies some seasonal patterns. Those choices help make the mechanisms transparent, but they also mean the results should guide judgment rather than substitute for project-level analysis. That said, the model performs well when compared with more detailed numerical simulations, which gives confidence that the main insights are not artifacts of simplification.

Overall, the research offers a practical message for leaders working on the energy transition. Storage strategy is not simply a choice between batteries and hydrogen. It is a question of how technologies interact, how incentives are shaped, and how operating rules influence investment. The best decisions are likely to come from a portfolio perspective, informed by the actual pattern of renewable surplus and by clear policy objectives.

For storage developers, utilities, and large industrial buyers, that means expanding their technology portfolio. For policy-makers, it means that the energy transition requires market design that takes into account the reality of intermittent generation and moves beyond just subsidy design. For both groups, it means treating storage not just as equipment, but as a strategic capability for managing renewable variability. As the share of renewable continues to rise, that capability will become increasingly central to cost control, emissions reduction, and the credibility of net-zero commitments. Policy-makers can reinforce this by designing tenders, dispatch rules, and procurement criteria that reward flexibility rather than a single technology label. The societal payoff is broader than project economics: electricity affordability, energy security, decarbonization credibility, and Europe's long-term energy independence all depend on managing variability well.

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