Energy Research & Social Science 131 (2026) 104508

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Perspective

Repurposing mines for renewable energy: Socio-environmental implications for local communities in Australia and Germany

Joshua Matanzima [a,*], Katharina Schramm [b], Hannah Uhrmann [b], Florian Heberle [b], Asta Vonderau [c], Timothy Weber [d], Christoph Helbig [b], Tim Werner [e]

[a] *The University of Queensland, Australia*
[b] *University of Bayreuth, Germany*
[c] *Martin- Luther- University Halle- Wittenberg, Germany*
[d] *Australia National University, Australia*
[e] *University of Melbourne, Australia*

ARTICLE INFO

Keywords:
Mine closure
Clean energy
Climate change
Social transformation
Geothermal
Pumped hydro
Australia
Germany

ABSTRACT

The demand for low-carbon energy to tackle the climate crisis requires large swathes of land to develop renewable energy infrastructure, such as wind, solar, geothermal, hydrogen, or pumped hydro. Claiming to avoid encroaching on already occupied landscapes where different forms of tenure exist, the energy industry is increasingly targeting closed and abandoned mine areas. This transformation not only promises to mitigate or address the ecological impact of mining but is also promoted as a means of local socio-economic development through employment creation, redressing energy poverty, and community benefit sharing within the renewable energy sector. However, these developments can have grave social and environmental impacts and thus may exacerbate transitional and intersectional inequalities and injustices. Hence, careful planning and stakeholder engagement are vital to ensuring that repurposing projects reflect the needs and values of impacted communities and the historical and political contexts of mining areas. Shedding light on the situation in Australia and Germany, two countries at the forefront of these new energy initiatives, this article presents perspectives from engineering and anthropology to discuss some of the social and environmental risks involved in the repurposing of mines. From these interdisciplinary conversations, we develop policy recommendations for a just energy transition and sketch some directions for future research.

1. Introduction

The urgent need to transition from the use of fossil fuels (such as coal, oil, and gas) to renewable energy sources (such as wind, solar, and geothermal power) generates an increasing demand for land upon which to establish this renewable energy and storage infrastructure. One of the solutions presented by the industry is the repurposing of old mines. In this article, we focus on two unique contexts in which this energy transition is progressing. We discuss recent geothermal initiatives in Germany and investigate Australia as a place where pumped hydro conversion potential is being explored. As an interdisciplinary team of anthropologists and engineers from both countries, we are interested in a cross-cutting conversation that seeks to identify the unique material, environmental and social challenges in specific locales and practices, thus allowing for a more nuanced approach in our understanding of these transitions.

Global efforts to locate suitable sites for renewable infrastructure need to consider a wide range of human and environmental factors [1–4]. Germany and Australia, both having long mining histories, have been at the forefront of these efforts. Previously developed “brownfield” land (e.g., abandoned mining sites) is attractive to the industry because it offers many advantages, such as existing transmission and water pumping infrastructure, road access, and a reduced environmental impact for development on previously disturbed land [5]. However, inactive mining voids also present risks to the environment and local social and political constellations, which need to be considered in conjunction with any future proposed developments. Repurposing projects can create or exacerbate a toll on communities and environments, and they cannot be used as a way to abrogate rehabilitation responsibilities related to previous mining activities. The persistence of

---

* Corresponding author.
E-mail address: matanzimajosh@gmail.com (J. Matanzima).

https://doi.org/10.1016/j.erss.2025.104508
Received 16 July 2025; Received in revised form 26 November 2025; Accepted 8 December 2025

these impacts often compromises the "just transition" goals. It is therefore essential to ensure that all energy initiatives acknowledge intersectional inequalities, environmental injustices, and social harms in communities or regions where these developments occur. Technology deployment needs to fit into the socio-cultural and bio-physical context of each place, attending to new and existing industry impacts on the landscape and also on the emotional attachments, quality of life, and past experiences that connect people and places, which in turn affect their perceptions of and reactions towards energy technologies [6].

Responsible repurposing of mines for clean energy must, therefore, engage with local understandings and meanings of justice and politics, informed by regional histories and complexities. Attention to environmental, social, and governance (ESG) issues is no one-size-fits-all solution but requires careful engagement with local specificities.

The conceptualization of just transitions originated with trade union movements and activists in the United States to protect the rights of workers during a wave of shutdowns of polluting industries (like coal) in the 1970s. This subsequently diffused into scholarly debates, particularly in the field of environmental justice [7]. While the first generation of environmental justice studies in the 1980s were about the distribution of ecological bads and goods with a particular focus on race and class, the field has since expanded to encompass a wide variety of justice dimensions, including intergenerational, cosmopolitan, distributional, recognitional, and procedural justice [6,8,9]. To understand the intricacies of ESG in converting abandoned mine sites for clean energy, aspects of distributional, procedural and recognitional justice are relevant.

Distributional justice examines the allocation of resources and the unequal distribution of environmental benefits and burdens, such as pollution or use of natural resources. Procedural justice focuses on the fairness and inclusivity of decision-making processes, analyzing whether all stakeholders, particularly marginalized and vulnerable groups, are meaningfully involved in decisions that impact their lives. Lastly, recognitional justice explores how diverse identities, cultures, and values are acknowledged in energy initiatives. Through identifying where conflicts and controversies emerge, engaging with local understandings and perceptions of energy justice makes us aware of potential and already existing social and environmental inequalities, which the introduction of new technologies in former mines might (re-)produce [10–12].

New energy initiatives are situated at the intersections of time, and social and environmental injustices. Mine closure and renewable energy-related policy discussions should therefore consider the existential and relational forms of injustices that occur in regions where these energy initiatives are taking shape. Regarding empty mines as multilayered and complex historically specific ecological and social landscapes, instead of seeing them as barren land, can raise our awareness about potential social conflicts and environmental changes. We argue that such awareness is a precondition for any meaningful discussions about the social and environmental impacts of repurposing mines for renewable energy, and the possible ways in which these impacts can be mitigated.

The proposition of this perspective article emerged from a series of meetings conducted in Australia and Germany in person and virtually. Our team, comprising of engineers and anthropologists, has previously worked in various projects in this field. Our shared interest was the increasing number of mines targeted for renewable energy repurposing, with some projects already underway in Australia and Germany. We noted that while there was a growing body of literature on this topic, both from the engineering point of view and critical social sciences and anthropology, industry typically presents the repurposing of mines as a rehabilitation opportunity, with limited discussion of socio-environmental justice associated with developing and operating the new asset. Also, the engineering and critical social studies on these processes are rarely brought into conversation. We, therefore, regard this article as an opportunity to open up such a translocal and transdisciplinary debate and thereby provide directions for future research and policy discussions.

Our study is grounded in an extensive review of the existing literature pertaining to mine closure and renewable energy initiatives in Australia and Germany. This literature predominantly comprises scientific articles that examine the regional dynamics where these energy initiatives are being implemented. In particular, we have referenced studies pertaining to the coal phase-out and energy transition process in Germany, which serve as critical precedents to the contemporary developments in renewable energy. For the Australian case study, we also refer to studies by Australian Indigenous scholars [13,14], including the First Nations Clean Energy Network of Australia. It is a network of First Nations people, community organizations, land councils, unions, academics, industry groups, technical advisors, legal experts, renewable energy companies and others, working in partnership to ensure that First Nations communities share in the benefits of the clean energy boom.

The paper is presented as follows: Section 2 lays out some of the historical, social, and environmental concerns related to the repurposing of mines; Section 3 introduces the technologies and discusses the specific environmental and social impacts in a comparative manner; Section 4 concludes the paper by providing policy recommendations and directions for future research.

2. Historical, social and environmental debates around the repurposing of mines

In the pursuit of just transitions through mine repurposing, best practice examples include cases in the UK, the USA, Poland, Germany, and Australia [2,5]. In countries like Germany and Australia, literature on repurposing mines for clean energy and storage is dominated by technological and engineering perspectives [5,9,15,16]. However, this literature is often unaware of the critical debates on socio-environmental implications of the development of new energy infrastructure and technologies on previously mined land. Yet, as de Souza [17] has argued, without social and environmental data on these developments, policy gaps will continue to persist, and eventually we risk creating new areas of "green sacrifice". Such "green sacrifice zones" would be mined regions and their communities and environments that will bear the impact of clean energy production - often due to industrial pollution, toxic chemical exposure, water contamination and depletion or other environmental injustices of energy capitalism and industrial interests [17–19]. Studies that raise questions surrounding mine transitions to renewable energy are emerging [20,21]. For example, Walters et al. [21] focus on media reporting of the notion of "justice" on the transition from coalfields to clean futures in Australia, signifying the need for deeper academic understanding of the issues. However, we not only differ in geographical focus and scope from these recent studies, but we propose a transdisciplinary approach, which provides an all-encompassing view of the problem, from research to policy translation. We also consider differing forms of justice expected in different jurisdictions based on variegated and entangled historical, social and environmental dynamics which are articulated not only on the scale of the nation-state, but also locally, as the case of Germany illustrates.

In anthropological debates, questions of justice, inequality, political participation, and future making in late-industrial contexts have been widely addressed [22,23]. Many studies focus on regions and places that have experienced (and are still experiencing) environmental degradation and 'slow violence' of fossil modernity and its industries [24]. These researchers emphasize that many historical, environmental, and social conflicts in these places remain unresolved, especially after the closure of mining industries, and require further negotiation and solutions. Furthermore, these studies observe that the introduction of sustainable energy production and new technologies does not automatically contribute to more just regional development, even when these technologies comply with official environmental regulations and standards. Techno-centric projects risk reproducing ecological injustice and social inequalities in the most vulnerable regions and communities, which have long served as resource frontiers and 'sacrifice zones' [25] of global capitalism.

Ethnographic accounts have shown that if technological projects do not take into account multiple local concerns and diverging understandings of justice and sustainable futures, they risk reducing public acceptance of the energy transition and support for environmental policies [26,27]. A negative public attitude towards the energy transition can affect its governance and policy implementation, since policies do not evolve as top-down linear processes, but are co-shaped, altered, and put into practice by multiple actors [28]. Even though, from a technological perspective, reusing old mines for sustainable energy production has many advantages, one should be cautious about viewing these mines as 'empty places'. An awareness is needed that these places represent multilayered, historically specific, and culturally meaningful landscapes and nodes of particularly intensive political and social negotiation in times of energy transition [29,30].

3. Critical reflections on the cases of Australia and Germany

Both Australia and Germany have long mining histories and stand out in the global movement for the repurposing of mines in clean energy initiatives. These cases are inherently complex, and our perspective accordingly describes only some of the important issues at play to initiate a wider interdisciplinary conversation. However, they are also radically different – both in terms of the technologies that are favored and the social and political aspects that need to be considered. So, within the limited contrasts we present, valuable findings can still emerge.

Where mining sites are repurposed for pumped hydro energy storage systems, there is a need to consider the disturbance of land and vegetation for reservoirs and pipes located outside the brownfield area, spoil disposal, water used for the initial fill and top-ups, and water contamination caused by seepage or releases into nearby waterways. Geothermal energy technologies that repurpose mining sites must also consider water usage and contamination, as well as the effects of subsurface construction, waste disposal, and indirect carbon emissions from electricity required by heat pumps.

In social and political terms, the mining history of Australia is linked to the settler colonial context that brought Indigenous dispossession, impoverishment, marginalization, discrimination, and loss of life. Mining projects have over time impacted Indigenous cultures and identities that are inextricably contingent on environmental features such as water and plant life [31–33]. Australian Indigenous connection to Country spans over 65,000 years [13]. Truth telling and reconciliation processes have not yet fully achieved their intended just outcomes [34] and are often bypassed by mining companies as evidenced by the perpetuation of human rights abuses and destruction of cultural property in mining regions [35]. This Indigenous history is critical to understanding Australia's unique context, and hence it is a key focus here, yet the injustices of industrial development naturally extend beyond this framing. Australia's agricultural sector, for example, is frequently placed at odds with both the mining and energy industries in Australia.

In Germany, we find quite a different initial setting. Here, coal and lignite extraction originally brought economic growth and stability to the surrounding communities. Post-World War II, mining became deeply linked to migration histories in West Germany and socialist experimentation in the German Democratic Republic (GDR). Deindustrialization and the growing political and environmental pressures to end fossil fuel dependence is experienced differently in our two contexts – and so are attempts towards the repurposing of brownfield land in the green energy transition. Therefore, it is vital to examine in detail how ESG issues manifest in each case. We first discuss technological and environmental aspects in Australia and Germany respectively, before going deeper into the political constellations that co-shape the repurposing of mines.

3.1. *Technological challenges and environmental issues*

In Australia, pumped hydro systems have gained increasing attention as an option for repurposing mines for energy storage. While other storage technologies, such as compressed air energy storage (CAES) have also been considered at smaller scales (e.g., Silver City 200 MW facility at Broken Hill) [36], we focus primarily on pumped hydro in Australia, given its large significance. Unlike conventional hydro, closed-loop pumped hydro systems avoid new river dams, requiring only two reservoirs at different elevations. Electricity is stored by pumping water to the upper reservoir. During periods of low electricity supply, water can be released from the upper reservoir to generate power (Blakers et al., 2021). Repurposing mining land for pumped hydro may reduce the size of the project footprint on other undeveloped land.

Example projects in Australia include the Kidston Pumped Storage Hydro Project [37], Muswellbrook [38], and Mt. Rawdon [39]. Although part of the project footprint is located on brownfield land, some of these systems still alienate between 30 and 52 ha of previously undeveloped land for the upper reservoir and penstocks. Larger reservoir elevation differences and increasing the dam wall height can reduce the land area required relative to the energy capacity. Excavation for reservoirs, tunnels and powerhouses produces rock spoil that can be prioritized for reuse in dam walls, aggregate, and road bases. Excess spoil may be disposed of on part of the brownfield land [38]. Temporary vegetation clearing may be required for surface penstocks or tunnel trenches. Steep mining pit walls risk collapse from surface erosion, necessitating reinforcement of unstable slopes [40–42]. Initial reservoir filling and top-ups for evaporation/seepage losses require water, with initial filling during high-flow periods minimizing downstream impacts [43].

In low-rainfall areas, evaporation suppressors may be used to reduce water consumption [44]. Aquatic ecology may be impacted in surface water used for the initial fill [45]. Australian brownfield pumped hydro options require an average of 1.6 gigalitres per gigawatt-hour of energy capacity, with larger systems generally requiring less water per unit of energy capacity [46,47]. This is because larger system sizes will typically be available in locations with larger reservoir elevation differences, and energy capacity is proportional to both the elevation difference and water volume.

During periods of high rainfall, even closed-loop pumped hydro systems may be required to spill water to nearby waterways to prevent over-topping. Water quality monitoring is necessary to prevent contaminant releases at this time. Porous rock also risks fluid exchanges between reservoirs and groundwater, impacting natural groundwater flows [48] and potentially contaminating aquifers. Disturbed mining land and tailings may contain sulphides that increase water acidity, increasing bioavailable concentrations of aluminium, zinc, cadmium, arsenic, mercury, and lead [49–54]. Sodium sulphate may contaminate freshwater ecosystems if released [55]. To address these concerns, reservoir linings can reduce seepage and limit groundwater contamination [56], and soil and water may be treated (e.g., via reverse osmosis and desalination ponds) before environmental release [54,57]. These environmental processes and impacts of pumped hydro can conflict with other local land uses including social, cultural, economic and conservation activities that are dependent on the environment. For example, in Australia, where Indigenous peoples' lives are tied with the land, ecological impacts such as erosion, evaporation and contamination of biodiversity can be substantial.

In Germany, repurposing of mines has focused primarily on geothermal energy technologies with a focus on heating applications. In general, deep geothermal systems utilize aquifers extracted via binary steam cycles or district heating systems. Shallow ground-source heat pumps are widely used for residential and commercial heating [58]. Flooded mines are implemented as aquifer storage systems providing heat or cold to district networks in urban regions [59]. Mine water with temperatures between 10 and 30 °C is used for cooling and heating via heat pumps. High-temperature heat pumps supply temperatures of up to 100 °C and allow integration into conventional heating networks and existing buildings [60,61].

Areas of application for mine-water utilisation in Germany include the Freiberg district in Saxony, specifically the Reiche Zeche [62], and the Ruhr area in North Rhine–Westphalia. Mine water utilisation in the Freiberg district is dominated by heating and cooling applications with small and medium capacity. At the Reiche Zeche mine in the Freiberg district, mine water with temperatures between 14 and 19 °C is extracted to provide heat supply by means of a downstream heat pump with 175 kW thermal power. A cooling capacity of 100 kW is realized through the direct use of mine water [63]. The described energy system is similar to the reuse of mines in the Ruhr area of Germany. In the Mark 51°7 project in Bochum, mine water at a temperature of around 25 °C is extracted from a depth of 800 m to provide a heat output of 3 MW using heat pumps. A cooling capacity of 900 kW is to be provided by mine water at a depth of 340 m with a temperature of 17 °C [64]. This clearly shows that the concepts for geothermal use are very similar. However, there are significant regional differences within Germany in the capacity of energy systems due to differing customer structures.

The differences in heat-demand density between Freiberg and the Ruhr area reflect broader demographic and structural trends across eastern and western Germany. Since reunification, most regions in Saxony, including Freiberg, have experienced population decline (Saxony lost nearly 700,000 inhabitants, about 14 %) [65], and over the longer term the state's population fell by approximately one fifth between 1982 and 2024 [66]. This demographic shrinkage limits the prospective heat demand and constrains the scale of district heating systems. In contrast, industrial centres in North Rhine–Westphalia, such as Bochum, maintain high population density. Bochum's population density is 2510 inhabitants/km^2 [67] and it ranks among NRW's most densely populated cities [68]. Such sustained urban density supports technically larger mine-water geothermal systems and integrated district energy networks. These demographic patterns thus directly influence the feasible capacity and scale of geothermal reuse in former mining regions across Germany.

Aside from such demographic concerns, geothermal systems also raise environmental issues related to water usage, which could conflict with other needs such as fish spawning, and contamination of aquifers through seepage of heavy metals and acidic sulphides. Mitigation options include the monitoring of surrounding groundwater wells. Geothermal systems typically alienate less land because, unlike pumped hydro, they do not need an uphill reservoir. Alienation of land can intersect and conflict with other land uses and different forms of tenure in the regional areas. Land subsidence, hazardous waste disposal such as contaminated sludge and scale, and indirect greenhouse gas emissions are other concerns related to geothermal. Consequentially, these concerns raise questions about the safety and health of surrounding communities and sustainability issues related to greenhouse gas emissions, potentially leading to community pushback against perceived environmental trade-offs. So far, Germany has no commercial heating project based on abandoned mine utilisation that has been analyzed from an environmental perspective. Despite the lack of literature on the subject, parallels can be drawn to existing geothermal systems, enabling assessments of risks.

Analogous to mine water systems, traditional geothermal heat plants require pumps to transport the water from the underground to the heat exchangers. For conventional deep geothermal heat projects, electricity consumption, especially for deep well pumps, is mostly the biggest single contributor [69–71]. Electricity consumption may also increase for lower temperature sources that require the additional use of heat pumps to achieve the required temperatures for the district heating networks [72,73]. In the case of Germany, the matter of indirect emissions is especially relevant since the German electricity mix still contains substantial amounts of fossil sources like lignite and gas [74]. Although due to efforts of the energy transition, the environmental footprint, especially the carbon footprint, is expected to decrease from 482.2 gCO$_2$eq./kWh in 2023 to 28.9 gCO$_2$eq./kWh in 2050 with the current mitigation strategies [75]. A system akin to abandoned mine water systems would be the use of aquifer thermal energy storages (ATES). Stemmle et al. [76] analyzed the "Bonner Bogen" ATES and concluded a Global Warming Potential (GWP) of 96 gCO$_2$eq./kWh applying the fossil-heavy German electricity mix of 2014 and a coefficient of performance of 3.5. Thereby, electricity consumption dominates the impact. By applying the expected mostly renewable German electricity mix of 2050, they were able to lower the impact substantially to 13 gCO$_2$eq./kWh. One additional aspect is that no further environmental burden arises from utilizing existing subsurface structures compared to the well construction of conventional geothermal systems. When using low-impact electricity sources for geothermal heating, such as those studied by Pratiwi and Trutnevyte [73], risks primarily stem from the subsurface construction for almost all impact categories. However, this impact can be eliminated by repurposing abandoned wells, enabling a highly sustainable, low-impact heating solution.

3.2. *Historical specificities, social conflicts and political negotiations*

The establishment of renewable energy technology on previously mined sites intersects with many historical, social and political characteristics of those places. Mined sites must not be seen as "empty sites" because they are uninhabited, but as storied places imbued with deep social and political histories. These characteristics must be considered because they are bound to be impacted by new energy technologies. The environmental dynamics discussed above have a bearing on social issues. Therefore, in this section, we discuss the historical and social specificities of Australia and Germany.

3.2.1. *Australia*

In Australia, renewable energy development across different land and waterscapes is closely tied to Indigenous land rights, community development, and social justice. Today, "First Nations people have legally recognised rights across 57% of the Australian landmass" [77], including a significant proportion of the regions increasingly considered for the development of renewable energy infrastructure [13,32]. Also, recent research found that "54.8% of Queensland's abandoned mines, [for example], are located where Indigenous peoples have rights to land" [78]. In Australia, renewable energy development specifically on mined sites raises concerns regarding Indigenous sovereignty. Historically, mines were opened in colonial contexts that disregarded Indigenous histories and rights. Therefore, renewable energy developments need to pay attention to these key issues to minimize recurring impacts on Indigenous people and to support a just energy transition.

While public discussions and policy debates are often centered on the sociotechnical imaginaries [79] of the green energy transition for a better future, Indigenous people are voicing critical concerns about the social, cultural, and environmental costs of this promise. For example, the establishment of proposed renewable hydrogen in rural Western Australia will require huge amounts of land regulated under the Native Title Act 1993 as Indigenous territory [14,33,80]. *The Native Title Act 1993* establishes a framework for the protection and recognition of native title. The Australian legal system recognises native title where: a) the rights and interests are possessed under traditional laws and customs that continue to be acknowledged and observed by the relevant Indigenous Australians, b) by virtue of those laws and customs, the relevant Indigenous Australians have a connection with the land or waters, and c) the native title rights and interests are recognised by the common law of Australia [81]. The *Native Title Act* sets up processes to determine where native title exists, how future activity impacting upon native title may be undertaken, and to provide compensation where native title is impaired or extinguished. The Act gives Indigenous Australians who hold native title rights and interests, or those who have made a native title claim, the right to be consulted and, in some cases, to participate in decisions about activities proposed to be undertaken on the land [81].

Some of the targeted mined sites intersect with native title interests. Specifically, the Kidston pumped hydro energy project, in the state of Queensland, is achieved by converting a gold mine within the Indigenous Country of the Gugu Badhum and Ewamian people. Each Australian state has specific regulations that protect Indigenous heritage and cultures and are administered and enforced by state and local authorities. For example, one of the chief instruments in Queensland is the *Aboriginal Cultural Heritage Act 2003* [82], administered by the Department of Aboriginal and Torres Strait Islander Partnerships (DATSIP), which requires that a person who carries out an activity must take all reasonable and practicable measures to ensure the activity does not harm Aboriginal Cultural Heritage [83].

Similarly, in the state of New South Wales (NSW), the Muswellbrook pumped hydro energy storage project is proposed for development on a closed coal mine within the Indigenous territory of the Wonnaruah people [38], who have strong cultural connection to Country. By law these Indigenous cultures must be protected. One of the regulatory instruments that is used to protect Indigenous heritage in NSW is the *National Parks and Wildlife Service Act 1974* [84], which provides statutory protection for all Aboriginal relics under Section 90 of the Act and for Aboriginal Places under Section 84 [84]. Another instrument is the *Aboriginal Land Rights Act 1983* (ALRA) which provides land rights for Aboriginal people, compensating for historical dispossession and addressing social and economic disadvantage. The ALRA Act established representative Aboriginal Land Councils that can claim certain Crown lands, receive guaranteed funding, and manage these lands for the benefit of their communities. These Acts, and the entities established under their auspices (i.e., Prescribed Body Corporates and Land Councils), form part of the governance architecture that will apply in most places where low-carbon energy projects are located.

The environmental and social impacts of projects that repurpose disused mines are interdependent and often cannot be considered in isolation. Abraham et al. [85] note that many legacy mines in Australia operated at a time when there were no environmental regulations, resulting in particularly high metal contamination. The authors found elevated concentrations of mercury and arsenic in the soil around a legacy mine in Victoria, Australia, with risk of rainfall runoff carrying the contaminants into downstream drinking water sources for the local community. It is reasonable to assume that a pumped hydro system repurposing a similar legacy mine could pose a risk to potable water when either spilling excess water or through seepage, creating similar negative health outcomes for local communities or Indigenous peoples if not properly controlled [86].

Water availability may also provide a tension between water required for mine rehabilitation versus the needs of local ecosystems or other water users. The Latrobe Valley Regional Rehabilitation Strategy is a plan for the rehabilitation of three coal mines. The preferred proposal for rehabilitation involved filling mine voids with water, providing landform stability and mitigating the risk of fire from exposed coal [87]. Amendments to the strategy were required due to limited availability of surface water, which created conflict with the needs of other water users. The amendments included the possibility of limiting water access to between winter and spring to prevent competition with irrigation and commercial water users, a minimum flow threshold for the Latrobe River to ensure sediment is properly flushed from aquatic ecosystems and pools remain oxygenated, and a limit on annual water releases for mine rehabilitation purposes from certain reservoirs to manage dry seasons [88]. The development of a pit lake is analogous to performing the initial fill of a pumped hydro system, so similar controls may be required in regions with high water demand or low availability. Policy related to brownfield pumped hydro development ought to take a holistic view of both social and environmental considerations, allowing it to manage tensions when they exist or consider synergies that can simplify policy design.

Calls are escalating for inclusive renewable energy development in regional Australia, including on formerly mined sites. Central to these calls is the involvement of local communities in renewable energy research, in decision-making surrounding these initiatives, and in offsetting the social burden of these energy initiatives through equitable benefit-sharing [14,80]. For First Nations people living in these regional communities, these recommendations are premised on the right to Indigenous self-determination stipulated in The United Nations Declaration on the Rights of Indigenous Peoples [89], and the argument that inclusive renewable energy initiatives can potentially culminate in sustainable and improved social outcomes for Indigenous people. As such, Australia's renewable energy transition must be on their terms. This is the key message of the Federal Government's new First Nations Clean Energy Strategy [90] which was launched after more than a year of consultations with First Nations communities across Australia, plus input from industry and state and territory governments. The Government committed AUD$70 million to help realize its aims. The strategy calls for First Nations peoples' connection to land and sea Country, and their cultural knowledge and heritage, to be respected during the clean energy transition. It acknowledges that clean energy harnesses the natural elements – such as sun, wind and water – and that First Nations peoples' knowledge of Country, developed over millennia, can greatly improve the way projects are designed and implemented. It says governments and the clean energy industry must become more "culturally competent" so they can work collaboratively with First Nations peoples. Consistently, the First Nations Clean Energy Network [91] has developed best practice principles for clean energy projects designed for the clean energy industry, government and communities and pushes for such initiatives as ensuring projects provide economic and social benefits, mutual respect, clear communication, cultural and environmental considerations, land care, business development opportunities and free, prior and informed consent (FPIC).

Equitable sharing also involves the consideration of other opportunities such as employment, connection to the electricity grid, and business procurement. This is particularly important in small mining towns, where life revolves around a mine and many people have been dependent on the mine for survival through jobs and business opportunities. Former mine workers might favour continuation of mining rather than closure and the introduction of new industries. A recent CSIRO [92] report documents ambivalent opinions about renewable energy infrastructure. While metropolitan and regional responses were largely similar, those living in rural areas (where mining is typically situated) had moderate to negative attitudes. All these factors need to be considered as well within the renewable energy projects that are situated on closed mines. The CSIRO report's key findings were: a) Australians are open to change, but unsure about the degree of change; b) Affordable energy is a priority for many, reducing emissions a priority for some; c) most people are unwilling to pay more or risk blackouts for a faster transition; d) Australians are interested in the energy transition, but reported limited knowledge about energy technologies. Consistently, a 2023 national enquiry into community engagement on renewable energy developments in Australia led by Mr. Adrew Dyer laid bare deep-seated social factors such as limited consultations, power imbalances between stakeholders and a perceived rural-urban divide [93]. It provided recommendations including improvement in complaint handling processes, keeping communities informed about the transition, including goals, benefits and requirements and equitable sharing of the benefits of the transition [94]. Factoring these diverse opinions, and the uneven distribution of impact, into renewable energy development can result in a fairer and more just transition.

3.2.2. Germany

In contrast, local communities in east and west Germany were affected differently, as the history of coal extraction, dating back to the 17th and 18th centuries, brought economic stability and growth to the surrounding areas. It also enabled energy autarky for various political regimes, such as National Socialist Germany and later the German

Democratic Republic (GDR). However, it also caused severe environmental destruction and the devastation of settlements and local life worlds. For instance, in the Central German coal district alone, 147 villages were destroyed and more than 50,000 people were relocated over the past 100 years [95]. In more recent history, the division of Germany after World War II led to different developments in the Rhenish coal district (located in West Germany) and the Lusatian and Central German coal districts (located in the former East Germany).

The reunification of Germany brought major transformations to the East German coal industry. These included the closure and privatization of extraction sites and power plants, as well as the restructuring of the collectivized and subsidized socialist industry into one based on the principles of the free market and private ownership. This transition had significant social effects, which remain anchored in the collective memory of local communities. For example, in Central Germany (the former GDR), the number of people employed in the coal industry fell dramatically from 60,000 in 1989 to just 2000 today, largely as a result of German reunification [96]. Finally, the German Government's recent decision in 2020 to phase out coal combustion and shut down all lignite power plants by 2038 has once again triggered major economic, political, and social transformations in the country's coal regions, both east and west [97]. This decision, driven by environmentalist protests and public pressure, has generated a wide range of expectations, but also anxiety and skepticism among regional communities and coal-related expert groups. Securing coal workers' livelihoods and regional social cohesion, finding new forms of energy production, remediating toxically polluted landscapes, and implementing sustainable lifestyles and alternative future scenarios are currently the subject of intense debate and controversy in these regions.

Coal mining in the western part of Germany (Saarland and the Ruhr region) was focused on hard coal extraction through underground mining. The deindustrialization of these regions began as early as the 1950s, as Germany's hard coal was no longer competitive on the international market. The resulting regional transformations lasted for several decades and were supported by state financial aid and policies.

While hard coal mining ended in 2018, brown coal extraction is still ongoing. The majority of brown coal mining sites are located in the eastern parts of Germany (Lusatia and the Central German coalfields) and are operated as open-cast mines. Being less technologically complex, this type of mining has had massive effects on the landscape. After being a major industry in the GDR, coal mining experienced a sharp decline following German unification. The mono-industrial character of these regions' economies made the decline of coal extraction even more dramatic. Consequently, these regions are still facing a lack of alternative job opportunities and demographic challenges. The negative experiences of past deindustrialization continue to contribute to regional communities' skeptical attitude towards the current coal phase-out and the state's attempts to cushion its negative effects.

The energy transition in Germany is often regarded as a showcase project in both European and transnational contexts for two main reasons. Firstly, because of the Government's efforts to achieve a coal phase-out through democratic means, based on a consensual decision by a special commission that included representatives from politics, the economy, and civil society groups. This commission also developed recommendations concerning the timeline and support required for the successful implementation of the transition. Secondly, due to the allocation of €40 billion in subsidies to mitigate the negative economic and social effects of the transition [97]. In addition to national funding, coal regions are also eligible for support through the European Just Transition Fund.

While national, European, and regional policies clearly promote an inclusive and democratic transition to a fossil-free society, these processes are often complex and controversial at the local level. While some regional actors have high expectations, anticipating that new technologies will generate economic growth, new employment opportunities, and revitalize post-industrial landscapes, others remain skeptical—particularly due to negative past experiences. In the eastern parts of Germany, for example, local communities often view state-led projects with distrust, shaped by the severe economic, demographic, and social dislocation experienced during and after reunification [98]. These experiences include not only the closure of industrial sites but also the failure of sustainable energy projects such as geothermal and solar parks, along with unfulfilled promises of prosperity over the past three decades. Other local groups question the need to replace former industrial sites with new industries, fearing a renewed cycle of mono-industrial dependency and different forms of environmental pollution emerging from such energy initiatives as geothermal. They advocate for more diverse local economies that include non-industrial employment opportunities. For instance, many small-town municipalities support the flooding of former coal mine pits to promote tourism and recreational activities. Converting former mines and industrial sites into museums and places of remembrance is also appealing, as it aligns with a strong regional identity rooted in coal and industrial labor. While these alternative mine pit reusages may be appealing options for some communities, they will still need to manage similar environmental impacts as the pumped hydro or geothermal projects, such as water seepage from a pit lake developed for recreation.

The implementation of renewable energy technologies is further questioned in light of ongoing (perceived or actual) economic and social inequalities between eastern and western Germany [99]. For example, there is public concern over why eastern regions are expected to host more wind turbines or to receive toxic waste to fill open pit mines—waste that is imported from western Germany or even from abroad. While coal-related local communities advocate for the heritagization and preservation of regional industrial history, environmental groups seek to protect closed mines and industrial ruins for their newly emerging ecologies—home to plants, birds, and other wildlife adapting to the remnants of fossil modernity. These groups also raise concerns about the resource demands of new industries, including geothermal, particularly water, pointing to climate-induced and industry water scarcity in the affected areas. In both eastern and western parts of the country, activists also oppose the destruction of further settlements and the privatization of "greenfields" by coal or other private companies. Instead, they promote new, experimental forms of (collective) ownership, sustainable lifestyles, and social cohesion [100].

4. Way forward and policy implications

In reference to the principles of social and environmental justice, we critically revealed the complex and intertwining social and environmental risks associated with the development of renewable energy infrastructures on closed mines in Australia and Germany. It is essential for policymakers to acknowledge these risks to ensure that policy formulation and praxis are tailored at mitigating harm in jurisdictions where these projects take shape. Doing so facilitates responsible energy transitions, ensuring a just and sustainable approach to renewables that aligns with the principles of development and sustainability. We consider applying a transdisciplinary approach from research to policy translation as key to promoting different forms of justice in the energy transition. In that regard, we propose the following policy initiatives and future research directions that have been developed by identifying general themes from the two case studies:

4.1. Proposed policy initiatives

It is imperative to recognize the wider spectrum of social and environmental values held by different stakeholders, including local communities and former mine workers, for mine closure and post-mining land use. Experts involved in mine reuse or the implementation of new technologies must be aware of the just transition's complexities. Public concerns are grounded in lived experiences and trans-generational—often also transnational—embodied everyday knowledge of climate change and the “slow violence” [24] of past and present industrial development. Policymakers should recognize the specific logic of social transformations, their open-ended and partially unpredictable nature, and remain open to questioning traditional political instruments of participation and inclusion. It is essential to ask what new forms and modes of public engagement may be required to foster a post-carbon democracy.

There is a need to consult with stakeholders to understand their concerns over new clean energy initiatives. This is a significant milestone in achieving the social license to operate, or public support and acceptance. Social licenses and public support obtained during mining cannot be depended upon as the transition to pumped hydro or geothermal occurs. Social license is an ongoing process contingent on space and time. We must also be cautious about assuming that a social license was previously obtained, given the nature of colonial forms of natural resource extraction that disregarded socio-environmental concerns of local communities. There is a need to delineate the distribution of renewable energy generation and storage projects and how they are intersecting with local communities and Indigenous peoples’ lands. We need to interrogate: What risks are communities exposed to? Can stakeholder engagement assist in identifying and managing these risks? Where negative social and environmental impacts occur, what remediation measures can be implemented?

In all instances where Indigenous peoples are involved - based on the principles of the UNDRIP [89] and its definition of Indigeneity - collaborative and participatory renewable energy projects must be promoted. This requires investments and government supportive policy frameworks that ensure Indigenous people hold a stake within these new energy initiatives. Renewable energy policy reforms that consider local and Indigenous communities’ rights and interests in land upfront – not as an afterthought - are required in the processes of converting mines into renewable energy.

Policy reform needs to be centered around better planning that measures potential environmental impacts such as biodiversity and biocultural loss, water contamination and depletion, environmental and noise pollution. Where these impacts occur, there should be remediation planning looking at how biodiversity and ecosystem impacts can be protected and restored. Existing planning processes for mining activities (e.g., the approval of mine water releases to nearby waterways) may provide a framework for comparable activities related to the development and operation of brownfield pumped hydro systems.

Policy discussion should consider the concerns of coal mine workers and communities. These communities fear deindustrialization and social decline. This study advocates for a just energy transition that addresses both the immediate material anxieties and the broader societal impacts experienced by mine workers and the wider community. Old mine sites may have ongoing pollution legacies that have to be stabilised. Ensuring that a site is safe, secure and stable and not producing ongoing environmental burdens is a necessary precursor step before considering whether it can be used for something else. Policies to promote integrated mine planning or closure and progressive rehabilitation can support repurposing initiatives.

Policy ought to clearly specify ownership of ongoing rehabilitation activities to ensure there is accountability for those plans - if land ownership is transferred to develop a clean energy project, does the ownership of those other rehabilitation activities transfer as well, or is it retained by the original mine owner? Developers and energy planners should consider the economies of scale for pumped hydro from an environmental perspective too - larger pumped hydro systems are cheaper per unit of energy storage ($ per kilowatt-hour of capacity), and also typically require less land and water per unit of energy storage (hectares per kilowatt-hour and gigalitres per kilowatt-hour). There may be an environmental benefit associated with building fewer, larger pumped hydro systems, though this must be balanced against the impact of specific projects on local communities. For geothermal energy, the contribution to the municipal heat planning for a low-carbon future and the co-benefits through integration with the renewable energy system are key for success. Communicating the positive impact of geothermal on other energy system transitions like wind power, solar, and domestic heat pumps, can increase the social license.

4.2. Proposed future research directions

Constant mapping of abandoned mined sites is required to update earlier findings by Weber et al. [5] to direct social and environmental scientists to the specific regions where more scientific research is imperative. This mapping can be conducted in conjunction with that of the social and economic characteristics or indicators of the areas to identify the potential environmental, social and governance (ESG) risks. Such an all-encompassing assessment of issues is important in promoting just transitions, particularly cosmopolitan and distributive justice. More social and environmental assessments drawing from anthropological methodologies, such as observations and engagement with relevant stakeholders (including impacted regional communities), significantly promotes epistemic justice within the energy transition. Anthropological methods can be corroborated with environmental modelling and mapping to provide a nuanced and all-encompassing analysis of social and environmental impacts.

There is emphasis on the need to include Indigenous people and local communities in renewable energy research projects from the research design stage to communication of results. This is to ensure that they can benefit from the research output. Indigenous people and local communities can also shape the renewable energy future and maximize benefits from renewable energy initiatives because they occur on their lands. As such, research with communities must take a participatory approach in design. Participatory research promotes research partnerships between community members and stakeholders, particularly Project Affected People, with researchers in a process of self-reflective inquiry to generate new knowledge and drive positive social outcomes [101]. Indigenous and non-Indigenous scholars suggest different ways by which First Nations people can be included in renewable energy research projects [102–105]. Interdisciplinary research that systematically traces these ESG risks over space and time is urgently needed and has motivated our interdisciplinary team to pursue this topic using Australia and Germany as case studies. Time and spatial scales are crucial components on matters of energy and environmental justice [106–108].

CRediT authorship contribution statement

Joshua Matanzima: Writing – review & editing, Writing – original draft, Validation, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Katharina Schramm:** Writing – review & editing, Writing – original draft, Resources, Project administration, Formal analysis, Conceptualization. **Hannah Uhrmann:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Florian Heberle:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Asta Vonderau:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Timothy Weber:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Christoph Helbig:** Writing – review & editing, Writing – original draft, Conceptualization. **Tim Werner:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Author J M acknowledges the short-term visit funding received in 2024 from the University of Bayreuth Centre of International Excellence "Alexander von Humboldt" (Short: Bayreuth Humboldt Centre) in Germany. The Chair of Social and Cultural Anthropology at the University of Bayreuth (Author K S) provided appropriate resources, organized a guest lectureship, facilitated participation in the Anthropology of Global Inequalities Group, and arranged meetings with interdisciplinary teams within and beyond Bayreuth. Authors H U and F H acknowledge funding from the Bavarian State Ministry of Science and Arts within the framework of the 'Geothermal Alliance Bavaria' project. Author T Weber's research was supported by an Australian Government Research Training Program (RTP) Scholarship. Authors J M, T Werner, and T Weber acknowledge the traditional custodians of the land upon which they work in Australia, and pay respects to their elders, past, present and emerging. We also appreciate constructive feedback received from the editor and three anonymous reviewers that helped improve this perspective.

Data availability

No data was used for the research described in the article.

References

[1] G. Lin, Y. Zhao, J. Fu, D. Jiang, Renewable energy in China's abandoned mines, Sci. Lett. 380 (6646) (2023) 699–700, https://doi.org/10.1126/science.adi1496.

[2] E. Mariotti, J. Engström, Transforming abandoned mines into solar farms: a pathway to renewable energy development and sustainable land use, Environmental Research: Energy 2 (2025) 015013, https://doi.org/10.1016/j.enre.2025.015013.

[3] V. Sharma, M. Aggarwal, Can meaningful consultation and consent advance fair and equitable large-scale renewable energy development? Reflections from India, Energy Sustain. Dev. 85 (2025) 101613, https://doi.org/10.1016/j.esd.2024.101613.

[4] J. Loginova, M. Landauer, J. Joona, R. Datta, T. Joona, Enabling Indigenous-centred decision-making for a just energy transition? Lessons from community consultation and consent in the circumpolar Arctic, Energy Res. Soc. Sci. 120 (2025) 103928.

[5] T. Weber, R. Stocks, A. Blakers, A. Nadolny, C. Cheng, A global atlas of pumped hydro systems that repurpose existing mining sites, Renew. Energy 224 (2024) 120113, https://doi.org/10.1016/j.renene.2024.120113.

[6] H.L. Lai, P. Devine-Wright, J. Hamilton, S. Mander, et al., A Place-based, Just Transition framework can guide industrial decarbonisation with a social licence, Energy Res. Soc. Sci. 121 (2025) 103967, https://doi.org/10.1016/j.erss.2025.103967.

[7] X. Wang, K. Lo, Just transition: a conceptual review, Energy Res. Soc. Sci. 82 (2021) 102291, https://doi.org/10.1016/j.erss.2021.102291.

[8] A. Blokzijl, E.D. Rasch, Sámi perspectives on energy justice and wind energy developments in Northern Norway, Energy Research and Social Sciences 122 (2025) 104004, https://doi.org/10.1016/j.erss.2025.104004.

[9] L.E. Ruoso, J. Roods, K. Nagrath, S. Niklas, S. Miyake, C. Briggs, E. Dominish, Building better practice for renewable energy: Six ways to improve ecosystem outcomes, Prepared for WWF-Australia by the Institute for Sustainable Futures, University of Technology Sydney, 2024.

[10] D. McCauley, V. Ramasar, R.J. Heffron, B.K. Sovacool, D. Mebratu, L. Mundaca, Energy justice in the transition to low carbon energy systems: exploring key themes in interdisciplinary research, Appl. Energy 233–234 (2019) 916–921, https://doi.org/10.1016/j.apenergy.2018.10.005.

[11] B. Sovacool, R. Heffron, D. McCauley, et al., Energy decisions reframed as justice and ethical concerns, Nature Energy 1 (2016) 16024, https://doi.org/10.1038/nenergy.2016.24.

[12] B.K. Sovacool, M. Martiskainen, A. Hook, et al., Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions, Clim. Change 155 (2019) 581–619, https://doi.org/10.1007/s10584-019-02521-7.

[13] H. Norman, After 65,000 years caring for this land, First Nations peoples are now key to Australia's clean energy revolution, The Conversation (2024). https://theconversation.com/after-65-000-years-caring-for-this-land-first-nations-peoples-are-now-key-to-australias-clean-energy-revolution-245022.

[14] H. Norman, A.M. Payne, Coming to terms with the past? Aboriginal history and the Great Australian Unknowing, History Australia (2025) 1–19, https://doi.org/10.1080/14490854.2025.2478885.

[15] E. Colas, P.A. Kukla, F. Amann, S. Back, Geological and mining factors influencing further use of abandoned coal mines – a multi-disciplinary workflow towards sustainable underground storage, J. Energy Storage 108 (2025) 115101.

[16] D.J. Williams, A. McGhie, T. Short, Repurposing of the Genex Kidston mine site in Queensland, Australia, in: A.B. Fourie, M. Tibbett, G. Boggs (Eds.), Mine Closure 2022: Proceedings of the 15th International Conference on Mine Closure, Australian Centre for Geomechanics, 2022, pp. 789–802, https://doi.org/10.36487/ACG_repo/2215_57.

[17] M.L. de Souza, 'Sacrifice zone': the environment–territory–place of disposable lives, Community Development Journal 56 (2) (2021) 220–243, https://doi.org/10.1093/cdj/bsaa042.

[18] R. Wallace, K. Schwemmlein, S. Batel, Solar industrialization, 'sacrifice zones,' and new environmental movements: emerging discourses of commonality and critique in Portugal's energy transition, Sustain. Sci. (2025), https://doi.org/10.1007/s11625-025-01661-3.

[19] C. Zografos, P. Robbins, Green sacrifice zones, or why a Green New Deal cannot ignore the cost shifts of just transitions, One Earth 3 (5) (2020) 543–546, https://doi.org/10.1016/j.oneear.2020.09.004.

[20] B. Tladi, N. Kambule, L.A. Modley, Assessing the social and environmental impacts of the just energy transition in Komati, Mpumalanga Province, South Africa, Energy Research & Social Science 111 (2024) 103489.

[21] R. Walters, M. Farrelly, W. Novalia, R. Raven, Headlining justice from coalfields to clean futures: how the Australian newsprint media frames a just energy transition, Energy Research and Social Science 125 (2025) 104131.

[22] K. Fortun, Advocacy After Bhopal: Environmentalism, Disaster, New Global Orders, University of Chicago Press, Chicago, 2001.

[23] P. Robbins, Political Ecology: A Critical Introduction, Wiley & Sons, London, U.K., 2012.

[24] R. Nixon, Slow Violence and the Environmentalism of the Poor, Harvard University Press, Cambridge, 2011.

[25] S. Lerner, Sacrifice Zones: The Front Lines of Toxic Chemical Exposure in the United States, MIT Press, 2010.

[26] A. Goldthau, Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism, Energy Res. Soc. Sci. 1 (2014) 134–140.

[27] J.K. Knudsen, L.C. Wold, Ø. Aas, J.J.K. Haug, et al., Local perceptions of opportunities for engagement and procedural justice in electricity transmission grid projects in Norway and the UK, Land Use Policy 48 (2015) 299–308.

[28] C. Shore, S. Wright, Anthropology of Policy: Critical Perspectives on Governance and Power, Routledge, London, 1997.

[29] C. Beckett, A. Keeling, Rethinking remediation: mine reclamation, environmental justice, and relations of care, Local Environ. 24 (3) (2018) 216–230, https://doi.org/10.1080/13549839.2018.1557127.

[30] M. A, Industrial Ruination, Community and Place: Landscapes and legacies of Urban Decline, University of Toronto Press, 2012.

[31] J. Burton, D. Kemp, R. Barnes, J. Parmenter, Mapping critical minerals projects and their intersection with Indigenous peoples' land rights in Australia, Energy Research and Social Science 113 (2024) 103556, https://doi.org/10.1016/j.erss.2024.103556.

[32] A. Fish, H. Norman, First Nations people must be at the forefront of Australia's renewable energy revolution, Retrieved from, https://theconversation.com/first-nations-people-must-be-at-the-forefront-of-australias-renewable-energy-revolution-222616, 2024.

[33] L. O'Neill, K. Thorburn, B. Riley, G. Maynard, et al., Renewable energy development on the Indigenous Estate: free, prior and informed consent and best practice in agreement-making in Australia, Energy Research and Social Science 81 (2022) 102252, https://doi.org/10.1016/j.erss.2021.102252.

[34] S. Maddison, J. Hurst, A. Thomas, The truth will set you free? The promises and pitfalls of truth-telling for indigenous emancipation, Social Inclusion 11 (2) (2023) 212–222, https://doi.org/10.17645/si.v11i2.6491.

[35] D. Kemp, K. Kochan, J. Burton, Critical reflections on the Juukan Gorge parliamentary inquiry and prospects for industry change, J. Energy Nat. Resour. Law 41 (4) (2023) 379–402.

[36] Hydrostor, Silver City Energy Storage, Available at: https://hydrostor.ca/projects/silver-city-energy-storage-center/, 2025.

[37] AECOM, Kidston Pumped Storage Hydro Project, Available from, https://eisdocs.dsdip.qld.gov.au/Kidston%20Pumped%20Storage%20Hydro%20Project/Impact%20assessment%20report/kidston-pumped-storage-hydro-project-iar-full.pdf, 2019.

[38] Muswellbrook Pumped Hydro, Scoping report: Muswellbrook Pumped Hydro Energy Storage Project, Available from: https://majorprojects.planningportal.nsw.gov.au/pr, 2023.

[39] ERIAS, Mt Rawdon Pumped Hydro Project: Initial Advice Statement, Available from, https://eisdocs.dsdip.qld.gov.au/Mt%20Rawdon%20Pumped%20Hydro%20Project/Initial%20Advice%20Statement/, 2022.

[40] F. Liu, K. Yang, T. Yang, Y. Gao, J. Li, Q. Liu, Q. Fu, Pumped storage hydropower in an abandoned open-pit coal mine: slope stability analysis under different water levels, Frontiers in Earth Science 10 (2022) 241119, https://doi.org/10.3389/feart.2022.941119.

[41] Z. Chen, Z. Wang, H. Xi, Z. Yang, L. Zou, Z. Zhou, C. Zhou, Recent advances in high slope reinforcement in China: case studies, J. Rock Mech. Geotech. Eng. 8 (6) (2016) 775–788, https://doi.org/10.1016/j.jrmge.2016.11.001.

[42] J. Menéndez, F. Schmidt, H. Konietzky, J.M. Fernández-Oro, M. Galdo, J. Loredo, M.B. Díaz-Aguado, Stability analysis of the underground infrastructure for pumped storage hydropower plants in closed coal mines, Tunn. Undergr. Space Technol. 94 (2019) 103117, https://doi.org/10.1016/j.tust.2019.103117.

[43] B.M. Pracheil, K.P. Duffy, L. Zeng, J.W. Saulsbury, Environmental Impacts of Closed-loop Pumped Storage Hydropower (No. PNNL-36322), Pacific Northwest National Laboratory (PNNL), Richland, WA (United States), 2024.

[44] S. Assouline, K. Narkis, D. Or, Evaporation suppression from water reservoirs: efficiency considerations of partial covers, Water Resour. Res. 47 (7) (2011), https://doi.org/10.1029/2010WR009889.

[45] B. Saulsbury, A Comparison of the Environmental Effects of Open-Loop and Closed-Loop Pumped Storage Hydropower [PNNL-29157], Available at: https://www.energy.gov/sites/prod/files/2020/04/f73/comparison-of-environmental-effects-open-loop-closed-loop-psh-1.pdf, April 2020.

[46] T. Weber, Pumped Hydro Shortlisting Tool, Available from, https://re100.anu.edu.au/shortlisting, 2025.

[47] M. Stocks, R. Stocks, T. Weber, A. Nadolny, B. Lu, A. Blakers, C. Cheng, RE100 Map, Available from, https://re100.anu.edu.au/##share=g-e803c2ae7c631a09df5ad0af2ddcf45d, 2025.

[48] E. Pujades, T. Willems, S. Bodeux, P. Orban, A. Dassargues, Underground pumped storage hydroelectricity using abandoned works (deep mines or open pits) and the impact on groundwater flow, Hydrgeol. J. 24 (2016) 441–453, https://doi.org/10.1007/s10040-016-1413-z.

[49] A. Punia, R. Bharti, P. Kumar, Impact of mine pit lake on metal mobility in groundwater, Environ. Earth Sci. 80 (2021) 1–13, https://doi.org/10.1007/s12665-021-09559-w.

[50] C.C. Gilmour, E.A. Henry, R. Mitchell, Sulfate stimulation of mercury methylation in freshwater sediments, Environ. Sci. Technol. 26 (11) (1992) 2281–2287, https://doi.org/10.1021/es00038a013.

[51] C.R. Cánovas, F. Macías, R. Pérez-López, Metal and acidity fluxes controlled by precipitation/dissolution cycles of sulfate salts in an anthropogenic mine aquifer, J. Contam. Hydrol. 188 (2016) 29–43, https://doi.org/10.1016/j.jconhyd.2016.02.005.

[52] R.M. González, C.R. Cánovas, M. Olías, F. Macías, Seasonal variability of extremely metal-rich acid mine drainages from the Tharsis mines (SW Spain), Environ. Pollut. 259 (2020) 113829, https://doi.org/10.1016/j.envpol.2019.113829.

[53] E. Kovács, J. Tamás, S. Frančišković-Bilinski, D. Omanović, H. Bilinski, I. Pižeta, Geochemical study of surface water and sediment at the abandoned Pb-Zn mining site at Gyöngyösoroszi, Hungary. Fresenius Environmental Bulletin 21 (5) (2012) 1212–1218.

[54] Government of Western Australia Department of Environment Regulation, Treatment and management of soil and water in acid sulfate soil landscapes, Available from, https://www.wa.gov.au/system/files/2023-04/Treatment-and-management-of-soil-and-water-in-acid-ss-landscapes.pdf, 2015.

[55] J.J. Leppanen, T.P. Luoto, J. Weckstrom, Spatio-temporal impact of salinated mine water on Lake Jormasjarvi, Finland, Environ. Pollut. 247 (2019) 1078–1088, https://doi.org/10.1016/j.envpol.2019.01.111.

[56] J. Hedien, M. Altinakar, S. DeNeale, V. Koritarov, Reservoir lining for pumped storage hydropower: Scoping study of geomembrane lining systems (No. ANL-22/90), Argonne National Laboratory (ANL), Argonne, IL (United States); Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States); Stantec, Inc., Edmonton, Alberta (Canada), 2023.

[57] GEI Consultants, Eagle Mountain Pumped Storage Project Draft Environmental Impact Report Volume I, Available from, https://www.waterboards.ca.gov/waterrights/water_issues/programs/water_quality_cert/docs/eagle_mountain_pumped_ferc13123/2_eagltmtn_deir_vol1_2.pdf, 2010.

[58] P. Hockenos, Geothermal energy – Germany's largely untapped renewable heat source, in: Journalism for the Energy Transition, 2020. Retrieved from: https://www.cleanenergywire.org/factsheets/geothermal-energy-germanys-largely-untapped-renewable-heat-source. (Accessed 21 June 2025).

[59] Z. Zhang, W. Zu, W. Zhang, K. Wang, X. Ma, P. Cui, Investigation of theoretical models, pumping-recharge well arrangements and system performance of abandoned mine water source heat pump, Energy and Built Environment 6 (3) (2025) 495–508, https://doi.org/10.1016/j.enbenv.2024.01.006.

[60] J. Jeßberger, H. Uhrmann, F. Scholderle, D. Pfrang, et al., Medium-deep geothermal resources in the Molasse Basin: a geological, techno-economic, and ecological study of large-scale heat pump integration, Renew. Energy 248 (2025) 123147, https://doi.org/10.1016/j.renene.2025.123147.

[61] A. Passamonti, F. Sachse, P. Bombarda, R. Bracke, Design, construction, and commissioning of a 500 kW high-temperature heat pump plant for the district heating network of Bochum, Germany, Energy Rep. 13 (2025) 548–561, https://doi.org/10.1016/j.egyr.2024.11.080.

[62] L. Oppelt, T. Wenzel, M. Bleidiessel, P. Heinrich, A. Arab, R. Wiedener, C. Engelmann, C. Chen, F. Schenker, T. Lotter, T. Schneider, F. Hellmuth, M. Binder, T. Nagel, T. Grab, T. Fieback, Seasonal heat storage in partially flooded mines: in-situ investigations at the Freiberg, Saxony site, Zenodo, 2025, https://doi.org/10.5281/zenodo.14849344.

[63] H.B. Mischo, Szkliniarz George, Kisiel Katarzyna, Site Description and Data of the Reiche Zeche. Site services, Characteristics and Data. Activity Report of WP3.3, 12/15/2021, Jan 2021.

[64] R. Verhoeven, Nutzung von Grubenwasser am Beispiel der Stadtwerke Bochum: Project Mark 51°7 DGK 2023, in: Stadtwerke - Workshop NRW "Kommunale und gewerbliche Wärmeversorgung mit Geothermie", Fraunhofer.IEG, 2023. Retrieved from: https://www.der-geothermiekongress.de/fileadmin/user_upload/DGK/DGK_2023/STW-WS_Verhoeven_Mark_51-7_DGK_Deutsch_19.10.23.pdf. (Accessed 6 June 2025).

[65] demografie-portal. Bevölkerungszahl in Sachsen, 2025.

[66] S.L.d.F. Sachsen, Bevölkerungsmonitor Bevölkerungsbestand - Statistik - Bevölkerungsmonitor - sachsen.de, 2023.

[67] Demographic statistics Province of BOCHUM, K.S, 2025.

[68] Statistics. RW, Top ten cities with the highest population density on December 31st, Retrieved from, https://statistik.nrw/gesellschaft-und-staat/gebiet-und-bevoelkerung/bevoelkerung/top-ten-der-staedte-mit-der-hoechsten-bevoelkerungsdichte-am-31-12?utm_source=chatgpt.com, 2024. (Accessed 6 June 2025).

[69] H. Uhrmann, F. Heberle, D. Brüggemann, Life cycle assessment and scenario analyses of an operating geothermal heat project in the Southern German Molasse Basin, in: J.R. Smith (Ed.), 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023), Las Palmas De Gran Canaria, Spain, ECOS, 2023, pp. 2992–3001, 2023.

[70] A.T. McCay, M.E.J. Feliks, J.J. Roberts, Life cycle assessment of the carbon intensity of deep geothermal heat systems: A case study from Scotland, Sci. Total Environ. 685 (2019) 208–219, https://doi.org/10.1016/j.scitotenv.2019.05.311.

[71] S. Gkousis, K. Welkenhuysen, T. Compernolle, Integrated assessment of deep geothermal heating investments in Northern Belgium through techno-economic, life cycle, global sensitivity, and real options analysis, Geothermics 121 (2024) 103027, https://doi.org/10.1016/j.geothermics.2024.103027.

[72] J. Jeßberger, F. Heberle, D. Brüggemann, Maximising the potential of deep geothermal energy: thermal output increase by large-scale heat pumps, Appl. Therm. Eng. 257 (Part A) (2024) 124240, https://doi.org/10.1016/j.applthermaleng.2024.124240.

[73] A.S. Pratiwi, E. Trutnevyte, Life cycle assessment of shallow to medium-depth geothermal heating and cooling networks in the State of Geneva, Geothermics 90 (2021) 101988, https://doi.org/10.1016/j.geothermics.2020.101988.

[74] P. Icha, T. Lauf, Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990–2023, Dessau-Roßlau, 2024.

[75] R.O. Harthan, H. Förster, K. Borkowski, H. Böttcher, S. Braungardt, V. Bürger, et al., Projektionsbericht 2023 für Deutschland, 2023.

[76] R. Stemmle, P. Blum, S. Schüppler, P. Fleuchaus, M. Limoges, P. Bayer, et al., Environmental impacts of aquifer thermal energy storage (ATES), Renew. Sustain. Energy Rev. 151 (2021) 111560, https://doi.org/10.1016/j.rser.2021.111560.

[77] First Nations Clean Energy Network, Community Energy Planning toolkits. https://assets.nationbuilder.com/fncen/pages/183/attachments/original/1706579654/Community_Energy_Planning_Toolkit_A4-web.pdf?1706579654, 2024.

[78] C.J. Unger, J. Burton, D. Kemp, Abandoned mine clusters and their intersection with Indigenous peoples' land rights in Australia, J. Environ. Manag. 385 (2025) 125357.

[79] Sheila Jasanoff, Sang-Hyun Kim, Sociotechnical imaginaries and national energy policies, Sci. Cult. 22 (2) (2013) 189–196.

[80] L. O'Neill, K. Thorburn, First Nations at the forefront: The changing landscape of clean energy agreements in Australia, Energy Res. Soc. Sci. 127 (2025) 104183, https://doi.org/10.1016/j.erss.2025.104183.

[81] Native Title Act 1993, Retrieved from, https://www5.austlii.edu.au/au/legis/cth/consol_act/nta1993147/, 1993. (Accessed 23 September 2025).

[82] Queensland Government, Aboriginal Cultural Heritage Act 2003, 2003.

[83] AECOM, Ministerial Infrastructure Designation Assessment Report Genex Kidston Connection Project: Chapter 3, Available from, https://www.powerlink.com.au/sites/default/files/2021-11/Genex%20-%20MIDAR%20-%20Chapter%203%20-%20Project%20Description_1.pdf, 2021.

[84] National Parks and Wildlife Act 1974, Retrieved from: https://legislation.nsw.gov.au/view/html/inforce/current/act-1974-080, 1974. (Accessed 23 September 2025).

[85] J. Abraham, K. Dowling, S. Florentine, Assessment of potentially toxic metal contamination in the soils of a legacy mine site in Central Victoria, Australia, Chemosphere 192 (2018) 122–132.

[86] J. Cortes-Ramirez, R.N. Michael, L.M. Toms, M. Haswell, The public health impacts of mining in Australia, Med. J. Aust. 223 (10) (2025) 541–548.

[87] Victoria State Government, Explanatory note: guidance on the type of access arrangements that could apply to surface water from the Latrobe River system for the purpose of mine rehabilitation, Available at: https://www.water.vic.gov.au/__data/assets/pdf_file/0030/684444/Explanatory-note-guidance-to-surface-water-access-for-Latrobe-Valley-mine-rehabilitation.pdf, 2023.

[88] Victoria State Government, Latrobe Valley Regional Rehabilitation Strategy, Available at: https://www.water.vic.gov.au/__data/assets/pdf_file/0034/684448/Latrobe-Valley-Regional-Rehabilitation-Strategy.pdf, 2020.

[89] UNDRIP, United Nations Declaration on the Rights of Indigenous Peoples, Retrieved from: https://www.un.org/development/desa/indigenouspeoples/wp-content/uploads/sites/19/2018/11/UNDRIP_E_web.pdf, 2007.

[90] First Nations Clean Energy Strategy, Retrieved from, https://www.dcceew.gov.au/about/news/first-nations-clean-energy-strategy, 2024.

[91] First Nations Clean Energy Network, Aboriginal and Torres Strait Islander Best Practice Principles for Clean Energy Projects. https://assets.nationbuilder.com/fncen/pages/183/attachments/original/1680570396/FNCEN_-_Best_Practice_Principles_for_Clean_Energy_Projects.pdf?1680570396, November 2022.

[92] CSIRO, Australian attitudes toward the renewable energy transition. https://www.csiro.au/en/research/environmental-impacts/decarbonisation/energy-transition, 2023.

[93] R.C.R.M. Cotton, J. Loginova, B. Witt, Renewable energy and regional Australia: The limits to "best practices" for engagement. Energy Research and Social, Science 130 (2025) 104426.

[94] Andrew Dyer, A.E.I.C, o.b.o.t.D.o. Community Engagement Review Report, and E. Climate Change, the Environment and Water, Canberra, 2023.

[95] A. Berkner, Kulturstiftung Hohenmölsen e.V., Bergbau und Umsiedlungen im Mitteldeutschen Braunkohlenrevier, Sax-Verlag, 2022. ISBN 978-3-86729-580-2, https://www.sax-verlag.de/detailview?no=29-580.

[96] P. Kropp, U. Sujata, A. Weyh, B. Fritsche, Kurzstudie zur Beschäftigungsstruktur im Mitteldeutschen Revier, Institut für Arbeitsmarkt- und Berufsforschung (IAB), 2019. http://doku.iab.de/regional/S/2019/regional_s_0119.pdf (Accessed 11 July 2025).

[97] F. Heilmann, R. Popp, How (not) to phase out coal: lessons from Germany for just and timely coal exits, in: E3G Briefing Paper, 2020. https://www.jstor.org/stable/pdf/resrep28821.pdf (Accessed 11 July 2025).

[98] N. Kleinheisterkamp-Gonzalez, Agencies of transition: why German coal workers are not accepting an energy transition despite social provisions, Environmental Research: Energy 2 (2025) 015005, https://doi.org/10.1016/j.enre.2025.015005.

[99] M. Pfeffer, M. Sonnberger, Rushing for the gold of the energy transition: an empirical exploration of the relevance of landownership for the wind energy expansion in Germany, Energy Res. Soc. Sci. 123 (2025) 104030.

[100] J. Radtke, M. David, How Germany is phasing out lignite: insights from the Coal Commission and local communities, Energ Sustain Soc 14 (2024) 7, https://doi.org/10.1186/s13705-023-00434-z.

[101] A. Cornwall, R. Jewkes, What is participatory research? Soc. Sci. Med. 41 (12) (1995) 1667–1676.

[102] C.E. Hoicka, K. Svic, A. Campney, Reconciliation through renewable energy? A survey of Indigenous communities, involvement, and peoples in Canada, Energy Research and Social Science 74 (2021) 101897, https://doi.org/10.1016/j.erss.2020.101897.

[103] K. Quail, D. Green, C. O'Faircheallaigh, Large-scale renewable energy developments on the Indigenous Estate: how can participation benefit Australia's First Nations peoples? Energy Res. Soc. Sci. 123 (2025) 104044 https://doi.org/10.1016/j.erss.2025.104044.

[104] R.D. Stefanelli, C. Walker, D. Kornelsen, D. Lewis, et al., Renewable energy and energy autonomy: how Indigenous peoples in Canada are shaping an energy future, Environ. Rev. 27 (1) (2019) 95–105, https://doi.org/10.1139/er-2018-0024.

[105] O. Zapata, Renewable energy and well-being in remote Indigenous communities of Canada: a panel analysis, Ecol. Econ. 222 (2024) 108219, https://doi.org/10.1016/j.ecolecon.2024.108219.

[106] S. Connelly, G. Halseth, J. Matanzima, M. Mateus, S. Markey, et al., Temporality and justice in mining impacted regions, Environmental Research: Energy 2 (2025) 015009.

[107] J. Matanzima, J. Loginova, Sociocultural risks of resource extraction for the low-carbon energy transition: evidence from the Global South, The Extractive Industries and Society 18 (2024) 101478, https://doi.org/10.1016/j.exis.2024.101478.

[108] J. Matanzima, "Disempowered by the transition": manipulated and coerced agency in displacements induced by accelerated extraction of energy transition minerals in Zimbabwe, Energy Res. Soc. Sci. 117 (2024) 103727.