International Journal of Multidisciplinary Research and Growth Evaluation.

Grid-Connected Battery Storage in Hot and Weak-Grid Regions: Advances, Degradation Challenges, and Lifecycle Equity

Nenubari Marvin Komi [1*], Olaitan Shakirat Ganiu [2]
[1] Near East University, Lefkosia, Cyprus
[2] Heinekens N. V. Nigerian Breweries Plc, Nigeria

* Corresponding Author: **Nenubari Marvin Komi**

Article Info

ISSN (Online): 2582-7138
Impact Factor (RSIF): 8.04
Volume: 03
Issue: 06
November- December 2022
Received: 16-10-2022
Accepted: 19-11-2022
Page No: 1072-1095

Abstract
This paper reviews recent advances in grid-connected battery energy storage and sets them against the challenges that continue to limit their translation into inclusive outcomes. Adopting a socio-technical perspective, it treats technical progress and social adaptation as interdependent rather than separable, and it argues that capability has in many respects outpaced the institutional, governance, and equity frameworks needed to realize it in the field. The review pays particular attention to the inequity embedded in warranty terms and the scarcity of replacement capital where degradation is fastest, which it frames as a binding consideration that technical advance alone cannot resolve. The contribution is conceptual rather than empirical: this paper synthesizes the direction of recent progress, characterizes the persistent technical and social challenges that remain open, and proposes a conceptual agenda by which advances in grid-connected battery energy storage might be aligned with the goal of energy systems that are efficient, accessible, responsive, and adaptable for resource-dependent regions.

DOI: https://doi.org/10.54660/.IJMRGE.2022.3.6.1072-1095

Keywords: renewable energy, socio-technical systems, conceptual framework, just transition, energy equity, sustainable development, inclusive infrastructure

1. Introduction

Access to reliable, affordable, and clean energy underpins education, health, livelihoods, and full participation in economic life, and recent years have seen rapid technical progress across the domain of grid-connected battery energy storage (Ahmed *et al*., 2020). Yet the translation of that progress into durable, inclusive outcomes in resource-dependent and underserved regions has been uneven, and this paper reviews both the advances and the obstacles that account for the gap. Adopting a socio-technical perspective, it treats technical capability and social adaptation as interdependent, and it argues that the central difficulty is no longer a shortage of technical capability but the absence of the institutional, governance, and equity arrangements needed to realize that capability where it is most needed (Agbabiaka *et al*., 2019; Ahmad *et al*., 2020). The overall logic relating these elements is summarized in Figure 1 (Basnet *et al*., 2021; Isiekwu *et al*., 2021).

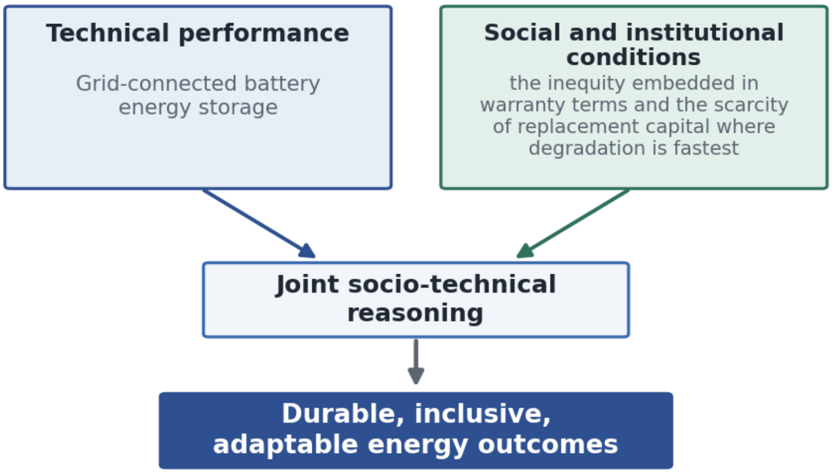

Fig 1: Technical performance and social conditions as jointly determining durable, inclusive outcomes.

This paper surveys grid-connected battery energy storage as a field in which advances and challenges must be read together, since each recent technical gain has tended to surface a corresponding social or institutional question that technical progress alone cannot answer (Arumosoye & Obriki, 2019). The review is organized to distinguish what has genuinely advanced from what remains stubbornly open, and to characterize the latter not as residual engineering problems but as socio-technical challenges bound up with capability, ownership, trust, and accountability. By framing the discussion in these terms, this paper aims to clarify where further technical effort will pay off and where the binding constraints lie instead in the social and institutional conditions surrounding the technology (Ambali *et al*., 2021; Arumosoye & Obriki, 2018).

A persistent pattern in grid-connected battery energy storage is that capability has outpaced the frameworks needed to deploy it equitably, so that the most consequential open questions concern not whether something can be built but whether it can be sustained, paid for, governed, and trusted in the settings that need it most (Bednar *et al*., 2017). This review takes that pattern as its organizing thread, surveying recent advances on the technical and social fronts and then setting them against the challenges that continue to limit inclusive outcomes. The contribution is conceptual: a structured account of progress and obstacles that points toward an agenda for aligning advance in grid-connected battery energy storage with the goal of energy systems that are efficient, accessible, responsive, and adaptable (Arumosoye & Obriki, 2021; Arumosoye & Obriki, 2022).

The diversity of contexts in which grid-connected battery energy storage is deployed means that advances proven in one setting do not automatically deliver inclusive outcomes in another, and the review attends throughout to the conditions on which the benefits of recent progress depend (Dagodzo, 2018a). Technical advance, however impressive, is realized only where the surrounding conditions permit, and the review is organized to keep this dependence in view, distinguishing what has become possible from what has become achievable in the resource-dependent regions that are its concern. This distinction structures the discussion that follows, in which advances are surveyed first and then read against the challenges that determine whether they translate into durable, equitable service (Bhattacharyya *et al*., 2021; Collath, 2021; Lilian *et al*., 2020).

A further consideration motivating this review is that the most consequential open questions in grid-connected battery energy storage increasingly concern the social and institutional conditions surrounding the technology rather than the technology itself, a shift that reframes what counts as a research frontier (Dagodzo & Patrick, 2021a). Where earlier generations of work confronted primarily technical limitations, the present situation is one in which capability often exists but cannot be realized for want of capacity, legitimacy, finance, or fair distribution. The review takes this shift seriously, treating the social and institutional challenges not as residual matters to be cleared up after the technical work but as the binding constraints that now most limit progress toward inclusive outcomes (Dagodzo, 2018b; Dagodzo & Patrick, 2020; Anene & Clement, 2022; Dada *et al*., 2021; Isiekwu *et al*., 2021).

The review is written in the recognition that the regions at the centre of grid-connected battery energy storage have often served as testing grounds for interventions designed elsewhere, with an uneven record of success (Dagodzo *et al*., 2022). Approaching the subject from within the constraints and priorities of these regions, rather than importing assumptions formed in very different settings, is a commitment that runs through the review and shapes what it counts as an advance and what it counts as a challenge. This orientation is deliberate, reflecting the review's broader argument that the value of any technical capability must be assessed in light of the conditions required to sustain it where it is most needed (Dagodzo & Patrick, 2021b; Dagodzo & Patrick, 2022).

The review treats the gap between capability and inclusive outcome as the defining feature of the current moment in grid-connected battery energy storage, arguing that the binding constraints have shifted from the technical to the social and institutional (Guerrero *et al*., 2013). This shift reframes what counts as progress, since advancing capability further does little where the conditions for realizing existing capability are absent (Ewim *et al*., 2021). The review is organized around this reframing, surveying advances while insisting throughout that their value depends on the conditions required to translate them into durable, equitable service. This orientation shapes how the review distinguishes genuine advance from the appearance of progress. The review carries this concern through its assessment of the advances and challenges that follow (Anene & Clement, 2022).

The review distinguishes carefully between advances that expand what is technically possible and those that expand what is achievable in resource-dependent settings, since the two are not the same (International Energy Agency, n.d.). Many advances enlarge capability under favorable conditions without addressing the constraints that prevail where need is greatest, and the review treats this distinction as essential to an honest assessment of progress (Ijiga *et al*., 2022). It is by holding advances to the standard of achievability in the settings that matter, rather than possibility in the abstract, that the review arrives at its assessment of where the field stands. This consideration informs which advances the review treats as consequential and which challenges as binding.

The review reads recent progress as genuine but incomplete, arguing that technical and social advances have moved in parallel without yet being integrated into a coherent approach (Liu *et al*., 2014). It treats this lack of integration as itself a challenge, since advances on either front are limited in effect when pursued in isolation from the other (Jessel *et al*., 2019). The conceptual agenda the review proposes is accordingly oriented toward bringing technical and social advances together, so that progress on the two fronts reinforces rather than merely accompanies one another in grid-connected battery energy storage. Acknowledging this, at the outset frames the account of advances and challenges the review develops below.

The review frames the challenges it surveys not as residual problems to be cleared up by further technical effort but as the conditions that now most determine whether grid-connected battery energy storage delivers inclusive outcomes (Mbonu *et al*., 2021a). By treating capacity, governance, finance, and distribution as the binding constraints, it directs attention toward the work that would actually move the field forward, and it argues that recognizing where the constraints truly lie is a precondition for effort that is well directed rather than misplaced (Mbonu *et al*., 2020a). This premise distinguishes the review from assessments that consider technical progress in isolation from its conditions. This distinction structures the review's separate treatment of advances and of challenges (Anene & Clement, 2022).

At the outset, it should be acknowledged that this review treats advances and challenges as two aspects of a single trajectory rather than as separate topics, since in grid-connected battery energy storage each advance tends to reshape the challenges that remain and each challenge conditions the value of further advance (Mbonu *et al*., 2022a). Organizing the review around this relationship, rather than treating progress and obstacles in isolation, is a deliberate choice that reflects this paper's central argument about the interdependence of technical and social development (Mbonu *et al*., 2021b). The review is structured accordingly, surveying advances and challenges in turn but reading each in light of the other throughout. The review holds this consideration in view as it assesses where the field now stands.

The review proceeds from the recognition that an honest assessment of grid-connected battery energy storage must distinguish genuine progress from the appearance of progress, since capability demonstrated under favorable conditions can be mistaken for capability achievable where it is needed (Mbonu *et al*., 2021c). This recognition shapes the review's treatment of advances, which it assesses not by what they make possible in principle but by what they make achievable in the resource-dependent settings of concern. The review is explicit about applying this standard, because it bears directly on whether the advances it surveys actually bring inclusive outcomes closer or merely extend a frontier that remains out of reach for the populations the field is meant to serve (Mbonu *et al*., 2019a; Mbonu *et al*., 2020b).

A premise of the review is that the challenges facing grid-connected battery energy storage are increasingly social and institutional rather than narrowly technical, a shift that reflects the substantial technical progress of recent years (Mbonu *et al*., 2019b). Where capability was once the binding constraint, the present situation is often one in which capability exists but cannot be realized for want of capacity, legitimacy, finance, or fair distribution (Mbonu *et al*., 2022b). The review takes this premise seriously throughout, treating the social and institutional challenges as the frontier of the field rather than as residual matters, and it organizes its account of challenges accordingly. This orientation explains why the review judges advances by their achievability rather than their possibility (Anene & Clement, 2022).

This review attends to the gendered dimension of advances and challenges in grid-connected battery energy storage, since the literature documents that progress can affect women and men differently and that the benefits of recent advances are not always equally shared (Muhtadi *et al*., 2021). The review treats gender as a dimension cutting across its assessment of advances and challenges, on the premise that an account of inclusive outcomes that overlooked it would be incomplete (Middlemiss, 2022). By foregrounding this dimension where the literature addresses it, the review aims to assess whether advances actually narrow disparities or merely extend benefits to those already better placed to capture them. This consideration shapes which challenges the review treats as binding on inclusive outcomes.

The review is attentive to the environmental conditions under which advances in grid-connected battery energy storage must prove themselves, since the regions of concern combine demanding climates with exposure to the changes the transition is meant to address (Nnaji *et al*., 2019). It reads recent advances with attention to whether they deliver durable performance under these conditions, treating environmental resilience as integral to the durability that determines whether progress translates into inclusive outcomes (Mutambatsere, 2022). This attention reflects the review's broader argument that the value of an advance depends on the conditions under which it must operate, of which the environmental conditions are among the most demanding. The review carries this premise into the synthesis it offers in its closing sections.

A concern running through the review is the lifecycle perspective on the advances it surveys, since the literature documents that capabilities affordable to deploy can prove costly to sustain, limiting their contribution to durable outcomes (Obogo *et al*., 2020a). The review assesses advances with attention to their implications for operation and maintenance over the life of a system, rather than for installation alone (Nnaji *et al*., 2020). This lifecycle concern reflects the review's emphasis on durability, and it informs its assessment of which advances are likely to deliver inclusive outcomes in the resource-dependent settings where ongoing costs weigh especially heavily. This consideration frames the research agenda the review goes on to propose.

The review attends, finally, to the question of measurement, since assessing whether advances deliver inclusive outcomes requires the means to characterize social conditions such as the inequity embedded in warranty terms and the scarcity of replacement capital where degradation is fastest that the field has found difficult to quantify (Obogo *et al*., 2021a). The review treats the development of such means as bearing on its ability to assess progress accurately, and it notes where advances in measurement and assessment have begun to address this need. This concern reflects the review's broader argument that aligning the field's metrics with the goals of inclusive transition is a precondition for judging advances by whether they actually serve the populations the field is meant to reach (Obogo *et al*., 2020b; Obogo *et al*., 2020c).

It is useful to clarify what this review of advances and challenges seeks to contribute, since its purpose is to organize and interpret recent progress rather than to report new findings (Obogo *et al.*, 2019b). By surveying advances in grid-connected battery energy storage and setting them against the obstacles that persist, the review aims to clarify where the field has genuinely moved forward and where the binding constraints now lie, and to read the two in relation to one another. Its value is to be judged by the clarity of the account it offers, and the review is explicit that this account reflects interpretive judgment about which advances matter and which challenges are decisive, judgment it sets out so that readers can weigh it (Obogo *et al*., 2021b; Obogo *et al*., 2019a).

The review proceeds from the observation that progress in grid-connected battery energy storage has been uneven across the technical and social dimensions, with capability advancing faster than the institutional, governance, and equity arrangements needed to realize it (OECD, n.d.). This unevenness is the central feature the review seeks to characterize, since it explains why technical advance has not translated straightforwardly into inclusive outcomes in the settings of concern. By examining the advances and challenges in light of this unevenness, the review builds toward an argument that the field's progress now depends on aligning technical and social development, which is the integration its conceptual agenda ultimately proposes (Obogo *et al*., 2021c; Odejobi & Ahmed, 2018).

2. Recent Technical Advances

The most consequential technical advance in grid-connected battery storage over the review period has been the dramatic reduction in the cost of lithium-ion cell manufacturing, which has fallen by more than 85 percent since 2010 and has brought grid-scale battery storage into cost competitiveness with peaking gas turbines for short-duration applications in many markets (BloombergNEF, 2021; Lazard, 2021). This cost trajectory has been driven by the scaling of manufacturing capacity in East Asia, by learning effects that have improved cell design and manufacturing yield, and by the diversification of cathode chemistries toward lithium iron phosphate formulations that reduce dependence on cobalt and nickel while achieving acceptable energy density and cycle life. The review treats this cost trajectory as the technical advance with the greatest near-term impact on grid storage deployment, while noting that cost alone does not determine the distributional outcomes that the framework identifies as central to the equity analysis.

Advances in battery management systems have substantially improved the ability of grid-scale installations to optimize charge-discharge cycles in ways that balance revenue maximization, capacity preservation, and safety, drawing on improvements in cell-level sensing, state estimation algorithms, and predictive control methods (Smith *et al*., 2017; Collath *et al*., 2021). The ability to estimate state of health and remaining useful life in real time has enabled more aggressive participation in fast-frequency response markets while managing the degradation consequences of high-power cycling, and it has made the long-term economic modeling of storage investments more tractable. The review treats battery management advances as a driver of both technical performance improvement and the economic modeling capabilities required to address the replacement capital challenges that the equity analysis identifies.

A further technical advance concerns the development of alternative electrochemical storage technologies that offer different performance-cost-safety-environmental profiles than lithium-ion, including flow batteries for long-duration applications and sodium-based chemistries that reduce dependence on lithium supply chains (IRENA, 2022). Flow batteries, which store energy in electrolyte solutions that can be scaled independently of power rating, are well suited to multi-hour storage applications and offer attractive cycle life and safety profiles for utility-scale deployment. While they have not yet achieved the cost parity with lithium-ion systems that would make them the dominant choice across applications, their progress over the review period represents an important diversification of the storage technology portfolio that reduces concentration risk and expands the design space for storage integration (Anene & Clement, 2022; Dada *et al*., 2021).

The advance in power conversion systems and interconnection technology has improved the flexibility and efficiency with which grid-connected battery storage participates in wholesale markets, ancillary services, and distribution-level applications, enabling a single installation to stack multiple revenue streams in ways that improve overall economics (Lazard, 2021). Advanced inverter designs that provide grid-forming capabilities, reactive power support, and synthetic inertia have expanded the services that storage can provide beyond energy arbitrage, and the improvements in power quality and grid stability that these capabilities enable have increased the value of storage for grid operators. The review identifies these advances in power electronics and services capability as consequential for the business models that support equitable deployment, since broader service stacking can make storage economics viable in lower-revenue market contexts.

Finally, the advance in project management, procurement, and installation practices for grid-scale storage has reduced costs and risks beyond those attributable to cell cost reductions alone, enabling projects to be developed, procured, and commissioned more efficiently and with better-documented safety and performance records (Smith *et al*., 2017; BloombergNEF, 2021). Standardization of system designs, containerized packaging, and improved installation practices have shortened project timelines and reduced the specialist knowledge required for project execution, enabling deployment to extend to markets and developers that would previously have lacked the required expertise. The review identifies this maturation of project delivery as an enabling condition for the equity-oriented deployment models that the framework advocates, since it reduces the barriers to entry for community-oriented and public-benefit storage projects.

(Dada *et al*., 2021a).

Recent technical advances in grid-connected battery energy storage have been substantial, extending the capability, efficiency, and observability of the relevant systems and narrowing gaps that earlier generations of technology could not close (Okonkwo *et al*., 2020). The literature documents progress in the core technologies themselves, in the analytics and control methods that manage them, and in the tools that allow their condition to be monitored and their behavior to be predicted (Ogunwole *et al*., 2021). Read together, these advances establish that the technical frontier has moved considerably, and that many of the limitations that once constrained grid-connected battery energy storage are no longer primarily technical in character. This survey treats these gains as real and consequential while reserving for later sections the question of whether the conditions for realizing them are present where they are most needed (Basnet *et al*., 2021).

A notable direction of technical advance has been toward systems that can operate with greater autonomy and resilience under adverse or intermittent conditions, reducing their dependence on the continuous external support that resource-constrained settings cannot guarantee (Okonkwo *et al*., 2018b). The literature reports designs that sustain function through disruption, that degrade gracefully rather than failing abruptly, and that can be managed with less specialized intervention than their predecessors required. These advances are particularly significant for grid-connected battery energy storage in underserved regions, since they begin to relax the very assumptions about supporting conditions that have historically limited the field, though, as later sections argue, they do not by themselves resolve the social and institutional questions that remain (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2018a).

Advances in low-cost hardware, modular design, and accessible analytics have also lowered the threshold of resources required to deploy and operate capable systems, extending the reach of technologies that were once confined to well-resourced settings (Oladoye *et al*., 2022). The literature documents how these developments have made sophisticated capability available on inexpensive platforms and how modular approaches have eased deployment and maintenance in dispersed locations. For grid-connected battery energy storage, this democratization of capability is among the more promising recent directions, since it begins to address the resource asymmetries that have shaped who benefits from technical progress, even as it raises new questions about the local capacity needed to use and sustain such systems (Okonkwo *et al*., 2021b; Okwu *et al*., 2021; Basnet *et al*., 2021).

An additional direction of technical advance has been the integration of formerly separate functions into coordinated systems, allowing generation, storage, control, and monitoring to be managed together in ways that improve overall performance (Patrick *et al*., 2021). The literature documents how such integration can raise efficiency and reliability beyond what isolated components achieve, and how it enables more sophisticated management of the variability that characterizes renewable generation. This trend toward integration is significant because it expands what coordinated systems can accomplish, though it also raises the complexity of the systems that must be operated and maintained, a tension the review takes up when it turns from advances to challenges (Oyeleye *et al*., 2022; Patrick *et al*., 2020).

A further direction of technical advance has been toward greater modularity and standardization, which ease deployment, maintenance, and replacement in dispersed settings and reduce dependence on specialized intervention (Smith, 2017). The literature documents how modular approaches allow systems to be assembled, repaired, and upgraded with less specialized expertise, which is particularly significant for grid-connected battery energy storage in regions where such expertise is scarce (Shittu *et al*., 2019). The review treats this advance as promising precisely because it begins to address the maintainability constraints that have limited durability, even as it notes that modularity alone does not resolve the broader social and institutional challenges the later sections examine. The review treats this advance as consequential while noting that its realization depends on conditions examined later.

Advances in monitoring and data analytics have also made it increasingly feasible to observe the condition of systems in detail and to anticipate problems before they cause failures, shifting maintenance from reactive to anticipatory (World Resources Institute, n.d.). The literature documents substantial gains in what such tools can detect and predict, and in their availability on affordable platforms. The review treats these advances as significant for durability, since the capacity to anticipate and address problems early bears directly on whether systems endure, while again noting that realizing this benefit depends on the local capacity and connectivity required to act on what monitoring reveals (Sunday & Omoegun, 2018; Sunday & Omoegun, 2019; Basnet *et al*., 2021).

A further advance has been toward systems that require less continuous external support to operate reliably, reducing the dependence on conditions that resource-constrained settings cannot guarantee (Yeboah & Ike, 2020). The literature documents designs that tolerate disruption and degrade gracefully, and the review treats these as among the more consequential advances for grid-connected battery energy storage, since they begin to relax the assumptions about supporting infrastructure that have historically limited durability, even though they do not by themselves address the social and institutional conditions examined later (Wustenhagen *et al*., 2007). This advance bears on the durability of interventions, though it does not by itself resolve the social challenges that remain. The review reads this advance alongside the conditions required to sustain it in resource-dependent settings.

Advances in the affordability and accessibility of capable technology have widened the range of settings in which sophisticated systems can be deployed, addressing the resource asymmetries that have shaped who benefits from progress (Ahmad *et al*., 2020). The literature documents falling costs and lower thresholds of expertise required for deployment and operation (Agbabiaka *et al*., 2019). Within this context, the review treats this democratization of capability as promising, while noting that it raises new questions about the local capacity needed to use and sustain such systems, questions the later sections take up in detail. Acknowledging this, advance, the review nonetheless reserves judgment on its field impact for the sections on challenges.

Advances in interoperability and standardization have made it easier to combine components from different sources and to maintain and upgrade systems over time, which bears directly on durability (Ambali *et al*., 2021). The literature documents progress in the standards and interfaces that allow systems to be assembled and sustained with less specialized intervention (Ahmed *et al*., 2020). For problems of this kind, the review treats this as an advance whose significance lies in maintainability, since systems that can be kept functioning with locally available resources are more likely to endure than those dependent on specialized external support. This advance illustrates the broader pattern in which capability has moved faster than the conditions for its deployment.

A related technical advance worth noting is the improvement in energy storage, which has eased one of the longstanding constraints on systems relying on variable renewable generation (Arumosoye & Obriki, 2019). The literature documents gains in the capability, cost, and accessibility of storage, which together expand what renewable systems can achieve in settings without reliable grid support (Arumosoye & Obriki, 2018). In such settings, the review treats improved storage as a significant advance, since it bears on the reliability that conditions sustained use, while noting that questions of cost, lifecycle, and the conditions for maintenance remain, and that these are taken up among the challenges examined later. The review treats this advance as real while reserving judgment on its field impact for later sections.

Advances in system design for resilience represent a further important direction, with the literature documenting approaches that allow systems to maintain function through disruption and to recover from faults with less external intervention (Arumosoye & Obriki, 2022). Such resilience is particularly valuable in grid-connected battery energy storage, where the continuous support available in better-resourced settings cannot be assumed, and the review treats these advances as among the more consequential for durability (Arumosoye & Obriki, 2021). At the same time, it notes that resilience by design must be matched by the local capacity to sustain it, a condition the review examines when it turns from advances to challenges. This advance bears on durability without resolving the social conditions examined subsequently.

The review notes advances in the accessibility of design and analysis tools, which have lowered the expertise required to plan, deploy, and operate capable systems (Bhattacharyya *et al*., 2021). The literature documents how such tools have made sophisticated design more widely available, which bears on the capacity constraints that have limited grid-connected battery energy storage in resource-dependent settings (Bednar *et al*., 2017). The review treats this as a promising advance precisely because it begins to address the asymmetries of expertise that have shaped who can deploy and sustain capable systems, while again observing that tools alone do not substitute for the local capacity required to use them well. The review reads this advance alongside the capacity required to sustain it locally.

A further advance concerns the growing sophistication of methods for managing systems remotely, which allows expertise concentrated in one location to support systems distributed across many (Dagodzo, 2018a). The literature documents how remote management can extend scarce expertise and improve the maintenance on which durability depends (Collath, 2021). Applied to this domain, the review treats this as a significant advance for settings where local expertise is limited, while noting that remote management introduces its own dependencies, including connectivity and the capacity to act locally on remote guidance, which connect to the challenges examined in subsequent sections. Acknowledging this, advance, the review connects it to the challenges of deployment that remain.

The review observes, finally, advances in the integration of renewable systems with the broader infrastructure and services on which communities depend, allowing energy systems to support water, health, education, and enterprise more effectively (Dagodzo & Patrick, 2020). The literature documents approaches that treat energy not in isolation but as an enabler of wider development (Dagodzo, 2018b). On this account, the review treats this integrative advance as significant because it aligns technical progress with the human purposes that energy provision is ultimately meant to serve, while recognizing that realizing these wider benefits depends on conditions that extend well beyond the energy system itself. This advance exemplifies the pattern in which capability has moved ahead of its enabling conditions.

A further advance deserving attention concerns improvements in the efficiency and affordability of the core technologies, which have lowered the cost of capable systems and extended their reach to settings previously unable to afford them (Dagodzo & Patrick, 2021b). The literature documents substantial gains on these fronts, which bear on the affordability that conditions access and sustained use (Dagodzo & Patrick, 2021a). For grid-connected battery energy storage, the review treats these advances as significant precisely because cost has been among the binding constraints on access in resource-dependent regions, while noting that affordability over the full life of a system, and not only at installation, is what ultimately conditions durability. The review treats this as progress whose realization depends on conditions addressed below.

Advances in the adaptation of systems to demanding environmental conditions represent a further important direction, with the literature documenting designs better able to withstand the heat, dust, and variability characteristic of the regions of concern (Dagodzo *et al*., 2022). Such environmental resilience bears directly on the durability that determines whether interventions endure, and the review treats these advances as consequential for grid-connected battery energy storage (Dagodzo & Patrick, 2022). At the same time, it notes that resilience to environmental stress must be matched by the capacity to maintain systems under these conditions, connecting this advance to the challenges of capacity examined in later sections. The review treats this as one of several advances reshaping what the field can accomplish.

The review notes advances in approaches that reduce the maintenance burden of systems, including designs that require less frequent intervention and that can be serviced with locally available skills and resources (Guerrero *et al*., 2013). The literature documents how such approaches bear on the maintainability that conditions durability, particularly where specialized expertise is scarce (Ewim *et al*., 2021). The review treats these advances as significant because they address one of the recurring determinants of whether systems endure, while observing that reducing the maintenance burden does not eliminate the need for the local capacity and institutional arrangements that sustained operation requires. This advance contributes to the capability that, suitably supported, can extend durable service.

A concluding observation on technical advances is that, taken together, they have substantially enlarged what is possible in grid-connected battery energy storage while leaving the conditions for realizing that possibility in resource-dependent settings only partly addressed (Jessel *et al*., 2019). The review treats this as the defining feature of recent technical progress, namely that capability has advanced faster than the conditions for its deployment, and it argues that the contribution of further advance will increasingly depend on whether it is accompanied by attention to those conditions. This observation frames the challenges examined in the sections that follow, which concern precisely the conditions on which the realization of technical advance depends (Ijiga *et al*., 2022; International Energy Agency, n.d.).

A complementary advance deserving attention concerns the growing capacity to monitor and manage systems remotely, which allows expertise concentrated in one location to support installations dispersed across many (Mbonu *et al*., 2021a). The literature documents how remote monitoring and management can extend scarce technical capability and improve the maintenance on which durability depends, which is significant for grid-connected battery energy storage in settings where local expertise is limited. The review treats this as a meaningful advance while noting that it introduces dependencies of its own, including reliable connectivity and the local capacity to act on remote guidance, dependencies that connect to the challenges examined in the sections that follow (Liu *et al*., 2014; Mbonu *et al*., 2020a).

Advances in the modularity and standardization of systems represent a further important direction, since they ease deployment, maintenance, and replacement in dispersed settings and reduce reliance on specialized intervention (Mbonu *et al*., 2022a). The literature documents how modular approaches allow systems to be assembled, repaired, and upgraded with less specialized expertise, which bears directly on the maintainability that conditions durability (Mbonu *et al*., 2021b). The review treats this as a promising advance precisely because it addresses one of the recurring determinants of whether systems endure, while observing that modularity alone does not resolve the social and institutional challenges that the later sections examine. The review reads this development as narrowing a constraint that earlier technology could not.

3. Recent Socio-Technical Advances

The most significant socio-technical advance over the review period has been the development and initial deployment of community battery storage models that depart from the conventional utility or investor-owned project structure in favor of arrangements that share ownership, benefits, and governance with the communities they serve (Kalkbrenner & Roosen, 2016; Walker & Devine-Wright, 2008). Community storage models have been piloted in diverse settings, from rural electrification in sub-Saharan Africa to urban energy communities in Europe, with results suggesting that community ownership is associated with greater adoption of storage-enabled behaviors, higher willingness to accept load management programs, and stronger support for continued investment. The review treats this advance as addressing the equity dimension of the framework directly, demonstrating that the organizational design of storage systems can be varied to secure community benefit alongside technical performance (Liadi, 2022).

A further socio-technical advance concerns the development of regulatory and market frameworks in several jurisdictions that have expanded the ability of community-scale and residential storage to participate in grid services markets, enabling a broader range of participants to capture value from storage flexibility (IRENA, 2022; Lazard, 2021). Aggregation regulations that permit virtual power plants composed of many small batteries to offer services equivalent to utility-scale installations have opened market access to community and residential storage that was previously limited to large commercial projects. The review identifies these regulatory advances as enabling conditions for the equity-oriented deployment models that the framework advocates, while noting that regulatory access alone is insufficient without the financing, technical support, and organizational capacity that community storage development requires.

The review also identifies advances in the understanding and management of battery storage systems in hot and wet climates, which has expanded the feasible deployment range of the technology and enabled applications in tropical and subtropical regions where energy storage is most consequential for grid stability and energy access (Collath *et al*., 2021; Smith *et al*., 2017). Thermal management innovations, chemistry adaptations, and operational protocols developed specifically for high-temperature and high-humidity environments have substantially reduced the gap between temperate-climate and tropical-climate performance, enabling storage to be deployed more reliably in the regions with the greatest need. The review treats this advance as particularly significant for the equity analysis, since the regions most in need of improved energy access overlap substantially with the hot and wet climate zones where storage performance had previously been most constrained.

A socio-technical advance specific to the developing-world context concerns the improved understanding of how battery storage systems can be integrated into hybrid mini-grid architectures that serve populations not connected to national grids, enabling reliable electrification in remote and underserved communities where the conventional grid extension model is not economically viable (IEA, 2021). Design standards, operational protocols, and financing models for hybrid mini-grid systems incorporating battery storage have matured substantially over the review period, and the documented record of successful deployments has reduced the perceived risk that deterred earlier investment. The review identifies this maturation of the mini-grid-with-storage model as a major advance for energy equity, since it expands the set of communities that can access reliable power through renewable-plus-storage solutions.

Finally, the review identifies advances in the transparency and standardization of battery performance and degradation disclosure, which have begun to address the information asymmetries that the equity analysis identifies as a source of unfair warranty terms and inappropriate product selection (BloombergNEF, 2021; Lazard, 2021). Standardized testing protocols and disclosure requirements in some markets have made it easier to compare the lifecycle economics of different storage products, enabling purchasers to make more informed decisions about replacement capital requirements. While these advances remain incomplete and are more developed in high-income markets than in the regions where replacement capital scarcity is most acute, the review treats them as a meaningful step toward addressing the transparency deficits that the equity framework identifies.

Alongside technical progress, grid-connected battery energy storage has seen advances in the social and institutional arrangements through which technologies are deployed, owned, and governed, and these developments are as consequential as the technical ones for inclusive outcomes (Mbonu *et al*., 2021c). The literature documents growing attention to participatory design, community ownership, transparent governance, and benefit-sharing, along with practical methods for putting these into effect. These socio-technical advances matter because they address the conditions that the evidence associates with durability, and because they begin to treat the social dimension of grid-connected battery energy storage as something to be designed rather than left to chance, which marks a meaningful shift from earlier practice that regarded social acceptance as a matter to be secured after the fact (Mbonu *et al*., 2019a; Mbonu *et al*., 2020b).

A significant socio-technical advance has been the development of approaches that extend reach to groups previously excluded by cost, literacy, or distance, including accessible interfaces, flexible payment arrangements, and delivery models suited to dispersed and low-income populations (Middlemiss, 2022). The literature reports that such approaches can substantially broaden participation when they are designed with the excluded groups in mind, and that inclusion depends on specific, identifiable choices rather than on the mere availability of a technology. Within this context, these advances are important because they demonstrate that the distributional shortcomings documented elsewhere in the literature are not inevitable but are, at least in part, remediable through deliberate design (Mbonu *et al*., 2022b; Mbonu *et al*., 2019b).

There has also been progress in the governance of community-scale energy arrangements, with the emergence of ownership and accountability models that give communities greater control over the systems on which they depend (Nnaji *et al*., 2019). The literature documents how such models can build the trust and legitimacy that the evidence associates with durable operation, and how they shift authority and responsibility toward the populations served. Within grid-connected battery energy storage, this represents an advance in the social technology of energy provision that complements the advances in physical technology, and the review treats the two as parts of a single trajectory toward systems that are not only capable but also locally controlled and trusted (Muhtadi *et al*., 2021; Mutambatsere, 2022).

A further socio-technical advance has been the growing recognition, reflected in both scholarship and practice, that the design of social and institutional arrangements is itself a form of engineering that warrants the same care as the design of physical systems (Obogo *et al*., 2020b). The literature increasingly treats participation, governance, and benefit-sharing as matters to be designed deliberately rather than left to emerge, and it documents methods for doing so. Within grid-connected battery energy storage, this represents a maturation of the field's understanding, in which the social dimension is no longer regarded as external to the technical work but as an integral part of it, a shift that aligns closely with the socio-technical perspective this review adopts (Nnaji *et al*., 2020; Obogo *et al*., 2020a).

A connected socio-technical advance has been the development of delivery and payment models suited to low-income and irregular-income populations, including flexible arrangements that accommodate the financial realities of the households served (Obogo *et al*., 2021a). The literature documents how such models can extend access to groups that conventional arrangements exclude, and how they bear on the affordability that conditions sustained use (Obogo *et al*., 2020c). For problems of this kind, the review treats these advances as important because they address the distributional shortcomings documented elsewhere in the literature, demonstrating that exclusion is not inevitable but can be reduced through delivery and payment arrangements designed with the excluded in mind. The review treats this advance as significant because it addresses a condition the evidence links to durability.

Progress has also been made in methods for engaging communities meaningfully in the design and governance of energy systems, moving beyond consultation toward genuine participation in decisions (Obogo *et al*., 2019a). The literature documents approaches that give communities real influence over the systems on which they depend, and it associates such participation with the legitimacy and trust that condition durability (Obogo *et al*., 2021b). Within grid-connected battery energy storage, the review treats this as a genuine advance in the social technology of energy provision, since it addresses the participation that the evidence identifies as a determinant of durable operation, while noting that meaningful participation is demanding to achieve and sustain. This advance illustrates that the social dimension of provision, like the technical, is susceptible to deliberate design.

A further socio-technical advance has been the growing sophistication of approaches to participation, which have moved beyond consultation toward arrangements that give communities genuine influence over the systems on which they depend (Obogo *et al*., 2021c). The literature documents methods for sharing decision authority and for building the legitimacy that sustained operation requires (Obogo *et al*., 2019b). In such settings, the review treats this as a meaningful advance, since it addresses participation, which the evidence identifies as a determinant of durability, and it reflects a maturing recognition that the social dimension warrants the same deliberate design as the technical one. The review reads this advance alongside the persistent difficulty of establishing such conditions durably.

Advances in transparency and accountability mechanisms have strengthened the governance of community-scale energy arrangements, giving communities clearer means to hold operators and managers to account (OECD, n.d.). The literature associates such mechanisms with the trust on which cooperation depends (Odejobi & Ahmed, 2018). Applied to this domain, the review treats these developments as advances in the social technology of energy provision, since they bear on the legitimacy that the evidence links to durable operation, and they complement the advances in physical technology surveyed elsewhere in this section. Acknowledging this, advance, the review connects it to the social and institutional challenges examined below. This advance reflects a maturing recognition that the social dimension warrants design rather than chance.

Advances in tailoring delivery to the circumstances of low-income and marginalized populations have extended access to groups that conventional approaches exclude, demonstrating that distributional shortcomings are not inevitable (Okonkwo *et al*., 2020). The literature documents arrangements designed around the realities of the households served, and it associates them with broader and more equitable participation (Ogunwole *et al*., 2021). On this account, the review treats these advances as significant precisely because they show that inclusion can be designed for, which supports the review's broader argument that equity is an achievable design outcome rather than a matter of chance. The review treats this advance as addressing a condition the evidence links to durability.

A further socio-technical advance concerns the development of financing arrangements suited to the circumstances of low-income communities, including approaches that spread costs over time and accommodate irregular income (Okonkwo *et al*., 2018a). The literature documents how such arrangements can make capable systems accessible to populations that conventional financing excludes, bearing directly on the affordability that conditions sustained use (Okonkwo *et al*., 2021a). For grid-connected battery energy storage, the review treats these advances as significant because they address a determinant of durability that technical progress alone cannot reach, demonstrating that the financial dimension of inclusion, like the technical dimension, is susceptible to deliberate design. This advance shows that the social dimension, like the technical, can be deliberately designed.

Advances in approaches to capacity building represent a further important direction, with the literature documenting methods for developing the local capability required to operate, maintain, and govern systems over their working lives (Okonkwo *et al*., 2021b). Since capacity emerges across the literature as a binding condition on durability, the review treats these advances as consequential for grid-connected battery energy storage, particularly where they establish capability that endures rather than depending on continued external support (Okonkwo *et al*., 2018b). At the same time, the review notes that building durable local capacity has proven difficult, a difficulty it examines among the persistent challenges in a later section. The review reads this advance against the difficulty of establishing such conditions durably.

The review documents advances in the design of arrangements that share the benefits of interventions with the communities that host them, an approach associated in the literature with the legitimacy and acceptance that condition durability (Oladoye *et al*., 2022). Such benefit-sharing appears to align the interests of communities with the sustained operation of systems, reducing the contestation that can undermine technically sound interventions (Okwu *et al*., 2021). The review treats these advances as significant because they address the distributional and legitimacy conditions that the evidence links to durability, illustrating that fairness in the allocation of benefits can be built into the design of interventions. Acknowledging this, advance, the review connects it to the institutional challenges examined later (Lilian *et al*., 2020).

Another socio-technical advance concerns the strengthening of approaches to community engagement that move beyond information-sharing toward genuine influence over decisions (Patrick *et al*., 2021). The literature documents methods that give communities real voice in the design and governance of the systems on which they depend, and it associates such influence with the trust and legitimacy that condition durability. The review treats this as a meaningful advance in the social technology of energy provision, since it addresses the participation that the evidence identifies as a determinant of durable operation, while noting that genuine engagement is demanding to achieve and to sustain over time (Oyeleye *et al*., 2022; Patrick *et al*., 2020).

The review notes, finally, advances in the development of standards and frameworks for assessing the social and distributional dimensions of interventions, which have begun to give these considerations a more systematic place in planning and evaluation (Smith, 2017). The literature documents growing attention to such frameworks, which bear on the broadening of evaluation criteria that the review elsewhere advocates (Shittu *et al*., 2019). Within this context, the review treats these advances as significant because they represent steps toward treating social outcomes with the rigor conventionally applied to technical ones, a direction consistent with the integration of technical and social analysis that the review ultimately calls for. This advance reflects a maturing recognition that social arrangements warrant design.

A further socio-technical advance concerns approaches that address the gendered dimensions of energy access, including designs and delivery models attentive to the differing circumstances and priorities of women and men within communities (Sunday & Omoegun, 2019). The literature documents growing recognition that interventions can narrow or widen gender disparities depending on how they are designed, and methods for narrowing them (Sunday & Omoegun, 2018). For problems of this kind, the review treats these advances as significant because they address a dimension of inclusion that aggregate approaches overlook, demonstrating that attention to intra-community distribution, like attention to other social conditions, can be built into the design of interventions. The review treats this as part of a trajectory toward locally controlled and trusted systems.

Advances in approaches to sustaining affordability over the life of a system represent a further important direction, with the literature documenting arrangements that provide for ongoing costs rather than only initial ones (Wustenhagen *et al*., 2007). Since affordability conditions sustained use, and since interventions affordable to build can become unaffordable to sustain, the review treats these advances as bearing directly on durability in grid-connected battery energy storage (World Resources Institute, n.d.). At the same time, it notes that sustaining affordability depends on institutional and financial arrangements that endure, connecting this advance to the challenges of institutional sustainability examined in subsequent sections. The review treats this as an advance in the social technology of energy provision.

The review documents advances in approaches that incorporate local knowledge and priorities into the design and governance of interventions, an approach the literature associates with the recognition and legitimacy that condition durability (Agbabiaka *et al*., 2019). Such approaches treat communities as sources of knowledge rather than only as recipients of technology, and the literature associates them with improved acceptance and stewardship (Yeboah & Ike, 2020). In such settings, the review treats these advances as significant because they address the recognition that the evidence links to durable operation, illustrating that the integration of local knowledge, like other social conditions, can be designed into interventions deliberately. This development addresses a determinant of durability that physical technology alone cannot reach.

A concluding observation on socio-technical advances is that the field has begun to treat the social dimension of grid-connected battery energy storage with a seriousness once reserved for the technical, designing for participation, governance, distribution, and recognition rather than leaving these to chance (Ahmed *et al*., 2020). The review treats this as a significant maturation, since it aligns practice with the evidence that social conditions govern durability, while noting that the advances remain uneven and that establishing the relevant conditions durably continues to challenge the field (Ahmad *et al*., 2020). This observation connects the advances surveyed here to the persistent social and institutional challenges that the following sections examine. The review reads this advance as complementing the technical gains surveyed alongside it (Liadi, 2022).

A further socio-technical advance concerns the development of methods for assessing and accounting for the social and distributional dimensions of interventions, which have begun to give these considerations a more systematic place in planning and evaluation (Arumosoye & Obriki, 2019). The literature documents growing attention to such methods, which bear on the broadening of evaluation criteria that the review advocates. Applied to this domain, the review treats these advances as significant because they represent steps toward treating social outcomes with the rigor conventionally applied to technical ones, a direction consistent with the integration of technical and social analysis that the review ultimately calls for in the field (Ambali *et al*., 2021; Arumosoye & Obriki, 2018).

Advances in arrangements for community ownership and control represent a further important direction, since the literature associates such arrangements with the legitimacy and stewardship that condition durability (Arumosoye & Obriki, 2022). The literature documents models that give communities greater authority over the systems on which they depend, shifting control and responsibility toward the populations served (Arumosoye & Obriki, 2021). On this account, the review treats these advances as significant because they address the ownership and governance that the evidence links to durable operation, illustrating that the social technology of energy provision has advanced alongside the physical technology in ways that bear directly on inclusive outcomes. In view of this, the review links it to the participation and legitimacy that sustain systems.

4. Persistent Technical Challenges

The most consequential persistent technical challenge for grid-connected battery storage in hot and wet climates concerns the accelerated degradation associated with elevated temperatures, which shortens effective service life and raises the lifecycle cost of storage in exactly those regions where replacement capital is least available (Collath *et al*., 2021; Smith *et al*., 2017). The electrochemical mechanisms of temperature-accelerated degradation, including lithium plating, electrolyte decomposition, and separator degradation, are well understood in the technical literature, and the negative feedback between degradation and capacity loss creates a nonlinear trajectory that makes service life prediction more difficult in hot climates than in temperate ones. The review identifies this challenge as central to the equity concern it foregrounds, since the combination of shorter service life and limited replacement capital creates a financial burden on communities in hot climates that the conventional warranty models do not adequately address.

An additional persistent technical challenge concerns the fire and safety risks associated with lithium-ion battery storage at scale, which require thermal management, monitoring, and response systems that add cost and complexity to deployments, particularly in settings where emergency response capability is limited (IRENA, 2022; IEA, 2021). High-profile fire incidents at grid-scale lithium-ion installations have raised regulatory and public concern about safety and have added permitting requirements and insurance costs that disproportionately burden smaller and community-scale projects. The review treats safety management as both a persistent technical challenge and a dimension of the equity analysis, since the costs and complexity of safety compliance fall more heavily on the community-scale and developing-world deployments that the equity framework prioritizes (Anene & Clement, 2022).

The challenge of second-life battery integration, which offers the prospect of reducing storage system costs by extending the useful life of batteries removed from electric vehicles, remains persistent despite progress in testing, repurposing, and safety certification methodologies (BloombergNEF, 2021; Smith *et al*., 2017). Second-life batteries offer lower upfront costs but carry uncertainties about remaining capacity, degradation trajectory, and safety that require more complex monitoring and management than new batteries. While these challenges are tractable in principle, the standards and certification frameworks that would enable reliable second-life integration are still under development, and the value chain coordination required to deliver second-life batteries at appropriate quality and price points to community storage applications in developing-world settings remains to be established. The review identifies this as a challenge that could, once resolved, substantially improve the economics of equitable storage deployment.

Notwithstanding the advances surveyed above, significant technical challenges persist in grid-connected battery energy storage, and the review characterizes these not as failures of effort but as genuinely difficult problems that remain open (Bhattacharyya *et al*., 2021). Among them are the constraints imposed by the operating environments typical of resource-dependent regions, where temperature, dust, intermittency, and limited infrastructure stress systems beyond the conditions for which they are often designed (Bednar *et al*., 2017). The literature documents how these conditions accelerate degradation, complicate control, and shorten effective lifetimes, and it makes clear that designs calibrated to temperate, well-supported settings do not straightforwardly transfer. Addressing these challenges requires not merely incremental refinement but design oriented from the outset toward the conditions that prevail where the technology is most needed.

A further technical challenge concerns the maintainability and security of systems deployed across many dispersed sites with limited local technical capacity, a problem that grows more acute as systems become more sophisticated (Dagodzo, 2018b). The literature notes that the same advances which increase capability also increase the burden of keeping systems functioning and protected over time, and that this burden falls hardest precisely where capacity is scarcest. For grid-connected battery energy storage, the challenge is therefore to reconcile sophistication with sustainability, ensuring that the capability built into a system does not exceed the local ability to maintain and secure it, a reconciliation that the literature identifies as necessary but does not yet resolve at scale (Collath, 2021; Dagodzo, 2018a).

A third persistent challenge is the difficulty of ensuring reliable, predictable behavior from increasingly complex and interconnected systems operating under the variable conditions of weak-grid and off-grid settings (Dagodzo & Patrick, 2021b). The literature documents that complexity introduces failure modes that are hard to anticipate and that the assumptions underlying many designs, regarding connectivity, data quality, and operating conditions, are frequently unrealistic for the contexts in question. Within grid-connected battery energy storage, this challenge underscores the limits of capability considered in isolation, since a system that performs impressively under ideal conditions may behave unpredictably under the conditions it will actually encounter, which returns the discussion to the dependence of technical performance on its operating environment (Dagodzo & Patrick, 2020; Dagodzo & Patrick, 2021a).

A further technical challenge concerns the integration of increasingly diverse components and the management of the interactions among them, since the coordination that enables advanced performance also creates dependencies that can propagate failures (Ewim *et al*., 2021). The literature documents that as systems grow more integrated, the consequences of a fault in one element can extend to others, and that ensuring reliable behavior across the whole requires attention to interactions that component-level analysis does not capture. This challenge underscores that advancing capability and ensuring dependability are not the same thing, and that the pursuit of the former must be accompanied by sustained attention to the latter if systems are to endure in the demanding conditions they will face (Dagodzo & Patrick, 2022; Dagodzo *et al*., 2022; Lilian *et al*., 2020).

A related technical challenge concerns the management of variability and uncertainty in renewable generation, which complicates the task of matching supply to demand reliably, particularly in systems with limited storage or weak grid connections (Ijiga *et al*., 2022). The literature documents the difficulty of maintaining stable, reliable service under such conditions, and the limits of current approaches in the resource-constrained settings the review addresses (Guerrero *et al*., 2013). This challenge underscores that the variability inherent in renewable resources remains a substantial technical obstacle, and that addressing it in settings without robust supporting infrastructure is among the open problems the field continues to confront. The review treats this as a persistent challenge whose resolution requires attention to the conditions of deployment.

Ensuring the security of increasingly connected and software-dependent systems represents a further and growing technical challenge, since each connected element introduces a potential point of vulnerability (Jessel *et al*., 2019). The literature notes that as systems become more digital and interconnected, protecting them against failure and interference becomes both more important and more difficult, particularly where local capacity to manage security is limited (International Energy Agency, n.d.). Within this context, the review treats this as an emerging challenge that accompanies the advances in connectivity and analytics, and one whose resolution requires attention to capacity and governance as much as to technical safeguards. This challenge underscores that advancing capability and ensuring durable performance are distinct achievements.

A persistent technical challenge concerns operation under the adverse environmental conditions characteristic of many target regions, where heat, dust, humidity, and intermittency stress systems beyond the conditions for which they are often designed (Mbonu *et al*., 2020a). The literature documents how these conditions accelerate degradation and complicate reliable operation, and how designs calibrated to temperate, well-supported settings transfer poorly (Liu *et al*., 2014). For problems of this kind, the review treats this as a challenge requiring design oriented from the outset toward the conditions that actually prevail where the technology is needed, rather than incremental adaptation of designs developed elsewhere. The review reads this challenge as connecting the technical and social dimensions of durability directly.

A further technical challenge concerns the reliability of complex, interconnected systems operating with limited supporting infrastructure, since complexity introduces failure modes that are difficult to anticipate and manage (Mbonu *et al*., 2021b). The literature notes that the assumptions underlying many designs, regarding connectivity, data quality, and operating conditions, are frequently unrealistic for the settings the review addresses (Mbonu *et al*., 2021a). In such settings, this challenge underscores that capability considered in isolation can mislead, since a system impressive under ideal conditions may behave unpredictably under those it will actually encounter. Acknowledging this, challenge, the review argues that it cannot be resolved by technical refinement alone. This challenge illustrates why technical capability considered in isolation can mislead about field outcomes.

Maintaining and securing systems distributed across many remote sites with limited local capacity presents a further and growing technical challenge, one that intensifies as systems become more sophisticated (Mbonu *et al*., 2019a). The literature observes that the same advances which increase capability also increase the burden of keeping systems functioning and protected, a burden that falls hardest where capacity is scarcest (Mbonu *et al*., 2022a). Applied to this domain, the review treats this as a challenge of reconciling sophistication with sustainability, ensuring that what is built does not exceed what can be maintained and secured locally over the working life of a system. The review treats this as a challenge whose resolution depends on the conditions of deployment.

A persistent technical challenge concerns the durability of components under the demanding conditions of resource-dependent settings, since the literature documents that systems frequently degrade faster in the field than their nominal specifications would suggest (Mbonu *et al*., 2021c). Heat, dust, humidity, irregular operation, and limited maintenance all contribute to accelerated wear, and the gap between specified and realized lifetimes is among the more consequential technical problems the review identifies (Mbonu *et al*., 2020b). On this account, this challenge underscores that durability is a function of conditions as much as of design, and that components calibrated to favorable environments cannot be assumed to endure where conditions are harsh. This challenge underscores that capability and dependability are distinct achievements.

A further technical challenge concerns the difficulty of ensuring adequate performance where the supporting infrastructure, including grid connections, communications, and supply chains, is weak or unreliable (Mbonu *et al*., 2019b). The literature documents how dependence on such infrastructure can undermine systems whose designs assume its availability, and how resource-dependent settings frequently cannot provide it (Mbonu *et al*., 2022b). For grid-connected battery energy storage, this challenge highlights the limits of designs developed for well-supported contexts, and it points to the need for approaches that reduce dependence on infrastructure that cannot be guaranteed, a need the literature recognizes but has not fully met. The review reads this challenge as connecting the technical and social dimensions directly (Anene & Clement, 2022; Lilian *et al*., 2020).

The review identifies the management of system complexity as a persistent technical challenge, since the advances that increase capability also increase the difficulty of operating and maintaining systems reliably (Muhtadi *et al*., 2021). The literature documents that complex, interconnected systems introduce failure modes that are hard to anticipate and that demand expertise often unavailable locally (Middlemiss, 2022). This challenge captures a central tension: the same sophistication that extends what systems can do can also make them harder to sustain, and reconciling capability with maintainability under local constraints remains an open problem the review treats as significant. Acknowledging this, challenge, the review argues that technical refinement alone will not resolve it.

A complementary technical challenge concerns adapting systems to the specific and varied conditions of the settings in which grid-connected battery energy storage operates, since designs that perform well in one environment frequently require substantial adaptation to perform in another (Nnaji *et al*., 2019). The literature documents the difficulty and cost of such adaptation, and the tendency of inadequately adapted designs to underperform (Mutambatsere, 2022). For the field, this challenge underscores that the diversity of deployment conditions is itself a technical problem, one that resists the straightforward transfer of solutions and that demands design oriented toward particular conditions rather than toward an idealized general case. This challenge illustrates why capability assessed in isolation can mislead about field outcomes.

A final technical challenge concerns the reliability and security of the increasingly digital and connected systems that characterize recent advances, since each connected element introduces potential points of failure and vulnerability (Obogo *et al*., 2020a). The literature notes that as systems become more dependent on software and connectivity, ensuring their dependable and secure operation becomes both more important and more difficult, particularly where local capacity to manage these aspects is limited (Nnaji *et al*., 2020). The review treats this as an emerging challenge that accompanies the digital advances surveyed earlier, and one whose resolution depends on capacity and governance as much as on technical safeguards. The review treats this as an open problem the field has recognized but not yet met at scale.

A further technical challenge concerns the design of systems that remain affordable to operate and maintain over their working lives, since the literature documents that lifecycle costs can undermine interventions whose installation was affordable (Obogo *et al*., 2020c). Reconciling capability with lifecycle affordability is difficult, particularly where resources for ongoing costs are scarce, and the review treats this as a persistent technical and economic challenge for grid-connected battery energy storage (Obogo *et al*., 2020b). The challenge underscores that durability depends not only on initial design and cost but on the economic sustainability of operation, a consideration the technical literature has been slow to incorporate into its assessments. The review treats this as a difficulty that conditions whether capability endures in the field.

A further challenge concerns the design of systems resilient to the environmental conditions and to the environmental changes that the regions of concern increasingly face, since the literature documents that these conditions stress systems in ways that compromise durability (Obogo *et al*., 2021b). Designing for resilience under demanding and changing conditions is technically difficult, and approaches developed for more stable environments transfer poorly (Obogo *et al*., 2021a). Within this context, the review treats environmental resilience as a persistent challenge, one that grows more pressing as the changes the transition is meant to address themselves intensify the conditions under which systems must operate. This challenge reflects the gap between performance under ideal and under realistic conditions.

The review identifies the matching of technical complexity to locally available capacity as a persistent challenge, since the literature documents that systems exceeding the capacity to operate and maintain them tend to degrade regardless of their technical quality (Obogo *et al*., 2019b). Designing systems whose demands are matched to local capacity, while still delivering adequate performance, is difficult, and the advances that increase capability often increase these demands (Obogo *et al*., 2019a). For problems of this kind, the review treats this as a central challenge, since it connects the technical and social dimensions directly and bears on whether technical capability is translated into durable service. The review reads this as a problem of deployment rather than of the underlying technology.

A concluding observation on the technical challenges is that they are, for the most part, challenges of realizing capability under adverse conditions rather than of capability itself, since the technologies underlying grid-connected battery energy storage are largely mature while their reliable operation in resource-dependent settings remains difficult (Odejobi & Ahmed, 2018). The review treats this as the characteristic shape of the field's technical challenges, namely that they concern the conditions of deployment, including environment, infrastructure, maintenance, and capacity, more than the frontier of what the technologies can do (Obogo *et al*., 2021c). This observation reinforces the review's argument that technical and social considerations are inseparable in determining whether interventions endure. In view of this, the review argues that addressing it requires design for actual conditions.

A connected technical challenge concerns the design of systems that perform reliably across the wide range of conditions encountered in resource-dependent settings, since variability in environment, demand, and supporting infrastructure complicates the task of ensuring dependable operation (Okonkwo *et al*., 2020). The literature documents how designs calibrated to stable conditions can behave unpredictably under variability, and how ensuring robustness across diverse conditions remains difficult. In such settings, the review treats this as a persistent challenge, since the populations the field serves require dependable rather than merely peak performance, and securing dependability under the variable conditions of deployment remains among the open technical problems the field confronts (OECD, n.d.; Ogunwole *et al*., 2021).

A further challenge concerns the integration of new technologies with the existing infrastructure and practices into which they are introduced, since interventions rarely operate on a blank slate (Okonkwo *et al*., 2018a). The literature documents how compatibility with existing systems, the availability of supporting infrastructure, and the fit with established practices condition whether new technologies can be deployed and sustained (Okonkwo *et al*., 2021a). Applied to this domain, the review treats this integration challenge as significant, since the technical merit of an intervention is not sufficient if it cannot be accommodated within the infrastructural and operational context of its setting, a condition that resource-dependent environments frequently complicate. This challenge remains among the open problems the field has yet to resolve at scale.

5. Persistent Social and Institutional Challenges

The most acute persistent social challenge for equitable battery storage deployment is the inequity in warranty terms and replacement capital availability documented in the framework, which creates systematically different lifecycle economics for installations in high-income and low-income settings (Walker & Devine-Wright, 2008; Kalkbrenner & Roosen, 2016). Manufacturers and project developers who offer warranties calibrated for temperate-climate performance may provide effectively shorter warranties in hot climates without proportional price adjustments, and the community or utility operators who bear replacement costs when warranties lapse may lack the reserve capital or access to finance required to execute timely replacements. The review documents this challenge as a structural feature of the current storage market that reproduces geographic inequity in the benefits of the storage transition, and it identifies the warranty reform, replacement capital mechanisms, and community finance instruments that would address it.

A further persistent challenge concerns the limited local technical capacity for battery storage operation, maintenance, and troubleshooting in many of the regions where storage deployment would be most consequential for energy equity (IRENA, 2022; IEA, 2021). Where remote technical support is the only available option, response times for failures are long, the diagnostic quality of remote assessments may be limited, and the costs of support are high relative to the scale of the installation. The review treats capacity constraints as a systemic challenge that requires both investment in training and the design of storage systems that are operable and maintainable by technicians with more limited technical backgrounds than is typical in high-income market deployments, identifying system simplification and enhanced diagnostic capability as design priorities for equity-oriented applications.

The challenge of community trust and social acceptance for battery storage installations has persisted despite the technical improvements in safety management documented in the recent advances section, in part because media coverage of fire incidents has shaped public perceptions in ways that community benefit framing has not yet overcome (Wustenhagen *et al*., 2007; Walker & Devine-Wright, 2008). In community contexts where prior infrastructure projects have not delivered promised benefits, trust deficits compound the general concerns about safety and fairness that any new energy technology must address. The review identifies trust building as a persistent socio-technical challenge that requires sustained engagement, transparent communication about risks and benefits, and the demonstration of community benefit through early projects, arguing that technical safety improvements are necessary but not sufficient for overcoming the social acceptance barriers that community storage faces.

The social and institutional challenges facing grid-connected battery energy storage are at least as consequential as the technical ones, and the review treats them as the binding constraints on inclusive outcomes in many settings (Okwu *et al*., 2021). Foremost among them is the difficulty of building and sustaining the local capacity required to operate, maintain, and govern systems over their working lives, a capacity that is unevenly distributed and that external programs have struggled to establish durably. The literature documents that systems exceeding the capacity available to sustain them tend to degrade regardless of their technical quality, which reframes capacity not as a soft accompaniment to deployment but as a hard precondition for durability within grid-connected battery energy storage (Okonkwo *et al*., 2018b; Okonkwo *et al*., 2021b).

A second social challenge concerns governance and accountability, and specifically the difficulty of arranging authority over shared energy systems in ways that communities accept and that endure (Patrick *et al*., 2020). The literature documents that technically optimal arrangements are sometimes rejected where they concentrate control outside the community, and that the legitimacy of an arrangement depends heavily on the fairness of the process by which it was established. On this account, this means that questions of who controls a system, who benefits from it, and who is accountable for its performance cannot be treated as administrative details, since they shape the cooperation on which durable operation depends and are frequently decisive where technical factors are not (Oladoye *et al*., 2022; Oyeleye *et al*., 2022). This balance of advances and challenges is depicted in Figure 2.

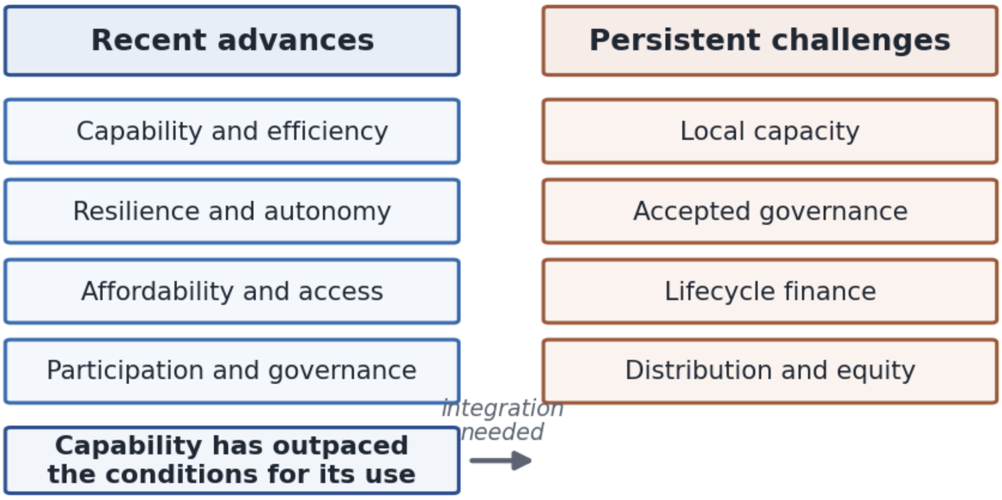

Fig 2: Recent advances set against the persistent challenges that condition inclusive outcomes.

A third challenge concerns distribution and equity, since the evidence indicates that interventions can improve aggregate conditions while leaving the most marginalized groups unreached, thereby reproducing rather than reducing existing inequalities (Smith, 2017). The literature documents that capital, capacity, and supporting infrastructure are scarcest exactly where need is greatest, and that arrangements calibrated to better-resourced contexts tend to disadvantage those least able to absorb their costs. Within grid-connected battery energy storage, this distributional challenge is central to the goal of inclusive transition, and the review argues that it cannot be addressed by technical advance alone but requires deliberate attention to who gains and who bears the cost of any intervention (Patrick *et al*., 2021; Shittu *et al*., 2019).

Another social challenge concerns the sustainability of financing and the alignment of incentives over the working life of a system, since the conditions that allow an intervention to be built are not the same as those that allow it to be sustained (World Resources Institute, n.d.). The literature documents that capital for replacement and repair is often scarcest exactly where it is most needed, and that financing arrangements calibrated to better-resourced contexts can leave resource-dependent communities exposed when systems require reinvestment. Within grid-connected battery energy storage, this challenge connects the social and economic dimensions directly, and the review argues that durable outcomes depend on financing and incentive structures designed for the full life of a system rather than for its installation alone (Sunday & Omoegun, 2018; Sunday & Omoegun, 2019).

A further social and institutional challenge concerns the establishment of governance arrangements that communities accept and that endure, since the literature documents that arrangements imposed without genuine participation are frequently contested even when technically sound (Yeboah & Ike, 2020). Designing governance that distributes authority fairly, holds operators accountable, and commands legitimacy is demanding, and the literature offers no settled solution (Wustenhagen *et al*., 2007). For grid-connected battery energy storage, the review treats this as among the binding challenges, since the cooperation on which durable operation depends rests on governance that communities regard as fair, and securing such governance is a social and institutional achievement that technical capability cannot substitute for. The review treats this as a binding challenge on which inclusive outcomes in the field depend.

A further challenge concerns the distribution of the benefits and burdens of interventions, since the literature documents that even well-intentioned programs can deepen inequality by directing benefits toward those better able to access them (Ahmed *et al*., 2020). Ensuring that interventions reach the most marginalized rather than the most advantaged requires deliberate design and sustained attention, and the literature suggests that this is rarely achieved by default. The review treats distributional equity as a central challenge for inclusive transition, one that cannot be resolved by technical advance alone and that demands explicit attention to who gains and who bears the cost of any intervention (Agbabiaka *et al*., 2019; Ahmad *et al*., 2020).

A binding social challenge concerns the establishment and sustaining of local capacity to operate, maintain, and govern systems, since the literature documents that systems exceeding available capacity tend to decay regardless of technical quality (Arumosoye & Obriki, 2018). Building such capacity durably has proven difficult for external programs, and the review treats it not as a soft accompaniment to deployment but as a hard precondition for it (Ambali *et al*., 2021). This challenge reframes capacity as central to durability, and it argues that matching system complexity to the capacity that can realistically be sustained is essential to inclusive outcomes. This challenge underscores that durable operation rests on social and institutional conditions, not technical capability alone.

An additional social challenge concerns governance arrangements that communities accept and that endure, since the literature documents that arrangements imposed without genuine participation are frequently contested even when technically sound (Arumosoye & Obriki, 2021). Designing governance that distributes authority fairly and commands legitimacy is demanding, and no settled solution exists (Arumosoye & Obriki, 2019). Within this context, the review treats this as among the binding challenges, since the cooperation on which durable operation depends rests on governance that communities regard as fair, which technical capability cannot substitute for. The review reads this challenge as central to the goal of inclusive transition the review takes as its standard. Acknowledging this, challenge, the review argues that it demands deliberate design and sustained attention.

A further challenge concerns equity in the distribution of benefits and burdens, since the literature documents that even well-intentioned interventions can deepen inequality by reaching those better able to access them (Bednar *et al*., 2017). Ensuring that interventions serve the most marginalized requires deliberate design and sustained attention, rarely achieved by default (Arumosoye & Obriki, 2022). For problems of this kind, the review treats distributional equity as central to inclusive transition, a challenge that technical advance alone cannot resolve and that demands explicit attention to who gains and who bears the cost of any intervention. This challenge illustrates why technical advance alone cannot secure the durability of interventions. The review treats this as a binding constraint on inclusive outcomes in the field.

A persistent social challenge concerns the alignment of incentives among the many actors involved in an intervention, since households, operators, financiers, and institutions do not always share an interest in the sustained operation of a system (Collath, 2021). The literature documents how misaligned incentives can undermine durability even where technical and financial conditions appear adequate, as when those responsible for maintenance lack the means or motivation to perform it (Bhattacharyya *et al*., 2021). In such settings, the review treats incentive alignment as a binding social challenge, since durable operation depends on arrangements in which the parties whose cooperation is required actually have reason to provide it. This challenge underscores that durability rests on social conditions, not capability alone.

A further social challenge concerns the sustainability of the institutions on which interventions depend, since the literature documents that community organizations, cooperatives, and governing bodies can weaken or dissolve over time, taking with them the capacity and governance that conditioned durability (Dagodzo, 2018b). Establishing institutions that endure has proven difficult, particularly where external support is withdrawn after deployment (Dagodzo, 2018a). Applied to this domain, the review treats institutional sustainability as central to durable outcomes, since the technical system depends on the institutional arrangements around it, and the erosion of those arrangements can undermine even well-functioning systems over time. The review reads this challenge as central to the goal of inclusive transition.

The review identifies the challenge of sustaining engagement and participation over the life of a system, since the literature documents that the involvement present at deployment frequently diminishes thereafter, weakening the participation that conditions durability (Dagodzo & Patrick, 2021a). Maintaining genuine community involvement over time requires effort and arrangements that many interventions do not provide (Dagodzo & Patrick, 2020). On this account, this challenge captures the dynamic character of the social conditions governing durability, which are not secured once at deployment but must be sustained, and whose erosion is associated with the decline of systems that began well. Acknowledging this, challenge, the review argues that it demands deliberate and sustained attention.

A related social challenge concerns equity not only at the moment of deployment but over time, since the literature documents that the distribution of benefits and burdens can shift as systems age and circumstances change (Dagodzo & Patrick, 2022). Interventions that begin inclusively can become less so, and those that serve a community as a whole may come to favor some groups over others (Dagodzo & Patrick, 2021b). For grid-connected battery energy storage, the review treats the maintenance of equity over time as a persistent challenge, one that requires attention to distribution as an ongoing concern rather than a condition established once and assumed to persist. This challenge illustrates why technical advance cannot by itself secure durable interventions.

A final social and institutional challenge concerns the relationship between interventions and the broader governance and policy environment, since the literature documents that supportive institutions, stable policy, and effective regulation condition the durability of interventions in ways that lie largely outside the control of any single project (Ewim *et al*., 2021). Where this environment is weak or unstable, even well-designed interventions can struggle to endure (Dagodzo *et al*., 2022). The review treats this as a challenge that situates individual interventions within a wider context, and it argues that durable, inclusive outcomes depend in part on conditions that extend beyond the boundaries of the intervention itself. The review treats this as among the conditions that now most limit progress in the field.

A further social challenge concerns the gendered distribution of benefits and burdens, since the literature documents that interventions can deepen gender disparities if they are not designed with attention to the differing circumstances of women and men (Ijiga *et al*., 2022). Ensuring that interventions narrow rather than widen these disparities requires deliberate attention, rarely achieved by default (Guerrero *et al*., 2013). The review treats the gendered dimension of distribution as a persistent challenge for inclusive transition, one that aggregate approaches overlook and that demands explicit attention to how benefits and burdens fall within communities and not only between them. The review treats this as a condition on which inclusive outcomes ultimately depend.

A further challenge concerns the sustaining of affordability over the life of a system, since the literature documents that arrangements affordable at installation can become unaffordable as systems age and require maintenance or replacement (Jessel *et al*., 2019). Ensuring that interventions remain affordable to sustain demands financial and institutional arrangements designed for the full life of a system, which the literature finds frequently lacking (International Energy Agency, n.d.). Within this context, the review treats lifecycle affordability as a persistent social and economic challenge, since the durability of interventions depends on whether the populations they serve can continue to afford their operation over time. This challenge reflects the social and institutional limits that capability cannot overcome.

A final social challenge concerns the incorporation of local knowledge and priorities into interventions, since the literature documents that systems designed without regard to these frequently encounter resistance or neglect that undermines durability (Mbonu *et al*., 2020a). Genuinely incorporating local knowledge requires arrangements and attitudes that treat communities as partners rather than recipients, which the literature finds are not easily established or sustained (Liu *et al*., 2014). For problems of this kind, the review treats this as a persistent challenge bearing on the recognition and legitimacy that condition durability, and one that technical capability and good intentions alone do not resolve. The review reads this as bearing directly on whether interventions are sustained over time.

A concluding observation on the social and institutional challenges is that they constitute, in many settings, the binding constraints on inclusive outcomes in grid-connected battery energy storage, since the conditions of capacity, governance, finance, distribution, and institutional sustainability determine whether technical capability is translated into durable service (Mbonu *et al*., 2022a). The review treats these challenges as the frontier of the field, arguing that progress now depends less on extending technical capability than on addressing the conditions for its deployment. This observation frames the conceptual directions and the synthesis that follow, which concern how advances in grid-connected battery energy storage might be aligned with the conditions required to realize them inclusively (Mbonu *et al*., 2021a; Mbonu *et al*., 2021b).

A complementary social and institutional challenge concerns the relationship between interventions and the wider policy and regulatory environment, since the literature documents that supportive institutions, stable policy, and effective regulation condition durability in ways largely outside the control of any individual project (Mbonu *et al*., 2021c). Where this environment is weak or unstable, even well-designed interventions can struggle to endure, and strengthening it lies beyond the reach of the intervention itself. In such settings, the review treats this as a challenge that situates individual interventions within a broader context, arguing that durable, inclusive outcomes depend in part on conditions established at the level of policy and institutions rather than at the level of the project (Mbonu *et al*., 2019a; Mbonu *et al*., 2020b).

A further challenge concerns the sustaining of the institutions and arrangements on which interventions depend, since the literature documents that community organizations, governance bodies, and management arrangements can weaken or dissolve over time, taking with them the capacity and legitimacy that conditioned durability (Mbonu *et al*., 2019b). Establishing institutions that endure, particularly after external support is withdrawn, has proven difficult (Mbonu *et al*., 2022b). Applied to this domain, the review treats institutional sustainability as a binding challenge, since the technical system depends on the arrangements around it, and the erosion of those arrangements is associated with the decline of interventions that functioned well at their inception. In view of this, the review argues that it requires arrangements designed and maintained deliberately.

6. Conceptual Directions and Research Agenda

The most consequential conceptual direction identified by the review concerns the development of warranty and financing instruments calibrated to the lifecycle economics of battery storage in hot and wet climates, addressing the equity gap that the framework foregrounds (BloombergNEF, 2021; Collath *et al*., 2021). Climate-adjusted warranty models that account for accelerated degradation in high-temperature settings, replacement capital reserve mechanisms embedded in project finance structures, and insurance products covering replacement costs that exceed initial estimates are among the instruments that the review identifies as requiring development. Addressing this gap would require collaboration among manufacturers, financiers, development banks, and regulators, and the review argues that the international development finance community has a role in catalyzing this institutional innovation alongside its project finance activities.

A further conceptual direction concerns the development of standard technical and financial assessment frameworks for community battery storage projects that are accessible to project developers without specialized energy storage expertise, enabling a broader range of community organizations and development practitioners to identify, design, and finance storage applications (Kalkbrenner & Roosen, 2016; Walker & Devine-Wright, 2008). Tools that translate the technical literature on storage performance and degradation into the financial projections required for project appraisal, and that incorporate climate-adjusted performance assumptions appropriate for the region of deployment, would substantially lower the technical barriers to community storage development. The review identifies this as a high-priority research and development direction, given the potential leverage of enabling community developers to access the storage technology whose benefits the equity framework identifies.

The review also identifies the integration of battery storage into community energy governance as a conceptual direction with significant practical consequences, since the organizational models that govern community storage will shape the distribution of its benefits and the conditions of community consent and engagement (IEA, 2021; IRENA, 2022). Community energy cooperatives, municipal ownership models, and hybrid arrangements that combine community ownership of storage with professional operation are among the governance forms that have been explored, with varying success in different regulatory and cultural contexts. Comparative research on these models, identifying the governance conditions that secure community benefit while maintaining operational quality, is identified as a research priority that would inform the design of equitable storage deployment programs.

The principal gap identified by this review is the absence of conceptual and methodological tools that bring technical and social criteria into a single, integrated evaluation of grid-connected battery energy storage, and closing it is the agenda the review proposes (Mutambatsere, 2022). The field possesses both technical sophistication and a rich understanding of the social conditions governing durability, but it lacks the means to consider them together, with the consequence that decisions carrying large social implications are made implicitly. The review calls for the development of frameworks that represent social conditions in commensurable terms alongside technical parameters, so that the two can inform design jointly rather than being handed off across a disciplinary boundary (Middlemiss, 2022; Muhtadi *et al*., 2021).

A second direction concerns the need for conceptual clarity about the social variables that the literature identifies as consequential, including the inequity embedded in warranty terms and the scarcity of replacement capital where degradation is fastest, which is frequently invoked but seldom defined in terms that support systematic reasoning (Obogo *et al*., 2020a). The review argues that progress requires giving these variables explicit conceptual definition, characterizing them in ways that could be observed and compared across settings, so that their influence can be analyzed rather than merely asserted. This is a conceptual task before it is an empirical one, since the variables must be well defined before they can be measured, and the review treats it as a precondition for the integrated evaluation it advocates within grid-connected battery energy storage (Nnaji *et al*., 2019; Nnaji *et al*., 2020).

A third direction concerns transferability, and specifically the need for frameworks that can carry insight across the diverse settings in which grid-connected battery energy storage is deployed without assuming that what holds in one context holds in another (Obogo *et al*., 2021a). The review calls for approaches that separate general structure from context-specific content, allowing the logic of an analysis to travel while its particulars are re-examined locally. Pursuing these directions together, the review argues, would move the field from a state in which technical and social knowledge sit side by side but unintegrated toward one in which they are combined in the service of energy systems that are efficient, accessible, responsive, and adaptable for resource-dependent regions (Obogo *et al*., 2020b; Obogo *et al*., 2020c).

A connected direction concerns the broadening of evaluation criteria, since the review has argued that the predominance of technical and cost metrics has steered the field away from the conditions that govern durability and inclusion (Obogo *et al*., 2019b). Closing this gap requires the development of evaluation approaches that treat durability, inclusion, and legitimacy as first-order outcomes, and that characterize them in terms commensurable with technical and economic measures. The review proposes this broadening as a central element of its conceptual agenda for grid-connected battery energy storage, on the reasoning that what is measured shapes what is built, and that aligning the metrics with the goals of inclusive transition is a precondition for designing interventions that actually serve the populations they are meant to reach (Obogo *et al*., 2021b; Obogo *et al*., 2019a).

A further conceptual direction concerns the development of approaches that treat the social conditions governing durability as dynamic rather than static, since the literature has tended to assess these conditions at a single moment rather than over the life of a system (OECD, n.d.). The review argues that capturing how participation, capacity, trust, and legitimacy evolve is essential to understanding durability, and it calls for conceptual tools capable of representing these trajectories. On this account, this direction reflects the review's broader argument that durability is sustained through ongoing socio-technical interaction, and that a field oriented toward installation rather than operation will continue to misjudge which interventions endure (Obogo *et al*., 2021c; Odejobi & Ahmed, 2018).

A further direction concerns transferability, and specifically the need for frameworks that separate the general structure of an analysis from its context-specific content, so that insight can be carried across settings without the assumption that what holds in one context holds in another (Okonkwo *et al*., 2021a). The review proposes this as a central element of its conceptual agenda for grid-connected battery energy storage, on the reasoning that the diversity of the field's settings makes transferability a precondition for cumulative knowledge. Pursuing this direction, the review argues, would allow the field to build on prior work rather than repeatedly rediscovering context-specific lessons, advancing understanding across the range of regions that inclusive transition must reach (Ogunwole *et al*., 2021; Okonkwo *et al*., 2020).

A central conceptual direction is the development of frameworks that represent technical and social factors in commensurable terms, so that they can be considered jointly rather than handed off across a disciplinary boundary (Okonkwo *et al*., 2018b). The review argues that such commensurable representation is the precondition for integrated evaluation, and that supplying it is a conceptual task the field has yet to complete (Okonkwo *et al*., 2018a). For grid-connected battery energy storage, pursuing this direction would allow the social determinants of durability to inform design with the same rigor as technical parameters, which is the integration the review identifies as most needed. The review proposes this as part of a coherent conceptual agenda oriented toward integrated evaluation.

Another direction concerns giving explicit conceptual definition to the social variables the literature identifies as consequential, including the inequity embedded in warranty terms and the scarcity of replacement capital where degradation is fastest, which is frequently invoked but seldom characterized in terms that support systematic reasoning (Okwu *et al*., 2021). The review argues that these variables must be well defined before they can be measured, making their conceptual specification a precondition for empirical progress (Okonkwo *et al*., 2021b). This direction reflects the review's broader contention that the field's difficulty with social factors is methodological rather than evidence of their unimportance. This direction reflects the review's broader argument that technical and social analysis must be combined. The review treats this direction as a precondition for the cumulative knowledge the field requires.

A further direction concerns the representation of the dynamic, evolving character of the conditions governing durability, since the literature has tended to assess these conditions at a single moment rather than over the life of a system (Oyeleye *et al*., 2022). The review calls for conceptual tools capable of capturing how participation, capacity, trust, and legitimacy change over time (Oladoye *et al*., 2022). This direction follows from the review's argument that durability is sustained through ongoing socio-technical interaction, and that a field oriented toward installation rather than operation will continue to misjudge which interventions endure. Acknowledging this, gap, the review identifies its closing as central to inclusive outcomes in the field.

A further conceptual direction concerns the development of approaches that integrate the perspectives and priorities of communities into the analysis and evaluation of interventions, addressing the gap the review identifies between the concerns that dominate the literature and those that matter to the populations served (Patrick *et al*., 2021). The review argues that incorporating these perspectives systematically, rather than treating them as external, is necessary if the field's knowledge is to support inclusive outcomes (Patrick *et al*., 2020). Within this context, this direction reflects the review's broader contention that recognition is a condition of durability, and that its neglect in the literature is a gap to be remedied. This direction contributes to the larger task of integrating technical and social analysis in the field.

An additional direction concerns the need for longitudinal understanding of how interventions perform over time, addressing the temporal bias the review identifies in a literature weighted toward the moment of deployment

(Smith, 2017). The review argues that understanding durability requires attention to the trajectories along which interventions succeed or fail, and to the conditions that shape those trajectories (Shittu *et al.*, 2019). For problems of this kind, this direction follows from the review's emphasis on durability as the central concern, and it calls for conceptual and empirical attention to the years of operation rather than the moment of commissioning, where the field's evidence has been concentrated. The review proposes this as part of a coherent agenda oriented toward integrated evaluation.

A further conceptual direction concerns the improvement of comparability across studies through shared frameworks, definitions, and metrics, addressing the heterogeneity that limits the field's ability to accumulate knowledge (Sunday & Omoegun, 2019). The review argues that such shared structures are a precondition for cumulative understanding, and that developing them is a conceptual task the field has yet to complete (Sunday & Omoegun, 2018). In such settings, this direction reflects the review's diagnosis of fragmentation as a central obstacle, and it identifies the establishment of common frameworks as a means of enabling the field to build systematically on prior work rather than repeatedly rediscovering context-specific findings. This direction reflects the review's argument that technical and social analysis must combine.

A further direction concerns the integration of the social and institutional environment into the analysis of interventions, addressing the gap the review identifies between the focus on individual projects and the wider conditions that condition their durability (Wustenhagen *et al.*, 2007). The review argues that interventions cannot be understood in isolation from the governance, policy, and institutional context in which they operate, and that conceptual tools are needed to represent this context (World Resources Institute, n.d.). Applied to this domain, this direction extends the review's socio-technical perspective from the system to its environment, recognizing that durable outcomes depend on conditions that extend beyond the boundaries of any single intervention. The review treats this as a precondition for the cumulative knowledge the field requires.

A final conceptual direction concerns the alignment of evaluation with the goals of inclusive transition, addressing the review's argument that conventional metrics, oriented toward capability and cost, omit the durability, inclusion, and legitimacy that the evidence identifies as decisive (Ahmad *et al.*, 2020). The review calls for the development of evaluation approaches that treat these wider outcomes as first-order objectives characterized in commensurable terms. On this account, this direction is central to the review's agenda, since what is measured shapes what is built, and aligning the criteria of evaluation with the goals of inclusive transition is a precondition for design that serves the populations interventions are meant to reach (Yeboah & Ike, 2020; Agbabiaka *et al*., 2019).

A related conceptual direction concerns the systematic incorporation of lifecycle costs into the analysis and evaluation of interventions, addressing the gap the review identifies in a literature weighted toward installation costs (Arumosoye & Obriki, 2018). The review argues that understanding the affordability that conditions durability requires attention to the costs of operation, maintenance, and replacement over the life of a system. For grid-connected battery energy storage, this direction reflects the review's emphasis on durability, and it calls for conceptual and analytical tools that represent lifecycle costs and their distribution, so that the economic sustainability of interventions can be assessed over time rather than only at the moment of deployment (Ahmed *et al.*, 2020; Ambali *et al.*, 2021).

A further direction concerns the incorporation of gendered and intra-community distribution into the analysis of interventions, addressing the gap the review identifies between aggregate distributional analysis and the disparities within communities that determine genuine inclusion (Arumosoye & Obriki, 2021). The review argues that conceptual tools are needed to represent how benefits and burdens fall among groups, including along lines of gender, within the populations interventions serve (Arumosoye & Obriki, 2019). This direction follows from the review's treatment of distribution as encompassing intra-community differences, and it reflects the contention that inclusive transition requires attention to disparities that aggregate measures obscure. Acknowledging this, gap, the review identifies its closing as central to inclusive outcomes.

A final direction concerns the integration of environmental resilience into the analysis of durability, addressing the gap the review identifies in a literature that unevenly accounts for the demanding and changing conditions of the regions of concern (Bednar *et al.*, 2017). The review argues that conceptual tools are needed to represent the environmental conditions a system will encounter and their bearing on its durability (Arumosoye & Obriki, 2022). This direction reflects the review's argument that durability cannot be assessed apart from the conditions of deployment, and it identifies the systematic incorporation of environmental resilience as part of the conceptual agenda the field requires. This direction contributes to the larger task of integrating analysis in the field.

A concluding observation on the conceptual directions is that they cohere around a single overarching need, namely the integration of technical and social analysis in grid-connected battery energy storage through frameworks that represent both in commensurable terms (Dagodzo, 2018a). The review argues that the specific directions it has identified, concerning measurement, dynamics, transferability, distribution, lifecycle cost, environmental resilience, and the incorporation of community perspective, are aspects of this larger task rather than independent agendas. This observation frames the directions as a coherent program for the field, oriented toward the integrated evaluation that the review identifies as the precondition for design serving the goal of inclusive transition (Bhattacharyya *et al.*, 2021; Collath, 2021; Anene & Clement, 2022).

A further conceptual direction concerns the development of approaches that treat the technical and social dimensions of grid-connected battery energy storage as a single design problem rather than as separate analyses to be reconciled after the fact (Dagodzo & Patrick, 2021a). The review argues that the integration it advocates requires not merely the juxtaposition of technical and social findings but a framework in which the two are represented together and reasoned about jointly, and that constructing such a framework is a conceptual task the field has yet to complete. This direction is central to the review's agenda, since it is the integration of technical and social analysis, rather than further progress within either, that the review identifies as the field's most pressing need (Dagodzo, 2018b; Dagodzo & Patrick, 2020).

A complementary direction concerns the alignment of the criteria by which interventions are evaluated with the outcomes that actually matter for inclusive transition, since the review has argued that conventional metrics capture technical performance and cost while omitting durability, inclusion, and legitimacy (Dagodzo *et al*., 2022). Closing this gap requires the development of evaluation approaches that treat these wider outcomes as first-order objectives and characterize them in terms commensurable with technical and economic measures. Within this context, the review treats this as a precondition for design that serves the populations interventions are meant to reach, on the reasoning that what is measured shapes what is built and rewarded (Dagodzo & Patrick, 2021b; Dagodzo & Patrick, 2022).

7. Synthesis and Implications

The synthesis identifies the relationship between technical advances in battery cost reduction and the persistent equity challenges around replacement capital and warranty terms as the central irony of the review period: costs have fallen dramatically while the gap between the lifecycle economics of storage in high-income and low-income settings has widened rather than narrowed (BloombergNEF, 2021; Lazard, 2021). Lower upfront costs have enabled more deployments, but the terms on which storage is deployed in equity-critical settings have not improved proportionally, and the replacement capital required when batteries reach end of life in hot climates remains as difficult to access as before. This synthesis argues that technical cost reduction is a necessary but insufficient condition for equitable storage transitions, and that the financing, warranty, and governance innovations required to complement it have received insufficient attention relative to the technical progress they depend on.

The synthesis also observes that the socio-technical advances of the review period, including community ownership models, regulatory access for aggregated storage, and improved tropical performance, have opened pathways toward equitable deployment that were not available at the period's start, but that these advances remain marginal relative to the scale of the challenge (Walker & Devine-Wright, 2008; Kalkbrenner & Roosen, 2016). Pilot projects and regulatory experiments have demonstrated feasibility, but the transition from demonstration to mainstream deployment has been slow, partly because the institutional and market conditions required for scale are still under development. The synthesis argues that accelerating this transition requires a concerted effort by development finance institutions, regulators, and technical researchers to address the institutional barriers that limit scale, treating institutional innovation as a priority investment alongside continued technical development.

A final synthesis finding concerns the relationship between battery storage equity and the broader energy transition, arguing that the patterns of deployment and benefit distribution that emerge during the current formative period of storage scaling will be path-dependent and difficult to reverse (IRENA, 2022; IEA, 2021). The governance models, business models, and institutional arrangements that become standard practice during this period will shape who benefits from storage for decades, and the opportunity to influence those arrangements is greatest now, when they are still being formed. This synthesis argues for deliberate attention to equity in the design of storage programs, markets, and governance frameworks, positioning it not as a secondary consideration to be addressed after the technical and financial foundations are established but as a core design requirement that should inform every dimension of the storage transition strategy.

Drawing the advances and challenges together, the review concludes that the central task facing grid-connected battery energy storage is integration: the alignment of technical progress with the social and institutional conditions required to realize it in resource-dependent settings (Ijiga *et al*., 2022). The advances surveyed establish that capability has moved substantially, while the challenges examined show that the binding constraints increasingly lie in capacity, governance, finance, and distribution. The synthesis the review offers is that progress now depends less on further technical advance in isolation than on bringing technical and social development into a coherent relationship, so that gains on one front reinforce rather than merely accompany gains on the other (Ewim *et al*., 2021; Guerrero *et al*., 2013).

The synthesis suggests that the relationship between advance and challenge in grid-connected battery energy storage is not one in which challenges are simply residual problems awaiting further technical effort, but one in which each advance tends to surface a corresponding social or institutional question (Liu *et al*., 2014). Greater capability raises the demands of maintenance and governance; wider connectivity raises questions of security and capacity; broader reach raises questions of distribution and fairness. Acknowledging this, pattern, the review argues, is essential to an accurate assessment of where the field stands, since it locates the frontier of progress at the interface of the technical and the social rather than within either alone (International Energy Agency, n.d.; Jessel *et al*., 2019).

A central element of the synthesis is the recognition that the value of any technical advance must be assessed in light of the conditions required to realize it where it is most needed (Mbonu *et al*., 2021b). The review has argued throughout that advances proven under favorable conditions do not automatically deliver inclusive outcomes in resource-dependent settings, and the synthesis draws this argument to its conclusion: that the field's progress should be judged by achievability in the settings that matter rather than by possibility in the abstract. For problems of this kind, this reframes the assessment of advance around the conditions of deployment rather than the frontier of capability (Mbonu *et al*., 2020a; Mbonu *et al*., 2021a).

The synthesis also brings together the review's treatment of the social and institutional challenges, arguing that capacity, governance, finance, and distribution are not separate obstacles but linked conditions that together determine whether interventions endure (Mbonu *et al*., 2019a). Capacity conditions whether systems can be sustained; governance conditions whether they are accepted; finance conditions whether they can be maintained; and distribution conditions whether they are legitimate (Mbonu *et al*., 2022a). The review treats these as an interconnected set, and its synthesis is that addressing them in isolation is unlikely to succeed, since they reinforce one another in determining the durability and inclusiveness of interventions in grid-connected battery energy storage. This element of the synthesis situates the review's account within the larger trajectory of the field.

Looking ahead, the synthesis points toward a research and practice agenda oriented around the integration of technical and social development, in which advances are pursued together with the conditions required to realize them (Mbonu *et al*., 2021c). The review argues that such an agenda would direct effort toward the binding constraints rather than toward further advance where capability already exceeds the conditions for its use (Mbonu *et al*., 2020b). In such settings, this outlook implies a shift in emphasis from extending the technical frontier toward establishing the conditions, including capacity and governance, under which existing and future capability can deliver durable, inclusive service. The review treats this element as part of the coherent agenda its synthesis of advances and challenges yields.

The synthesis carries implications for how the field's progress is measured, since the review has argued that conventional metrics, oriented toward capability and cost, capture advance while obscuring the conditions that govern whether advance translates into outcome (Mbonu *et al*., 2019b). Broadening the measures by which progress is judged to include durability, inclusion, and legitimacy would, the review argues, better reflect what actually matters for grid-connected battery energy storage and would steer effort toward the conditions the synthesis identifies as decisive (Mbonu *et al*., 2022b). This implication extends the review's argument from the assessment of individual advances to the standards by which the field as a whole judge its progress. This observation connects the review's assessment to the goal of durable, inclusive outcomes.

A further element of the outlook concerns transferability, since the review has emphasized the diversity of the settings in which grid-connected battery energy storage operates and the corresponding difficulty of carrying lessons across them (Mutambatsere, 2022). The synthesis argues that progress depends on distinguishing what is general about advances and challenges from what is specific to particular settings, so that insight can accumulate rather than being repeatedly rediscovered. For the field, this implies developing approaches that separate general structure from context-specific content, allowing the lessons of the advances and challenges surveyed here to inform practice across the range of regions that inclusive transition must reach (Middlemiss, 2022; Muhtadi *et al*., 2021).

The synthesis also reflects on the role of the communities at the centre of grid-connected battery energy storage, arguing that the advances most likely to deliver inclusive outcomes are those designed with genuine community participation and governed in ways communities accept (Nnaji *et al*., 2020). The review has documented advances in participation and governance alongside persistent challenges in establishing them durably, and its synthesis is that the social technology of energy provision must advance together with the physical technology (Nnaji *et al*., 2019). For the field, this implies treating participation and legitimacy not as accompaniments to technical advance but as conditions for its translation into durable service. In view of this, the review presents integration as the direction in which progress most clearly lies.

For practice and policy, the synthesis implies that support for grid-connected battery energy storage should be directed toward the conditions that the review identifies as binding, including the building of local capacity, the establishment of accepted governance, the provision of finance for the full life of systems, and attention to the distribution of benefits and burdens (Obogo *et al*., 2020c). The review argues that effort and resources directed toward these conditions would address the constraints that most limit inclusive outcomes, and that this directing of effort follows directly from the synthesis of advances and challenges the review has assembled for the field. This element reflects the review's argument that technical and social development must advance together (Obogo *et al*., 2020a; Obogo *et al*., 2020b).

In closing, the synthesis situates the review's account within the larger project of inclusive energy transition, observing that the regions at the centre of grid-connected battery energy storage are those where the transition is most consequential and most fraught (Obogo *et al*., 2019a). By drawing advances and challenges together into a coherent account, the review aims to clarify where the field stands and where its efforts would be best directed, contributing to the broader goal of a transition that is not only rapid but fair, and of energy systems that are efficient, accessible, responsive, and adaptable for the regions that need them most. This element of the synthesis situates the account within the field's larger trajectory (Obogo *et al*., 2021a; Obogo *et al*., 2021b).

A further element of the outlook concerns the integration of lifecycle considerations into the field's understanding of durability, since the synthesis has emphasized that affordability and capacity over the working life of a system condition whether interventions endure (Obogo *et al*., 2021c). The review argues that progress depends on treating the costs and conditions of operation as integral to the assessment of interventions rather than as matters secondary to installation (Obogo *et al*., 2019b). Applied to this domain, this element of the outlook directs attention toward the working life of systems, where the advances and challenges surveyed actually bear on whether progress translates into durable, inclusive service over time. The review treats this as part of the agenda its synthesis of advances and challenges yields.

A connected element of the outlook concerns attention to the distributional dimensions of advances and challenges, since the synthesis has emphasized that progress can affect groups within communities unequally and can narrow or widen disparities, including along lines of gender (OECD, n.d.). The review argues that an account of inclusive outcomes must attend to these intra-community dimensions, which aggregate assessments obscure (Odejobi & Ahmed, 2018). On this account, this element of the outlook directs attention toward whether the advances surveyed actually reach the groups that need them most, and toward the design choices through which the distributional challenges identified might be addressed. This observation connects the assessment to the goal of durable, inclusive outcomes.

A final element of the outlook concerns the incorporation of environmental resilience into the field's assessment of advances and challenges, since the synthesis has emphasized that the demanding and changing conditions of the regions of concern bear heavily on durability (Okonkwo *et al*., 2021a). The review argues that progress depends on advances that deliver durable performance under these conditions, and on addressing the challenges that environmental stress poses. For grid-connected battery energy storage, this element of the outlook directs attention toward whether the advances surveyed can withstand the conditions of deployment, and toward the integration of environmental resilience into the design and assessment of interventions in the field (Ogunwole *et al*., 2021; Okonkwo *et al*., 2020).

A concluding observation on the synthesis is that the advances and challenges surveyed converge on a single conclusion, namely that the future of grid-connected battery energy storage depends on the integration of technical progress with the social and institutional conditions required to realize it inclusively (Okonkwo *et al*., 2021b). The review argues that this integration is the task that recent advances have made both possible and necessary, since capability now frequently exceeds the conditions for its deployment. This observation situates the review's account within the larger trajectory of the field, presenting the integration of technical and social development as the direction in which progress toward durable, inclusive outcomes is most clearly located (Okonkwo *et al*., 2018a; Okonkwo *et al*., 2018b).

A further element of the synthesis concerns the way advances and challenges in grid-connected battery energy storage bear on one another over time, since progress on the technical front tends to reshape rather than resolve the challenges that remain (Oyeleye *et al*., 2022). As capability advances, the binding constraints shift toward the social and institutional conditions for its deployment, so that the challenges the field faces evolve alongside its advances. The review treats this dynamic as central to its outlook, arguing that an accurate sense of where the field is heading requires attention to how advances and challenges interact, and that the frontier of progress lies at their interface rather than within either alone (Okwu *et al*., 2021; Oladoye *et al*., 2022).

A further element of the outlook concerns the conditions under which the advances surveyed will reach the populations that need them most, since the review has argued that capability proven under favorable conditions does not automatically deliver inclusive outcomes in resource-dependent settings (Shittu *et al*., 2019). The synthesis points toward an agenda in which advances are pursued together with the capacity, governance, finance, and distributional arrangements required to realize them, rather than in isolation from these conditions. This outlook implies that the field's contribution to inclusive transition depends on aligning technical progress with the social and institutional conditions on which its realization in the field ultimately rests (Patrick *et al*., 2020; Patrick *et al*., 2021).

8. Conclusion

The review concludes that the central challenge for equitable grid-connected battery storage is not the absence of suitable technology but the absence of the financial instruments, governance models, and institutional arrangements required to deploy existing technology in ways that distribute its benefits fairly (Collath *et al*., 2021; BloombergNEF, 2021). This conclusion positions the equity challenge as a problem of institutional design and market structure rather than one of technical capability, and it argues that progress on equity requires investments in institutional innovation that are at least as consequential as continued investments in technical performance improvement. The framework developed in this paper provides a structure for reasoning about these institutional challenges, and the conclusion presents it as a foundation for the interdisciplinary research and policy development that addressing them requires (Liadi, 2022).

A final conclusion concerns the contribution of the equity analysis to the broader storage transition strategy, arguing that ignoring the replacement capital and warranty challenges identified by the framework is not only unjust but strategically shortsighted, since the long-term expansion of storage deployment depends on demonstrating durable and beneficial operation in diverse settings including those in hot and wet climates (Walker & Devine-Wright, 2008; IRENA, 2022). Storage systems that are installed but not maintained, that fail prematurely due to inadequate replacement capital, or that concentrate benefits in high-income settings while leaving others underserved will generate the distrust and disillusionment that undermine the social license for the technology at scale. The conclusion argues that addressing equity is therefore not only a moral imperative but a precondition for the sustained social support that the storage transition requires.

This paper has treated grid-connected battery energy storage as an integrated socio-technical concern, developing the argument that engineering performance and social outcomes are interdependent and must be reasoned about together rather than in sequence. Its central conclusion is that the durability and inclusiveness of interventions depend jointly on technical capability and on social and institutional conditions, centrally the inequity embedded in warranty terms and the scarcity of replacement capital where degradation is fastest, and that the field's progress has been limited less by technical capability than by the absence of means to bring these dimensions into a single account. The contribution has been conceptual throughout, offering a way of organizing and reasoning about the subject rather than a body of empirical results, and it is intended to support more durable and equitable outcomes in resource-dependent regions.

The conclusion that technical and social factors must be considered together carries implications for how interventions in grid-connected battery energy storage are designed, funded, and evaluated, suggesting that the social determinants of durability deserve the same rigor conventionally reserved for technical parameters. This paper has argued that doing so is feasible, that the relevant social conditions can be given explicit conceptual definition and brought into design, and that the result is a richer and more realistic basis for decision than technical analysis alone provides. In this sense the work is offered not as a final word but as a foundation, one that reframes the design task in a way that subsequent empirical work can build upon and test.

Future work should extend the framework in three directions: empirically, by testing and refining the relationships it posits against evidence from diverse settings. Comparatively, by applying it across regions to establish where its structure holds and where its content must be recalibrated; and methodologically, by developing measures for the social conditions it identifies as consequential. Pursuing these directions would consolidate the conceptual foundation laid here into a tested and transferable approach, advancing the broader goal of energy systems that are simultaneously technically efficient, economically accessible, socially responsive, and adaptable to the developing and resource-dependent regions where the need is greatest within grid-connected battery energy storage.

Another conclusion concerns the transferability of the account developed here, since the framework has been constructed so that its general logic can be carried across the diverse settings in which grid-connected battery energy storage is deployed while its specific content is re-examined locally. This design reflects the review's recognition that the conditions governing durability vary across regions even when the technology does not, and it is intended to allow insight to travel without the assumption that what holds in one context holds in another. The conclusion emphasizes that this transferability is a deliberate feature rather than an afterthought, and that it is essential if the conceptual contribution is to be of use across the range of regions that inclusive energy transition must reach.

A related conclusion involves the implications of the analysis for practice and policy in grid-connected battery energy storage, since the account developed here suggests that the social determinants of durability deserve the same rigor conventionally reserved for technical parameters. For practitioners, this implies attending to participation, capacity, fairness, and governance as integral parts of design; for the institutions that fund and regulate energy systems, it implies weighing demonstrated attention to these conditions in appraisal and support. The analysis underscores that these implications follow directly from the analysis, and that acting on them would help align the design and funding of interventions with the conditions that the evidence identifies as governing durability.

A final conclusion concerns the broader significance of the work for inclusive energy transition, since the regions at the centre of grid-connected battery energy storage are precisely those where the transition is most fraught and where the cost of designing without regard to social conditions has been highest. By providing a structured way to bring social and technical factors together, the analysis contributes to the larger project of ensuring that the transition is not only rapid but fair, and that the systems built to advance it actually serve the populations they are meant to reach. The conclusion situates the contribution within this wider purpose, presenting it as a step toward energy systems that are efficient, accessible, responsive, and adaptable at once.

The conclusion emphasizes that the central lesson of the review is the interdependence of technical and social factors in determining the durability and inclusiveness of interventions in grid-connected battery energy storage. Neither dimension is sufficient alone, and the review argues that the field's progress depends on its willingness to treat them together, bringing the rigor of the technical tradition to bear on the social conditions that govern outcomes. This interdependence is the thread that runs through the review, and it is the basis for the conceptual agenda the review proposes. This conclusion underpins the broader argument that technical and social factors must be considered together.

The conclusion reflects on the significance of the review for inclusive energy transition, observing that the regions at the centre of grid-connected battery energy storage are those where the transition is most consequential and where designing without regard to social conditions has been most costly. By providing a structured account of how technical and social factors combine, the review contributes to the larger project of ensuring that the transition is both rapid and fair, and that the systems built to advance it actually serve the populations they are meant to reach. The conclusion treats this as part of the contribution this paper offers to the field.

The conclusion identifies directions for future work, including the development of measures for the social conditions the review identifies, the application of an integrated approach across diverse settings, and the refinement of the conceptual tools the review calls for. Pursuing these directions, the conclusion argues, would move the field from a state in which technical and social knowledge sit side by side but unintegrated toward one in which they are combined in the service of energy systems that are efficient, accessible, responsive, and adaptable for the regions that need them most. This observation connects the conclusion to the directions for future work this paper identifies.

A further point addresses the methodological lesson that emerges from the analysis, namely that the social conditions governing durability in grid-connected battery energy storage can be brought into systematic reasoning rather than left to intuition or treated as qualitative background. The analysis has argued that these conditions can be given explicit conceptual standing and considered alongside technical factors, and the conclusion treats this as among its more significant contributions, since it extends the possibility of rigorous analysis to dimensions that the field has tended to address informally. This methodological lesson underpins the broader argument that technical and social factors can and should be considered together.

The analysis also bears on the practical orientation of the analysis, which has been directed throughout toward the improvement of real interventions rather than toward abstraction for its own sake. A central lesson is that the value of the account developed here lies ultimately in its bearing on the durability and inclusiveness of systems in the field, and that its concepts and arguments are offered as aids to better design, funding, and governance. This practical orientation reflects the conviction that scholarship on grid-connected battery energy storage should serve the populations that interventions are meant to reach, and it frames the contribution as a means to that end.

A second consideration concerns the honesty about limitations that the analysis has maintained, since the account developed here is conceptual and its value depends on application and refinement against experience. The conclusion restates plainly that the relationships posited are claims that evidence must test, and that the definitions adopted involve choices others might make differently. Treating these limitations as the natural boundaries of a conceptual contribution rather than as defects to be concealed, the conclusion identifies them as among the matters that subsequent work would address, and it presents the contribution in the spirit of a foundation to be built upon.

A final conclusion situates the work within the larger trajectory of the field, observing that the integration of technical and social analysis it advocates is part of a broader movement toward understanding energy systems as socio-technical. The conclusion expresses the view that this movement is necessary if the field is to address the persistent gap between technically sound interventions and durable outcomes, and that the account developed here contributes to it. By framing the contribution in these terms, the conclusion connects the specific argument about grid-connected battery energy storage to the wider project of designing energy systems that are efficient, accessible, responsive, and adaptable for the regions that need them most.

Another conclusion involves the lifecycle perspective that has run through the analysis, namely that the durability and affordability of interventions in grid-connected battery energy storage are determined over their working lives rather than at the moment of deployment. It warrants emphasis that this perspective reframes the assessment of interventions around the years of operation, where the conditions governing durability actually bear on outcomes, and it identifies the neglect of lifecycle considerations as a recurring source of the gap between technical promise and field result. This perspective underpins the broader argument that durability must be designed for and sustained rather than assumed at commissioning.

A further conclusion concerns the distributional dimensions the analysis has emphasized, namely that the inclusiveness of interventions in grid-connected battery energy storage depends on how their benefits and burdens fall within as well as between communities, including along lines of gender. The work makes clear that an account of inclusive outcomes confined to aggregate measures would overlook the disparities that determine genuine inclusion, and that attention to intra-community distribution is therefore integral to the analysis. This conclusion reflects the broader argument that equity is a determinant of durability and a criterion of success, and not a consideration secondary to technical and economic performance. Accordingly, the conclusion presents the contribution as a foundation for subsequent investigation.

A final conclusion concerns the environmental dimension the analysis has emphasized, namely that the durability of interventions in grid-connected battery energy storage depends on their resilience to the demanding and changing conditions of the regions of concern. What stands out is that durability cannot be assessed apart from the environmental conditions of deployment, and that these conditions, intensified by the very changes the transition is meant to address, bear heavily on whether interventions endure. This conclusion reinforces the broader argument that durability is conditional on the full set of factors, environmental as well as social and technical, that the analysis has sought to bring into a single account.

A related conclusion involves the relationship between the conceptual contribution offered here and the practice it is ultimately meant to serve, since the framework is intended not as an abstraction but as a guide to the design, funding, and governance of interventions in grid-connected battery energy storage. This paper has argued that the social determinants of durability can be brought into systematic reasoning alongside technical considerations, and the conclusion emphasizes that the value of doing so lies in improving the prospects of real interventions in the field. The contribution is therefore offered in a practical spirit, as a way of reasoning that practitioners and decision-makers can apply to the problems they actually face.

An additional point addresses the broader significance of the approach for the field's understanding of itself, since the integration of technical and social analysis advocated here reflects a wider movement toward treating energy systems as socio-technical. The conclusion expresses the view that this movement is necessary if the persistent gap between technically sound interventions and durable outcomes is to be closed, and that the account developed here contributes to it. By situating its specific argument about grid-connected battery energy storage within this larger trajectory, this conclusion connects this paper to the broader project of designing energy systems that are efficient, accessible, responsive, and adaptable for the regions that need them most.

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