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Emergent landscapes of renewable energy storage: Considering just transitions in the Western United States

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Abstract
Governments, utilities, and energy companies are increasingly looking toward energy storage technologies to extend the availability of variable renewable power sources such as solar and wind. In this *Perspective*, we examine these fast-shifting developments by mapping and analyzing landscapes of renewable energy storage emerging across the Western United States. We focus on the rollout of several interrelated leading technologies: utility-scale lithium-ion batteries, supported by increasing regional lithium mining, and proposals for new pumped storage hydropower. Drawing on critical resource geography, we examine energy storage as both a component of renewable transition and as its own driver of landscape transformation, resource extraction, and conflict. By mapping and interpreting emerging Western landscapes, we show that leading energy storage technologies and the materials needed to make them can require extensive surficial land use and have significant regional water impacts, and that they are generating opposition from groups concerned about environmental degradation and (in)justice. We propose an agenda for future research on energy storage aimed at rendering its development more socio-ecologically beneficial and just.

Keywords: Western United States, renewable energy transition, energy storage, lithium, hydropower

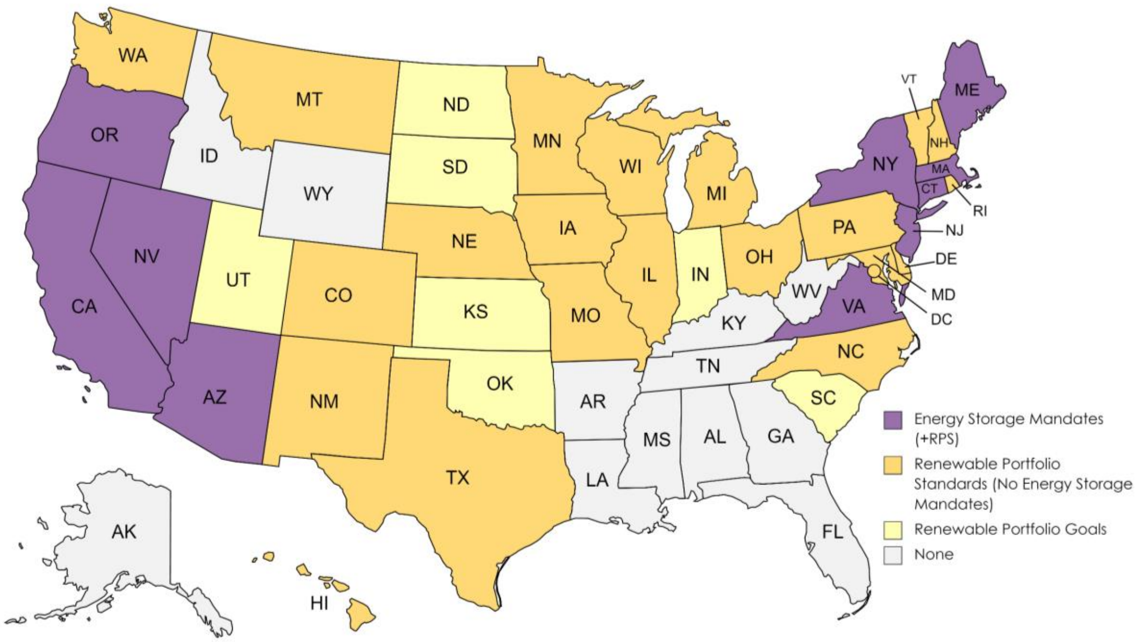
Introduction

"The sun doesn't always shine and the wind doesn't always blow!" So goes a common critique of renewable energy. Renewable sources such as solar and wind produce variable amounts of electricity, creating a balancing challenge to match electric power supply to daily and seasonal demand [1]. This emerging dilemma has acquired new urgency as renewable power becomes a key climate action priority and renewables begin to reach high levels of deployment. In California, a leading U.S. state for renewables, there is even an affectionate regionally coined term for the balancing problem, "the duck curve."[i]

The balancing or duck curve problem has driven a boom in the development and integration of energy storage into renewable energy projects and power grids, supported by federal and state policy incentives and deployment mandates [2]. Demand for the resources—critical metals, minerals, land, and water—needed to produce and site these energy storage infrastructures is reshaping or poised to reshape social, cultural, and physical spaces in varying ways across space, time, and place, and at many scales.

The push for the development of energy storage projects and supply chains is transforming contemporary energy landscapes [3,4] and opening new resource frontiers. In 2020, the U.S. accounted for 40% of the world's currently operational energy storage projects, and the National Renewable Energy Laboratory expects the U.S. to more than quintuple storage capacity in the next 30 years [5]. However, to date U.S. policy commitments to deploy storage have been regionally uneven (Figure 1) [6,7]. The Western United States is a front-runner in both existing energy storage and new policy commitments. For example, California leads the country with 4.5 gigawatts (GW) of operational pumped hydro storage capacity [8], about 1.5 GW of that from batteries operating by spring 2021 [9]. Meanwhile, renewable portfolio standards in the Western States and subsequent renewables procurement are driving new energy storage policies and a related wave of investment in the region.

Figure 1. U.S. states with current energy storage mandates (in addition to renewable portfolio standards), renewable portfolio standards without energy storage, and renewable portfolio goals (e.g., voluntary targets), as of 2021.



This paper examines landscapes of energy storage emerging across the Western U.S. Despite broad interest in low-carbon energy transitions and growing critical scholarship on renewable energy, critical analysis of energy storage and its supply chains remains limited. In foregrounding energy storage for more concentrated analysis, we emphasize that these technologies and infrastructures are not only significant as a component of renewable power systems. Rather, storage technologies and infrastructures have their *own* distinctive (and varying) qualities. As such, they must be considered as important drivers of landscape transformation, resource extraction, and socio-environmental justice conflicts in their own right.

In this *Perspective* article, we map emerging landscapes of energy storage and consider site-specific environmental justice concerns emerging alongside proposed projects. We aim to bring environmental justice concerns into conversation with studies on renewable energy infrastructures' "acceptability" [10,11], and to prompt further investigation into the land and water impacts of energy storage infrastructures. Our analysis focuses on several key activities within the energy storage sector in the Western U.S.: pumped storage hydropower (hereafter, "pumped storage"), utility-scale battery systems, and proposed regional lithium mining. A regional view helps capture the rapid rollout of multiple storage technologies and the cumulative emerging impacts of this rollout. Storage technologies inherit legacies of land and hydrological alteration and dispossession in the Western U.S., a region already facing environmental degradation and justice conflicts around under-regulated renewables booms [12,13]. We use this regional case study to develop an agenda for future research on energy storage as an integral component of a just energy transition. This research and proposed agenda for future research is relevant for other regions around the world that are experiencing transformations from energy storage development.

Theoretical framings

Critical energy scholars have considered the distinctive materialities, spatialities, and politics of renewable energy forms. This scholarship has scrutinized renewables' high surficial land demands relative to subterranean fossil fuels, and highlighted dependence on new or different place-based extractive resources as key qualities distinguishing renewable generation infrastructures from fossil-fueled power [12,14].

Renewable energy generation brings together new sets of socio-ecological relationships between lands, waters, and stakeholders, such as the push to map, territorialize and develop rural desert land in the United States [12,15], which can spark new conflicts between land and water users, exacerbate existing problems, and create novel environmental degradation and environmental justice problems [12,15–17]. Variable renewable generation sources require energy storage as a proximal support infrastructure, and its technologies raise additional land and water use questions. Simultaneously, as with renewable generation, the impacts of energy storage extend beyond individual infrastructure projects into broader landscapes of resource extraction, supply chains, and flows of minerals and water, both within and beyond the Western U.S. region. These include, for example, issues associated with extraction and mining of minerals and metals [18,19], as well as life-cycle toxics challenges in production and disposal of devices [12,20]. These issues are provoking conversations about the costs of green extractivism [21], amid rising political conflicts and justice challenges [22,23].

We situate our analysis within "critical resource geography," a subfield of human-environment geography that examines "the systems through which resources are made and circulated," and reflects on "how things become resources, as well as the work that these resources do in the world." [24]. Critical resource geography examines power relations, values, and political economic dimensions of resource extraction and use, connecting biophysical, infrastructural, and sociocultural dimensions of energy, land, and water [19,25,26]. Resource storage has recently received closer consideration, with attention to how resource circulations shift when storage infrastructures are developed [27]. Energy storage-relevant scholarship in critical resource geography has primarily examined fast-evolving extractive frontiers and strategic resource politics developing around lithium mining worldwide [28]. Particularly, the rise of South American lithium mining has provoked a wave of recent scholarship examining the region's neo-extractivist politics and new strategic and justice conflicts [29,30]. Scholars have noted the complex geopolitical dimensions of extraction for green energy, as lithium and other metals and minerals key to energy transitions become recognized as strategic global resources [31]. Meanwhile, critical resource geography has contributed a stronger understanding of precisely how siting renewables in new land and places is enabled through processes of large-scale territorialization. Scholars argue that in addition to important concerns such as public opinion and acceptability, state policies that encourage or discourage extraction and development render new spaces suitable and fit for development [32,33]—while shaping who is affected, and in what ways. Such questions are highly relevant as storage is developed, in and beyond the Western U.S.

Ultimately, concerns about territorialization, land and water use, and socio-environmental impacts are linked to questions about political and discursive power. Benefits and impacts of energy transitions may not be distributed evenly, creating new patterns of uneven development [25]. In examining renewables siting conflicts and green extraction problems, critical scholars and social movements have called for *just* energy transitions, arguing that socio-technical/ecological transitions to renewable energy must not reproduce or worsen environmental and economic harms [12,32,34,35]. Land and water questions in siting and extracting resources for energy storage pose similarly crucial challenges for just energy transitions [36,37].

Methods

To understand the spatial and territorial patterns of the emerging energy storage sector, we generated and mapped a comprehensive geospatial dataset of existing and proposed energy storage infrastructures and mine sites from energy storage supply chains in the Western U.S. We created a data set and mapped a range of energy storage projects in the Western U.S. including hydrogen storage, natural gas storage, and salt cavern storage among other types. We then focused on projects along the following criteria: projects that are land and water intensive; projects that have multiple examples being proposed across the west (as compared to projects with a single project example). Based on these criteria, we focused on the sector's currently leading technologies: 1) utility-scale lithium-ion batteries, supported by 2) regional lithium mining, and 3) pumped storage, including new proposals joining existing infrastructures. To create this dataset, we systematically searched online resources including federal documents (such as Federal Energy Regulatory Commission (FERC) permits and notices), records of permitting processes, news articles (primarily the *LA Times*, as well as smaller regional publications), and renewable energy-specific blogs and publications (e.g., *GreenTech Media*). For the map of lithium claims, we also utilized a data set created by the Center for Biological Diversity [38]. We then examined qualitative trends, including opposition around concerns of environmental justice and environmental degradation. We used the above sources as well as environmental and community organizations' blogs and newsletters to understand local resistance and environmental justice concerns.

Results and discussion

Types and landscapes of energy storage in the Western United States

Energy storage technologies currently being deployed across the Western U.S. include utility-scale battery energy storage systems, large-scale pumped storage, and distributed energy resource projects, such as behind-the-meter residential batteries, microgrids, and peak flow reduction programs (which we do not examine in this paper). From the dataset, over 95% (22 GW) of renewable energy storage comes from pumped storage, while less than 5% of energy storage capacity is in large-scale battery projects (~1 GW). However, rapid growth in battery storage, particularly lithium-ion batteries, means that this mix may change in the future [5]. Novel technologies and techniques including other advanced batteries, compressed-air energy storage, flywheels, thermal and ice, hydrogen, and behind-the meter demand-side management are also emerging. Storage types range from short duration technologies such as lithium-ion batteries, providing about four to eight hours of energy, to long duration sources, including pumped storage, that provide eight or more hours of storage [39]. Each technology comes with unique water and land uses and impacts up the supply chain. We consider today's most common storage technologies, focusing on utility-scale lithium-ion battery energy storage systems (and related lithium extraction) and pumped storage (Table 1).

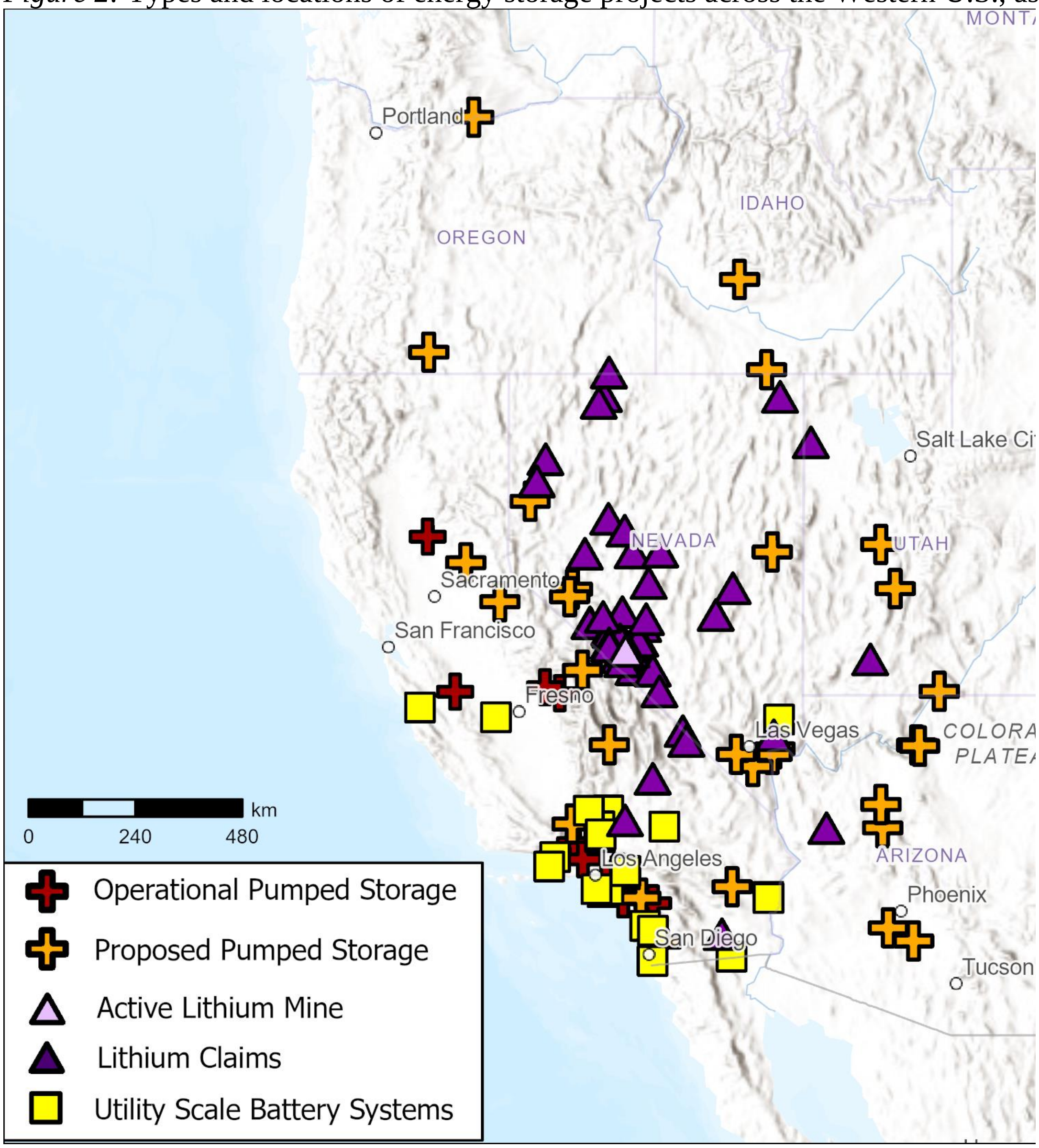
Table 1. Typology and characteristics of major energy storage-related technologies in study region.

Project type	**Storage temporality**	**Fixed-resource dependence**	**Scale and land use impacts**	**Water usage and impacts**	**Land and property type**	**Examples of proposed or existing projects**
Utility-scale battery energy storage systems	Daily energy storage	Requires mined materials (e.g., lithium) and manufactured technology.	Can be large scale and land intensive. Includes stand-alone projects in urban settings and solar-plus-storage in rural areas	Virtual water use (water required for lithium extraction; see below)	Public and private land	Chuckwalla Solar-Plus-Storage Energy System, CA; Eland Solar & Storage Center, CA; Moss Landing Energy Storage Facility, CA
Hard rock lithium mining	Used for batteries, supporting shorter duration storage	Fixed resource mineral	Can be large scale, land intensive. Affects many plant and animal habitats	Water lost during extraction processes. Potential water quality impacts, especially on groundwater.	Typically Bureau of Land Management public lands	Rhyolite Ridge, NV; Thacker Pass, NV; many other new claims & proposals in NV
Lithium brine recovery	Used for batteries, supporting shorter duration storage	Brine deposits in fixed locations	Can be large scale, land intensive. Affects many plant and animal habitats	Brine recovery is water intensive.	Public and private land	Salton Sea Geothermal Lithium Recovery Demonstration Project, Calipatria, CA
Pumped storage hydropower	Daily energy storage with potential for seasonal	Preexisting dam infrastructure	Involves large scale infrastructure. Affects many	Intensive water use; drawn from rivers and/or	Various, public and private land,	Lake Elsinore (LEAPS), CA; Goldendale, WA; Eagle Mountain

	storage/long duration storage	or mountain topography	plant and animal habitats	pumped groundwater	including on or near tribal lands	Pumped Storage Project, CA; Owens Valley, CA

Rising interest in energy storage has propelled the expansion of projects across new territories (Figure 2). Proposed projects exhibit a much wider spatial extent than currently existing ones, and different types of energy storage have different extended impacts.

Figure 2: Types and locations of energy storage projects across the Western U.S., as of 2021.



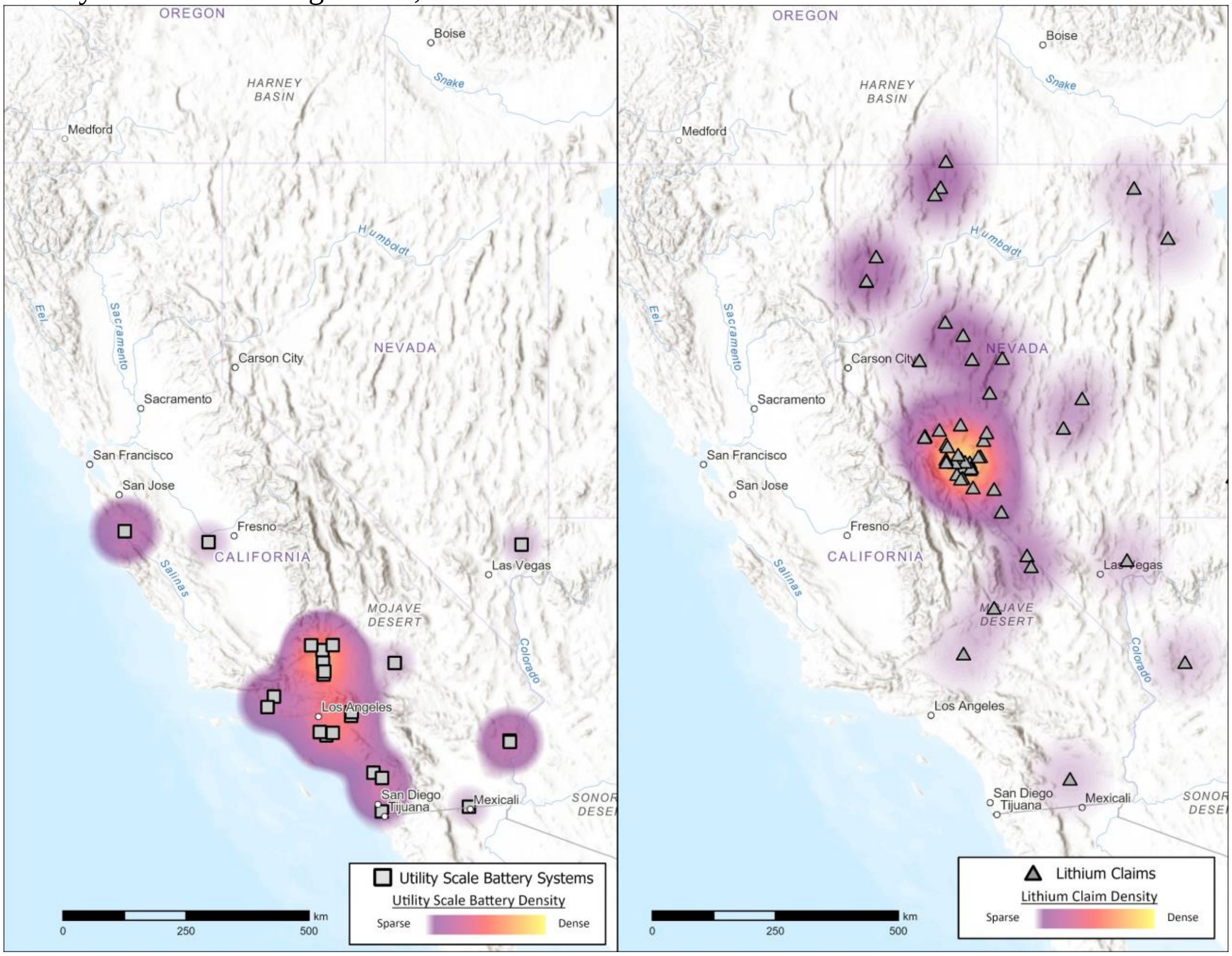
Utility scale battery energy storage systems

Lithium-ion batteries were introduced at scale in the 1990s around growing technological and consumer electronics applications and power tools. The boom over the past decade is due primarily to increasing demand for electric vehicles and innovations that allowed for greater energy density. Stationary lithium-ion battery storage for electric power grid applications are driving additional growth and are increasingly being adopted for energy storage across urban and rural locales.

Some battery installations are located alongside utility scale solar farms in a hybrid solar-plus-storage configuration (30%) or fossil fuel generators (8%), while the majority are co-located but stand-alone utility-scale battery projects feeding directly into the grid (62%) [40]. Most batteries have the primary job of delivering electric power, but they can fulfill other tasks to modify power quality. Battery energy storage is anticipated to help phase out natural gas peaker plants in service of full-grid decarbonization. For example, Southern California Edison sought fast-tracking of utility-scale battery storage to replace its reliance on natural gas after the 2015 Aliso Canyon natural gas leak [41]. Battery companies are competing to build larger and larger utility-scale battery systems [42]. In 2021, Vistra Energy brought online the largest battery in the world, the 400 megawatts/1,600 megawatt-hours Moss Landing Energy Storage Facility, in Moss Landing, California [43].[ii]

Figure 3 situates emerging landscapes of energy storage by showing both existing and proposed utility-scale battery systems and related lithium claims, which occupy different but connected spaces. Existing scholarship warns that developing utility-scale renewable energy projects such as solar and wind farms in desert environments threatens ecologically damaging land use changes, by fragmenting desert habitat, and using water in arid environments [12]. Recent renewables booms in the Western U.S. have opened up frontiers outside of preexisting paths of development, generating additional environmental impacts [10]. Energy storage projects may worsen this problem. For example, in some project designs, battery systems added to utility-scale renewable generation installations increase both these projects' surficial land use and the amount of manufactured technologies that must be produced, installed and maintained on project sites [44]. Constructing new transmission infrastructures presents additional siting issues. Furthermore, in addition to direct water use on-site in arid land projects [12], batteries have an "embodied water" or "virtual water" component— water that is used in the production of the materials for batteries and during manufacturing [45]—that must be considered in regional sourcing.

Figure 3: Density of existing and proposed utility-scale battery energy storage systems (left) and density of lithium mining claims, as of 2021.



Lithium mining

Lithium is prized for its lightweight attributes and reactive properties that allow it to readily release electrons for electricity. Demand for lithium as the electrode in a wide variety of different batteries is driving expansion of lithium mining, with new clusters of extraction linked to specific lithium deposits, particularly in Nevada (Figure 3). Lithium is an abundant and widespread mineral, but ore deposits with sufficient quantities for profitable mining are uncommon. Currently most lithium is mined or produced in Australia and South America, in particular the Atacama Desert and surrounding drylands spanning parts of Chile, Argentina, and Bolivia. However, the U.S. reports some of the largest lithium reserves after South America, and U.S. lithium production is developing rapidly—increasingly driven by strategic alliances between domestic technology companies and international mining corporations [46]. Demand for lithium is likely to heighten as demand for battery storage increases and the price of lithium batteries falls [5].

Nevada is poised to dominate U.S. lithium mining. The U.S. currently has only one existing lithium mine, Silver Peak in Nevada, which has been producing lithium using brine recovery processing since the 1960s. Many of the U.S.'s known lithium deposits are in Nevada, and the state currently has over 14,000 placer claims [47,48]. Many multinational companies have rushed to purchase mineral claims to U.S. lithium sources due to the expectation of dramatically increased demand for the metal. New legal and investment patterns have accompanied the rapid rise of these new mining ventures [49–51]. The boom in lithium extraction joins broader issues of green extractivism [19–23] in which renewable energy technologies fuel mineral extraction and extractive industries. Two prominent lithium development proposals in Nevada include Thacker Pass and Rhyolite Ridge, both in exploration and permitting phases. Ioneeer, the company exploring Rhyolite Ridge, claims it could produce 20,000 tons of lithium annually [47].

Current and proposed mines across Nevada have generated significant opposition, particularly around threats to critical wilderness areas, groundwater, and important cultural sites for Indigenous communities [52]. The Nevada environmental organization Basin and Range Watch has documented the large-scale use of pumped groundwater for lithium extraction [53]. There is also controversy over impact to endangered species [54]. In particular, the development of the Rhyolite Ridge Lithium-Boron Project stands to destroy the small habitat of the endemic Tiehm's buckwheat plant [47]. Developers have suggested moving the plant, while conservation groups, such as the Center for Biological Diversity, have sought protection under the Endangered Species Act [47]. Meanwhile, protesters camped at the site of the proposed Thacker Pass mine for about 1 year, lawsuits have been filed by environmental and environmental justice organizations, and there have been multiple protests by Indigenous community members [51]. This resistance may encourage exploration of other sources like California's Salton Sea, which has been considered as a source of lithium from geothermal brine in an already-developed area [55]. Whether Salton Sea lithium development could obviate the need for the more controversial mining projects in Nevada remains to be seem; the relationships and dynamics between these multiple U.S.-based lithium sources are evolving dynamics that warrant further study.

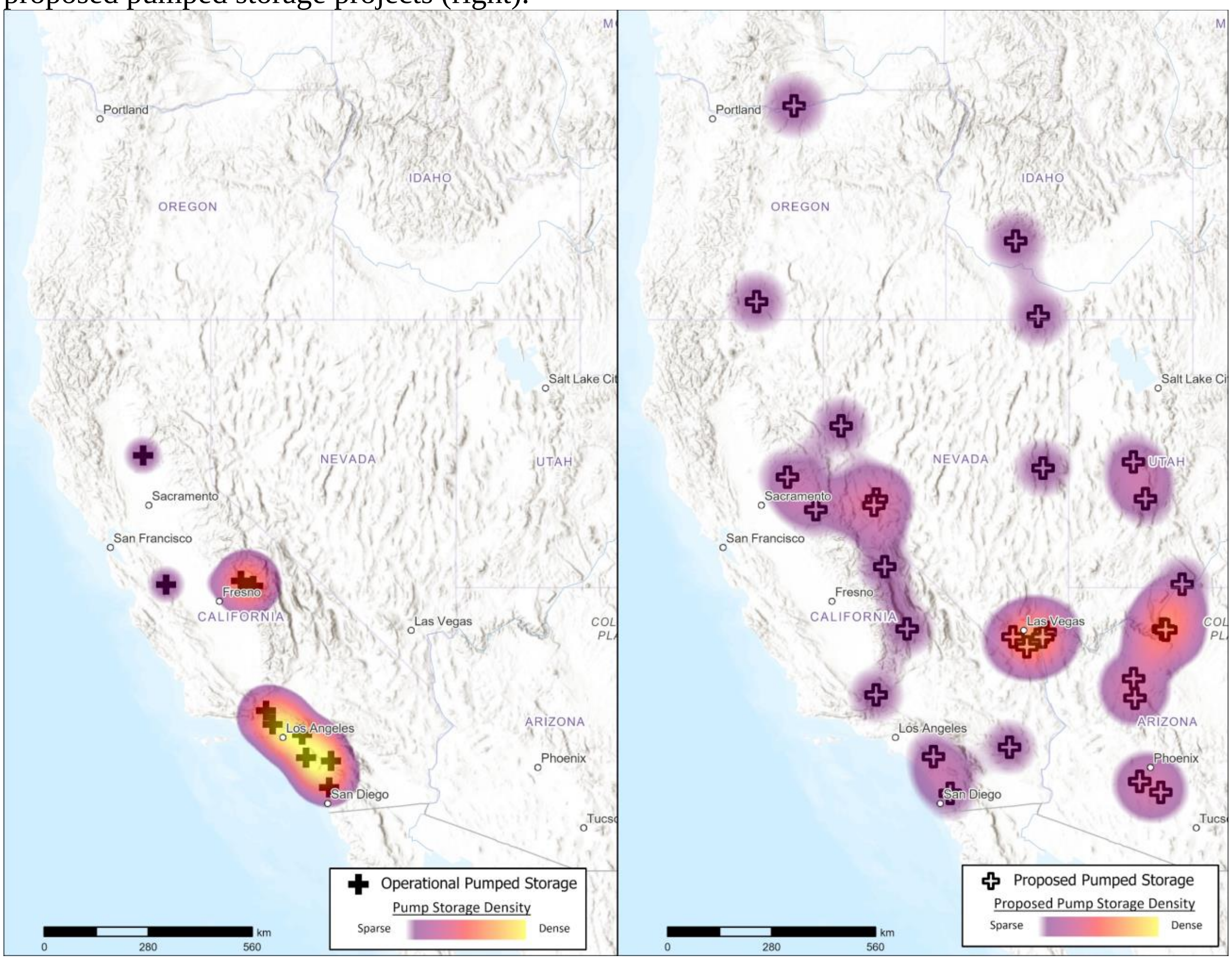
Pumped storage hydropower

Pumped storage is an older form of short- and long-duration energy storage introduced in 20th century hydroelectric dam projects that can be used to meet daily and seasonal energy demand [56]. This storage form is currently dominant for long-duration grid storage in and beyond the U.S., referred to as "the backbone of storage" [5]. Despite increasing controversies over hydroelectric dams, rising energy storage needs have provoked a wave of new proposals for pumped storage projects.

In pumped storage systems, renewable energy sources can be used to power pumps that move water into a high-elevation reservoir at times of high energy production, then use gravity to release the water to a lower reservoir at times of higher demand, producing electricity These projects are overall net energy users, in that they use on average 15-30% more energy to pump water than what they later produce [57]. However, their benefit is that they use excess peak energy for pumping, and then later produce high-value electricity at times of peak demand [58]. Pumped storage infrastructures are either open-loop systems that draw water from rivers or streams or closed-loop systems that are not connected to a river or stream but instead have a contained water body that is moved back and forth between two reservoirs.

California has the most pumped storage capacity in the U.S., with 4.5 GW, or 17% of the national total [8]. Currently, dozens of new pumped storage projects are proposed and under review across California and the Western U.S. (Figure 5). This new wave differs from the previous generation of pumped storage and hydroelectricity projects constructed throughout the 20th century. While earlier projects were typically built by utility companies through an integrated resource management plan, most newly-proposed projects are spearheaded by private energy, development, and technology companies aiming to secure power purchase agreements or operate as merchant power plants. Many of the new projects are to be sited on public lands in rural, arid locations in California and surrounding states, and several are planned to be near or on tribal reservations. As Figure 5 shows, newly proposed facilities span a far wider geographic range than existing projects.

Figure 4: Density of operational pumped storage hydropower projects (left) and density of proposed pumped storage projects (right).



Most of California's existing pumped storage projects are open-loop, as they were built as one element of large hydropower projects. Most newly proposed projects are closed-loop, using reservoirs pumped from a stream or groundwater source. A few of the proposed projects will be built as part of existing dam infrastructures; these projects have sparked less public controversy than ones proposed in less developed areas. In contrast, many of the proposed projects that require new infrastructures (reservoirs, pumps and/or transmission lines) have sparked significant controversies involving issues of desert conservation, water use, and sacred tribal lands.

For example, the Lake Elsinore Advanced Pumped Storage project (LEAPS), an open-loop project proposed in southern California, has generated significant public opposition. Although from a technical point of view, the project has ideal topographic conditions, opponents' concerns include transmission line development and impacts on water quality and aesthetics of the lake [59]. The Pechanga Band of Luiseño Indians are fighting the building of LEAPS due to Lake Elsinore and surrounding lands being part of their history and Creation Account [60]. The case of LEAPS is indicative of the types of conflicts spurred by new pumped storage infrastructures in the rural Western U.S.

Although many new proposals exist, few of the proposed projects have been constructed yet due to their expense, long construction timelines, and public opposition. Controversy about land and water use has created roadblocks for some proposed projects. For example, a pumped storage project proposed for California's Owens Valley—an area well known for historical water controversies and conflicts with the city of Los Angeles—received so much public pushback over concerns about wildlife disturbances that the project developers withdrew their proposal, at least temporarily [61]. Another proposed pumped storage project in Goldendale, Washington, which has generated opposition from regional tribal and environmental organizations, was delayed after it was denied a key permit in June 2021. However, the potential for major regional pumped storage expansion remains due to its low-tech fundamental technologies and long-term storage capacity [1,62].

Conclusions

Energy storage represents a distinct element of renewable energy transitions, both in terms of *where* energy storage is being developed and in the *impacts* of energy storage on land and water resources, people, and ecosystems. In a broader sense, all forms of energy can be conceptualized as energy storage: fossil fuel energy can be thought of as an extremely stable and long-duration form of storage of solar energy [32]. Given the variability of renewable energy sources such as solar and wind, however, storage deserves targeted consideration. Energy storage technologies have distinctive footprints. Many require considerable surficial land use, are significant regional water users, and stand to fuel new land and water use conflicts. Many of the projected transformations and impacts of storage rollout mapped here fall in rural California, Nevada, and across the Western U.S., including tribal lands, raising issues of green extraction and new sacrifice zones.

The issues raised in this research are significant within renewable energy transitions more broadly, from resource extraction frontiers and supply chains, production and operation and infrastructural landscapes, to end-of-life disposal. Examining energy storage brings them out in specific and pronounced ways that deserve further attention. In Table 2 we propose a typology of factors that future scholarship on energy storage might apply to unpack specific projects or broader trends empirically and conceptually.

Table 2: Considerations for further research on energy storage

Type of consideration	Specific dimensions
Material dimensions	Energy storage duration Relationship to fixed resources Spatial extent/footprint Water dependence & water footprint Dependence on mined resources Life cycle analysis
Socio-political, territorial, & governance dimensions	Ownership of infrastructure Land ownership Water rights ownership Spatial overlap with tribal lands Urban-rural linkages and connections Financial backing of projects Regulation & permitting processes Agencies/institutions involved Scales of governance (local, county, state, federal, etc.) Lawsuits & legal dimensions
Environmental, social, & environmental justice dimensions	Water quality impacts Air quality impacts Land use impacts Endangered or threatened species impacts Spatial overlap with existing water quality and quantity issues Spatial overlap with existing environmental justice issues Impacts on marginalized communities Impacts on culturally sensitive lands & resources Conflicts and inequities generated or perpetuated Consultation with the public and with Tribes
Ideological & discursive dimensions	Concepts of justice & equity at multiple scales Local understandings of histories and places National, regional & community identities

Many questions remain open for further exploration and research. For example, the push for pumped storage is unfolding alongside increasing concerns about how hydropower dams affect river ecologies, as well as increasing recognition of the role of dams in Indigenous displacement throughout the Western U.S. [63]. The reliance of lithium mining on water resources also raises new questions about how mining-related water use interacts with factors such as climate change, intermittent drought in the Western U.S., groundwater overdraft, and water overallocation [64]. There are also other technologies, resources, and minerals used to make devices for energy storage, such as copper, cobalt, vanadium, manganese, graphite, and molybdenum [37,65]. Additional phases of the life-cycle of critical minerals and energy storage technologies remain to be explored. Further, while we focus on the Western U.S. for this case study, the issues presented here are relevant for areas around the world that are developing energy storage technologies and/or extraction projects related to energy storage.

Energy storage is rapidly developing as part of the broader renewable energy transition. We concur with critical scholars of just energy transitions who argue that a full accounting of renewable energies' environmental and social impacts should not be diminished despite the urgency of climate change and the need for climate solutions. Instead, it should be acknowledged that, like any technical solution, energy storage technologies and techniques will have spatial consequences and justice dilemmas [66]. Future research can help understand the spatial transformations and socio-environmental impacts of infrastructures, supply chains, waste products, and effects on land and water resources at multiple scales. Taking these impacts into consideration may shift the calculus on sustainability of an energy storage project, point out social or environmental costs that should be accounted for, encourage policy or regulatory changes or perhaps support the application of alternate technologies. Careful attention can help identify areas for improvement to make renewable energy storage more socially just and environmentally beneficial. Energy storage, like energy production itself, must be critically examined to avoid perpetuating longstanding injustices associated with the energy sector.

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[i] The duck curve in California represents a "ramping up" problem—on some days 13 Gigawatts (GW) of power needs to come online as the sun sets to meet peak power demands. Much of this ramp-up is provided through dispatchable natural gas power plants, but recent years have seen an increase in the amount of energy storage. The graph of the timing imbalance between energy production and peak power demands is shaped like the back of a duck. While the duck curve focuses on balancing between supply and demand, such daily (or seasonal) periods of overabundant renewables-based generation may prompt curtailment, or the shedding of excess electricity at a loss.

[ii] However, part of the project is offline due to overheating issues caused by a bearing failure and computer programming error.