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# A co-design framework for wind energy integrated with storage

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## SUMMARY

**The global growth of wind energy markets offers opportunities to reduce greenhouse gas emissions. However, wind variability and intermittency (across multiple timescales) indicate that these energy resources must be carefully integrated into the power system to avoid mismatches with grid demand and associated grid reliability issues. At the same time, community concerns regarding the local installation of renewable energy and energy storage systems have already delayed or even halted the proposed projects. We propose a broadly defined, co-design approach that considers wind energy from a full social, technical, economic, and political viewpoint. Such a co-design can address the coupled inter-related challenges of cost, technology readiness, system integration, and societal considerations of acceptance, adoption, and equity. Such a successful design depends on the understanding of the needs of relevant communities, the regional grid infrastructure and its demand variability, local and global grid decarbonization targets, available land and resources for system siting, policy and political constraints for energy development, and the projected regional and global impact of these systems on the environment, jobs, and communities.**

## CONTEXT & SCALE

The rapidly growing penetration of renewables on the power grid is critical to achieve a carbon-free power supply in the next few decades. However, the inherent variability of renewables indicates that new cost-effective energy storage integration paradigms are needed. Herein, we propose a new and broadly defined co-design approach for wind energy with storage that considers the coupled social, technical, economic, and political challenges and opportunities along with a proposed approach for solution. Such a coupled multidisciplinary approach can lead to unique regionalized solutions that consider daily and seasonal grid demand profiles, proximity of wind farms to the grid, available storage technologies, compatibility of solar energy profiles, and most importantly socio-political aspects, including broad stakeholder engagement and impact on environment, infrastructure, and jobs.

## THE SOCIETAL CASE FOR WIND ENERGY AND STORAGE

Wind energy is undergoing a revolution in growth and advancement in response to a combination of technological, social, political, and economic factors. It is especially fueled by goals to decarbonize the power grid and the entire economy.[1,2] The result is an unprecedented increase in wind energy, now the largest globally growing energy source. In particular, the world added 61 GW of wind capacity in 2019 and 93 GW in 2020, a 53% increase in just 1 year.[3] Although it is difficult to predict future growth rates, it is worthwhile to consider several published forecasts to gain a sense of the potential magnitude of installed capacity increases in the coming decades. Wind energy capacity has been projected to continue its rapid rise. For example, US electricity production supplied by wind has been projected to increase from ∼8% in 2020% to ∼20% by 2030 and to ∼35% by 2050.[4–8] Specifically, the installed wind power capacity in the United States has been forecasted to grow from 122 GW in 2020[9] to over 400 GW in 2050.[4] Relatedly, the installed wind power capacity worldwide has been forecasted to increase from 743 GW in 2020[3,9] to more than 6,000 GW in 2050.[3,5] Although still much less common than onshore wind,[9] offshore wind may be especially poised for a high percentage growth compared with today's installations, with global offshore capacity projected to jump 8-fold from 29 GW in 2020 to 234 GW by 2030.[3] Due to its advantages of higher wind speeds and coastal proximity to some large population centers, offshore wind has been growing at twice the annual rate of onshore wind over the last decade. Offshore wind is projected by some to continue to grow at more than 20% per year worldwide, with the United States planning to increase its capacity of offshore wind from 0.04 GW currently to 39 GW by 2040.[10,11] Rapid increases are also expected for solar energy, with added photovoltaic capacity projected to be even greater than that for wind energy by 2023.[7,8]

However, multiple challenges exist for the wide scale deployment of wind energy. First, addressing the impacts of wind energy's inherent intermittency (variability that is often unpredictable for more than a few days) on regional power grids is a growing challenge. Wind energy is non-dispatchable. When available energy from a wind farm is high and exceeds grid demand, any energy that cannot be stored must be curtailed. This idling of equipment is not entirely different from the operation of thermal power plants that sit idle as energy demands fall periodically throughout the day. However, this curtailed wind energy does represent a lost opportunity for revenue generation and for decarbonization. In addition, intermittency can pose a risk to the reliability of systems, which is an obvious concern if left unaddressed.[12] When the available wind energy drops and/or there is an increase in grid demand, options must be available to avoid a "wind energy mismatch." Such options include using power from other sources, some of which may emit greenhouse gasses, or relying on shifting flexible demand in time, although that potential is currently limited. Overall, significantly decarbonizing the grid with substantial amounts of variable renewable energy at low cost requires new approaches to ensure the resilience of a power grid whose physics of operation requires supply-demand balance. Various options are being developed to address this objective, which can be used together or individually, but each one presents challenges.

Currently, the fluctuations in the availability of wind (and solar) energy resources are typically addressed via capacity from dispatchable power sources, which are generally carbon based. In particular, gas-fired peaker plants and other carbon-based ancillary services readily address these fluctuations. However, they contribute to greenhouse gas emissions and associated global warming, and they can be expensive if additional capacity is required specifically for this purpose. Supplemental power generation from other sources is another option that can offer low emissions in some cases (e.g., if these systems rely on carbon-free energy conversion processes or incorporate carbon capture and storage), but they can also increase the cost of electricity significantly.

Another option is demand-response strategies to encourage power usage when renewable energy is plentiful, but their impact has historically been modest. Although this option can be effective in theory, societal and policy pressures have generally maintained fixed-price energy rates for most consumers (commercial and residential) that are independent of temporary increases in grid demand or weather events. Without a price signal, it can be challenging to incentivize participation in demand-response programs.

An alternative strategy is to expand transmission infrastructure connections to other grids. These options also require investment in physical infrastructure and, often, a significant land area. They can face regulatory issues as transmission lines cross borders causing delays and increasing costs. For example, transmission lines crossing state lines in the United States require detailed interstate cooperation that can be difficult to achieve. Furthermore, the presence of high-voltage lines can be locally undesirable for the impacted communities (in populated regions) or for natural habitats (in unpopulated regions).

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https://doi.org/10.1016/j.joule.2022.08.014

A further option is energy storage, which is the focus herein. Energy storage is already widely used at short timescales (from a few seconds to many minutes), but there is increasing interest in using long-duration storage (operating following daily, seasonal, or more sporadic cycles) to solve the growing wind energy mismatch issue.[13,14] However, long-duration GW-scale storage is relatively expensive[15] because of the large energy capacities required and the high costs of current storage technologies. Energy storage costs are projected to be a strong function of regional grids and their resources and demands[2] but are relatively high across many different contexts. Thus, for long-duration, grid-scale energy storage to be a viable solution, new advances are needed in wind energy harvesting and energy storage technology, as well as in economic evaluation and, as discussed next, community integration. It is anticipated that storage would be used in conjunction with other options (including demand-response, increased capacities of solar and wind energy systems, supplemental generation, and transmission line expansion) to provide the most cost-effective and performance-effective solution for a particular grid.

In addition to developing low-cost and scalable technical solutions for addressing wind intermittency, the ultimate goal of decarbonizing the grid is to benefit society. Therefore, regardless of which technological solution addresses the question of intermittency, implementing these systems at specific sites requires careful consideration of the interplay between communities and engineered systems, otherwise projects may not achieve their promised benefits. There have been examples of strong public opposition to wind farm developments as well as to large-scale storage systems; hence, potential opposition to the combination of co-located wind and storage is expected to be ever more complex. The failure of such wind energy with storage projects, even when there are strong technical and economic advantages,[16] highlights the need to consider the socio-political aspects from the beginning of any project design. As such, social acceptance is a general challenge that should be addressed by any wind development project, including those with integrated storage.

Herein, we propose an approach for co-designing low-cost, socially designed wind energy with storage. The basic elements that make up this challenge and a roadmap for its solution are the focus of this article. In the following sections, we first define and envision socio-technical-economic-political co-design for wind energy with storage. We then discuss the dynamic relationships between wind farms and the power grid, the technology developments for long-duration storage, economic valuation of the market benefits, and the social adoption issues that often serve as critical gatekeepers for the techno-economic solutions. This socio-techno-economic-political (STEP) co-design can directly address issues of public resistance with related measures such as public input, community ownership, and local economic benefit. Finally, a technology roadmap for the key research challenges associated with this approach for wind energy and storage is discussed.

## CO-DESIGN AS A SOCIAL, TECHNICAL, ECONOMIC, AND POLITICAL APPROACH

### Socio-techno-economic-political (STEP) co-design concept

To achieve long-term sustainability, it is important to tackle the various techno-economic (e.g., storage cost, scalability, and safety) and socio-political challenges (e.g., local suitability and permitting) of energy design and development by adopting a holistic approach.[17] We do this with a new and broad definition of "co-design." Conventionally, co-design is a technology perspective to integrate and co-optimize the disparate components of wind power generation, energy storage, and other aspects of the electrical grid for minimum cost of energy.[18] Expanding this concept to include a social perspective engages diverse stakeholders in problem definition (impacting the types of solutions even considered),[19] technology planning, and development and focuses the specifications of the technology on local needs. This process extends collaborative planning by facilitating democratic development and deployment of the technology from the design phase.[20] Furthermore, economic impact can be highly socio-political, through government subsidies, policies, and mandates as well as through the sustainability vision of large and small corporations.[21]

A broad techno-economic socio-political co-design framework is not only useful for guiding technology development, it can also be extended to identify the optimal system architecture and its design parameters relative to local resources. For example, integrating a compressed air energy storage system with a wind farm may be optimal where transmission lines are expensive[22,23] but requires consideration of local community acceptance and environmental impact if large underground reservoirs are to be used. On the other hand, incorporating battery banks at power substations may be an optimal solution when there are broad ranges of power sources being provided to the grid or there is significant probability of high congestion,[24–26] but this may lead to intensified and unwanted infrastructure nearby and within large population centers. The co-design process allows stakeholders to directly assess the technological parameters of a system and to assess tradeoffs of different designs to better meet the specific regional needs. One example is to include community collaboration for wind farm siting, i.e., determining locations to install wind turbines.[27] However, the proposed STEP co-design considers how the turbines themselves can be re-designed to address varied stakeholder interests and concerns rather than principally designing them based on efficiency and cost.[28,29] For example, it addresses questions such as "can blade speeds be significantly slowed and blade aerodynamic profiles be modified to reduce potential impact to birds and bats and to reduce acoustic emissions?"

Including socio-political aspects (such as user concerns, economic opportunities, and interaction with important landscape features) adds complexity but is critical to achieve the various technical, economic, societal, and environmental goals within geographic and community-level constraints. For example, a key barrier to widespread adoption of wind energy is the "social acceptance gap," whereby people support renewables in the abstract but not specific projects. This gap is especially evident when projects are sited in their communities.[30] Koirala and Hakvoort[31] describe the ways in which integrated community energy systems are socio-technical systems containing a complex set of actors and technologies but that integrating their design can add value compared with traditional energy systems via engagement of communities, which can increase acceptance, community economic benefits, and build a stronger sense of community. Full socio-political and techno-economic co-design therefore requires deliberate teaming of diversely trained scientists, including social scientists, engineers, and policy officials with community stakeholders guiding the attention to local social, economic, and ecological contexts.

Co-design and integration across the social, technical, and economic systems can be evaluated using a convergent approach.[32] Socio-technically co-designed wind energy integrated with storage (and other technology issues that

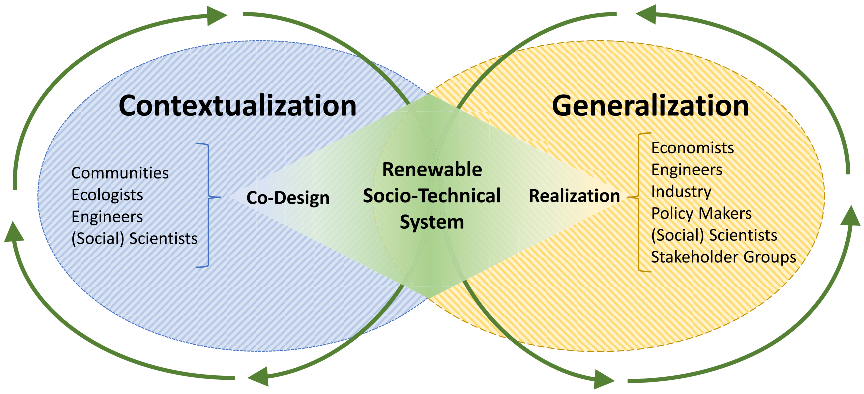


**Figure 1. Framework for convergence through socio-techno-economic-political co-design**

integrate directly with society), this convergence can be defined using two distinct domains:

- local/contextual
- global/generalizable

These contextualization and generalization domains, shown in Figure 1, ideally operate simultaneously and iteratively.[33]

Contextualization aims to embed the socio-technical system by considering the needs of local communities and the ecosystem for co-benefits. In tandem, generalization aims to understand the requirements and impacts of scaling up technologies (such as wind co-design with storage systems) from local test beds through regional, national, and international perspectives and settings. The generalization domain necessarily advances convergence at larger geographical scales by considering the full manufacturing supply chain and infrastructure interactions as well as the economics, policy, and ecosystems of integrated wind storage technologies.[34] Communities, research centers, policy makers, and industry leaders are collaboratively engaged across all phases of design and deployment. This convergence framework employs key concepts of the STEP approach of Daher et al.[35]

This definition of convergence brings each end of the wind and storage socio-technical system (local and contextualized, as well as general and universalized), and the various impacts (social, economic, environmental) into synchronous dialog, such that each factor is considered and addressed uniquely, but also importantly, in relation to the rest.[36] This convergent approach gives greater voice to the diversity of stakeholders and considers the societal impacts of the technology. The aim is a sustainable socio-technical system capable of delivering long-term equitable value.

The broad definition of co-design viewed through the lens of convergence can help generate positive socio-economic impacts of wind development with storage that can enhance procedural justice, increase acceptance, and better address noise, visual impacts, and wildlife externalities.[37,38] This convergence of research, design, and public engagement in emerging technologies additionally enables one to tackle broader issues such as economic and workforce equity when developing a renewable (zero-carbon) grid solution. As such, it goes far beyond collaborative community discussions on where turbines should be placed[27] and even post-design mitigation strategies[39] to instead consider how the core wind turbine technology itself can be re-designed.

### Wind energy dispatchability and grid interaction

The power grid is a network of electrical transmission and distribution systems used to connect power generation plants to the electrical loads. It is crucial to keep the power grid frequency and supply-demand balance within a close tolerance to ensure the reliability of the grid. However, the rapid growth of inherently variable wind energy and the increased sensitivity of the grid can lead to sudden imbalances between electrical generation and load that may cause large fluctuations in grid frequency. This can result in load shedding, brownouts, and even blackouts. Even a momentary loss of power is highly undesirable for the grid customers, which is why grid operators strive to ensure reliable service.[40,41]

Grid operators maintain a reliable and balanced system by coordinating the generation to match the variable demand in real time. Power generation is typically procured and scheduled to match the load forecast through power markets that operate in advance, ranging from 1 day to just 5 min ahead of time. Operational reserves must be procured by the grid operators to participate in regulating the balance of generation and load. The need to maintain sufficient operational reserves becomes more complicated and costly when there is significant integration of wind power. This is because the turbulent, stochastic nature of the wind causes fluctuations in wind power generation, which must be accommodated by utility grid operators.

Fortunately, recent studies[42–45,46] have shown that wind energy can provide grid frequency regulation services at timescales ranging from milliseconds to tens of minutes, even reducing the maximum and settling frequency deviations more effectively than conventional generators. Moreover, short-duration energy storage can provide further cost-effective frequency regulation. However, over longer timescales (hours or days or even weeks), conventional batteries and wind energy (with high intermittency) are not as effective at providing these balancing services; hence, other strategies are needed for long-duration power fluctuations.

At low wind energy penetrations of less than 10% (the average in the United States is 8%), grid operators view variable wind power generation as an unmodeled disturbance and can use operating reserves to handle the long-duration power fluctuations. At higher average wind energy penetration levels of 10%–20% (being reached in many areas), grid operators utilize wind power forecasts to schedule other forms of generation to avoid the cost of procuring larger amounts of operating reserves. Further increases in wind penetration above 20% (as expected in the next decade in many regions) require expanded solutions. In the United States, although some states (e.g., Iowa, Kansas, Oklahoma, and North & South Dakota) have wind penetrations higher than 30%, these states do not have isolated power grids. There are two major wide area synchronous power grids in North America: the Eastern Interconnection (which handles peak power needs of about 700 GW) and the Western Interconnection (which handles peak power needs of approximately 150 GW of power). The Eastern and Western Interconnections have wind penetrations below 10%. A third power grid in the United States is the Texas Interconnection, which handles peak loads of about 70 GW. Texas has about 23% wind penetration,[9] and due to grid stability issues during a cold weather event in February 2021, ramped up from about 0.225 GW of storage at the end of 2020 to over 1.7 GW of storage at the end of 2021 and is expected to exceed 3 GW of storage by the end of 2022.[47] For these power grids and others worldwide, long-duration storage (hours, days, or even weeks) can enable:

(1) energy time-shifting throughout the day to reduce curtailment of wind energy and reduce the electricity cost during peak demand,

(2) provision of reliable capacity for long-term system reliability, even at high penetrations of wind energy, and
(3) provision of on-call operating reserves needed to manage grid frequency.

These benefits are driving significant research in this area in the context of rapidly growing intermittent renewables (solar and wind energy) capacity.[10]

As large-scale storage technologies develop and their cost declines, their integration with wind energy, along with improving wind power forecasts, can enable increasingly dispatchable wind power. This integration can fundamentally change how wind participates in grid frequency regulation and other ancillary services, especially over longer time horizons. With storage integration, wind farm and turbine designs can continue to evolve to expand their role as sustainable, cost effective, and reliable power systems.

For wind-integrated-with-storage power plants to have high viability and impact, they would ideally operate in day-ahead and real-time energy markets and provide reliability and resiliency services to the grid. Such power plants will enable wind energy to be used efficiently because they will reduce curtailment and hence increase capacity factors and also smooth variability. The result would be high-value grid services and a more secure and resilient power supply. This added resilience can be particularly important when locations with wind energy resources have limited transmission infrastructure, e.g., offshore of Humboldt, California.[10] In such cases, incorporating storage as new wind farms are developed can mitigate transmission requirements. Thus, co-design approaches should account for constraints that are specific to a region and establish design paradigms to better site and develop the next generation of wind farms and turbines as well as to better value energy storage and grid integration.

One consequence of evolution is that wind turbine and wind farm design should change when storage is integrated. For example, the traditional paradigm that guides their design is to minimize the levelized cost of energy (LCOE). LCOE for a turbine is based on capital expenditures (CAPEX), operational expenditures (OPEX), the fixed-charge rate (FCR) based on the operational lifetime (OL) of the system and financing costs and balance of station (BOS) expenditures, and power generation (G) as a function of time (t) integrated over 1 year

$$\mathrm{LCOE} = \frac{\text{Generation Annual Costs}}{\text{Annual Energy Production}} = \frac{[(\mathrm{CAPEX}+\mathrm{BOS})\mathrm{FCR}+\mathrm{OPEX}]_{\mathrm{turbine}}}{\int G_{\mathrm{turbine}}\,dt} \quad \text{(Equation 1)}$$

The BOSs costs include assembly, installation, and connecting electrical infrastructure costs, whereas soft cost can be added to include financing and decommissioning. In these equations, LCOE has units of cost per energy (e.g., \$/kW-h), CAPEX and BOS have units of costs per project (e.g., \$), OPEX has units of annual costs per project (e.g., \$/year), G has units of energy per time (e.g., kW), and FCR has units of %/year, which is typically taken as 5.5% for long lifetime systems (e.g., 25–30 years). In this context, technical co-design of wind turbines can be optimized over aerodynamic, structural, and control systems for minimum LCOE.[27] However, LCOE generally increases when storage is considered since it does not consider any dispatchability benefits. Therefore, other design metrics may be needed. For example, grid engineers instead often design wind farms to maximize grid-system value and manage competing logistical, regulatory, and social constraints.[40,41,48,49] Fundamentally, the evolution of design of wind turbines and farms with storage depends on the characteristics of the storage technologies themselves.

Table 1. Current characteristics of long-duration storage technologies, primarily ordered by TRL and secondarily ordered by RTE

| Technology (and ~TRL) | Recent breakthroughs | Cost of storage capacity | Round-trip efficiency | Operational lifetime | Primary challenges for long-duration storage |
|---|---|---|---|---|---|
| Pumped hydro storage (TRL 9) | N/A | \$197/kWh | 80% | 40 years | regulation, community opposition, environmental impact |
| Li-ion (TRL 9) | longer duration; cobalt-free chemistries | \$356/kWh | 86% | 10 years | fire threat at large scale; resource scarcity; and replacement lifetime |
| Lead-acid (TRL 9) | N/A | \$360/kWh | 85% | 12 years | highly unlikely since limited to 200–300 deep cycles (due to chemistry) and one deep cycle per day (due to heat issues) |
| Flow batteries (TRL 9) | organic active species | \$399/kWh | 68% | 15 years | low volumetric energy density and high cost |
| Liquid-metal (TRL 6) | durable seal insulation; cost reduction of active components | \$90/kWh (projected) | 70%–80% | 20 years | high operating temperature of 500°C requires integrated thermal packaging |
| CAES (TRL 5) | rapid isothermal compression/ expansion | \$119/kWh (projected) | 52% | 30 years | low volumetric energy density and pressure vessel cost |

## Emerging energy storage solutions

The co-design approach discussed above will require novel engineered solutions that can break technology cost barriers to enable MW and GW scale storage with a variety of discharge times. The challenges associated with these barriers are expected to be amplified as renewable energy penetration increases. Integrating energy storage with power generation provides a relatively low emissions technology approach to address both variability and intermittency. However, economic evaluations indicate that currently available storage technology options are either too expensive or are limited to some geographic regions and that newer options require additional technological advances to improve performance and reduce costs.

In this section, we provide a brief overview of currently available as well as merging options and the key features to consider for integration. In doing so, we demonstrate the inherent diversity of energy storage options available and, therefore, the potential to match the selection of storage technologies to local contexts.

In comparing the various technology options for long-duration energy storage (as shown in Table 1), four key quantifiable factors are important: technology readiness level (TRL), Cost of Storage Capacity (COSC), round-trip efficiency (RTE), and OL. The system TRL addresses the level of development. For example, TRL 9 systems are commercially available and have been already integrated in relevant environments, e.g., Lithium-Ion (Li-ion) batteries have already been used at large scale on the grid. On the other hand, TRL 5 reflects high-fidelity, laboratory-scale system success in a simulated environment with a wide range of simulated operating conditions. Such lower TRL levels are helpful to see when the technologies might be available for utility-scale usage.

The COSC includes the storage CAPEX (CAPEX, based on active components and integration packaging) and BOS costs (based on installation and any electrical infrastructure to connect to the turbine and/or grid) both normalized by the storage system rated energy capacity (REC), i.e.,

$$\mathrm{COSC} = \frac{\text{Annual Storage Costs}}{\text{Rated Energy Capacity}} = \frac{(\mathrm{CAPEX}+\mathrm{BOS})_{\mathrm{storage}}}{\mathrm{REC}_{\mathrm{storage}}} \qquad \text{(Equation 2)}$$

In this relation, COSC has units of cost per energy (e.g., \$/kW-h) and REC has units of energy (e.g., kW-h). For long-term duration storage, operational expenses are typically secondary costs and can be factored into BOS costs based on battery lifetime as in Table 1. As such, the COSC in this table includes capacity cost and operational costs.[50] RTE is also important as it determines the net loss of energy due to incorporating storage. Ideally, the RTE is high, and Li-ion batteries are highly attractive in this respect. For systems with a low RTE, overcapacity of generation may be a better option than storage.

In addition, OL should be considered, and this can be defined as the estimated period after which the battery would need to be replaced, e.g., assuming a few cycles a day when coupled with a wind turbine/farm. For flow batteries, the lifetime is not strongly dependent on cycle count and is essentially the reciprocal of the decomposition rate (expressed e.g., as percent lost per day). Since wind turbines are typically designed for 25 years of OL, the annual CAPEX for adding storage are a combination of the initial outlay as well as the costs for replacing key aspects. Of course, all technologies have challenges that must be considered, and these can be significant for GW-scale long-term energy storage. The various storage technologies of Table 1 are discussed in more detail below in order of those currently in use (high TRL) to those that are still in development (lower TRL).

One practical and low-cost solution for long-duration storage that has been long used is pumped hydro-storage (PHS), where excess electrical energy is used to pump water up a dam, whereas needed energy can later be extracted by letting the water return down through turbines. For example, the Bath County Virginia Pumped Storage Station 24 GWh of capacity (perhaps the largest battery in the world). This cost-effective PHS was realized using existing reservoirs and an existing dam. However, PHS does not represent a good option for new grid storage capacity in North America or Europe as few, if any, new dams are being built, due to a combination of community opposition and potential impact of a dam on riverine habitats.[14] As such, public objection can limit PHS in general (whether coupled with wind or not. The situation may be different for other regions with an abundance of natural reservoirs and/or where communities may not be as opposed to new dams and reservoirs (e.g., Norway and China). For example, a PHS plant was recently brought online in Hebei, China, for use during the Winter Olympics in 2022.[51]

Li-ion batteries are highly compact (avoiding the major land use issues of PHS), and their costs have significantly decreased in the last few years (along with increased performance). However, they are still quite expensive. For example, employing Li-ion batteries at current costs for four hours of storage at rated power, under a particular set of assumptions, could more than triple the cost of energy for the grid in California.[14] Another drawback of using Li-ion based batteries is the environmental and political cost of extracting and processing the raw materials which often have a high carbon footprint for GWh systems. Their finite lifetime also contributes to increased costs when considered over the projected lifetime of a wind turbine. With a volatile and flammable electrolyte, the Li-ion based battery in large format, e.g., MWh, installations need aggressive thermal management to prevent fire.

Flow batteries are actively being deployed at scales up to hundreds of MW[52] as they offer reduced environmental impacts and hazards. New flow batteries with exceptional promise include those with aqueous-soluble organic active species.[53,54] Although the TRL of these new concepts is not as high (TRL 4), this novel chemistry class has the potential to significantly reduce the cost of storage, and recent developments have greatly increased battery life.

Isothermal compressed air energy storage (i-CAES)[55] stores and regenerates energy by directly compressing and expanding air to and from high pressure. Unlike conventional CAES plants in operation that utilize the diabatic process, it does not require the use of a fossil fuel. It offers extremely long charge/discharge cycles while utilizing environmentally benign materials like steel, water, and air. However, thermal losses result in RTE of ~50% in MW-scale demonstration plants, making them impractical for wind energy storage.[56] Enhanced heat transfer and optimized control to isothermalize the compression/expansion process is projected to allow an RTE of >70%,[28,57,58] although this RTE has not been demonstrated at MW-scale yet. The high cost of pressure containers for the typical pressures of ~100 atmospheres has driven focus to pre-existing containers, e.g., tower of a wind turbine or existing geological structures, such as abandoned mines or natural caverns.[21,22] Other long-duration mechanical storage options, such as flywheels, are relatively expensive and/or only suitable for durations of less than an hour.[59]

New long-duration storage alternatives include a rapidly expanding suite of storage modalities[60,61] based on breakthroughs in storage chemistry, materials, thermodynamics, and control. This includes liquid-metal batteries,[62,63] which have high energy density and are strong candidates due to recent advances in materials and manufacturing. Projected cost estimates when integrated with wind in Table 1 are based on Simpson et al.[63]

Which storage option is best will depend on these technology developments but also on both the communities in which they are located and how storage is situated between the points of generation and usage. On the supply side, (1) "farm-based storage" is physically co-located within the turbine structure or at the wind farm. On the demand side, "grid-based storage" is located within transmission and distribution grids for improved market coordination. The choice of which integration modality may be driven by turbine technology and size, e.g., grid-based may be best for incorporating small onshore wind farms that are part of a more heterogeneous power system. On the other hand, large offshore wind farms may benefit from farm-based storage to best utilize the capacity of the expensive farm-to-shore transmission infrastructure. However, the choice of the storage technology is primarily driven by socio-economic factors, as discussed in the next two sections.

## Evolving economic valuations for wind and storage

Several metrics have been proposed to estimate the economic value of added energy storage, as we discuss in this section. We note that these quantitative estimates require assumptions about optimal system capacities (e.g., the capacity of wind generation and storage) which are typically optimized through simulating the power system's operation.

For grid-integrated storage, a common approach to determine whether an energy storage technology can "buy its way" to the grid is to employ arbitrage analysis.[64] Arbitrage compares the cost of storage to the revenue gained by storing energy when its prices are low and regenerating (dispatching) it when the prices are high. However, one must consider the drivers for auction-based pricing of energy for a specific regional grid. In particular, the regional power supplies in terms of capacity and typical production variations should be compared with the demand variations. Such comparisons should be considered in terms of hourly, daily, seasonal cadences, as well as less regular operational profiles, as well as in terms of current and projected regional characteristics, especially if rapid decarbonization is planned. A key issue is whether the current auction paradigm is optimal for growth of offshore wind and the expected integration of storage systems of unprecedented duration and size. To address this, economic valuations are needed to exploit technology innovation in the wind-storage system in terms of targeted cost.[65,66]

In developing storage technologies to participate in arbitrage, the effective cost of storage energy generation is often considered in an annualized approach, e.g., via the levelized cost of stored electricity (LCOSE) which includes the cost of energy charging (ECEX, based on the energy used for charging assuming an average energy price)[67] and the energy delivered by the storage (equal to the product of the energy used for charging and RTE) as

$$\text{LCOSE} = \frac{\text{Storage Annual Costs}}{\text{Annual Energy Delivered}} = \frac{[(\text{CAPEX} + \text{BOS})\text{FCR} + \text{ECEX} + \text{OPEX}]_{\text{storage}}}{\int G_{\text{storage}} dt} \quad \text{(Equation 3)}$$

In this equation, LCOSE has units of cost per energy (e.g., $/kW-h) and ECEX has units of annual costs (e.g., $/year). The CAPEX and BOS costs can be obtained from Equation 2, whereas the storage FCR, is based on storage system OL. For example, FCR is about 10% for a Lithium-Ion battery with a 10-year lifetime and about 5% for PHS with a 50-year lifetime. The cost of OPEX represents the operational and maintenance expenses for the storage system. This cost can be difficult to assess for MW-scale systems without sustained operational experience (and thus can only be reasonably obtained for TRL 9 systems).

Based on the terms of Equation 3, LCOSE can be minimized by reducing COSC and/or by increasing OL and RTE, where the target reductions are determined by the operational characteristics of the plant and the system in which it is embedded. A recent arbitrage study using recent California grid demand profiles and energy pricing showed the effect of these drivers in a modeled scenario.[14] In the particular system that was modeled, arbitrage profit was maximized for systems with capacities of 6–12 h of rated storage with OL and RTE values at low COSC. However, storage of only 4 h may be more cost-effective if viewed from the grid's point of view.[68] Of the primary storage options,[14] PHS generally provides the best cost benefit at these duration lengths due its favorable overall combination of these metrics. In comparison, Li-ion batteries (despite their favorable RTE) currently have high costs of capacity that often precludes them from long-duration storage. Similar results were obtained by Schmidt et al.,[67] whereby Li-ion batteries were found to perform best for storage duration requirements of 1 h or less, whereas PHS was found best for 6–12 h storage and CAES best for 2–20 days of storage. Earlier studies have also arrived at similar results.[68] It should be noted that several of the emerging technologies in Table 1 have costs that are projected to be favorable compared with Li-ion batteries and thus can be highly effective, but the TRL levels are too low for current grid implementation.

For farm-integrated storage, there are also potential cost savings involved with integrating the storage system at the point of energy generation, which can help lower LCOSE. As an example, compressed air energy storage can make use of the turbine towers for an effectively free pressure vessel to reduce storage CAPEX.[69,70] As another example, hot liquid metal batteries can be integrated within the towers of offshore turbines to minimize cooling and integration costs associated with storage CAPEX and can also levelize the farm output to reduce the required capacity of the power transmission to shore, thereby reducing $\text{BOS}_{\text{turbine}}$.[63] However, one must consider the potential increase in storage OPEX if located offshore where ease of access is reduced.

Other metrics include the effects of market-based policy-driven financial incentives that favor storage.[71] For example, this LROE (levelized revenue of energy) has been developed to incorporate other revenue streams, including preferential tax and depreciation rules as well as broader infrastructure and development expenditures that benefit a project.[72] Such a metric could be applied to systems that include energy storage.

However, other metrics consider the energy price variation during the time of energy generation, which can strongly favor storage systems that can discharge at times when energy prices are high. To more effectively evaluate farm-integrated or turbine-integrated storage, one may employ the cost of valued energy (COVE) to value the energy generation based on energy price.[66] In particular, COVE weights the energy generation with the non-dimensional energy price (p, where $p_{avg}=1$) at the time of production

$$\mathrm{COVE} = \frac{[(\mathrm{CAPEX}+\mathrm{BOS})\mathrm{FCR}+\mathrm{OPEX}]_{\text{generation \&storage}}}{\int (G_{\text{delivered}}\, p)\, dt} \qquad \text{(Equation 4)}$$

In this equation, *COVE* has units of cost per unit energy converted (e.g., \$/kW-h). Notably, COVE = $\mathrm{LCOE}_{turbine}$, if price variations are ignored and there is no storage. However, these variations can be large in many energy markets, resulting in spikes of more than 5-fold and even negative energy prices.[63] The hourly variation in p can be modeled using a linear price-demand relationship combined with expected hourly profiles of energy demand and wind energy generation. Using historical data to create standardized profiles, large-scale underground compressed air energy storage integrated with wind farms was projected to have strong potential based on COVE reductions.[21,22] The result is that COVE (a more accurate valuation) will have larger costs of energy than LCOE for most wind turbines (since it effectively includes the cost of intermittency), but incorporation of energy storage can appropriately reduce COVE (a characteristic that is not valued by LCOE).

The price weighting in Equation 4 for COVE may be similarly used in LCOSE in terms of storage ECEX and AEP (annual energy production) to improve the storage valuation effectiveness for a particular grid. However, it should be kept in mind that the above techno-economic analysis of grid-integrated and farm-integrated storage does not account for capacity payments, policy developments, and government directives, which often change and are difficult to forecast. Moreover, one must also consider societal adoption aspects, which can be even more complex.

### Participatory co-design for societal adoption

Beyond the above techno-economic aspects, engineered systems must be sensitive to socio-political contexts if they are to be successful.[73] Wind farms have been subject to public opposition for multiple reasons, including visual and landscape, socio-economic and environmental concerns, and procedural factors,[74] which will likely continue to apply to new projects, irrespective of whether storage is integrated.

Significant research exists on the contested social and political dimensions of wind energy development in North America and Europe, but the reliance on individual case studies makes it difficult to identify more systems-level patterns on the path to project realization or rejection.[36,37,75,76] In fact, a new U.S. DOE Request for Information for "Offshore Wind Social Science Research Needs" suggests a growing recognition of the need for research in this.[77] Despite this gap, some common key issues have arisen in the existing research. Although the benefits of decarbonization accrue at national and international scales, most negative externalities are localized, raising the issue of equity.[78] A lack of procedural justice (or fairness in the processes that resolve disputes and allocate resources) erodes social acceptance of wind energy.[36,38,75,79] Land use conflicts have sparked increased siting restrictions that models predict will hinder future wind development and can result in higher electricity prices, $CO_2$ abatement costs, and $CO_2$ emissions.[80] This is a challenge that extends beyond participatory decision-making of planning and siting and into the form and function of the technology itself.

New strategies for integrating wind energy with storage present an opportunity to equitably co-design projects with a range of stakeholders from the beginning and continuing throughout the project into its operation. Our proposed STEP co-design process (detailed in the next section) departs in significant ways from existing efforts, where invited stakeholder participation constitutes the majority of these activities.[38,81] In these projects, invited stakeholder participation is concentrated in planning rather than design phases and rests on project proponents pre-defining the issues and participants. Although valuable, invited stakeholder participation does not encompass the crucial phases of "technical design, implementation, and ongoing operation of wind energy installations," which renders public participation "largely symbolic."[81] Although there is much deliberative "speak" surrounding wind, true participatory co-design is elusive.[82] What is needed are platforms for public participation, such as the STEP co-design process (detailed in the next section), that begin from the design rather than planning, siting, or implementation phases and continue throughout.

Although stakeholders can participate in decisions about wind turbine technology, including their design, operation, and maintenance, "empirical examples of such engagement remain limited."[81] The STEP co-design process seeks to achieve social acceptability by addressing landscape, environmental, social, and procedural concerns of wind-energy deployment across the full life cycle of technology design, procedural siting and deployment, and infrastructure operation and maintenance. We join calls to shift research away from mere acceptance to "a more inclusive and dynamic process of coproducing technologies and the landscapes in which they exist."[81] Participatory and deliberative engagement techniques facilitate direct collaboration between stakeholders and project representatives to create wind technologies and installations that are responsive to local concerns, desires, and landscapes. For example, one preliminary U.S. model employed deliberative workshops to create a list of regionally appropriate recommendations for acceptable designs, sites, and mitigation techniques for local wind energy development, which varied by region, given different landscape values and histories of industrial activity.[83] Participatory engagement such as this holds great promise for promoting engineering that facilitates sustainable development and promotes equity among differently positioned stakeholders.[84]

The coming green energy revolution will regionally redistribute the risks and benefits of industrial energy production. In the United States, onshore and offshore locations have strong regional variations in wind resources, storage opportunities, grid demand, infrastructure, workforces, and socio-political characteristics.[85–87,88] STEP co-design enhances equity and attention to local regional variations. Implementation of a wind farm with storage on farmland in rural Iowa is likely to lead to much different co-design optimization decisions than at a site near a major population center in California. This is due both to differences between the community attitudes as well as the differences in the wind resources and grid characteristics between the two locations.[89,90,46] Similarly, an offshore wind farm in a remote area would ideally have a different configuration compared with one near a popular vacation destination due to visual and auditory impacts.[75,91]

Cape Wind, a failed offshore wind farm planned and sited 4.8 miles off the coast of Mashpee, Massachusetts provides a useful case example. Cape Wind would have had a capacity of 1,500 GW-h and supplied nearly 75% of the electric power of Cape Cod, Nantucket, and Martha's Vineyard.[92] Despite having broad-based support across the State of Massachusetts, the project was beset by lawsuits and eventually stopped in 2017 through a well-organized and powerful local coalition. The project saw federal and state authorities try to override local opposition by issuing permits.[93] Similar to other projects, the lack of consultation led to a project design and structure that did not suit the needs or desires of local communities. This is a project that would have benefited from a STEP co-design approach. Although Cape Wind was planned 4.8 miles off-site, there were concerns with sight lines, impacts on birds and fisheries that could have been alleviated through a design process targeted at these issues.[94] In addition, the project experienced resistance due to the cables and roads needed to deliver power transmission on shore. Here, community co-design of an integrated storage model would have helped to streamline transmission. Such a process would have sought to further accelerate local buy-in and tenure over the project to enhance trust and project support.

There are several ways in which technical changes including integrated storage solutions may have been beneficial to the Cape Wind project. For example, the project could have been sited further offshore utilizing floating turbine technologies, "DeepWind,"[95] which would have minimized sight and environmental impacts. DeepWind projects, which can be situated as far as 50 km offshore, have the potential to operate at greater capacity because of the stronger winds offshore while minimizing sight impact concerns, as well as impacts on fisheries and other wildlife located closer to shore, but at a cost of higher transmission infrastructure.[96] One solution to reduce the transmission costs is to integrate storage into the turbines themselves so that lines are sized for the smaller average-delivered power, instead of the peak wind-generated power. A range of storage options exist for DeepWind including hydro-pneumatic energy storage,[97] gravity energy storage,[98] or buoyancy storage.[99] Reduced transmission infrastructure may reduce costs but more importantly will minimize the onshore impact of substations, roads, and paths for transmission lines. Following the STEP co-design process described in this article, project proponents, scientists, engineers, and advisors could have worked together with the community to minimize the onshore impacts and to select and design a storage and transmission system that would enhance efficiency and minimize environmental impact. This may have saved the Cape Wind project. The advantages of this approach have potential to address similar concerns in future projects.

Finally, contextualization can also promote more just energy transitions. For example, wind farms integrated with abandoned oil/gas wells or coal mines for storage in economically depressed areas have the potential for significant new infrastructure investment and green jobs.[21] In Montana, the recently approved Beaver Creek Wind Farms II and III include battery storage to address intermittency issues. Local ranchers who were otherwise critical of the construction impacts of the project expressed curiosity and positive interest in the storage features.[100] These examples reinforce the case for considering participatory co-design of the technology itself to address the opportunities and challenges of wind energy with storage to ensure socio-environmental co-benefits and project success.

## RECOMMENDATIONS FOR WIND ENERGY WITH STORAGE CO-DESIGN

### Integrated STEP co-design process

Although the various technological, economic, and societal aspects of wind energy with storage are discussed above, this section posits a fully cohesive STEP process to achieve responsible "wind energy on demand." In such a model of equitable green energy co-design, wind energy can be transformed from an intermittent resource into a demand-driven dispatchable resource capable of improving grid resilience, cutting the grid's carbon footprint economically, and supporting the wellbeing of nearby communities by promoting sustainable development.

Co-design and integration can be used to develop and incorporate new turbine and wind farm control algorithms, thus improving energy efficiency. In addition, a methodology should identify the optimal system configuration, such as storage size, power, and efficiency, as well as dispatch control and operation strategies based on both grid and socio-political objectives rather than isolated turbine LCOE objectives. In particular, markets and regulatory structures where wind energy penetration is rising fastest should consider different system modalities for storage (e.g., co-located versus distributed) while taking into account site-specific resources, opportunities, and constraints. However, as outlined above in the participatory co-design for societal adoption section, innovation in fundamental technologies is necessary, but not sufficient in itself, and it also must be accompanied by co-design involving socio-political elements to promote community acceptance. In particular, the STEP co-design process should include:

(1) Stakeholder engagement and buy-in, which includes how energy systems can asymmetrically impact communities and how educational and workforce programs can reach under-served communities broadly. Stakeholders include grid operators in electricity markets, such as regional transmission organizations (RTOs) and electric power transmission system operators (TSOs), regulators, as well as the general public. This step is important to ensure optimal socio-political and techno-economic *problem definition*, which then leads to better solutions.
(2) System level design and integration, which develops fundamental socio-technical knowledge, promising ideas and concepts that can solve the difficult problem of providing low-cost community-friendly wind energy on demand. The goal should also be to use co-design and integration to build dialog and design with local communities for various dispatchable wind farm technologies.
(3) Large scale roll-out, which combines the first two elements and brings the final concepts to fruition.

This high-level process of STEP co-design is depicted in Figure 2, which illustrates the cyclical nature of problem definition and a process for design to achieve maximum societal, economic, and technological success based on iteration between stakeholder engagement with system-level design and integration specific to a region. This fundamental iteration is often completely absent in current energy system designs.

As discussed above, the importance of direct community engagement during the problem definition stage is a key aspect of participatory co-design. The engagement should continue throughout the process to create procedural justice and ultimately community support for the project. This engagement helps in defining constraints

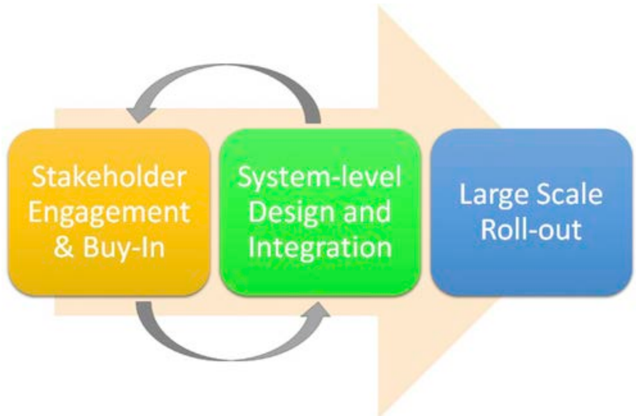


**Figure 2. High-level process to achieve successful engineering system implementation, whereby engagement and design are iterated prior to large-scale roll-out**

and goals, which would then be used in the technical system design. These technical designs would then be brought back to the community through additional engagement phases until the technical and social components have been co-optimized prior to large-scale implementation. As mentioned in Bell et al.,[30] benefits of a socio-technical approach to energy systems flow to the community, the system operators, and the policymakers. Since each locality is unique, an optimal design will also differ based on the different problem definitions as well as existing infrastructure of wind farms, storage systems, and grid transmission lines. In one community, noise might be the biggest concern, whereas in another, it may be bat populations that need to be protected. During the process, a special emphasis should be placed on the needs of underprivileged groups that have historically been excluded from land use decisions,[77] whereas previous community surveys often mentioned waterfront property owners.[38]

Engaging community stakeholders early in the process promotes equitable design optimization. Stakeholders generally include:

- institutional entities associated with industry and energy distribution
- government regulatory and advisory bodies
- communities served by and/or located nearby the renewable energy systems
- the local environment and ecosystems
- non-local stakeholders with broad concerns on environment and economy
- the workforce that will install and maintain these systems

Stakeholders also include those who may join the associated workforce in the future. The wind industry in the United States has a growing workforce gap, with 68% of employers unable to fill positions.[101] In order to sustain economic and employment growth, a pool of trained and qualified workers is needed to fill the wind industry's workforce.[102] As such, approaches like those described herein may be crucial as the transition of workers from carbon-based industries to wind energy will require broadscale financial investments in education and retraining, all with an eye to diversity and equity issues.

## Co-design roadmap for storage with wind and renewables

The above process for STEP co-design of wind and energy storage requires several steps to implement as outlined in the roadmap of Figure 3. In this process, the

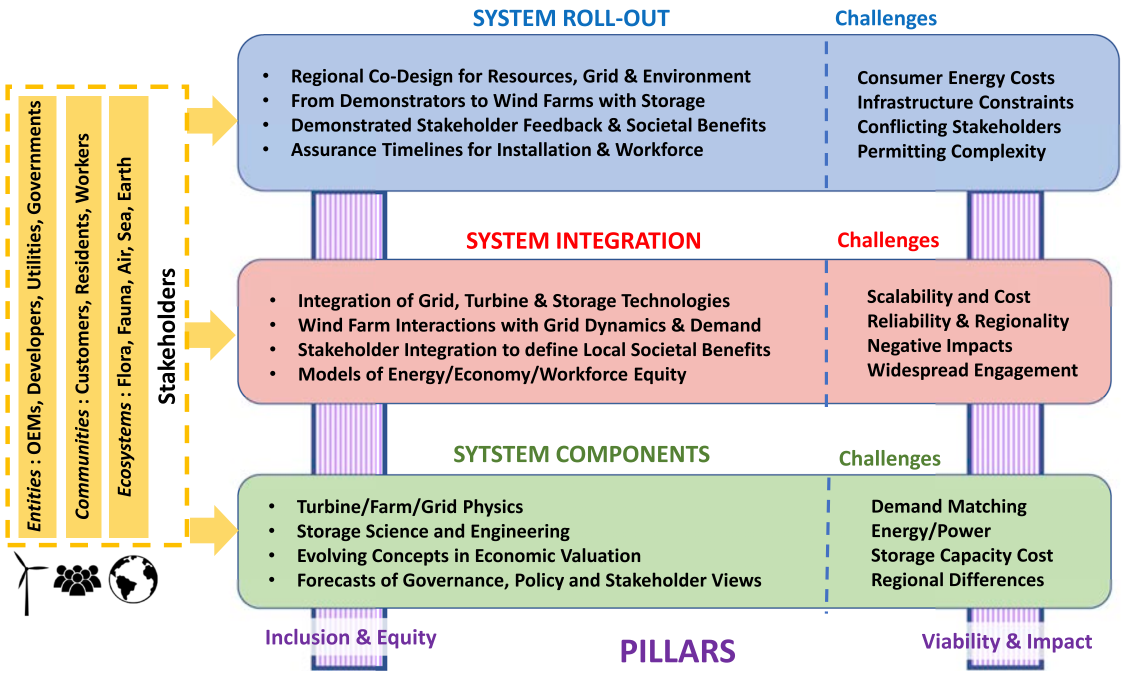


**Figure 3. Roadmap for STEP co-design of wind energy and storage**

stakeholders drive the process at all levels, as shown on the left. These stakeholders include entities, communities, and ecosystems, all of which will be impacted by a wind farm with energy storage. In conjunction, research and development are needed for the system components. The most promising solutions available in component form can then be considered for integration in sub-systems and systems at the simulation level or with sub-scale demonstrators. With the understanding of the integration characteristics, system roll-out can be developed. Typically, costs and complexity become much greater at this level and the challenges are more difficult as they constantly evolve and/or harden. This highlights the importance of STEP co-design.

At all stages, stakeholder considerations are key drivers for the interdependencies for optimal solutions and should be coupled with site-specific resources, constraints, and opportunities. For example, the important question of whether energy storage should be integrated at the source or distributed strategically within the grid depends not just on the available technologies, but on regional grid demands, expected capacity of solar and other decarbonized energy sources and socio-political settings. To ensure success, all these elements should be based on key STEP principles, shown as pillars in Figure 3, of Inclusion and Equity as well as Viability and Impact. Using this framework, STEP co-design can be used to consider new modalities of wind farms (e.g., the rapid developments of offshore and floating systems), recent developments in storage (isothermal compressed air energy and organic flow batteries), evolving grid economics (based on demand and resource forecasting as well as arbitrage and capacity reserve) with the full understanding of societal impact as well as policy developments and directives (local, national, and global).

Notably, the challenges and opportunities for storage outlined above are not unique to wind energy. The solar energy resource is also highly variable and, like wind, poses an increasing challenge in the form of a potential demand-supply mismatch as its market share increases. Although these two energy resources—wind and solar energy—exhibit fluctuations with different spatial and temporal characteristics, both appear to present challenges in the form of higher and lower frequency fluctuations requiring augmenting technologies such as supplemental generation, energy storage, demand management, and transmission infrastructure expansion.[13] The most challenging resource shortages may be those occurring during extended periods of low solar and wind energy resource availability, which vary from year to year and affect both solar and wind energy.[12] The combination of solar and wind energy and augmenting technologies can be expensive and, if not co-designed with communities, with economic and societal considerations in mind, may not capture the full set of environmental and societal benefits that they would otherwise offer. At worst, without a sound co-design approach, they may create unanticipated problems in the form of local job losses and environmental degradation. A holistic co-design approach will endeavor to consider all of these aspects in concert to ensure wholesale benefits.

Although the conceptualization and roadmap of this approach is herein focused on wind energy and storage, it can also be applied to a range of other technologies required to support a decarbonization transition, such as geothermal, hydrokinetic, etc. but particularly solar energy, as it faces similar issues of variability and intermittency. Moreover, models of the mechanisms of technological improvement[65,103]—at the level of devices and infrastructures—can help inform participatory processes by highlighting how investments and technology design decisions can lead to innovation outcomes. The problems encountered in wide-scale adoption of solar and wind energy therefore relate to a range of economic, technical, political, and societal barriers that need to be considered to ensure successful implementation.

In summary, the STEP co-design approach developed herein can be applied to arrive at solutions to dispatchable wind energy (coupled with solar and other renewables) that address stakeholder interests along multiple dimensions. This approach can also be employed to support the development of many other emerging technologies by considering their economic performance and the social and political contexts in which they will be deployed. The potential benefits of this approach include supporting a clean energy transition that succeeds not only in reducing greenhouse gas emissions but also in creating locally specific benefits to communities and job growth opportunities. We recommend carrying out case studies to better understand how this approach will impact: (1) a system's characteristics or designs as well as (2) the potential for wind and storage facilities to be successfully deployed.

## ACKNOWLEDGMENTS

The authors wish to thank Prof. Jessika Trancik of Massachusetts Institute of Technology (MIT) for feedback on the manuscript and set of topics covered, particularly on the potential to incorporate a participatory process and broader societal considerations into the design and advancement of clean energy technologies. The authors also wish to thank William W. Hogan of the Harvard Kennedy School at Harvard University for key advice on economic issues and the support of the National Science Foundation, award number 1937039. Finally, support from a Palmer Endowed Chair Professorship at the University of Colorado is also gratefully acknowledged.

## AUTHOR CONTRIBUTIONS

The authors contributed equally.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

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