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Critically reviewing the 50 sociotechnical risks of building sector decarbonization: Conceptualizing risk as a proximity spiral

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ABSTRACT

Deep decarbonization of the building sector requires a widespread shift in the processes, materials, energy sources, and technologies used for homes, hospitals, factories, and other structures and infrastructure by 2050. While the goal of deep decarbonization and the broader energy transition is to minimize the potential for catastrophic climate change effects brought on by carbon emissions, the transition to new technologies and processes can introduce new, unanticipated risks. This paper critically reviews the risks associated with the decarbonization of buildings. By categorizing fifty identified risks into six themes, this study highlights the dominance of a technical–economic perspective in discussions of risk in building decarbonization and shows that the literature focuses on immediate construction and operational risks, overlooking important environmental and social risks associated with design and deconstruction of buildings. The paper concludes by proposing a conceptual sociotechnical model to account for spatially and temporally diffuse risks across the building life-cycle and stakeholder population.

1. Introduction

Decarbonization of the built environment is essential to meet global goals to reduce greenhouse gas emissions by 2050 and mitigate catastrophic outcomes from the fossil fuel energy regime [1]. The building sector contributes 37 % of global greenhouse gas emissions [2], making it a high impact space for innovation. Efforts to decarbonize the building sector include improving energy efficiency, electrification, shifting to renewable energy sources, and generating opportunities for carbon capture [3]. Mainstream decarbonization efforts are grounded in a techno-economic approach which prioritizes technological solutions aimed at reducing greenhouse gas emissions while supporting current levels of consumption and further increasing capacity to meet new energy demands without disruption [4]. More practically, a sociotechnical model acknowledges that technical advances are embedded in broader social, behavioral, and political contexts that shape what is considered feasible and what risks and tradeoffs (lifestyle, economic, or otherwise) are socially acceptable [5]. The contribution of this review is to map the sociotechnical risks specific to the decarbonization of the building sector. This research is guided by the question: what does existing literature tell us about the risks associated with decarbonization of the building sector, and in what ways does it incorporate or overlook sociotechnical risks across the building lifecycle?

Risk has become an inevitable attendant of modern living so much so that sociologist Ulrich Beck (1992) characterized the modern era a "risk society" by the widespread acceptance of inevitable global, human-caused, complex risks, including catastrophic risks, such as those associated with nuclear power or fossil fuel use [6]. As we understand these risks more fully through improved data and probability models, the risks associated with the ongoing scale of fossil fuel use are now understood as producing incontrovertibly negative outcomes for non-human ecologies and human well-being [7]. While renewable energy has been presented as a benign cure to the ills of fossil fuels, a growing field of research anticipates the potential risks of implementing low-carbon technologies at scale [8]. For example, it is well known that photovoltaic cells present additional hazards during disposal and decommissioning because they contain high levels of lead and cadmium [9]. The difficulty of any novel technology adoption is to anticipate their potential for increasing net risk to society [10].

Given the inevitability of risk and uncertainty that accompanies any new technology, a precautionary approach to launching technologies is prudent [11]. However, the urgency of action makes delays and inaction

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costly. Furthermore, to reject deep decarbonization efforts because of potential risks is counter-productive; greenhouse gas emissions continue to climb each year, increasing likelihood of catastrophic climate change [12]. Thus, the paradox for deep decarbonization is balancing low-risk options, such as degrowth (a form of down-scaling) [13], with global technological interventions that anticipate risk and can therefore model and mitigate risk. Decarbonization requires a complex transition and adapting to evolving information gleaned from real-world applications [14]. Deep decarbonization requires pursuing multiple solution pathways simultaneously to ensure eventual success [15]. Not merely a technological adoption, for the sake of economic stability, deep decarbonization of the construction sector requires pathways for transformation of "technologies, infrastructures, organizations, markets, regulations, and user behaviors" that ensure stability and profitability [16]. A sociotechnical approach adds a more contextual, spatially and temporally expansive approach, better accounting for social and environmental risk. As Lembert and Trujillo (2018) wrote, "we do not ask 'what will happen,' but instead, 'how do we shape a complex, hard to predict, and transformative future more to our liking?" [17].

In this paper, we offer a systematized, mapping review, and qualitative analysis of the risks of decarbonization of buildings. Using a corpus of the most relevant and prominent academic studies, we identify fifty barriers categorized by six themes. This work extends several recent reviews that highlight general risks associated with decarbonization and the energy transition. Sun and Zhou (2024) identify risks within the energy sector and note the dominance of a narrow techno-economic perspective focused on operational energy efficiency [18]. This review also finds a strong reliance on the techno-economic framework but goes further to examine how risks are distributed across the building life cycle. Additionally, this work introduces a sociotechnical lens to reveal overlooked risks that affect a broader range of stakeholders both geographically and across stages of building development. Another review by Mikulėnas and Šeduikytė (2025) emphasizes the value of circular and integrated approaches to overcome barriers to decarbonization strategies [19]; our work builds on this by assessing the risks of implementing such strategies and challenging the limits of the prevailing techno-economic model. While other reviews have addressed regional building decarbonization efforts [20,21], this review takes a global perspective. Finally, this review contributes a novel sociotechnical conceptual model that maps the risk landscape and shows how perceptions of risk vary by stakeholder role.

2. Literature review and analytical framework: hazards, risks, and justice considerations in deep decarbonization

As a guiding lens to our analysis, we draw from the literature on hazards, risks, energy and equity, and energy justice to first define risk and hazards and their inevitable attendance to new technology, (2.1). We then point to the likelihood of ongoing equity and justice considerations in the current techno-economic model, (2.2), and then outline potential of using a sociotechnical framework to atone for the limitations of the mainstream techno-economic approach to decarbonization (2.3).

2.1. Risk and envisioning performance, operations, economic, and environmental hazards

Within the risk analysis literature, risk is a concept of probability that refers to the likelihood of an occurrence. Negative risk can be defined as: "the probability of potential losses, (e.g. injuries, losses of human lives, disturbances of economic activities, destroyed or deteriorated goods, alternations of the environment)" [22]. Hazards are sources of potential harm (e.g., pollutants). Uncertainty is inherent to the concept of risk and estimation is part of its calculation [23]. Making accurate estimations of potential losses is particularly difficult for emergent technologies [27].

In the prevalent techno-economic paradigm, risk management, organizationally, is often strategic, relying on top-down assessment which frames risks as uncertainties that are to be managed or mitigated as a way to buffer against instability and unwanted financial outcomes [24]; but risk is not necessarily a barrier to progress. Barriers – even political, social, or economic barriers – are distinct from risks in that they connote an obstruction that must be overcome to allow forward momentum. Risks can be acknowledged, assessed, and then managed, overlooked, or ignored. Yet even careful management is not always prudent, as past technological disasters of the fossil fuel and nuclear epoch point to occurrences of low-probability but catastrophic outcomes (i.e. Exxon-Valdez, Chernobyl, or Jharia Coalfields) which merits a precautionary approach to scaling novel energy sources and material development [25]. Yet, decarbonization still requires technological advances, which presents a what Sovacool (2025) calls a "risk–risk" dilemma [26]. Risk-risk tradeoffs introduce novel risks while attempting to address existing risks [10]. For example, replacing asbestos insulation with spray foam has improved performance and reduced carcinogenic risks, but it has also introduced new hazards, such as toxic isocyanates and higher greenhouse gas emissions from foam blowing agents [27]. As even low-carbon technologies carry intrinsic risk, tradeoffs between new and existing technologies should be assessed according to a broad spatial and temporal framework that captures the certainty of risk, its magnitude, the extent of population impacted, and severity of negative consequence [28].

Despite uncertainties of emergent technological performance a rapid transition is seen as preferable to the gradual integration of decarbonization practices and renewable energy infrastructure [29]. Yet, an aggressive transition may risk worsening building system performance, reliability, durability, and unforeseen social inequities which might be better addressed in a more gradual energy transition [30]. On the other hand, a gradual transition risks catastrophic outcomes and other systemic costs for global climate change from inadequate decarbonization in the coming decades [31,32].

2.2. Health, justice, and social equity considerations

While all humans face potential harm from experimental technologies of the energy transition, one central equity finding from the literature is that hazards and risks of technological innovations tend to be unequally distributed [33], mapping onto the existing landscape of social inequality, which has resulted in worse health outcomes for frontline communities [34,35]. Potential for social injustice is rife in the broader decarbonization transition, with many injustices invisible at the outset, only appearing later in the process [36]. As is, existing low-income communities and majority communities of color have been shaped by legacies of inequitable burdens of development and have been saddled with disproportionate levels of environmental pollutants [37–39]. This inequitable distribution has been defined in work on environmental justice and environmental racism [40].

If not deliberately counteracted using environmental justice and a holistic sociotechnical framing, new technologies can carry the same propensity for unjust distribution of environmental burdens. Otherwise, Sovacool et al. (2019) argues, "low-carbon transitions are often assumed as positive phenomena… yet without vigilance, there is evidence that they can in fact create new injustices and vulnerabilities, while also failing to address pre-existing structural drivers of injustice in energy markets and the wider socio-economy" [36].

2.3. Spatial and technological hazards and risk proximity

Compared to the traditional techno-economic framework of risk assessment, a sociotechnical approach acknowledges the social contexts and the central role that social perception play in determining collective tolerance of risk [41]. Risk perception is social and relational and only partially shaped by statistical probabilities of risk [42,43]. A non-expert's risk assessment is shaped by additional factors including the degree of one's trust of available information, perceived ability to cope with a negative outcome, and geographic proximity [41]. Inconsistency between assessments from experts and a non-expert's perception of risk can generate public opposition to new enterprises, such as the installation of a new nuclear facility [69]. Even for experts, assessing magnitude of emergent risks is difficult, particularly for complex, sociotechnical systems. Social tolerance of risk and public perception of accidents also defines what technologies are socially acceptable and therefore feasible [44]. For example, risks of climate change are often perceived as distant in time and space, which contrasts with new technologies where risks can seem more immediate, more certain, and more quantifiable [45].

Geographic proximity to risk actively shapes perceptions of immediacy [46]. Geographic proximity is important as a social equity consideration. For example, in the United States, populations of color and low-income households are significantly more likely to be located near hazardous industrial processes and waste facilities [47,48]. Proximity can also be considered as an abstraction of immediacy of close interaction or involvement. For example, an installer working with spray foam has an immediate risk of toxin exposure. Unsurprisingly, risks to health and unemployment consistently rank as the top concerns for individuals when surveyed on perceptions of risk to new developments or technologies [49,50]. Yet, it is more difficult to account for the indirect or long-term risks of continued use of hazardous materials and practices. To expand this idea of hazard immediacy, the discussion below recommends mapping risks in a more temporally and spatially expansive space – in a way that parallels conceptualizing a building as a series of life-cycle phases from its design to its disposal. By mapping risks in accordance with life-cycle analysis (LCA), the risks, like the carbon footprint of a building, are assessed across the streams of material inputs and disposal. Scrutiny of both risk and embodied carbon during acquisition, processing, manufacturing, and decommissioning, better accounts for greenhouse gas emissions, hazards, and risks of the building sector [51,52].

3. Research design

This section classifies and describes the type of review undertaken (3.1), the specific search terms and parameters (3.2), and limitations to the study's approach (3.3).

3.1. Review type and scope

This paper relies on methodology spanning three distinct types of reviews: a systematized review, a scoping review, and a critical qualitative review [53]. A systematized review ensures transparency and reproducibility by analyzing studies with varying methodologies, applying inclusion and exclusion criteria, and utilizing a consistent Boolean search vocabulary and strategy. A scoping review offers a descriptive overview of this building-specific topic, sliced out of the broader research question (what are the sociotechnical risks of decarbonization?) [54]. Finally, this work analyzes the findings, aiming to provide a novel conceptual framework to consider risk in relation to role proximity. The findings here point towards directions for further research while generating additional considerations for practitioners and policymakers in forwarding decarbonization of the building sector.

3.2. Search terms, parameters, and inclusion and exclusion criteria

This review relies on three scholarly resource datasets which are known for their comprehensiveness: Web of Science (Core), ProQuest, and EBSCO (Environmental Complete). To define the scope of this review, this corpus was selected following a rubric of inclusion and exclusion criteria including: 1) studies from the 2014 to 2024 to include the most contemporary discussion of risks, 2) in English-language, and 3) from relevant scholarly and grey literature. The initial search, when filtered by abstract and title screening, returned 124 results, and was further screened for relevance to forty-eight publications (Fig. 1). These forty-eight full-text documents were manually coded by reading the papers line-by-line to identify key subjects and themes as defined by the project's codebook. A codebook is an iterative (both deductive and inductive) rubric that acts as a systematic guide for reading and categorizing the documents. Examples of qualitative codes are provided in Table 1. The identification of risks emerged inductively from the corpus of literature.

3.3. Limitations

While efforts were made to ensure reasonable comprehensiveness, the databases are limited by available publications and licensing. This sample draws from a global set of literature, although the corpus is limited to works written in English or with available English translations. Given that many countries in Europe have been proactive in encouraging decarbonization, it is not surprising that over half of the studies included in the sample are from Europe (62 %), followed by the United States (17 %), China (8 %) and other countries (13 %). This literature review offers a high-level view of the research, which is appropriate for breadth rather than depth and discussions of causality. As a review, this work does not weigh the quality of the existing research, although the resources are screened to include peer-reviewed resources or come from reputable sources such the UN or the ACEEE. This work offers a conceptual foundation to guide future primary data collection. This review explores the existing ways that risks are understood as associated with the technology transition in building technology.

4. Results: contextualizing the 50 distinct risks of building decarbonization

This review identifies fifty risks, categorized by six themes which fall into the three broad dimensions of our analytical framework (section 2). The authors inductively identified six thematic areas to examine potential risk–risk tradeoffs by clustering related risks (Fig. 2). The first theme, *performance* speaks to the various ways that novel decarbonization interventions address energy efficiency (section 4.1.1). Second, *operation and systems* refer to technological processes for production and distribution (4.1.2). The *economic and financial* theme points to economic feasibility (4.1.3). Of course, a central expectation is that solutions should be less *environmentally* damaging than existing practices (4.1.4); and any transition should ideally improve the *health and safety* of stakeholders engaged in designing, constructing, occupying, maintaining, and decommissioning buildings (4.2.1). Finally, *social* well-being and justice outcomes are expected to improve in the decarbonization transition (4.2.2). By categorizing risks by these six distinct but interconnected sociotechnical themes, the framework captures how risks may not only exist independently but also unfold across multiple areas simultaneously. Indeed many risks emerge in tandem: for example, a technological risk can emerge alongside or exacerbate an environmental risk. Each theme captures a mixture of direct risks (i.e. high cost of energy) and indirect risks (i.e. increased energy poverty).

The authors also describe the distribution of risks by building phase (4.3.1). Finally, the discussion offers an additional conceptual way to model risks, not by theme, but by "stakeholder proximity," or immediacy to stakeholder role (5).

4.1. Performance, operations, health, economic and environmental hazards

Risks falling into this category include performance and inefficiency (4.1.1), operations and systems challenges (4.1.2), economic and financial impact (4.1.3), and ecological impacts (4.1.4).

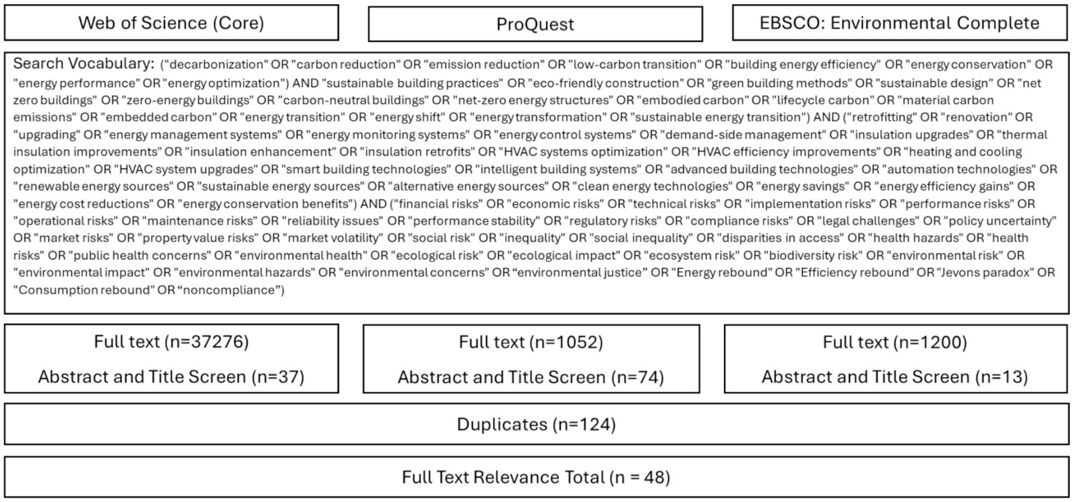

Fig. 1. Literature review sample inclusion processing.

4.1.1. *Performance and inefficiency risks*

A critical challenge for decarbonization technologies is whether they can match the performance of existing fossil fuel-based solutions. Technology replacement risks failures and disruption resulting in increased costs, poor quality installation, and client dissatisfaction. These risks are particularly difficult in attempting to find adequate solutions for concrete and steel. For example, biomaterials for more carbon-intensive concrete fillers require additional research on moisture management to prevent mold and structural failure [61]. Substitutions must meet the code specifications for structural and durability, including seismic performance standards. Novel material substitutions risk additional delays in terms of material testing and designing, procurement, and installation to meet existing regulatory specifications [61]. Building envelopes, including moisture barriers, sidings, and roof coatings must meet or exceed conventional material performance to endure heat, cold, UV, and other weathering conditions [62].

Electrification requires a reliably performing energy grid, without disruptions. Renewable energy solutions have faced ongoing unreliability. Solar and wind power require both short-term and long-term energy storage solutions which rely on a limited global supply of lithium. As is, even shifting from natural gas to renewable electricity sources brings risk of disrupted energy service [63]. As seen in California's rolling blackouts during heatwaves in 2020, where high electricity demand and low solar output led to controlled outages [64]. Existing infrastructure also challenges perfect integration of renewables. As one current challenge, buildings powered by photovoltaic panels can generate excess energy that can be fed back into the grid. This requires interoperability with the existing power grid to both feed extra power back into the grid and draw from the grid when necessary. Awkwardly, grid infrastructure originally designed for unidirectional power flow risk disrupted operations as the number of net zero energy buildings increase the demands on two-way energy capabilities [65].

While decarbonization aims for increased energy efficiency, in some events a transition can result in a risk of *decreased* energy efficiency. For one, modeling novel HVAC performance tends to be conservative, which can result in overfitting, or installing appliances that exceed the requirements of a space, reducing a building's overall efficiency [66]. Additionally, modeled performance may not account for extreme temperature conditions, unanticipated occupant behavior, or emergent installation issues, leading to an energy performance gap [67]. Even passive building strategies can risk inefficiencies. For example, the Trombe wall, a passive heating design for building envelopes, is effective in decreasing energy use in cooler months, but risks overheating in the summer months, requiring additional cooling systems and energy input to maintain occupant comfort [68]. Occupants' behavior can also lead to increased energy use after making efficiency retrofits – a phenomenon called, “energy rebound” [69,70]. One explanation for this increase of energy use is that the owners feel they have “done their part” by making retrofits, therefore take more license to consume more energy [71].

4.1.2. *Operations and systems challenges*

For deep decarbonization, changes require dismantling operations and systems that are “locked-in” to fossil fuel usage [72]. For example, adopting renewable energy sources can be difficult because the energy infrastructure still relies on fossil fuel inputs to reduce risks of unreliability or high costs. As a cleaner burning alternative to coal, natural gas is considered an intermediary to minimize risks associated with a fully renewable energy grid. Still, continued reliance on fossil fuel crutches like natural gas risks exceeding global carbon emission goals.

An example of an infrastructural and economic risk in the wider energy transition, is that of “stranded assets.” In fossil fuel infrastructure, these assets, often structural, become a financial liability before the end of their useful life, for example oil pipelines or coal refineries [73]. At the scale of an individual building, a stranded asset might also materialize; if regulations push for a household to replacing a gas stove before the end of appliance's operational life, this may risk additional carbon emissions for out-of-cycle upgrades and additional appliance production [74]. At the same time, delaying efficient updates due to cost concerns or in consideration of broader diffuse risks of embodied carbon might exacerbate more immediate health risks, like poor indoor air quality for occupants [75]. These examples demonstrate that risks are inevitable, but might be considered in systemic ways to make the best decisions for both occupant and broader societal well-being.

To manage the increasing complexity of building systems, the building sector has turned to digital solutions. Digitalized solutions are used for modeling building design and systems, estimating material use, and by adjusting energy use by occupancy. However, increasingly automated systems can add additional complications; for example, occupancy sensors can fail on occasion, leading to misalignment between expected energy performance and reality [76]. One report found that occupancy sensors saved energy overall, but sometimes erred by failing to detect sleeping occupants and shutting down the residential HVAC systems at night [77]. Using digital systems to manage complex energy demand systems also generates risk of cyber security breaches, which can disrupt performance reliability and create opportunities for malicious actors to compromise security of energy use and privacy of users [78].

4.1.3. *Economic and financial impact*

The economic risk of bringing a new technology to market is high

Table 1
Qualitative coding examples.

Theme	Code Example	Example
Performance	Overfitting For Energy Needs	"In performing load calculations for larger retrofit projects, most designers apply safety factors to the peak heating load (most commonly 10–20 % is added to the calculated peak load). Designers also need to consider equipment redundancy (most commonly installing 2 boilers at 50–66 % of peak heating load), and then the load is rounded up to the next available equipment size. These design elements compound and result in the installation of what are often oversized boilers. Ultimately, the majority of participants tend to install boiler plants with greater than 100 % of the calculated heat load for the building, which already includes conservative energy model assumptions and safety factors" [55].
Operations and Systems	Cyber Security	"These new realities of widespread energy production and consumption involve the use of ICT-Information and Communication Technologies without which the production, distribution, and use of renewable energy integrated and managed in a cost-effective and environmentally friendly manner would be impossible. However, while the massive use of ICT technologies is necessary for the operation of such systems, it also brings with it vulnerabilities that are easily exploited by malicious actors, undermining the stability, operation, and reliability of the entire community" [56].
Health, Safety and Comfort	Increased Manual Labor	"Intensive green roofs are usually associated with roof gardens, which need a reasonable depth of soil and require skilled labor, irrigation, and constant maintenance." [57].
Economic and Financial	High Costs	"Given that electricity rates are generally higher than gas, [electrification] could have the undesired effect of increasing utility bills." [58].
Environmental	Resource Depletion	"Relative to major end-uses such as fuel and paper, the conversion of timber into wood building materials offers huge carbon reductions because these materials can serve as long-term carbon storage over a building's lifetime. However, this model of building materials as a "carbon sink" assumes that sustainable replanting of trees occurs. Currently, this is the case only partially in Europe and North America, where the rising demand for wood products is coupled with a capacity for afforestation practices. In tropical and subtropical forests, increased logging drives dangerous levels of deforestation, ultimately reducing the long-term capacity of natural forests to sequester carbon" [59].
Social	Aesthetic	"Installing induction stoves in participants' homes required upgrading each apartment's electrical wiring so it could accommodate the increased electrical load. Several participants were dissatisfied with the installation process via an independent contractor, which seemed to have been done without consulting them about their preferences regarding the appearance of the end result. They explained that, at the end of the installation, there were exposed wires cutting across their walls or ceilings. Several participants shared that despite being grateful for the stove swap, they wish their input had been incorporated in the process so that the appearance of their homes would be safeguarded" [60].

Source: Authors.

because the costs of upfront design, development, permitting, and testing all rely on future revenue for investment recovery [79]. For building owners, price uncertainty increases the risk of financial loss from upfront investments, For example, installing a green roof requires high upfront costs and maintenance that is unlikely to be offset by cost of energy savings within the operational life of the building [80]. Yet, despite the financial risk, green roofs still contribute other incommensurate benefits such as air cleaning, urban heat island effect mitigation, and noise pollution reduction.

New building technologies increase the uncertainty of cost estimates for labor, materials, and additional structural or electric updates needed to support installation [81]. Additionally, introducing building technologies increases the market complexity and necessary maintenance skills to support both conventional and new technologies in operation. This risks more complex installation and maintenance for technicians, as the components and replacement parts (i.e. low GWP refrigerants, compressors, valves, heat exchangers) evolve in availability over the 15 to 25-year of equipment lifecycle, increasing costs of parts and challenges of sourcing parts for repair [82,83].

For residents, additional costs accompany the shift from current fossil fuel infrastructure. High prices of electricity from renewables can risk increased energy burden for fully electric low-income households [84]. A 2024 ACEEE report suggests that a transition away from natural gas may risk an economic "death spiral" where the declining customer base for natural gas without reducing the infrastructure will increase the cost per user (since fewer customers pay in to support the system) [85]. The higher costs would be borne by those who could not afford to adopt energy alternative solutions, therefore facing increased costs of energy, inability to make decarbonization upgrades, risking sinking deeper into energy poverty [86].

4.1.4. Ecological impact

Additional risks of resource depletion and use of novel, yet finite materials, can challenge supply chain reliability and ability to scale low-carbon technologies. Scaling a technology for widespread use, brings the potential for global depletion of accessible stocks of rare minerals or critical minerals used in that technology's production [87]. Use of rare earth minerals in ubiquitous technologies like phones, personal computers, and electric vehicles may risk shortages for other uses like in high-performance magnets used for wind turbines [88]. The exploitation of rare earth minerals limits the material options for unanticipated future uses, challenging the intergenerational promise of sustainable development and limiting the scalability of these fossil fuel alternatives.

Net zero material production is not immune to the ecological risks of conventional material production at scale, including ecological destruction, extinction of species, and potential degradation of water quality [89]. Incidents of water acidification, eutrophication, and other contamination have accompanied biomass material production [90]. Furthermore, use of renewable materials and fuels, like wood pellets, can increase fine particulate matter formation and reduce indoor air quality for occupants [90]. At scale, land use shifts that accompany biomaterials and biogas production risk further deforestation and compromise carbon sequestration [91]. Additional land use concerns

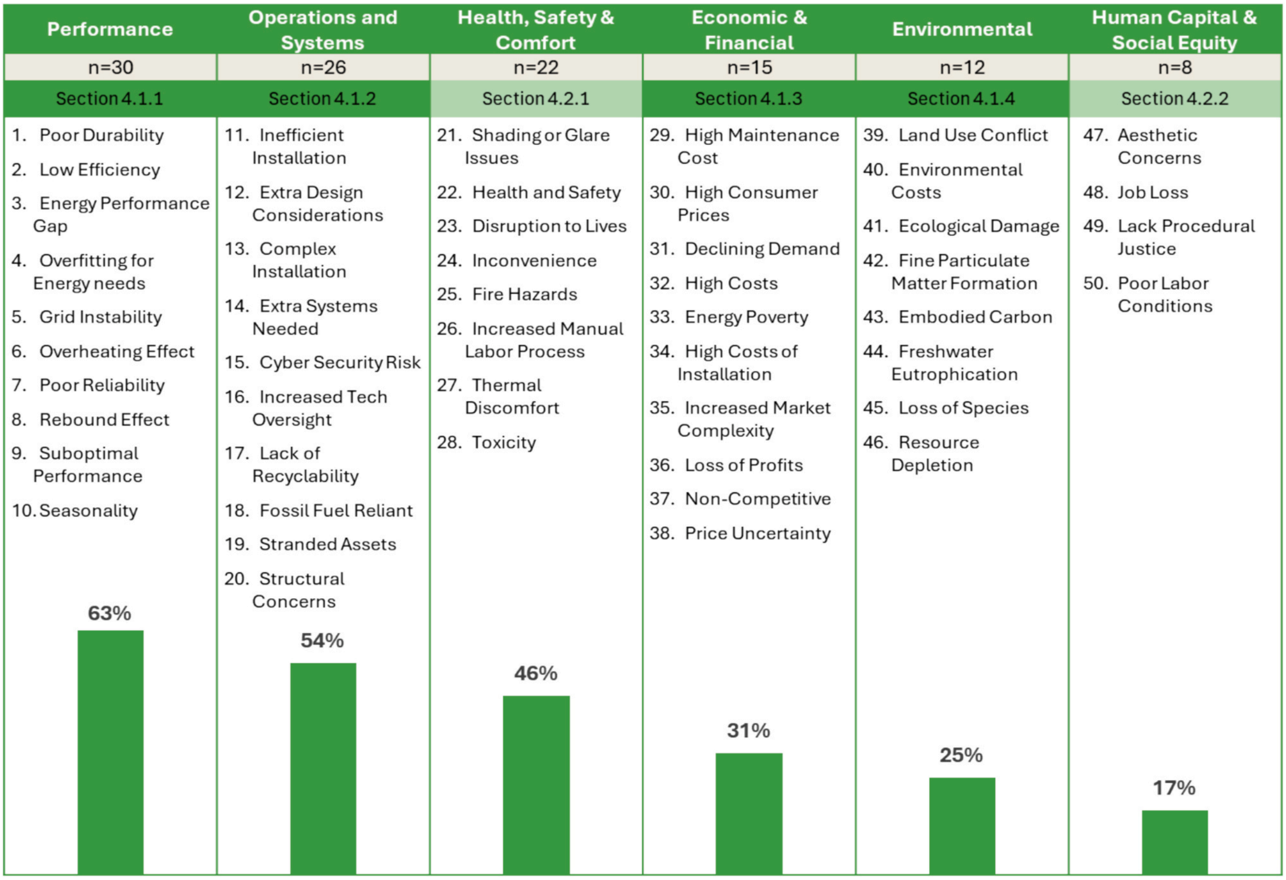

Fig. 2. Fifty sociotechnical risks to building decarbonized organized by six thematic areas. Note: n represents the number of resources that highlight the categorized risks. Note that some resources highlight multiple risks. The percentage refers to the percentage of resources that mentions these risks. For example, 63% of resources highlight performance risks. Source: Authors.

and social risk come from communities' valuing of land and their sense of place which can impact the feasibility of using land for decarbonized material generation or renewable energy generation. Land use conflicts can generate further social risks of resident resistance and culturally unacceptable uses of land [92].

4.2. *Health, justice, and social equity considerations*

Risk considerations in this section involve health, safety and comfort (4.2.1), as well as issues of human capital and social equity (4.2.2).

4.2.1. *Health, safety, and comfort*

During construction and maintenance, occupational risk is salient for builders, given the jobs' propensity for on-the-job hazards. A shift to new practices – for example, green roofs, solar installations, and wind turbine installation and maintenance – increase risk of falls and injuries from heavy lifting [93–95]. Alternative roof membranes, such as those for high albedo, can be slippery, heavy, and "blindingly bright" to work on [94]. In deconstructing a building, material separation for salvage or waste diversion can increase risk of lacerations, sprains, or strains for workers [95].

During the construction process, occupants also face indirect risks including exposure to noise, dust and other construction inconveniences, which risks stress and loss of productivity [96]. For occupants, definitions of risk are less clear. Still, decarbonization interventions, such as residential building retrofits, risk inconvenience and introduction of unwanted energy efficiency or electrification "solutions." This can include unsatisfactory aesthetic outcomes for residents or "improvements" that fail to reference how people actually use living spaces and appliances in their daily lives. In one case, installation of new appliances in low-income housing left unsightly wiring from a pilot project installing induction stoves, leading to aesthetic dissatisfaction, despite the improved performance of the new appliances [97].

In a poorly operating building, occupants can also face the slow decline physical and mental health from poor building comfort. Furthermore, poor comfort can result in inefficient occupant behaviors increasing the risk of inefficient energy use. For example, passive strategies like high albedo roof coatings, or extra glazing to capitalize on natural daylight can risk glare issues leading to occupant or installer discomfort. In one researched case, the glare from a net-zero building's façade forced occupants of an adjacent building to close blinds and rely on artificial light, thus increasing the use of energy [98].

Additional safety issues include risks of flammability of building materials and energy storage solutions that increase risk of fires [99]. Some energy storage systems carry potential risk of thermal runaway and corrosion over time [100]. While a low risk, thermal runaway of lithium-ion batteries hold a powerful place in collective imagination given their role in aviation disasters since 2006 [101].

Less immediately, novel material development also risks generation of hazardous waste throughout their lifecycles. For example, the use and disposal of rare minerals as in the case of energy efficient lighting, which contain cadmium, aluminum, copper, gold, and zinc, create the potential for toxicity in disposal, a risk that increases with scale [87].

4.2.2. *Human capital and social equity*

Desire to explicitly address social risk in ESG metrics and other standards has gained traction in the last decade. In these metrics, social risk tends to refer to intra-organizational risks associated with human capital (workforce management), product liability (product safety and quality), and stakeholder opposition or conflicts (from sourcing conditions) [102]. Thus, social risks exist throughout the building lifecycle, including material sourcing and procurement.

For contractors and laborers, decarbonization presents a human capital risk, as a shifting market brings the risk of job loss. In California alone, 2024 estimates indicate 1,650 natural gas pipefitters are vulnerable to losing high-wage, unionized jobs [103]. On site, the construction sector has the highest rates of workplace accidents globally, [104,105] with significantly higher rates of accidents among young men with less experience and education, and temporary migrant workers [106]. Globally, migrant workers are highly vulnerable to forced labor, with construction ranking third in risk—behind services and manufacturing—and exploiting an estimated 2.8 million workers under conditions of modern slavery [107]. The construction sector's reliance on low-paid migrant labor, excessive work hours, cost-cutting pressures, weak labor condition oversight, and complex, opaque supply chains make it fertile soil for labor exploitation [107–110]. Poor labor conditions present risks both in terms of worker health and safety and economic costs from customer boycotts or legal action [111]. Some low-carbon materials, such as bricks, have been flagged as particularly vulnerable to forced labor [112].

Risks of unethical and unsafe labor practices can be mitigated on building sites and in the material supply chain by enforcing labor regulations, educating construction professionals the importance of ethical sourcing and health and safety, and adopting third-party oversight that ensure safe and ethical labor practices [113].

In terms of production of environmental pollutants during energy production, material production, and disposal, the energy transition risks retracing the social landscape of inequality by race and socioeconomic class unless distributional inequities of technological benefits and environmental burdens are mitigated by redistributive policies [114]. Case studies to illustrate thematic risks in real world examples can be seen in Table 2.

4.3. Spatial and technological hazards and risk proximity

This section lastly discusses spatial and multi-scalar risks present across the lifecycle or supply chain of a building.

Table 2
Risk case study example by theme.

Performance	Operations and Systems	Health, Safety & Comfort	Economic & Financial	Environmental	Social
Risk: Disrupted Energy Service	**Risk: Complex Systems and Poor Management Integration**	**Risk: Overheating, Discomfort and Safety**	**Risk: Higher Costs**	**Risk: Material Environmental Hazards**	**Risk: Poor Labor Conditions**
Case: California Heat Waves Rolling Outages:	**Case: Ventilation Fitting Complexity in University Lab**	**Case: Occupant Behavior and Overheating in Passive Homes in the UK**	**Case: The Bullitt Center, Seattle**	**Case: Polyurethane foam insulation (PUF)**	**Case: Forced Labor Conditions in Solar Supply Chain**
On August 14 and 15, 2020, the California Independent System Operator Corporation (CAISO) was forced to institute rotating electricity outages in California in the midst of an extreme heat wave. These power outages were in part due to "changes in the resource mix," – which included increased solar and wind energy – and the timing of the net peak demand of air conditioner use. In this case, the solar generation declined in the late afternoon at a faster rate than demand decreased. [115]	In 2020, a New York City medical college's science facility retrofit for a laboratory system with "dynamic airflow optimization" failed in early-stage performance testing. This failure resulted in unsafe ventilation conditions, including instances where variable air volume (VAV) boxes were programmed to zero, causing no airflow into laboratory spaces. A critical factor was the lack of involvement of the facilities management team from the design outset, leading to confusion over control sequences. The project, which was expected to take nine to twelve months, extended over two years to rectify these issues [116]	A case study in the UK on two side-by-side homes demonstrated how occupant use of passive technologies impacts energy efficiency and risks of overheating. Louvres and external blinds were installed to manage solar gains and allow for passive cooling. However, tenants' suboptimal use of the passive technologies contributed to overheating and worse-than-modeled efficiency performance. For example, the occupants didn't like to close the blinds in the summer because they blocked the daylight and view. They also didn't like to leave the louvres open for passive cooling because they didn't want spiders to get inside the house. Due to suboptimal practices of occupants, this case recommended better efficiency might come from installing fixed overhanging shading in designs rather than user-operated technologies. [117]	Due to uncertainty of process, integrating new building technologies can result in increased cost estimates for labor, exclusive materials, and additional structural or electric installation needed to support integration. The Bullitt Center, in Seattle, a pioneering, net-positive building, cost $32.5 million to build. In the Center's financial case study, they state how future buildings using the same technology would cost less. For one cost saving they would install less solar panels, as they admitted to underestimating the envelope's efficient performance and therefore providing 60 % more solar than necessary to operate the building. Additionally, because it was such a difficult site (chosen for reasons including walkability, transit, and solar access) there were increased costs for staging, drilling geothermal wells, and hoisting the PV array. Pre-construction costs, design problems and regulatory hurdles also added additional costs due to the innovative nature of the project. [118]	Polyurethane foam insulation (PUF) is widely used in the construction industry due to its excellent thermal insulating properties and versatility. It is often applied in both residential and commercial buildings to reduce energy consumption by preventing heat transfer. Yet, PUF presents some environmental challenges. The primary environmental concern of PUF insulation stems from the chemicals used as blowing agents during the manufacturing process. Historically, these include hydrofluorocarbons (HFCs), which have a much higher global warming potential compared to carbon dioxide. Even though HFCs are now being phased out in favor of less harmful alternatives, many older installations of PUF still contain HFCs. Their use in the production of PUF undermines its energy-saving benefits. [119]	"Solar power is critical to achieving a green future, but there is extensive evidence of labor abuse across much of the solar supply chain. Nearly half of the world's polysilicon, a key material used to produce solar panels, comes from the Xinjiang Uyghur Autonomous Region (XUAR or Xinjiang), a region of China where members of ethnic and religious minority groups are forced by the government to work against their will … [Factories] have engaged in coercive recruitment; intimidation and threats; limited workers' freedom of movement and communication; subjected workers to constant surveillance, retribution for religious beliefs, exclusion from community and social life; and threatened workers' family members." [120]

4.3.1. Risks by building phase

While use of LCA has expanded the scope of carbon emissions that can be attributed to a single building, the discussion of risks in the literature remains focused on the building's physical construction and operation. The focus on energy efficiency in building operations stems from a 1980s U.S. political strategy, which shifted the responsibility for CO2 reduction and environmental management onto building owners, rather than material producers and the industry [121,122]. In so doing, the U.S. promoted a model that facilitated technological innovation and, placed environmental management on individual owners [121]. This is reflected in the data here, as risks are most discussed in the material and construction phase of development (39 %) or the operation and use phase (44 %). Relatively little research focuses on the final phase of the life cycle (2 %) which reflects an important direction for future research to better understand the risks associated with decomissioning and recycling a building. Some risks did not fit neatly into one building phase category such as gentrification, or economic instability (7 %) (Fig. 3**)**. The use of LCA to map risks is an important first step in conceptualizing how risks also map onto stakeholder roles.

5. Discussion: Prioritizing and comparing risks through a risk spiral analysis

Risk assessment reflects broader social valuation, policies, and risk perception. Mainstream corporate assessment of risk is typically measured in terms of "exposure" to a particular hazard [123]. Yet, exposure to financial disruption does not account for systemic social and environmental impacts (i.e., externalities), Thus, to capture a more complete picture of the landscape of risk, the authors propose defining risks in terms of stakeholder immediacy *and* perceived exposure. This review indicates a strong propensity for respondents to frame risks under a techno-economic model, which has overlooked the necessity for a more spatially and temporally comprehensive model. We propose using a stakeholder-driven sociotechnical model to encourage future work and better account for more distal social and environmental risks in our decarbonization models.

Risks gain prominence when they are geographically proximate [124], but we also suggest here that stakeholder role is a key determinant in how risks are perceived, valued, and acted upon. Stakeholder role proximity might offer analytical leverage to investigate how risk perceptions vary among stakeholders and help explain the disconnect between layperson and expert assessment of risk **(**Fig. 4**)**. We model this concept as a spiral, where stakeholder role shapes the perspective of risk immediacy or proximity. For this conceptual model, we offer one example to quantify this concept of immediacy. The risk-proximity score for the standard stakeholder is created by an ordinal ranking of "proximity to risk" by one's role (in this example, as a building occupant, contractor, or owner/developer). The proximity score is here an ordinal ranking of *direct risk* (1)*, indirect risk* (2)*, and remote risk* (3) encountered by each ideal stakeholder (Table 3, Fig. 4). The lower the average proximity score for the stakeholder, the more central the risk on the spiral. Stakeholder proximity could be validated and applied onto a larger map of stakeholders using additional qualitative data or survey instruments that assess respondents' perceptions of particular risks. For example, data from U.S. Occupational Safety and Health Administration can provide data on workplace injuries or incidents can provide data on direct risks associated with health and safety [125], but we also note that more indirect risks (i.e. decline of air quality, production of environmental hazards, violations of environmental justice, or moral injury) can contribute to a more complete assessment of risks. Like the IPCC's Livelihood Vulnerability Index, which captures non-technological vulnerabilities, the proximity model includes both social and distal criteria [126]. We argue that mapping a relativistic sociotechnical landscape of risk aligns conceptually with the broadening accounting of emissions accounting enabled by using LCA. Our approach enables the systematic identification of both immediate and long-term risks, potentially supporting policies and practices that reduce social and environmental risk in the building sector. Moreover, it offers a framework for addressing social equity by incorporating broader social and environmental risks into evaluative and decision-making processes.

The risk spiral and concept of role proximity to risk helps explain why some risks gain wide social consciousness, and invite political or

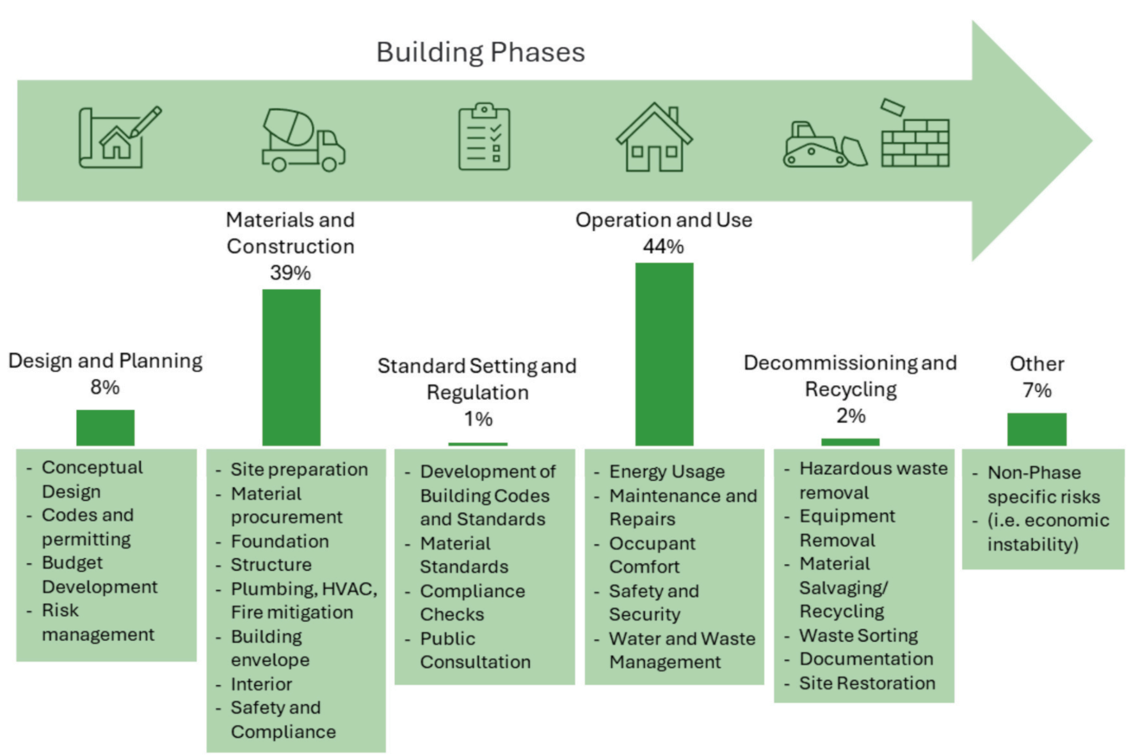

Fig. 3. Sociotechnical risks across the lifecycle phases of building decarbonization. Source: Authors.

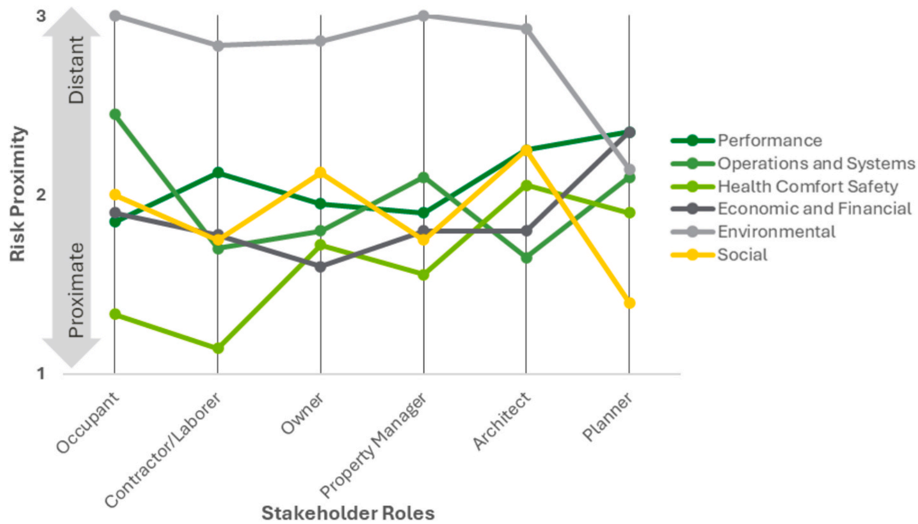

Fig. 4. Ordinal building decarbonization risk proximity by stakeholder role. Note: This conceptual figure demonstrates how stakeholder roles can be modeled and compared using an ordinal model aggregated across risks in each theme. It provides a visual hypothesis of how risk proximity and perception might vary by stakeholders. Source: Authors.

Table 3
Ordinal spacing for visualizing building decarbonization risks as a "risk perception spiral".

	Occupant				Contractor				Owner/Investor				Total
Risk Example	Direct	Indirect	Remote	Average	Direct	Indirect	Remote	Average	Direct	Indirect	Remote	Average	**Average**
Social Inequity			3	3			3	3			3	3	**3**
Suboptimal Performance	1			1	1			1		2		2	**1.3**
Embodied Carbon			3	3			3	3			3	3	**3**
Supply Shortage	1	2		1.5	1			1	1			1	**1.2**
High Maintenance Cost	1			1		2		2	1	2		1.5	**1.5**
Price Uncertainty		2		2	1			1	1			1	**1.3**
Poor Labor Conditions			3	3	1			1		2		2	**2**

Note: 1=Direct Risk, 2=Indirect Risk, 3=Remote Risk, Numeric values represent an ordinal ranking based on whether risks would, conceptually, be considered direct (1), indirect (2) or remote (3). Average scores are mapped onto spiral. It would also be possible to map risks based on a more diffuse group of stakeholders and use this model to map risks based on other forms of exposure data.
Source: Authors

social action, while others do not. In this risk spiral concept, social inequity and environmental damage is distant from the immediate individual experience of occupants, contractors, and owners alike (see Fig. 5). Alternatively, risks like cost, health, and personal safety are central as they are more proximate to daily activities and labor conditions. Thus, the potential added value of the risk-as-proximity concept is the ability to map risks in a way that is: 1) systemic, 2) lateral not hierarchal, 3) accounts for variation of risk proximity by stakeholder, and, 4) helps explain why some risks have gained prominence or have social valuation of high costs, rather than social inequity. The risk spiral also provides a conceptual framework grounded in a sociotechnical understanding of risk, in contrast to conventional techno-economic risk models that have largely failed to address the social and environmental harms associated with conventional building materials and practices.

Further research is needed to validate the risk proximity spiral and to further understand the risks of deep decarbonization across the building life cycle, including filling the research gap to identify risks of social exclusion in planning and design stages. An example of how this might be validated is by surveying stakeholders from across the building life cycle (i.e. experts in design, construction, operations, and decommissioning), asking them to rate the risk level (0 = no risk, 100 = high risk) of possibilities highlighted in the literature review of possible risks associated with low-carbon building technologies.

More work is also necessary to extend energy justice discussions and develop transformative frameworks for decarbonization strategies in the building sector that draw from anti-racism, Indigenous theories, postcolonialism and feminism [127]. These frameworks have not been specifically analyzed in building decarbonization strategies and could be an important pathway to understand more transformative pathways forward. The risk spiral model offers a means of accommodating broader conceptions of time and space, allowing for integrated planning and design for both proximate and distal risks. The risk proximity model further incorporates the idea of situatedness enabling analysis of how perceptions of risk vary among stakeholders [128,129]. This allows for

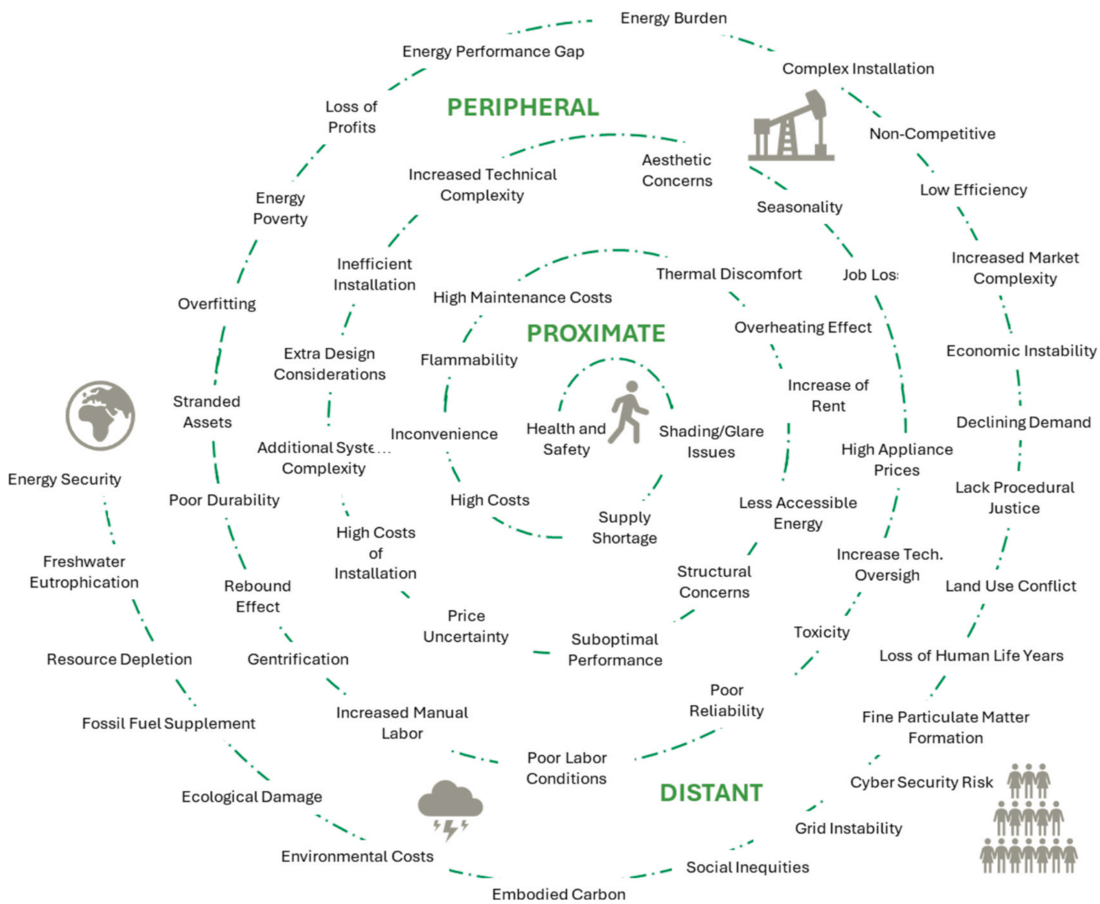

Fig. 5. Visualizing building decarbonization through a "Risk Perception Spiral". Source: Authors.

the generation of multiple, individualized spirals that reflect diverse understandings of risk immediacy. Comparing these individualized spirals to an aggregated or "average" model can reveal whose perspectives are prioritized in dominant risk narratives. These comparisons support discussions of procedural justice and epistemic power to help reveal previously overlooked externalities and knowledge gaps. By redefining risk as a relational, and temporally and spatially expansive concept, the risk proximity model encompasses the risks identified in the existing literature and effectively integrates social and environmental externalities through a comprehensive sociotechnical understanding of risk.

The risk spiral has several practical implications. It enables the identification of hidden or deferred risks, supports the integration of risk assessment across spatial and temporal scales, and facilitates a more comprehensive understanding of distribution of risks and responsibility among stakeholders. By highlighting how different stakeholders perceive risk, the model can help individuals and organizations recognize their specific roles in mitigating both immediate and long-term hazards. For example, stakeholders may take greater responsibility for enforcing and promoting an institutional culture of safety, seeking transparency of supply chains to ensure ethical procurement practices, and pursuing voluntary certifications to set social and environmental goals. Leaders in professional organizations can promote oversight practices for materials sourced from regions with weak governance or histories of labor exploitation and invest in continuous technical training to ensure safe and responsible practices across the building lifecycle. The spiral model also brings attention to the later stages of the building lifecycle, emphasizing the importance of design and construction practices that facilitate safer and more efficient decommissioning. This includes using methods that enable easy disassembly – such as opting for screws over nails – and selecting natural materials that can be reused or disposed of without introducing additional hazards.

While these approaches may involve higher upfront costs, they increase the likelihood of material reuse. This reflects the need for a more systemic end-of-life process oversight—similar in principle, though not in scale, to the decommissioning protocols used for high-risk infrastructure like nuclear power plants [130]. Despite the risks buildings pose over their lifecycle, current decommissioning practices remain far less comprehensive. It is therefore reasonable to require that new builds include a clear and responsible decommissioning plan. One pathway is requiring building-specific Extended Producer Responsibility (EPR) policies, which assign long-term accountability for materials and construction impacts (see [131] for existing material EPR legislation in the United States). At a minimum, policymakers should strengthen building codes to restrict the use of environmentally and socially hazardous materials. A non-prescriptive yet effective example is to ban building materials included on the International Living Future Institute's *Red List;* a list of chemicals used in building materials that contain chemicals with serious risks to human health and the environment [132]. Additionally, there is a need for more comprehensive financial models that accurately reflect the costs of environmentally harmful practices and unethical material procurement, both locally and globally [see 133].

6. Conclusion

Despite the critical importance and urgency of decarbonizing the building sector, efforts carry potential for risk–risk tradeoffs, continued carbon emissions, worse social inequality, and continued environmental damage. With 340 billion square feet of existing buildings in the United States alone [134], and anticipation of increasing building stock globally to meet a 20 % population increase by 2050, decarbonization of the building sector is urgent at both a national and global scale to have any chance of meeting emission reduction benchmarks to mitigate climate change [135]. In this work, we used a systematic literature review to map risks associated with decarbonization of the building sector, and highlight how a sociotechnical framework can supplant the techno-economic framework to provide a more spatially and temporally expansive concept of risk, and their relevance to diverse stakeholders across the building lifecycle. We identified 50 distinct sociotechnical barriers at multiple levels of the building lifecycle or supply chain, including issues of performance and inefficiency, damage to the environment, health and safety concerns, to hazardous waste removal and site restoration.

The steep challenge is to minimize the panoply of fifty risks evident in the decarbonization of the building sector while also improving performance, optimizing technical systems, improving social well-being, ensuring health, safety, economically profitability, and environmental restoration within 25 years. After identifying the scope and magnitude of these risks, the next task must be to determining how to mitigate these risks – a critical task for future research. Meeting this monumental challenge requires an integrated effort including mapping and assessing the risks of decarbonization of the building sector to ensure that potential risks do not exceed the known risks that we face under the continued emissions of the fossil fuel regime. With this, it is prudent to consider interventions required at a technical level in tandem with the social and political interventions needed to reframe collective responsibility of energy use. Understanding the risks in terms of impacted stakeholder populations and building phases allows for better accounting for less visible, but important risks. By integrating interests of stakeholders, often excluded from decision-making spaces, like laborers, renters and building occupants, we can better assess risk distribution from an environmental justice framework, and work to minimize risks for those for whom the negative outcomes exacerbate legacies of disadvantage.

In highlighting the risks of decarbonization of the building sector, we provide a strong case to extend beyond a techno-economic calculus to use a sociotechnical lens that accounts for risks across building phases and diverse stakeholder populations to avoid risk–risk tradeoffs. However, these potential negative outcomes must be balanced against the unsustainable fossil fuel regime, as alternatives are needed – imperfect as they may be – within 25 years. This compression of time makes precautionary inaction less feasible, as delays compromise the ability to meet emission benchmarks. The timeline demands drastic interventions that leave little time to pilot case studies and minimize uncertainty before proposing action at scale.

CRediT authorship contribution statement

Erin Heinz: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Benjamin K. Sovacool:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. **Thomas Kwan:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Vincent Petit:** Writing – review & editing, Funding acquisition, 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.

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Data availability

The data is the literature which is listed in the reference section, and it is publicly available.

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