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Renewable Electricity Production in Mountain Regions: Toward a People-Centered Energy Transition Agenda

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This paper examines progress and limitations in the transition from current dependence on carbon-based energy toward clean, renewable, and socially just energy in the Hindu Kush Himalaya and the Andes. Focusing on electricity production from sustainable hydropower, solar, and wind energy, the assessment does not cover biomass energy, although this is recognized to be an important energy source in these regions. Using meta-analysis methods, a set of 68 peer-reviewed publications was reviewed to systematically address 2 research questions: (1) Which electricity generation options in mountains can address local demands and adaptation needs while supporting broader decarbonization efforts? (2) What technical innovations, policy, and governance mechanisms can aid this transition? Considering governance, finance, individual and collective action, and science and technology dimensions of the transition challenge, recommendations for policymakers, mountain communities, and practitioners are made. These include setting up clear and effective policy measures, programs, and incentives to support energy transition plans and help mountain communities and energy practitioners to fully embrace the transition. Strong political commitment supported by international cooperation for a transition agenda centered on mountain people will enable community participation, stimulate technological innovation, and establish mechanisms to monitor and enforce social and environmental impact remediation.

Keywords: *energy transition; climate change; hydropower; renewable electricity production; mountain development.*

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Introduction

The impact of climate change is heightened in mountain regions (Beniston and Stoffel 2014; Gobiet et al 2014; Palomo 2017) and is visible in glacial retreat (Immerzeel et al 2020; Adler et al 2022) and ecological disturbance (Ruiz-Labourdette et al 2013), with changes in vegetation patterns (Telwala et al 2013; Ingty 2017; Fadrique et al 2018). The resulting ecosystem service effects (Viviroli et al 2007; Habit et al 2019) include altered provisioning and regulation of renewable energy sources. Energy transitions toward lower carbon energy (Lucena et al 2018) in mountains can be constrained because of inadequate infrastructure, remoteness, and reliance on traditional energy sources (Dhakal et al 2019). This paper addresses a subset of climate adaptation pathways for mountain regions, focusing on renewable energy use and transitions from conventional sources in the Hindu Kush Himalaya (HKH) and the Andes. The findings complement the Intergovernmental Panel on Climate Change Sixth Assessment Report's "Mountains" cross-chapter paper (Adler et al 2022). The analysis and discussion are focused on people-centric socioeconomic development and just energy transitions under climate change in mountain regions, primarily the HKH and Andes, while, in some cases, evidence from the Alps, Central Asia, and the Rockies is also discussed.

Methods

This meta-analysis (Mengist et al 2020) is based on a review of peer-reviewed journal articles and book chapters addressing 2 research questions: (1) Which electricity generation options in mountains can address local demands and adaptation needs while supporting broader decarbonization efforts? (2) What are the technical innovations, policy, and governance mechanisms that can aid this transition? Emphasis is placed on empirical case studies published in the past 10 years. Searches were conducted in Google Scholar for *energy* (*generation*, *supply*, *demand*, *renewable$*, *hydropower*, *solar*, *wind*, *biomass*), *climate* (*change*, *impact$*, *adaptation*, *adaptive capacity*, *mitigation*, *water resource$*, *seasonality*, *flood*, *drought*), *mountain$*, *livelihood$*, *agriculture*, *industries*, *urban*, and *economic development*. Relevant sources were reviewed and their references consulted for additional publications. Energy sources reviewed include hydropower, solar, wind, and biomass, noting also fossil fuels (gas, etc). Vulnerability, adaptive measures, and recommendations were identified for urban and rural populations and for economic sectors (food, water supply, sanitation, energy supply, and other). A total of 95 publications were systematically coded. Omitting those not addressing the research questions, a final set of 68 references was used.

The coded publications focus on the HKH (22), Alps (14), Andes (11), Central Asia (5), Rockies (3), and, in some cases, multiple regions. The meta-analysis assessed hydropower (36.3% of energy sources coded for), solar (15.6%), wind (14.8%), biomass (11.1%), fossil fuels in transition (6.7%), and unspecified energy sources (15.6%). Climate change impacts included altered seasonality of river flows, including from temperature-induced glacial melt, glacial lake outburst floods (GLOFs), and drought (29.1% of multiple impacts coded for); variable or declining precipitation and runoff (23.4%); increased flooding (11.3%); altered wind patterns (7.1%); severe or extreme weather (6.4%); and other (22.7%). The energy system adaptation responses to these impacts are discussed below.

Energy systems

Energy transitions are vital especially for developing nations in meeting the United Nations Sustainable Development Goals (SDGs), including SDG 7 for energy (UN 2015; IEA 2022). There is broad consensus that clean energy transitions will be centered on electricity generated with renewable energy (Bogdanov et al 2021). Thus, having an electricity grid connection to households is also considered a part of energy transition, regardless of the energy source (Liao et al 2021).

Climate change is expected to change the demand and supply of electricity (Chandramowli and Felder 2014; Ciscar and Dowling 2014). Along with increasing population, rapid industrialization, urbanization, rural–urban migration, exploitation of resources, and lack of rural infrastructure (Rawat and Tiwari 2014), climate change is expected to create impediments to the development (Kusters and Wangdi 2013) of renewable energy in developing-country mountain regions. As many mountain communities in the HKH and Andes depend on agriculture, conflicts over water allocation for agriculture and hydropower generation (Chevallier et al 2011; Buechler et al 2016; Crootof et al 2021) or rights over common pool resources (Carey et al 2012) may be exacerbated with increasing demand for resources (Jalilov et al 2013).

Mountain communities use a diversity of energy sources for cooking and space heating (Ershad et al 2016; Gould et al 2020). Mountain communities in developing countries rely heavily on wood and manure biomass for energy. Although these are beyond the scope of the present analysis, it is useful to briefly set the context for the transition toward renewable electricity in the Andes and HKH. In the Andes, despite some transition to cleaner energy sources, reliance on solid-biomass-based energy remains high (Martinez et al 2020). In the HKH, wood and manure remain popular because of availability and relatively low cost (Rahut et al 2017). With climate change, tree lines have shifted upward (Liang et al 2016; Gatti et al 2019), increasing the potential for more vegetation and the availability of biomass resources, but can also be nonuniformly spread spatially (Fadrique et al 2018). However, high consumption of fuelwood can harm fragile mountain ecosystems (Bhatt et al 2016). In the HKH, for women, the drudgery of collecting firewood and black carbon from in-home biomass burning have negative health outcomes (Malla 2013; Nautiyal 2013), necessitating a shift toward fuel-efficient stoves and electricity from renewable sources (Dhakal et al 2019).

In the HKH region, hydropower accounts for the majority of power generation, especially in Nepal, Bhutan, and mountains of India. Yet India and Pakistan continue to be highly dependent on fossil fuel energy. However, distributed solar power combined with pumped storage is now being explored, and adopted if appropriate, as an alternative to fossil fuel energy to provide clean energy to households, agriculture, and businesses. This combination of solar and pumped-storage hydro is an example of the hybridization of multiple forms of renewable energy (Mahmud et al 2022) that is becoming more prominent in government policies and initiatives in the HKH.

Access to low-carbon energy sources to alleviate energy poverty in the mountains has numerous barriers, chiefly cost, technical capacity, cultural values, and, increasingly, reduced reliability and heightened risk of climate change (Nasirov et al 2015; Ghimire and Kim 2018). Transitioning to clean renewables, both on and off-grid, is one means of alleviating energy poverty (Katsoulakos 2011).

Geographical isolation, unreliability of electricity or gas supply, unaffordability, low income, and extra energy demand during winter months are some of the factors that contribute to energy insecurity in the mountains (Katsoulakos 2011; Papada and Kaliampakos 2016). Thus, many mountain populations are vulnerable to energy poverty despite being rich in energy resources (Katsoulakos and Kaliampakos 2014).

Energy demand may be slow to respond to price changes in the short run (Labandeira et al 2017). This lack of sensitivity is accentuated in mountain regions where energy alternatives are limited (Malla 2013) and energy prices are uncertain (Steinbuks and Hertel 2013). Clean energy transitions can also be stimulated by competitive pricing of renewable technologies in the long run, for example, for solar photovoltaics (Victoria et al 2021), as consumption of natural gas and fossil fuels seems to be more sensitive to price increases over longer time frames.

Climate change impacts

Climate change impacts and energy-related adaptation responses in mountains vary by location (including regionally), by energy system, and by vulnerability of different stakeholders (communities, infrastructure operators, policymakers, etc). In Table 1, we broadly synthesize responses as reported in the literature.

Water resources and extreme hydrometeorological events

If carbon dioxide and other greenhouse gas emissions are not reduced in the next decade, warming is projected to surpass 2°C during the 21st century (IPCC 2021). It has been

TABLE 1 Principal climate change impacts on energy systems in mountain regions, resulting vulnerabilities, and associated adaptation strategies, as derived from review of 68 peer-reviewed publications.

Climate-change effect	Impacts on energy systems	Socioeconomic vulnerability	Adaptation strategies
Altered seasonality and timing of river flows, including from temperature-induced glacial melt and GLOFs	(+) Increase in average annual electricity supply from hydropower plants due to increase in river discharge from melting glaciers	Population growth, urbanization, and industrial demand for electricity continue to outpace aggregate hydropower supply	Use of storage and pumped storage hydropower; reservoir management strategy based on water availability
	(−) Risk to energy infrastructure from GLOFs	Risks to economy and livelihood from extreme events—both GLOFs due to warming and floods due to precipitation change (see below)	Opposing adaptation measures: mitigate risk of hydropower and other clean renewable energy through early warning, or reduce hydropower dependency and diversify energy sources
	(−) Reduced water storage in reservoirs, increased debris flow, sedimentation	Competition for water and energy result in irrigation–hydropower trade-offs	Local water supply, rejuvenation of springs and watershed management; increase irrigation efficiencies
	(−) Increase in energy demands for cooling during summer months	Urban electricity demand in summer may result in rural power shortages, exacerbated by remoteness, difficult access, poor infrastructure	Energy sector regulation; reliability in load shedding; development of synergies among urban, industrial, and rural development policy frameworks at national and regional levels
Precipitation variability and change	(−) Decrease in electricity from hydropower during dry season	Reduced social equity from intermittent hydropower	Clean energy source diversification from hydropower to solar and wind
	(−) Risk to energy infrastructure from flooding during wet season	Flood, landslide, and infrastructure risk; economic/livelihood loss in communities	Community disaster risk resilience, planning, diversification
	(+) Varying impacts on forests and ecosystem, including decreased biomass/fuel	Drought impacts on local livelihoods, decreased biomass	Sustainable forestry, biochar, climate-smart agrosilvipastoral systems
Wind pattern change	(−) Reduced wind energy generation	Potential for off-grid clean renewable energy	Improve design standard and installation of new technologies
	(+/−) Changes in diurnal and seasonal wind pattern	Local technical capacity limited	Capacity building
	(+/−) Energy output characteristics of mountain wind farms are still unclear	Lack of data for robust planning, reliable energy supply; visual distraction	Strengthen hydrometeorological data collection and public availability
Solar radiation or cloud cover change	(+/−) Increase or decrease in solar generation (location dependent) due to change in solar radiation and increased ambient air temperature	Potential for off-grid renewable energy	Improve reliability through increased energy storage (batteries, pumped storage, etc); manage cost; capacity building, shift to renewable energy from fossil fuel, smart infrastructure; integrate water–energy–food nexus approach
		PV panels are fragile, subject to damage or theft, often not possible to meet higher amperage demand (heating, refrigeration)	
	(−) In high latitudes, projected increase in cloudiness will decrease thermal heating performance	Remote high-latitude mountain communities that rely on solar thermal heating will be affected	Insulation, diversification of heating sources

Note: +, positive impact, significant potential for adaptation; −, negative impacts; +/−, no discernible change; PV, photovoltaic.

estimated that a 1.5°C global rise in temperature will lead to warming of Asian mountain glaciers of 2.1 ± 0.1°C, with major loss of Asian glaciers by the turn of the century (Kraaijenbrink et al 2017). Similar trends are reported for the Andes (Chevallier et al 2011), Central Asia (Vidadili et al 2017), East Africa (Said et al 2019), and New Zealand (Caruso, King, et al 2017). Although change in glacier stock is one of the most visible impacts of climate change (Beniston and

Stoffel 2014), the entire mountain cryosphere (snow, ice, and permafrost) will be impacted by climate change, causing a cascading impact on the development and livelihoods of communities, including energy choices as well as biodiversity and ecosystem services (Mukherji et al 2018; Adler et al 2022).

Hydropower remains central to clean renewable energy potential (IEA 2019) and is a major energy source for mountains. Temperature-induced glacial melt will result in short-term increases in water flows and medium- to long-term loss of glacial water storage (Scott et al 2019), with negative impacts on annual river flow and especially dry-season runoff. This in turn will lead to reduction in generation in both storage and run-of-river hydropower (Caruso, Newton, et al 2017; Puspitarini et al 2020) and severe energy uncertainty (Laghari 2013; Fan et al 2020), with higher impacts in arid mountains (Rangecroft et al 2013). GLOFs that result from melting glaciers, changing permafrost, and altered precipitation patterns pose severe risks to infrastructure including hydropower facilities (Kumar and Katoch 2014; Schwanghart et al 2016; Poudel and Duex 2017; Huber 2019).

Some of the adaptations proposed and practiced to address the fluctuations in availability in water for energy infrastructure (Turner et al 2017) are constructing and managing storage and pumped-storage hydropower; installing low-flow, high-head (large-elevation-drop) hydropower (Shirsat et al 2021); managing headwater lakes; and relocating energy infrastructure to safer sites (Schaeffer et al 2012). Improved governance is also needed at local, national, and regional levels (Scott et al 2019). Some governance aspects include integrating the water–food–energy–environment nexus (Momblanch et al 2019), adopting flexible and iterative rules and plans (Hill 2013) to address uncertainties (Ahlers et al 2015), using integrated assessment of climate change impacts (Mishra et al 2020), and so forth. Adaptations to reduce the risk to energy infrastructure include diversifying the sources of clean renewable energy by including energy from solar and wind technologies where electricity grids are connected, integrated planning for energy infrastructure, and improved governance of energy systems. However, all these adaptive measures may involve complexities and, at times, may have to be dealt with on a case-by-case basis (Gaudard et al 2014).

Run-of-river hydropower is expected to be the most vulnerable form of clean renewable energy because of erratic rainfall patterns. While droughts may lead to a severe undersupply of electricity from hydropower, unpredictable water flows, especially during the wet season, may threaten the energy infrastructure and render it economically unviable (Majone et al 2016; Caruso, Newton, et al 2017).

Wind pattern alteration

The alteration of wind patterns with increased variability is observed as the localized impact of climate change on wind resources in mountain regions (Pryor and Barthelmie 2013; Proietti et al 2017; de Jong et al 2019). Therefore, improving estimations for wind energy generation (Dai et al 2019) is essential to cope with the climate threats that would also require upgrading management and operations (Watts et al 2016). For example, technical measures may include dynamical adaptation of turbines, upgrading design standards, and new installations (Pryor and Barthelmie 2013).

Solar radiation and cloud cover

Climate impacts on solar radiation and cloud cover that would have an impact on solar energy generation do not show discernible trends. Nevertheless, solar photovoltaic generation is seeing increasing adoption both globally (Proietti et al 2017) and in the HKH specifically (Fang and Wei 2013; Duan et al 2014; Ershad et al 2016), Central Asia (Vidadili et al 2017), the Alps (Grilli et al 2016; Hastik et al 2016; Kahl et al 2019), the Andes (Nasirov et al 2015), and the Rockies (Olson-Hazboun et al 2016). A promising solution is decentralized solar projects with battery energy storage, now being adopted on a pilot scale in HKH, especially in the mountain regions of India. Solar thermal applications continue to be adopted to reduce gas dependence (Barragán-Escandón et al 2022).

Renewable electricity in mountain regions

Mountains provide unique opportunities for harnessing hydropower. Because of climate change, hydropower projects in mountain regions experiencing marked wet–dry contrasts will face adaptation challenges (Majone et al 2016; Patro et al 2018). Run-of-river hydropower systems without water storage are particularly susceptible to climate impacts (Kuriqi et al 2021). Some researchers advocate for water storage to address these changes (Björnsen Gurung et al 2016; Hunt et al 2020), while others emphasize water management to adapt to climatic variability (Gaudard et al 2014; Caruso, King, et al 2017).

Solar energy remains a viable energy source for rural mountain communities in remote off-grid areas (Bhandari et al 2014; Proietti et al 2017). In urban areas, grid connections can be provided through large solar farms or net metering to add solar energy from home or commercial generation to the grid. For photovoltaics to be more attractive, researchers suggest policies that encourage incentives for solar adoption (Fang and Wei 2013), as for example in Chile and India.

The discourse on solar energy is dominant in clean energy transition narratives compared with climate change impacts (Grilli et al 2016). However, the increasing use of solar panels and batteries and the challenges of disposal of solar equipment with often-hazardous content after its useful life cycle can have impacts on public health and the environment. These necessitate additional policies for reuse and recycling of solar waste (Xu et al 2018).

Synthesis

Because economic growth and livelihoods are closely linked with energy availability (Di Sbroiavacca et al 2016; Labandeira et al 2017), development opportunities arise from meeting energy demand with cleaner energy sources and generating employment in the process.

Mountain communities in the HKH and Andes face uneven access to conventional energy sources, often entailing continued reliance on biomass (Malla 2013; Rasul 2014), because of remote and dispersed settlement patterns. Research has shown that rural communities are less likely to adopt renewable energy technologies compared with their urban counterparts; households with higher levels of education and income, availability of credit and subsidies, and higher levels of energy consumption and engagement with energy-related organizations were positively associated with adoption of renewable energy technologies (Liao et al 2021). While hydropower-led development offers solutions for both energy storage and availability, the dependence on climate-vulnerable water sources increases energy system and community vulnerability (Postic et al 2017; Xenarios et al 2019).

Hybrid systems (eg energy generation by combined hydropower, wind, and solar) can reduce energy insecurity (Bhandari et al 2014). However, technical solutions require supportive institutions (Pfenninger et al 2014; Xenarios et al 2019). Energy mix optimization is most feasible when based upon technical innovation, citizens' support (Volken et al 2018), acceptance of energy infrastructure in local social contexts and landscapes (Salak et al 2022), regional cooperation, and coordinated economic policies, as indicated below.

In the HKH and Andes, transitions to cleaner renewable energies will be led by hydropower (Hussain et al 2019). Although some positive steps toward energy transitions have been documented, this shift is slow in most mountain regions globally (Cronin et al 2018; Dhakal et al 2019).

Conclusions: toward a people-centered agenda

Adaptation to climate impacts and the imperative of carbon mitigation through renewable energy technologies are inextricably linked (Postic et al 2017). Energy transitions to cleaner, low- (or zero-) carbon sources meet both adaptation and mitigation imperatives in such a way as to address local, in this case mountain people's, needs.

Hydropower has the greatest potential for the clean renewable energy transition in mountains but requires significant investment and measures to address social and environmental impacts. Yet this is also the energy source with the greatest impacts from climate change, especially unpredictable precipitation and river flows, GLOF disasters, and seasonal downstream flooding when surplus reservoir storage is released. Additionally, upstream–downstream water sharing, especially related to hydropower in transboundary river basins, remains a challenge (Hanasz 2014; Huda and McDonald 2016; Llamosas and Sovacool 2021) but also presents an opportunity in the HKH for water and energy security (Saklani et al 2020; Murshed 2021).

Wind energy is nascent but has considerable opportunities for growth, given both its major potential in mountain regions, where wind resources are abundant, and rapidly declining costs. However, climate and extreme-event impacts pose risk to wind energy, while grid connection problems and the need to address environmental impacts on migrating birds and bats pose challenges.

Solar photovoltaics show major promise in terms of price and scalability. However, there are landscape impacts, and the public needs to be made aware of the health and environmental risks of disposing of hazardous battery and panel materials. Policymakers and development practitioners must address this.

Based on this analysis of published sources and our collective field experience in the HKH and Andes, 3 main emphases were noted for the transition to renewable electricity production in mountain regions in the context of climate change.

1. Technical innovation usually predates, but requires, supporting policies for development and adaptability assessment of new technologies for energy generation and storage. These should consider spatiotemporal assessment of climatic conditions, seasonality, and stakeholders' capacity to adopt technological improvements.
2. Regional cooperation calls for collaborative national efforts across countries with similar energy matrix characteristics in mountain regions to assess technical suitability, policy-support needs, linkages of energy with other sectors (especially water and food), and adaptive capacity to climate change.
3. Economic and development policy involves both public- and private-sector interests, requiring robust political commitment, policy coordination, and equity between upstream and downstream communities, as well as countries with transboundary rivers. This involves regional and international agreements for energy pricing, financial support for renewable energy transitions, and fiscal benefits for public–private partnerships.

Recommendations

Our recommendations for transformative energy transitions in the mountains are in line with levers identified by the UN (2019) for achieving SDG 7, which include governance, finance, individual and collective action, and science and technology. We have discussed the regional and energy system technology dimensions of the challenge above, and below we seek to generalize the findings for policymakers in government and civil society organizations and members of mountain communities, giving particular attention to the HKH and Andes, and practitioners including scholars and implementation agency personnel.

Policymakers

1. Removal of policy barriers for new renewable technologies will promote mountain-relevant technological innovations, prioritize mitigation of climate change impacts, and create robust markets for investors.
2. In larger countries that contain mountain regions with specific needs (to address risk and marginalization), attention must be paid to location-specific energy policies and long-term plans. Policies on renewable electricity infrastructure must strengthen stringent social and environmental impact assessments. Specifically for the case of hydropower, current and future vulnerabilities of water resources to climate change must be planned for, and mountain-specific policies and plans are needed for pumped-storage hydropower in locations where population relocation and cultural sites are concerned.
3. Fostering international cooperation is vital to provide technical support and funding to aid local transition efforts. Government agencies, nongovernment organizations, and local populations will embark on energy transitions when strategies prioritize clean energy through legislation, economic incentives including progressive reallocation of fossil fuel subsidies to

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renewables, improved information availability supported by research, and communication of climate impacts and hazards.

Mountain communities

1. Enabling community participation in energy planning through open forums will support both policy and the development goals addressed in these recommendations. Furthermore, social mobilization and awareness generation are also recommended as effective tools to influence personal and community choices for efficient and clean energy use. It is also useful to demonstrate the energy savings from efficient use and consumption. This entails providing awareness training and financial incentives for solar energy adoption by communities.
2. Since both rural and urban mountain communities in the HKH and Andes experience unacceptably high social and environmental impacts of energy development exacerbated by climate change, mountain communities must be integral to the process of transitioning to clean energy security and autonomy. Thus, energy infrastructure should also provide access and benefits to these communities.
3. Advancing transitions from fossil fuel to clean renewable electricity may leave some community members behind if adequate incentives (subsidies, capital), training, and other capacity building are not supported. The promise of renewable energy jobs, including for efficiency retrofits and local skilled technicians, especially in household and community solar and wind, must be intentionally developed to ensure individual and community benefits beyond access to clean energy.

Practitioners

1. Mountain-specific challenges and opportunities for policy and planning should be emphasized when addressing SDG 7 in meeting the 2030 agenda.
2. Energy SDG 7 and its targets cannot be addressed in isolation, as energy accessibility and reliability are dependent on progress toward other SDGs. Practitioners should advocate for innovative financial incentives that are appropriate for the mountains as an economic lever for transitioning to renewable electricity in the mountains. Unlike in most lowlands, energy access and reliability in the mountains are influenced by remoteness and climate impacts that can accentuate energy poverty.
3. Science and technology can play an integral role in improving accessibility to clean energy by enabling newer business models through digitizing data dissemination. Increasing application of new information technology tools in the operation and maintenance of clean electricity generation plants will allow greater deployment of distributed power projects in remote regions, which are often characterized by restrictions to mobility and a limited skilled workforce.

Vigorously pursuing these recommendations in a holistic manner by supporting just and sustainable energy transitions will contribute to transforming economic growth and development in the mountains.

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OPEN PEER REVIEW

This article was reviewed by Astrid Björnsen and Anandajit Goswami. The peer review process for all MountainAgenda articles is open. In shaping target knowledge, values are explicitly at stake. The open review process offers authors and reviewers the opportunity to engage in a discussion about these values.

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