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Interpretable Machine Learning for Early Failure Prediction in Distributed Renewable Energy Assets

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Abstract

This paper develops a conceptual framework for predictive maintenance of distributed renewable assets that treats engineering innovation and socio-technical analysis as a single integrated design problem rather than as separate concerns addressed in sequence. The framework is motivated by a persistent pattern in which technically sound interventions falter in the field because the social and institutional conditions that govern their durability are neither measured nor designed for. In response, this paper articulates a model in which social variables, centrally the gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones, are rendered explicit and brought into the design problem on the same footing as technical parameters. The contribution is conceptual: this paper sets out the foundations of the framework, specifies its components and the relationships among them, illustrates its reasoning, and derives design and policy implications, with the aim of supporting energy systems that are simultaneously technically efficient, economically accessible, socially responsive, and adaptable to developing and resource-dependent regions

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, productive enterprise, and full participation in modern economic life, yet a large share of the population in low-income and resource-dependent regions still lacks dependable electricity (Ahmed *et al*., 2020). This paper takes predictive maintenance of distributed renewable assets as its subject and treats it not as a narrow engineering problem with a social footnote, but as a problem whose technical and social dimensions are entangled from the outset. The motivation is both scholarly and practical: the field has tended to optimize technical performance and social acceptance in sequence, producing solutions that perform well in models yet underperform in deployment, and this paper sets out a conceptual framework intended to bring the two dimensions into a single, coherent design problem oriented toward inclusive transition (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).

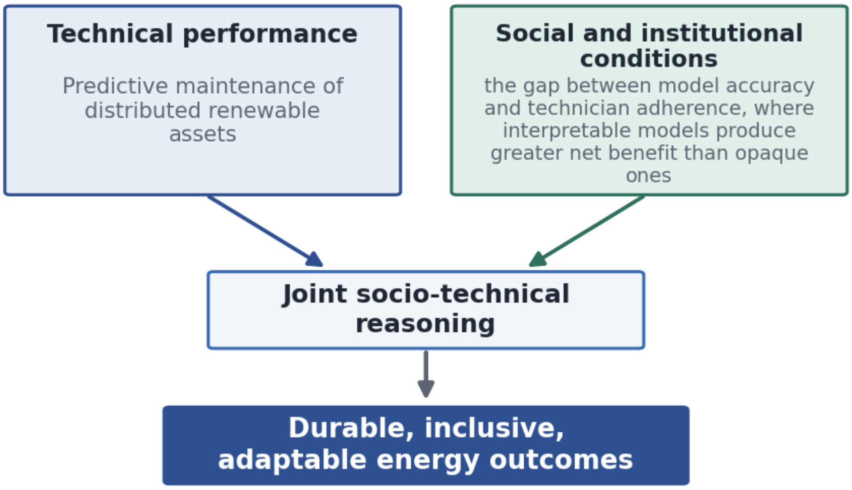

Fig 1: Technical performance and social conditions as jointly determining durable, inclusive outcomes.

The central proposition of this paper is that engineering performance and social outcomes are not separable matters to be handled one after the other, but interdependent variables that must be reasoned about together within a single framework (Arumosoye & Obriki, 2019). The decades-long record of energy interventions in underserved regions contains many instances of technically sound systems that fell into disuse within a few years, and post-mortem assessments attribute these failures less to engineering defects than to mismatches between the system and the social and institutional context into which it was placed. A framework for predictive maintenance of distributed renewable assets that does not represent those contextual conditions explicitly will therefore tend to recommend designs that look strong on paper while remaining fragile in service, which is the deficiency this work is intended to remedy (Ambali *et al*., 2021; Arumosoye & Obriki, 2018).

Energy poverty is not merely the absence of electricity but a compound condition entangled with income, geography, gender, and exposure to environmental harm, and interventions that treat it as a purely technical deficit frequently fail to achieve durable improvement (Bhattacharyya *et al*., 2021). Within predictive maintenance of distributed renewable assets, the conceptual tools used to design and evaluate systems rarely make social factors measurable alongside engineering ones, with the consequence that decisions carrying large distributional implications are made implicitly, without the rigor applied to technical parameters. This paper responds to that gap by proposing a way of representing the relevant social conditions in a form that can enter design and evaluation directly, so that equity and efficiency, often presented as competing aims, can be pursued together rather than traded against one another (Arumosoye & Obriki, 2021; Bednar *et al*., 2017).

The framework developed here is organized around three guiding questions that recur across the literature on predictive maintenance of distributed renewable assets (Dagodzo, 2018a). The first concerns what level of technical performance is attainable under the constraints typical of resource-dependent regions, where intermittent grid availability, limited maintenance capacity, and constrained finance shape what is feasible (Collath, 2021). The second concerns the extent to which social and institutional conditions independently govern realized outcomes once technical factors are accounted for. The third, and the one this paper foregrounds, concerns how these dimensions can be integrated within a single conceptual model that practitioners can apply. Posing the questions together, rather than in isolation, is itself part of the contribution, since it reframes the design task as inherently socio-technical (Dada *et al*., 2021; Isiekwu *et al*., 2021).

The diversity of the contexts in which predictive maintenance of distributed renewable assets is deployed, spanning climate, terrain, settlement density, and institutional maturity, means that a configuration validated in one place cannot be assumed to perform in another without deliberate adaptation, and this variability is one of the reasons a purely technical framework proves insufficient (Dagodzo & Patrick, 2021a). A conceptual model adequate to the field must therefore represent not only the technology but the conditions surrounding it, and must do so in a way that supports reasoning across settings rather than within a single one. The framework developed in this paper is built with exactly this requirement in mind, separating its general logic from the context-specific conditions that determine how that logic applies in any particular case (Dagodzo, 2018b; Dagodzo & Patrick, 2020; Lilian *et al*., 2020).

A further motivation for the framework is the observation that the populations served by predictive maintenance of distributed renewable assets are not passive recipients of technology but active participants whose choices, capacities, and trust shape whether an intervention succeeds (Guerrero *et al*., 2013). Treating them as such reframes the design problem, since it implies that the conditions for durability include the willingness and ability of communities to use, pay for, maintain, and govern the systems on which they depend. The framework makes this participation explicit, representing the community not as the setting in which technology operates but as a co-determinant of the outcomes that technology produces, which is a conceptual move with substantial consequences for how design is approached (Dagodzo & Patrick, 2021b; Ewim *et al*., 2021).

This paper is written in the recognition that the stakes of predictive maintenance of distributed renewable assets are not abstract, since for the households and communities concerned reliable and affordable energy is bound up with health, safety, education, and the possibility of economic advancement (Liu *et al*., 2014). It is against this human standard, rather than a narrowly technical one, that the framework evaluates interventions, and this orientation shapes the criteria of success it adopts, which extend beyond performance and cost to encompass durability, inclusion, and legitimacy. By foregrounding these wider outcomes from the start, the framework keeps in view the purposes that energy provision is ultimately meant to serve, and it resists the tendency to mistake technical achievement for the achievement of those purposes (International Energy Agency, n.d.; Jessel *et al*., 2019).

At the outset, it should be noted that the framework advanced in this paper is offered as a mode of structured reasoning rather than as a prescription, since the conditions that govern durability in predictive maintenance of distributed renewable assets are too varied for any single recipe to suffice (Mbonu *et al*., 2021b). What the framework provides is a disciplined structure for asking the right questions: whether a design is sustainable under the conditions it will meet, whether the social conditions on which it depends are present, and what would be required to establish them where they are not. This emphasis on structured reasoning rather than fixed prescription reflects this paper's conviction that the value of a conceptual contribution lies in how it reshapes the questions designers ask (Mbonu *et al*., 2020a; Mbonu *et al*., 2021a).

The framework also takes seriously the long time horizons over which energy infrastructure operates, recognizing that decisions made at the design stage commit communities to particular technologies, costs, and dependencies for many years (Mbonu *et al*., 2021c). This longevity raises the stakes of getting the design right and argues for considering, before commitments are made, not only whether a system will function but whether it will continue to be operated, paid for, maintained, and trusted across the full span of its working life. By building this temporal perspective into its foundations, the framework directs attention away from the moment of commissioning and toward the years of operation in which the interaction of technical and social factors actually determines whether an intervention in predictive maintenance of distributed renewable assets endures (Mbonu *et al*., 2019a; Mbonu *et al*., 2020b; Lilian *et al*., 2020).

A central premise underlying the framework is that the apparent tension between efficiency and equity in predictive maintenance of distributed renewable assets is, in many cases, an artifact of analyzing the two separately rather than a genuine trade-off (Nnaji *et al*., 2019). When technical and social factors are considered in isolation, measures that improve one often appear to come at the expense of the other, but when they are considered together the framework frequently reveals configurations in which both are served. Demonstrating this possibility, and providing a structured way to find such configurations, is among the framework's principal aims, and it reflects the broader argument that efficiency and equity are more often complementary than opposed once the analysis is properly integrated (Mbonu *et al*., 2019b; Muhtadi *et al*., 2021).

The framework is deliberately constructed to be usable by practitioners rather than to remain an academic abstraction, and this practical orientation shapes its design (Obogo *et al*., 2020b). Its components are defined in terms that correspond to questions a designer or decision-maker can actually pose about a candidate intervention, and its logic is intended to guide the sequence of design decisions rather than merely to describe them after the fact. For predictive maintenance of distributed renewable assets, this means the framework is meant to be applied at the point where choices are still open, informing design and implementation decisions, and this paper develops it with that application in view throughout (Nnaji *et al*., 2020; Obogo *et al*., 2020a).

Underlying the entire inquiry is a normative commitment that the communities served by predictive maintenance of distributed renewable assets are entitled to systems that are not merely installed but sustained, not merely available to some but accessible to all, and not merely efficient in aggregate but fair in their distribution (Obogo *et al*., 2021b). This commitment defines the standard against which the framework evaluates interventions, and it explains why the framework treats durability, inclusion, and legitimacy as first-order objectives rather than as incidental considerations. This paper is explicit that this is a normative starting point, and it argues that making such commitments explicit, rather than leaving them implicit in technical choices, is itself a contribution to more honest and accountable design (Obogo *et al*., 2020c; Obogo *et al*., 2021a).

Finally, the framework is positioned as a foundation for subsequent empirical work rather than as a substitute for it, since the relationships it posits are ultimately claims about the world that evidence must test (Obogo *et al*., 2021c). This paper acknowledges that its contribution is conceptual, and that the framework's value will be established only as it is applied, examined, and refined against experience across diverse settings. In offering the framework in this spirit, this paper aims to provide a structure within which future investigation of predictive maintenance of distributed renewable assets can be organized, and to reframe the design task in a way that makes the social determinants of durability as tractable an object of study as the technical ones have long been (Obogo *et al*., 2019a; Obogo *et al*., 2019b).

A further consideration motivating the framework is that the same conceptual clarity long applied to technical variables has rarely been extended to the social conditions that govern durability, leaving design to rely on intuition where it could rely on structured reasoning (Ogunwole *et al*., 2021). The framework responds by giving these conditions explicit conceptual standing, so that they can be reasoned about with the same discipline as technical parameters. This extension of conceptual rigor to the social dimension is among the framework's central contributions, and it reflects the conviction that the social determinants of durability are as amenable to systematic treatment as the technical ones (Odejobi & Ahmed, 2018; OECD, n.d.).

The framework is motivated, too, by the recognition that interventions in predictive maintenance of distributed renewable assets are embedded in wider development efforts, so that their success or failure reverberates through the schools, clinics, water systems, and enterprises that depend on reliable power (Okonkwo *et al*., 2021a). A framework confined to the energy system alone would miss much of what is at stake, and the one developed here keeps these wider dependencies in view, treating reliable energy as a means to broader human development (Okonkwo *et al*., 2020). This breadth of concern shapes the criteria of success the framework adopts and the purposes against which it evaluates interventions. This framing establishes the orientation that the remainder of this paper develops in detail.

The framework finally rests on the conviction that the persistent gap between technically sound interventions and durable outcomes can be narrowed by design, through methods that bring the social determinants of durability into the analysis from the start (Okonkwo *et al*., 2018b). This paper is explicit that this is the deficiency it aims to remedy, and that doing so is both feasible with the conceptual tools it develops and necessary if energy transition in resource-dependent regions is to be inclusive and lasting (Okonkwo *et al*., 2018a). This conviction animates the framework and defines the contribution this paper sets out to make to predictive maintenance of distributed renewable assets. This paper returns to this consideration repeatedly as it elaborates the framework and its application.

A consideration that motivates the framework is the gendered dimension of energy access, since the literature documents that the burdens of energy poverty and the benefits of energy access often fall unequally across gender lines within the same community (Patrick *et al*., 2020). A framework that attends only to aggregate household outcomes risks overlooking these intra-household and intra-community differences, which bear on both equity and durability. The framework set out here is constructed to accommodate such distinctions, treating the distribution of benefits and burdens within communities as part of what design and evaluation must consider in predictive maintenance of distributed renewable assets, rather than as a matter beyond the reach of systematic analysis (Okonkwo *et al*., 2021b; Okwu *et al*., 2021). (Dada *et al*., 2021a).

The framework is also motivated by the environmental conditions under which systems in predictive maintenance of distributed renewable assets must operate, since the regions of concern frequently combine demanding climates with exposure to the very environmental changes that the energy transition is meant to address (Shittu *et al*., 2019). Designing for these conditions requires treating environmental resilience as integral to durability rather than as a separate concern, and the framework is constructed accordingly (Patrick *et al*., 2021). By representing the environmental conditions a system will encounter alongside its social and technical characteristics, the framework keeps in view the full set of conditions on which durable operation depends in the settings it addresses. This consideration informs both the structure of the framework and the criteria by which it judges interventions.

An additional motivation concerns the measurement problem that has limited the integration of social factors into design, since the difficulty of quantifying conditions such as the gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones has often been treated as a reason to exclude them from systematic analysis (Sunday & Omoegun, 2019). The framework reframes this difficulty as a conceptual task to be addressed rather than a barrier to be accepted, arguing that the relevant conditions can be given definitions precise enough to support reasoning even where exact measurement is difficult. This reframing is central to the framework's contribution, since it opens to systematic treatment the social dimensions that the field has tended to handle informally (Smith, 2017; Sunday & Omoegun, 2018).

The framework is motivated, finally, by the observation that the costs of energy interventions extend well beyond their initial construction to encompass operation, maintenance, and eventual replacement, so that affordability must be understood over the full life of a system rather than at the moment of installation (Yeboah & Ike, 2020). A framework attentive only to upfront cost would misjudge the affordability that conditions sustained use, and the one developed here is constructed to consider lifecycle costs and their distribution. This lifecycle orientation is essential, since the durability the framework seeks to support depends on whether a system remains affordable to operate and maintain over the years of its working life (World Resources Institute, n.d.; Wustenhagen *et al*., 2007).

It is useful to clarify at the outset what kind of contribution a conceptual framework makes, since it neither reports new measurements nor proposes a single technique, but rather supplies a structured way of reasoning about a class of problems (Ahmed *et al*., 2020). The approach developed here for predictive maintenance of distributed renewable assets is intended to organize thinking, to make explicit the assumptions on which design rests, and to bring into a single view the technical and social considerations that determine whether an intervention endures. Its value is to be judged not by the novelty of any individual claim but by whether, taken as a whole, it helps practitioners and analysts reason more clearly about the conditions on which durable, inclusive outcomes depend in the settings that concern this work (Agbabiaka *et al*., 2019; Ahmad *et al*., 2020).

The argument advanced in this paper proceeds from a simple but consequential observation, namely that the criteria by which interventions in predictive maintenance of distributed renewable assets are conventionally judged are narrower than the criteria by which they actually succeed or fail in the field (Arumosoye & Obriki, 2019). Technical performance and unit cost dominate appraisal, yet durability and inclusion turn on conditions these criteria do not capture, and the gap between the two sets of criteria is where many interventions falter. The framework responds by widening the criteria of evaluation deliberately, treating durability, inclusion, and legitimacy as objectives to be designed for rather than hoped for, and this paper develops this widening as its central organizing move (Ambali *et al*., 2021; Arumosoye & Obriki, 2018).

2. Background and Related Work

The literature on predictive maintenance in industrial settings has documented a consistent gap between the technical performance of diagnostic models and the rate at which maintenance decisions are actually changed in response to model outputs, a phenomenon sometimes called the last-mile problem of predictive analytics (Mobley, 2002; Lee *et al*., 2014). Model developers focus on accuracy metrics while system operators focus on interpretability, actionability, and the fit between model recommendations and established workflows. For distributed renewable assets, this gap is particularly consequential because maintenance decisions are made by field technicians whose schedules, skills, and risk tolerances may not be aligned with the assumptions embedded in the models that generate alerts. The framework developed in this paper is positioned at this interface, treating the gap between model accuracy and technician adherence as the central design problem rather than as a post-deployment implementation issue (Basnet *et al*., 2021).

Human factors research has established that the adoption of diagnostic tools by practitioners depends on more than technical performance, encompassing factors such as trust in the tool's reasoning, consistency with prior experience, integration with existing workflows, and the organizational incentives that shape how recommendations are acted upon (Kahneman, 2011; Endsley, 1995). In the context of predictive maintenance for distributed renewable assets, these factors interact with the time pressures, resource constraints, and informational environments characteristic of field maintenance settings. A model that performs well on held-out test data but produces recommendations that technicians cannot interpret, verify, or integrate into their work will systematically underperform relative to its technical potential, and the gap between potential and realized performance will itself have maintenance and reliability consequences. The framework therefore treats technician adoption as an explicit design requirement, not an assumption.

The organizational literature on technology adoption in field settings emphasizes the role of organizational structures, training systems, and incentive arrangements in mediating the relationship between tool availability and tool use (Rogers, 2003). Predictive maintenance systems for distributed renewable assets are deployed into organizations with existing maintenance cultures, hierarchies, and performance metrics, and whether a system is used effectively depends as much on these organizational conditions as on its technical characteristics. The framework developed here acknowledges this by treating organizational adoption conditions as variables that must be assessed alongside technical performance, arguing that a system whose adoption conditions are unfavorable is, for practical purposes, less useful than its technical performance would suggest, regardless of how accurate its predictions.

The literature on explainable artificial intelligence has produced a growing set of techniques for making the outputs of machine learning models interpretable to non-specialist users, including visualization approaches, feature importance indicators, and natural-language explanation generators (Ribeiro *et al*., 2016). For predictive maintenance of distributed renewable assets, these techniques are directly relevant because the technicians who act on model recommendations are not data scientists, and their understanding of why a model flags a particular asset for attention is a determinant of whether they act on the flag. The framework draws on this literature in specifying interpretability as a dimension of model design that must be addressed alongside accuracy, treating explainability not as a nice-to-have feature but as a core requirement for closing the gap between model performance and technician adherence.

A further body of relevant literature concerns the economics of maintenance in distributed infrastructure settings, where the costs of unnecessary maintenance visits and of failure to act on genuine early warnings create a bilateral cost structure that predictive maintenance is intended to navigate (Smith *et al*., 2017). The value of predictive maintenance depends on the sensitivity and specificity of the system, but it also depends on the decision-making behavior of the technicians who translate model outputs into maintenance actions. A model that generates accurate predictions but is rarely acted upon may produce worse outcomes than a less accurate model that reliably prompts appropriate action, because the expected value of a predictive system depends on the full chain from sensor data to model output to human decision to maintenance action. The framework represents this entire chain, treating each link as a potential source of failure that design must address.

Research relevant to predictive maintenance of distributed renewable assets spans several scholarly traditions that have historically developed in relative isolation, with engineering studies emphasizing performance and reliability, economic studies emphasizing cost and viability, and social-science studies emphasizing acceptance, equity, and governance (Bhattacharyya *et al*., 2021). Each tradition has produced valuable insight, but their separation has limited understanding of systems whose success depends on all three at once, and it has left the field without a shared vocabulary for reasoning about technical and social factors together. The framework developed in this paper draws deliberately on all of these traditions, treating their separation as a methodological inheritance to be overcome rather than a natural division of the subject, and it positions its own contribution precisely at the interface where prior work has been thinnest (Arumosoye & Obriki, 2021; Bednar *et al*., 2017).

The technical literature on predictive maintenance of distributed renewable assets has advanced rapidly and has established the performance frontiers of the relevant technologies, yet much of it evaluates performance under assumptions, including reliable communication, adequate maintenance capacity, and stable financing, that do not hold in the settings this paper addresses (Dagodzo, 2018b). The external validity of results obtained under such assumptions is therefore an open question, and a central aim of the conceptual framework developed here is to make the dependence of technical performance on these enabling conditions explicit. By representing the conditions that idealized analyses hold constant, the framework seeks to explain why field outcomes so often diverge from what laboratory or simulation results would predict (Collath, 2021; Dagodzo, 2018a; Lilian *et al*., 2020).

Economic analyses of predictive maintenance of distributed renewable assets have generally relied on aggregate metrics such as levelized cost, which are indispensable for comparison but incomplete, since they capture average efficiency while obscuring the distributional consequences that determine whether a system is affordable for and accepted by the populations it serves (Dagodzo & Patrick, 2021b). A growing body of social-science and environmental-justice scholarship has documented the centrality of participation, trust, legitimacy, and fairness, establishing that these factors are causally significant rather than peripheral. What this literature has less often supplied is a way of rendering social factors measurable and comparable to technical parameters, and the framework proposed here is constructed to fill exactly that gap within predictive maintenance of distributed renewable assets (Dagodzo & Patrick, 2020; Dagodzo & Patrick, 2021a).

A reading of the empirical and conceptual literature suggests that the conditions associated with durable interventions in predictive maintenance of distributed renewable assets are remarkably consistent across technologies and regions, recurring with a regularity that points to general socio-technical regularities rather than the idiosyncrasies of particular cases (International Energy Agency, n.d.). Attributes such as community ownership, transparent governance, local capacity, and procedural fairness appear repeatedly among the factors that distinguish lasting interventions from those that falter. The framework developed in this paper takes this consistency as a point of departure, treating the recurring conditions not as anecdotes but as candidate variables for systematic representation, and organizing its account of the prior literature around the question of how these conditions might be defined and brought into design (Ewim *et al*., 2021; Guerrero *et al*., 2013).

The theoretical literature on socio-technical transitions provides a foundation for treating technology and society as co-evolving, offering a vocabulary in which technical change and social change are understood as proceeding together rather than independently (Mbonu *et al*., 2020a). The framework proposed here draws on that foundation while extending it in a specific direction, namely toward the conceptual definition of the social variables that the theory identifies as consequential but often leaves abstract. In positioning predictive maintenance of distributed renewable assets within both the engineering literature and the transitions and justice literatures, the background establishes that neither tradition alone is sufficient, and that the contribution of the present work lies precisely in combining their respective strengths into an integrated account (Jessel *et al*., 2019; Liu *et al*., 2014).

Prior attempts to combine technical and social analysis in predictive maintenance of distributed renewable assets have tended to place them in sequence, introducing social considerations only after technical design is largely fixed, and the literature on the resulting interventions suggests that this sequencing is itself a source of failure (Mbonu *et al*., 2019a). By the time social factors are considered under such an approach, the decisions that determine their influence have already been made, and the scope for adjustment is correspondingly narrow. The account developed here is constructed precisely to avoid this trap, admitting social variables into the design problem from the outset, and the background situates this design choice against the documented shortcomings of the sequential approaches that have predominated (Mbonu *et al*., 2021a; Mbonu *et al*., 2021b).

A persistent feature of the literature bearing on predictive maintenance of distributed renewable assets is terminological and disciplinary fragmentation, in which similar phenomena are studied under different names by communities that rarely cite one another, and this fragmentation has slowed the accumulation of integrated knowledge (Mbonu *et al*., 2019b). The background to this paper therefore involves not only summarizing what is known but reconciling vocabularies, since the same underlying conditions are described in engineering terms in one literature and in social or institutional terms in another. By drawing these descriptions together, this paper lays the groundwork for a framework that can represent technical and social factors in commensurable terms, which is a precondition for the integrated reasoning it seeks to support (Mbonu *et al*., 2020b; Mbonu *et al*., 2021c).

The development and energy-access literatures have documented in rich detail the social and institutional determinants of success in predictive maintenance of distributed renewable assets, yet they have rarely expressed those determinants in forms that can enter technical design directly, leaving their insights at the level of interpretation (Nnaji *et al*., 2020). The engineering literature, by contrast, has developed precise methods for the variables it considers but has tended to omit the determinants that the development literature emphasizes. This asymmetry, in which one tradition measures precisely what matters least for durability while the other identifies what matters most but measures it least, is the central feature of the prior work that the framework is designed to address (Muhtadi *et al*., 2021; Nnaji *et al*., 2019). Across the bodies of work reviewed, the most durable interventions in predictive maintenance of distributed renewable assets are repeatedly associated with attributes, such as community ownership, transparent governance, and local capacity, that lie outside the variables technical optimization typically considers (Obogo *et al*., 2020c). The background treats this recurring association not as a coincidence but as evidence for the socio-technical premise on which the framework rests, namely that these attributes are causally implicated in durability rather than merely correlated with it. Organizing the prior literature around this association allows this paper to identify which conditions warrant explicit representation in the framework, and to ground that selection in the consistency with which the conditions appear across otherwise diverse studies (Obogo *et al*., 2020a; Obogo *et al*., 2020b).

This background section also considers the limited body of prior work that has attempted to integrate technical and social analysis in predictive maintenance of distributed renewable assets, since these efforts point toward the approach this paper develops while also revealing its difficulty (Obogo *et al*., 2019a). Such work has often succeeded within single case studies but has struggled to generalize, in part because it has lacked a framework for separating the general from the context-specific. This paper treats these prior efforts as valuable precedents whose limitations are instructive, and it positions its own framework as an attempt to supply the generalizable structure that earlier integrative work has lacked, thereby enabling insight to be carried across the varied settings in which predictive maintenance of distributed renewable assets operates (Obogo *et al*., 2021a; Obogo *et al*., 2021b).

A further element of the background concerns the theoretical resources available for treating energy systems as socio-technical, including the literatures on sustainability transitions, on the social construction of technology, and on energy justice (Odejobi & Ahmed, 2018). Each of these offers concepts that the framework draws upon, from the co-evolution of technology and institutions to the distributional and procedural dimensions of justice. The background reviews these resources not for their own sake but to establish the conceptual lineage of the framework, showing how it synthesizes ideas developed across several theoretical traditions into a structure specifically adapted to the analysis and design of interventions in predictive maintenance of distributed renewable assets (Obogo *et al*., 2019b; Obogo *et al*., 2021c).

The background also situates the framework against the limited prior work that has attempted to quantify social factors in predictive maintenance of distributed renewable assets, treating these efforts as valuable precedents whose difficulties are instructive (Ogunwole *et al*., 2021). Such work has shown both that social conditions can be characterized systematically and that doing so is demanding, and the framework builds on these lessons while seeking to provide the generalizable structure that earlier efforts have lacked (OECD, n.d.). By engaging with this prior work directly, the background establishes that the framework's ambition is continuous with existing scholarship rather than a departure from it. This strand of prior work grounds the corresponding element of the framework developed in later sections.

A related element of the background concerns the distributional scholarship that documents how interventions can improve aggregate conditions while leaving the most marginalized unreached, a finding central to the framework's attention to equity (Okonkwo *et al*., 2021a). This literature establishes that distribution is not a secondary concern but a determinant of whether an intervention is genuinely inclusive, and the framework incorporates it accordingly (Okonkwo *et al*., 2020). Within this context, the background uses this scholarship to justify the framework's treatment of distribution as a first-order consideration rather than an afterthought. The framework draws on this body of scholarship in constructing its own integrated account. This element of the background establishes part of the conceptual lineage on which the framework builds.

The background draws, finally, on the literature documenting the long-term trajectories of interventions, which shows that initial performance is a poor predictor of eventual durability (Okonkwo *et al*., 2018b). This evidence motivates the framework's dynamic treatment of the conditions governing durability, and the background uses it to argue that any adequate account of predictive maintenance of distributed renewable assets must attend to how systems and their social conditions co-evolve over time rather than assessing them at a single moment (Okonkwo *et al*., 2018a). This observation from the prior literature motivates the design choices the framework subsequently makes. This consideration situates the framework as continuous with, rather than a departure from, existing scholarship. This body of work informs the corresponding design choice the framework makes.

The background includes the literature on the gendered dimensions of energy, which documents that access and its absence affect women and men differently and that interventions bear on these disparities (Okwu *et al*., 2021). This literature establishes gender as a dimension of the distributional concerns central to the framework, and the background draws on it to justify the framework's attention to differences within communities and not only between them (Okonkwo *et al*., 2021b). For problems of this kind, this strand of prior work grounds the framework's treatment of distribution as encompassing intra-community as well as inter-community differences, reflecting the evidence that aggregate outcomes can obscure significant disparities. The framework treats this prior scholarship as a foundation rather than a point of departure.

A further element of the background concerns the literature on environmental resilience, which documents how the demanding and changing conditions of the regions concerned bear on the durability of energy systems (Patrick *et al*., 2021). This literature establishes environmental conditions as part of the context the framework must represent, and the background draws on it to justify the framework's treatment of resilience as integral to durability (Patrick *et al*., 2020). In such settings, this strand of work grounds the framework's representation of the environmental conditions a system will encounter as among the conditions on which its durable operation depends, alongside the social and technical factors. This element of the literature establishes part of the rationale for the framework's structure.

The background draws on the literature concerning the lifecycle costs of energy interventions, which documents that the costs of operation, maintenance, and replacement can exceed those of installation and can undermine durability when they are not provided for (Smith, 2017). This literature establishes the lifecycle perspective that informs the framework's treatment of affordability, and the background uses it to justify considering costs over the full life of a system (Shittu *et al*., 2019). Applied to this domain, this strand of prior work grounds the framework's attention to whether interventions remain affordable to sustain, which the evidence identifies as a determinant of whether they endure. This pattern in earlier work clarifies what the framework must add to it.

A final element of the background concerns the literature on the measurement of social phenomena, which offers approaches to characterizing conditions that resist direct quantification (Sunday & Omoegun, 2019). This literature establishes that conditions such as the gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones can be given definitions precise enough to support systematic reasoning, and the background draws on it to justify the framework's treatment of social factors as amenable to analysis (Sunday & Omoegun, 2018). On this account, this strand of work grounds the framework's central methodological move, namely the bringing of social conditions into systematic reasoning alongside technical parameters rather than treating them as beyond the reach of analysis. The framework extends this prior understanding toward systematic, integrated reasoning.

A concluding element of the background concerns the cumulative lesson of the prior literature, namely that durability in predictive maintenance of distributed renewable assets is consistently associated with the joint presence of technical capability and favorable social conditions, and consistently undermined by the absence of either (Wustenhagen *et al*., 2007). The background treats this lesson as the foundation on which the framework builds, since it establishes both the importance of the social conditions and the inadequacy of considering them apart from the technical (World Resources Institute, n.d.). This element situates the framework as a response to a lesson the prior literature has taught but has lacked the means to act upon systematically. This strand of scholarship situates the framework within an established line of inquiry.

A useful way to situate the framework is to consider how the boundaries of the relevant literature have been drawn historically, since the separation of technical from social scholarship on predictive maintenance of distributed renewable assets reflects disciplinary conventions rather than the structure of the problem itself (Ahmad *et al*., 2020). Engineering, economics, and social science have each claimed a portion of the subject and developed it with their own methods and vocabularies, with the consequence that the interactions across these portions, which field experience shows to be decisive, have fallen between the disciplines. The framework developed here is positioned precisely at these interfaces, and the background establishes that its contribution lies in addressing what the conventional division of the literature has left unattended (Yeboah & Ike, 2020; Agbabiaka *et al*., 2019).

The background also considers the methodological inheritance that shapes how predictive maintenance of distributed renewable assets is studied, since the dominance of approaches oriented toward measurable technical and economic variables has influenced which questions are asked and which are neglected (Arumosoye & Obriki, 2018).

Where social conditions resist easy quantification, they have tended to be excluded from systematic analysis rather than addressed through the development of suitable concepts, and this methodological pattern helps explain the gap the framework seeks to close. By situating its own approach against this inheritance, the background clarifies that the framework's central move, the systematic treatment of social conditions alongside technical ones, responds to a methodological limitation as much as to a substantive one (Ahmed *et al*., 2020; Ambali *et al*., 2021).

3. Conceptual Foundations and Framework Design

A foundational distinction in the framework is between the technical performance of a predictive model, measured by its accuracy on held-out data, and the operational performance of the predictive maintenance system, measured by the improvement in asset reliability, maintenance efficiency, and cost that it actually produces in the field (Lee *et al*., 2014). This distinction is foundational because the two can diverge substantially when the organizational and human factors that mediate model use are not addressed, and because optimizing for technical performance alone leaves the operational gap unaddressed. The framework is built around this distinction, treating operational performance as the ultimate criterion and technical performance as a necessary but insufficient condition for achieving it.

The framework treats interpretability as a design property with multiple dimensions, encompassing the clarity of the model's output, the extent to which the reasoning behind a prediction can be explained, the consistency of predictions with technician experience, and the accessibility of explanations to users with varying technical backgrounds (Ribeiro *et al*., 2016). Each of these dimensions bears on the probability that a prediction will be understood, trusted, and acted upon, and the framework represents them collectively under the concept of actionable interpretability, distinguishing it from interpretability in the narrow technical sense. By treating actionable interpretability as a design criterion alongside accuracy, the framework provides a principled basis for evaluating the trade-offs between predictive power and usability that arise in the design of maintenance systems for distributed renewable assets.

The framework also builds on a sociotechnical understanding of the maintenance setting, treating the technician not as a passive recipient of model outputs but as an active agent who integrates those outputs with prior experience, contextual knowledge, and practical judgment (Endsley, 1995). This treatment recognizes that experienced technicians possess domain knowledge that models do not fully capture, and that the relationship between model recommendations and technician decisions should be one of augmentation rather than replacement. By positioning the model as a tool that enhances technician judgment rather than supplants it, the framework designs for a human-machine partnership that is more robust than either pure automation or pure human judgment, and it identifies the interface design principles that make this partnership effective in the diverse settings of distributed renewable asset maintenance.

A further foundational element concerns the organizational conditions that govern whether predictive maintenance systems are used effectively, including the incentive structures, training programs, and management practices that shape how technicians engage with model recommendations (Rogers, 2003). The framework treats these conditions as part of the design problem rather than as external variables that practitioners must simply accept, arguing that they can and must be addressed alongside the technical design of the model if operational performance is to be achieved. This means that a complete design for a predictive maintenance system encompasses not only the model and its interface but the organizational arrangements that determine how it is integrated into maintenance workflows and how its recommendations are acted upon.

The framework rests on an explicit account of the feedback dynamics through which model recommendations shape maintenance actions and maintenance actions shape asset condition, which in turn determines the distribution of future model training data (Kahneman, 2011). This feedback creates the risk of systematic biases in model performance if the training data reflects not the actual distribution of asset conditions but the distribution that emerges from biased maintenance decisions. The framework addresses this risk by representing the feedback loop explicitly and directing attention toward monitoring and calibration mechanisms that detect and correct for biases as they develop. This dynamic treatment of model performance reflects the framework's commitment to operational rather than static technical performance as the criterion of success.

The conceptual foundation of the framework is the treatment of energy systems as socio-technical systems in which technical and social elements are mutually constitutive, so that the boundary conventionally drawn between them is understood as a methodological choice rather than a feature of the world (Bednar *et al*., 2017). On this view, the design of a system for predictive maintenance of distributed renewable assets is simultaneously the design of a social arrangement that distributes capability, cost, and risk among households, operators, financiers, and institutions. The framework makes this dual character explicit and builds from it a representation in which technical specifications and social conditions are expressed in commensurable terms, so that they can be reasoned about jointly rather than handed off from one discipline to another at the boundary of a project (Arumosoye & Obriki, 2019; Arumosoye & Obriki, 2021).

From this foundation the framework derives its central design principle, namely that social and institutional variables should enter the design problem from the outset rather than being introduced after technical choices have been fixed (Dagodzo, 2018a). This principle responds directly to a pattern documented across the literature, in which sequential design, technical first and social afterward, produces systems whose social fit is determined by decisions already made before social considerations were ever weighed. By admitting variables such as the gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones into the problem at the stage when the design space is still open, the framework changes which configurations are considered viable and thereby alters the outcomes that design can reach, a shift that is conceptual in character but practical in consequence (Bhattacharyya *et al*., 2021; Collath, 2021).

The framework is constructed so that the social conditions it represents are not treated as qualitative background but are given explicit conceptual definition, with each condition characterized in terms that could in principle be observed and compared across settings (Dagodzo & Patrick, 2021a). This insistence on definition is what distinguishes the approach from accounts that acknowledge social factors rhetorically while excluding them from systematic reasoning. In specifying predictive maintenance of distributed renewable assets in these terms, the framework provides a structured way to ask, of any candidate design, not only whether it performs but whether the conditions on which its durability depends are present, and where they are absent, what would be required to establish them (Dagodzo, 2018b; Dagodzo & Patrick, 2020).

A complementary foundational commitment of the framework is that it is built to be recalibrated rather than copied, since the conditions that govern durability vary across regions even when the underlying technology does not (Guerrero *et al*., 2013). The framework therefore separates its general structure, the claim that technical and social variables jointly determine outcomes and must be jointly considered, from the particular weightings and conditions that apply in a given setting. This separation is what allows the framework to travel: its logic can be carried into a new resource-dependent or transitioning region while its specific content is re-examined against local conditions, an approach that respects context without abandoning generality (Dagodzo & Patrick, 2021b; Ewim *et al*., 2021).

The framework rests on a clear distinction between the quality of a design and the conditions under which it is deployed, a distinction that much of the technical literature collapses by assuming favorable conditions as a systematic consequence (Liu *et al*., 2014). By holding the two apart, the framework is able to ask, of any intervention in predictive maintenance of distributed renewable assets, not only whether its design is sound but whether the conditions required for that design to perform and endure are present. This separation is foundational because it locates the explanation of many documented failures not in the design itself but in the mismatch between design and context, and it directs attention toward the conditions that determine whether technical soundness is actually realized in service (International Energy Agency, n.d.; Jessel *et al*., 2019).

A foundational feature of the framework is its treatment of the social conditions governing durability as variables that can be characterized, compared, and influenced, rather than as fixed background or as matters beyond the reach of design (Mbonu *et al*., 2021b). This treatment is what allows the framework to be more than a restatement of the truism that context matters, since it specifies which aspects of context matter, in what way, and through which mechanisms. In giving the gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones and related conditions explicit conceptual standing, the framework provides a structured basis for reasoning about interventions that would otherwise rest on intuition, and it does so in terms general enough to apply across the varied settings in which the field operates (Mbonu *et al*., 2020a; Mbonu *et al*., 2021a).

A foundational commitment of the framework is to representing the interaction between technical and social factors rather than merely listing them side by side, since it is the interaction that distinguishes a genuinely socio-technical account from the simple addition of social commentary to technical analysis (Mbonu *et al*., 2021c). The framework posits that the returns to technical quality depend on social conditions and that the returns to social investment depend on technical adequacy, and it builds this mutual dependence into its structure. For predictive maintenance of distributed renewable assets, this means that the framework does not treat a system as the sum of separately optimized technical and social parts, but as an integrated whole whose performance emerges from the interplay of both, which is the conceptual heart of the approach (Mbonu *et al*., 2019a; Mbonu *et al*., 2020b).

The framework's foundations include an explicit account of how the conditions it represents change over time, since participation, capacity, trust, and legitimacy are not fixed at deployment but are built or eroded through the way a system is operated and governed (Nnaji *et al*., 2019). By treating these conditions as dynamic rather than static, the framework captures the trajectories along which interventions in predictive maintenance of distributed renewable assets succeed or fail, and it avoids the error of inferring long-term durability from initial performance. This temporal dimension is foundational because it reframes durability as something sustained through ongoing socio-technical interaction rather than secured once at commissioning, with corresponding implications for how systems should be designed and governed (Mbonu *et al*., 2019b; Muhtadi *et al*., 2021; Lilian *et al*., 2020).

A further foundational element is the framework's treatment of distribution, which it incorporates from the outset rather than appending as an afterthought, on the reasoning that the allocation of benefits and burdens across groups is integral to the evaluation of any intervention (Obogo *et al*., 2020b). The framework represents not only whether a system performs but for whom it performs, capturing the distributional outcomes that aggregate measures obscure. Particularly for regions transitioning away from fossil fuel dependence, this foundational attention to distribution is essential, since the legitimacy and durability of an intervention depend on whether its benefits are seen to be fairly shared among the populations it affects (Nnaji *et al*., 2020; Obogo *et al*., 2020a).

The framework rests, finally, on a commitment to commensurability, namely the requirement that technical and social factors be represented in terms that allow them to be weighed together in a single analysis (Obogo *et al*., 2021b). Without commensurability, integration is impossible, and the framework would collapse into the parallel consideration of technical and social factors that prior work has already shown to be inadequate. The foundations therefore specify how the social conditions are characterized so that they can sit alongside technical parameters in a common analysis, and this insistence on commensurable representation is what enables the framework to support genuinely joint reasoning about interventions in predictive maintenance of distributed renewable assets rather than merely sequential consideration of their technical and social aspects (Obogo *et al*., 2020c; Obogo *et al*., 2021a).

A further foundational element is the framework's explicit treatment of context, which it represents so that the general logic of the analysis can be applied to the specific conditions of a given setting (Obogo *et al*., 2021c). This treatment is what allows the framework to be transferable without being generic, since it separates the enduring structure of the analysis from the variable conditions that must be re-examined locally. The explicit representation of context is foundational because it guards against the assumption that an intervention suited to one environment will perform in another, an assumption the literature repeatedly identifies as a source of failure (Obogo *et al*., 2019a; Obogo *et al*., 2019b).

The framework rests, additionally, on a clear account of the relationship between participation and durability, treating the willingness and ability of communities to use, pay for, maintain, and govern a system as conditions on which its endurance depends (OECD, n.d.). By representing participation as a determinant rather than a byproduct of success, the framework captures a relationship the evidence consistently identifies (Odejobi & Ahmed, 2018). Within this context, this foundational treatment of participation reframes the community as a co-author of outcomes rather than a passive setting, with corresponding implications for how interventions are designed and governed. This foundational commitment shapes the components of the framework specified in the following section.

A final foundational commitment concerns the framework's orientation toward action, since it is built to inform the choices through which interventions are designed rather than merely to describe them (Okonkwo *et al*., 2020). Its foundations are specified in terms that correspond to questions practitioners can pose about candidate interventions, and its logic is intended to guide the sequence of design decisions (Ogunwole *et al*., 2021). This action orientation is foundational because it determines whether the framework remains a theoretical abstraction or becomes an operational instrument that informs design and implementation decisions, which is its intended application. The framework operationalises this commitment by representing technical and social factors within a common analytical structure.

A connected foundational element concerns the framework's treatment of distribution within communities as well as between them, since the conditions governing durability include not only how interventions affect different communities but how their benefits and burdens fall among groups within a community (Okonkwo *et al*., 2018b). The framework is constructed to represent these intra-community distributions, recognizing that an intervention improving a community's circumstances overall may still affect its members unequally. In such settings, this foundational attention to internal distribution reflects the evidence that aggregate outcomes can mask disparities, and it ensures that the framework's account of equity encompasses differences within as well as between the populations served (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2018a).

The framework rests, additionally, on an account of environmental resilience as integral to durability, treating the conditions a system will encounter, including climatic stress and exposure to environmental change, as part of what determines whether it endures (Patrick *et al*., 2020). By representing these conditions among the factors governing durability, the framework avoids the error of assessing a system's prospects apart from the environment in which it must operate. Applied to this domain, this foundational treatment of resilience reflects the demanding conditions of the regions concerned, and it ensures that the framework's account of durability accommodates the environmental as well as the social and technical determinants (Okonkwo *et al*., 2021b; Okwu *et al*., 2021).

A foundational commitment of the framework concerns its lifecycle perspective, since it treats the conditions governing durability as extending over the full working life of a system rather than as established at its deployment (Smith, 2017). This commitment shapes the framework's representation of cost, capacity, and the social conditions, all of which it treats as matters to be sustained over time. On this account, this lifecycle foundation reflects the evidence that durability is determined less by the moment of commissioning than by the years of operation, and it orients the framework toward the conditions that govern whether a system continues to function and to serve its population over time (Patrick *et al*., 2021; Shittu *et al*., 2019).

The framework rests, finally, on the conviction that the conditions it represents, however difficult to quantify, can be given conceptual definitions precise enough to support reasoning, so that the difficulty of measurement is not a reason to exclude them (World Resources Institute, n.d.). This commitment to the systematic treatment of social conditions distinguishes the framework from approaches that acknowledge such conditions rhetorically while leaving them outside analysis. For predictive maintenance of distributed renewable assets, this foundational move is what enables the framework to consider social factors alongside technical ones in a single account, and it reflects the broader argument that the social determinants of durability are as amenable to systematic treatment as the technical determinants (Sunday & Omoegun, 2018; Sunday & Omoegun, 2019).

A useful way to understand the framework's foundations is to consider the alternative it is meant to replace, namely the sequential approach in which technical design is completed first and social considerations are introduced afterward (Agbabiaka *et al*., 2019). The framework rejects this sequence on the grounds that it determines the influence of social conditions before those conditions have been weighed, foreclosing options that an integrated approach would keep open. By admitting social and technical considerations into the design problem together, the framework changes which configurations are considered viable, and this foundational reordering of the design process, rather than any single technical or social insight, is what distinguishes the approach and gives it its practical consequence for predictive maintenance of distributed renewable assets (Wustenhagen *et al*., 2007; Yeboah & Ike, 2020).

The framework's foundations also rest on a particular understanding of how generality and context relate, since the conditions governing durability vary across settings even where the underlying technology does not (Ambali *et al*., 2021). Rather than seeking a universal prescription or retreating into case-by-case description, the framework separates a general structure, the claim that technical and social factors jointly determine outcomes, from the context-specific content that must be re-examined in each setting. This separation is foundational because it allows the framework to be applied across the diverse contexts in which predictive maintenance of distributed renewable assets operates without assuming that what holds in one place holds in another, reconciling generality with sensitivity to context (Ahmad *et al*., 2020; Ahmed *et al*., 2020).

4. Components of the Proposed Framework

The framework's component addressing data quality and representativeness treats the provenance and coverage of sensor data as a first-order design concern, recognizing that models trained on data from well-maintained assets in favorable conditions may perform poorly when applied to assets in different states or environments (Lee *et al*., 2014). For distributed renewable assets, where conditions vary widely across geography, age, and maintenance history, representativeness is a particular challenge, and the framework specifies the data auditing and augmentation strategies required to address it. By treating data quality as a component of the design problem rather than a precondition to be assumed, the framework brings an important source of performance variability under systematic analysis rather than leaving it to emerge as an unexplained source of field disappointment.

A further component addresses the design of the human-model interface, which the framework treats as a distinct engineering task with its own requirements and criteria (Ribeiro *et al*., 2016). The interface must present model outputs in forms that are interpretable to technicians with varying backgrounds, must communicate the model's uncertainty so that users can calibrate their response appropriately, and must integrate with the mobile and communication tools that technicians use in the field. The framework specifies these interface requirements in terms that can guide design, drawing on the human factors and user experience literatures to identify the principles that make maintenance support interfaces effective rather than merely technically capable. This component reflects the framework's treatment of the gap between model accuracy and technician adherence as a design problem with an engineering solution.

The component addressing workflow integration treats the fit between predictive maintenance recommendations and established maintenance routines as a determinant of adoption that must be designed for explicitly (Mobley, 2002). Systems that require technicians to interrupt existing workflows, learn new procedures, or navigate unfamiliar interfaces are less likely to be adopted than those whose recommendations arrive in forms that fit naturally into how maintenance work is organized. The framework specifies workflow analysis as a required step in system design, arguing that understanding how maintenance decisions are currently made is a precondition for designing a system that improves on them rather than creating additional friction. This component positions human factors research as a legitimate input to engineering design rather than a post-hoc consideration.

The training and capacity component of the framework addresses the knowledge and skills that technicians require to use predictive maintenance systems effectively, treating training as a design input rather than a deployment afterthought (Rogers, 2003). Effective training for distributed renewable asset maintenance must cover not only how to interpret and act on model outputs but also the principles that make the model's predictions meaningful, so that technicians can recognize when the model is operating outside its training distribution and apply appropriate judgment. The framework specifies the training requirements that follow from the model's design, arguing that the complexity of the model determines the complexity of the training required and that designing a model without considering its training implications is a form of planning for the gap between accuracy and adherence.

A concluding component addresses the monitoring and continuous improvement arrangements through which the operational performance of a deployed predictive maintenance system can be tracked and improved over time (Smith *et al*., 2017). Models trained on historical data become stale as asset conditions, maintenance practices, and environmental conditions evolve, and the mechanisms for detecting and correcting for this staleness are part of the system design. The framework specifies the monitoring indicators, update protocols, and retraining triggers that constitute a complete continuous improvement arrangement for a predictive maintenance system, treating the post-deployment lifecycle as a design domain rather than an operational afterthought. This component reflects the framework's dynamic treatment of model performance and its commitment to operational rather than static technical criteria.

The first component of the framework concerns the representation of technical performance under realistic operating conditions, capturing not only nominal capability but the dependence of that capability on the maintenance, connectivity, and environmental conditions characteristic of resource-constrained settings (Arumosoye & Obriki, 2021). Rather than assuming that performance demonstrated under favorable conditions will be realized in the field, this component makes the gap between the two an explicit object of reasoning. In doing so it reframes a question that idealized analyses tend to settle by assumption, asking instead what level of performance is sustainable given the conditions a system will actually encounter over its working life within predictive maintenance of distributed renewable assets (Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2019).

The second component concerns the representation of social and institutional conditions, centrally the gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones, expressed in a form that can sit alongside technical specifications rather than in a separate register (Collath, 2021). This component identifies the conditions that the literature associates most consistently with durable outcomes, including participation, local capacity, governance legitimacy, and procedural fairness, and it gives each a conceptual definition that supports comparison across settings. By treating these conditions as design variables rather than as fixed background, the framework makes them objects that design and governance can deliberately influence, transforming the recognition that social factors matter into a structured account of which factors matter and how (Bednar *et al*., 2017; Bhattacharyya *et al*., 2021). These components and the relationships among them are depicted in Figure 2.

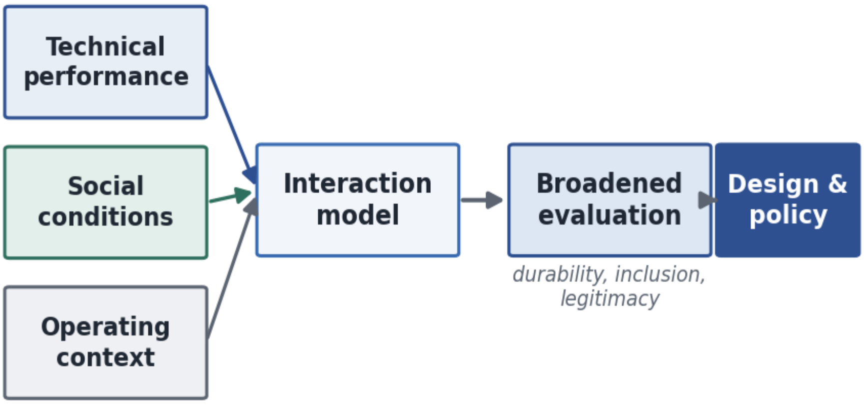

Fig 2: Components of the proposed conceptual framework and the relationships among them.

The third component specifies the relationships between the technical and social elements, and in particular the interaction through which the returns to technical quality depend on social conditions and the returns to social investment depend on technical adequacy (Dagodzo & Patrick, 2020). This interaction is the conceptual heart of the framework, since it is what distinguishes a genuinely socio-technical account from the mere addition of social commentary to technical analysis. By representing the two sets of variables as jointly determining outcomes, the framework explains why interventions strong on only one dimension tend to disappoint, and it identifies the configurations in which technical capability and social legitimacy reinforce rather than undercut one another within predictive maintenance of distributed renewable assets (Dagodzo, 2018a; Dagodzo, 2018b).

The fourth component concerns evaluation, and it broadens the criteria of success beyond technical performance and unit cost to encompass durability, inclusion, and legitimacy, which the framework treats as first-order objectives rather than incidental byproducts (Ewim *et al*., 2021). Because what is measured tends to be what is optimized, this broadening of the evaluation criteria is a lever for broadening what design seeks to achieve. The component specifies how these wider outcomes can be characterized in commensurable terms, so that a design which performs well technically but poorly on the conditions governing durability is recognized as deficient rather than counted a success, as it would be under a narrowly technical standard (Dagodzo & Patrick, 2021a; Dagodzo & Patrick, 2021b).

A further component of the framework concerns the representation of context, capturing the climatic, infrastructural, economic, and institutional conditions that distinguish one setting from another and that determine how the general logic of the framework applies in a particular case (Jessel *et al*., 2019). This component is what makes the framework transferable, since it separates the enduring structure of the analysis from the variable conditions that must be re-examined in each new setting. The explicit representation of context guards against the error of assuming that an intervention suited to one environment will perform in another, an error that the literature identifies as a recurrent source of failure and that the framework is designed to help practitioners avoid (Guerrero *et al*., 2013; International Energy Agency, n.d.).

The components of the framework are designed to operate together rather than in isolation, and their integration is itself a defining feature of the model (Mbonu *et al*., 2021a). The representation of technical performance, of social conditions, of their interaction, of context, and of the broadened evaluation criteria are not separate modules to be considered one at a time but interdependent elements of a single account, in which a change in one bears on the others. This interdependence reflects the socio-technical premise on which the framework rests, namely that the factors governing the outcomes of interventions in predictive maintenance of distributed renewable assets are themselves interconnected, and it is what distinguishes the framework from approaches that treat technical and social analysis as additive rather than integrated (Liu *et al*., 2014; Mbonu *et al*., 2020a).

A component of the framework concerns the explicit representation of stakeholders and their relationships, since the outcomes of interventions in predictive maintenance of distributed renewable assets emerge from the interaction of households, community institutions, operators, financiers, and regulators whose interests are not always aligned (Mbonu *et al*., 2020b). By representing these actors and the ways their interests bear on the system, the framework captures the negotiation and accommodation through which what is actually built and sustained is determined. This stakeholder component is what allows the framework to reason about questions of authority, benefit, and accountability, which the evidence identifies as decisive for durability and which a purely technical representation of a system would entirely omit (Mbonu *et al*., 2021b; Mbonu *et al*., 2019a).

Another component addresses the matching of system complexity to local capacity, which the literature identifies as a binding condition on durability across many settings (Muhtadi *et al*., 2021). The framework represents the capacity available to operate, maintain, and govern a system as an explicit constraint, against which the complexity of a candidate design must be assessed. This component embeds the principle that capability exceeding the local ability to sustain it tends to decay regardless of its initial quality, and it directs design toward configurations whose demands are matched to the capacity that can realistically be established and maintained in the setting concerned (Mbonu *et al*., 2021c; Mbonu *et al*., 2019b).

The evaluation component of the framework deserves particular emphasis, since by broadening the criteria of success beyond technical performance and unit cost to encompass durability, inclusion, and legitimacy, it changes what design is oriented toward achieving (Obogo *et al*., 2020a). The framework specifies how these broader outcomes can be characterized in terms commensurable with technical and economic measures, so that they enter evaluation on an equal footing. Within this context, this component operationalizes the framework's central conviction that what is measured shapes what is built, and that aligning the criteria of evaluation with the goals of inclusive transition is a precondition for designing interventions that serve the populations they are meant to reach (Nnaji *et al*., 2019; Nnaji *et al*., 2020).

A final component concerns the framework's diagnostic use, namely its capacity to anticipate the likely failure modes of a proposed intervention from its treatment of the social and institutional conditions governing durability (Obogo *et al*., 2021a). By examining whether the conditions on which an intervention depends are present and likely to be sustained, the framework allows weaknesses to be identified and addressed before commitments are made rather than discovered after a system has faltered in service. For problems of this kind, this diagnostic component is among the framework's most practically valuable features, since it turns the analytical insight that social conditions govern durability into a forward-looking tool for improving the design of interventions before they are built (Obogo *et al*., 2020b; Obogo *et al*., 2020c; Basnet *et al*., 2021).

A further component concerns the representation of time, since the framework treats the conditions governing durability as evolving over the life of a system rather than fixed at its deployment (Obogo *et al*., 2019a). This temporal component captures the trajectories along which interventions succeed or fail, and it directs design toward establishing conditions that will be sustained rather than conditions that merely exist at commissioning (Obogo *et al*., 2021b). In such settings, the temporal component is essential because it reframes durability as something achieved through ongoing socio-technical interaction, with implications for how systems are operated and governed across their working lives. This component operates together with the others to support the framework's integrated analysis of interventions.

A further component addresses the relationship between an intervention and the prior context into which it is introduced, recognizing that systems are never deployed onto a blank slate (Obogo *et al*., 2021c). The framework represents the histories, expectations, and sometimes the distrust that condition a community's reception of an intervention, since these bear on the legitimacy and trust on which durability depends (Obogo *et al*., 2019b). Applied to this domain, this component captures why interventions with identical technical specifications may be received very differently depending on what preceded them, a consideration that purely prospective technical analysis omits. The framework relies on this component in reasoning jointly about technical and social determinants of durability.

The components are designed, finally, to support the framework's diagnostic use, allowing the likely failure modes of a proposed intervention to be anticipated from its treatment of the conditions governing durability (OECD, n.d.). By examining whether those conditions are present and likely to be sustained, the framework enables weaknesses to be identified before commitments are made (Odejobi & Ahmed, 2018). On this account, this diagnostic capacity is among the framework's most practically valuable features, since it turns the recognition that social conditions govern durability into a forward-looking tool for improving the design of interventions before they are built. This element of the framework captures a determinant of durability that narrower analyses tend to omit.

An additional component of the framework concerns the representation of distributional outcomes, capturing not only whether an intervention improves conditions but how its benefits and burdens fall across and within the communities it serves (Okonkwo *et al*., 2020). This component renders explicit the distributional consequences that aggregate measures obscure, including differences along lines of income and gender (Ogunwole *et al*., 2021). For predictive maintenance of distributed renewable assets, the distributional component is essential to the framework's account of equity, since it allows an intervention that improves aggregate conditions while leaving some groups unreached to be recognized as falling short of the inclusive outcomes the framework treats as a criterion of success. Including this as a component reflects the framework's treatment of the relevant factors as design variables.

A component of the framework addresses environmental resilience, representing the conditions a system will encounter over its life and the demands these place on its design and operation (Okonkwo *et al*., 2018b). This component captures the climatic stress and environmental change that bear on durability in the regions of concern, ensuring that a system's prospects are assessed in light of the environment it must withstand. The resilience component reflects the framework's treatment of durability as conditional on the environment of deployment, and it guards against assessments that consider technical and social factors while neglecting the environmental conditions that can undermine even well-designed systems (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2018a).

A further component concerns lifecycle cost, representing the costs of operation, maintenance, and replacement alongside those of installation, and their distribution over time and across groups (Okwu *et al*., 2021). This component captures the affordability that conditions sustained use, which a focus on upfront cost would misjudge (Okonkwo *et al*., 2021b). The lifecycle cost component reflects the framework's emphasis on durability, since it directs attention to whether an intervention remains affordable to sustain over its working life, a condition the evidence identifies as bearing directly on whether systems continue to function and to serve their populations over time. This component contributes to the framework's capacity to anticipate the conditions on which durability depends.

A final component concerns the representation of the conditions under which the framework's general logic applies to a particular setting, capturing the environmental, institutional, economic, and social characteristics that distinguish one context from another (Shittu *et al*., 2019). This component is what makes the framework transferable without being generic, since it separates the enduring structure of the analysis from the variable conditions to be re-examined locally. Within this context, this contextual component ensures that the framework can be applied across the diverse settings the field encompasses, by relating its general structure to the specific conditions that determine how that structure applies in any given case (Patrick *et al*., 2020; Patrick *et al*., 2021).

A concluding note on the components is that their value lies in their integration, since the framework is constructed so that the representations of technical performance, social conditions, their interaction, context, distribution, environmental resilience, lifecycle cost, and evaluation function together as a single account rather than as separate analyses (Sunday & Omoegun, 2019). The note emphasizes that this integration is what distinguishes the framework from the parallel consideration of technical and social factors that prior work has shown to be inadequate, and that the components are designed accordingly to inform one another in the analysis of interventions in predictive maintenance of distributed renewable assets. This component contributes to the framework's capacity to reason about durability before deployment (Smith, 2017; Sunday & Omoegun, 2018).

It warrants emphasis that the components of the framework relate to one another, since their value lies less in any single element than in the way they combine to support integrated reasoning about predictive maintenance of distributed renewable assets (Yeboah & Ike, 2020). The representation of technical performance, the representation of social conditions, the model of their interaction, the account of context, and the broadened evaluation criteria are designed to inform one another, so that a judgment about any one draws on the others. This interdependence is what distinguishes the framework from the mere juxtaposition of technical and social analysis, and it reflects the socio-technical premise that the factors governing outcomes are themselves interconnected rather than separable (World Resources Institute, n.d.; Wustenhagen *et al*., 2007).

A further consideration in the design of the components is that each is specified at a level of generality that supports application across settings while remaining concrete enough to guide reasoning about particular interventions (Ahmed *et al*., 2020). The components identify what must be considered, the technical capability under realistic conditions, the social conditions governing durability, their interaction, the context, and the criteria of success, without dictating the specific content that applies in a given case. This balance between generality and concreteness is deliberate, since a framework too abstract would offer little guidance while one too specific would not transfer, and the components are calibrated to be useful across the range of settings in which predictive maintenance of distributed renewable assets is pursued (Agbabiaka *et al*., 2019; Ahmad *et al*., 2020).

5. Socio-Technical Analysis

The socio-technical analysis of predictive maintenance for distributed renewable assets identifies a set of trust dynamics that are central to the gap between model accuracy and technician adherence (Endsley, 1995). Trust in a diagnostic system is built through consistent performance, transparent reasoning, and alignment between system recommendations and technician experience, and it is eroded by false alarms, opaque outputs, and recommendations that appear arbitrary or inconsistent with what experienced technicians know. The framework represents these trust dynamics explicitly, arguing that the design of predictive maintenance systems must treat trust as a behavioral outcome to be engineered rather than a social phenomenon beyond the reach of design. This means attending to accuracy on the cases that matter most to technicians, to the quality of explanations for counterintuitive recommendations, and to the mechanisms through which model errors are acknowledged and corrected.

A related dimension of the socio-technical analysis concerns the organizational politics of introducing predictive maintenance systems into settings where they may be perceived as threatening the autonomy or status of experienced technicians (Rogers, 2003). Where technicians experience model recommendations as challenges to their expertise rather than supports for their judgment, resistance is a predictable consequence, and this resistance can manifest as selective adherence, superficial compliance, or active undermining of the system. The framework identifies this organizational dynamic as a risk factor that design must address, arguing that the positioning of predictive maintenance systems as expertise-augmenting rather than expertise-replacing tools is both a communication strategy and a design principle that shapes how the system is experienced by its users.

The analysis also considers how the organizational setting of distributed renewable asset maintenance, often characterized by geographically dispersed field teams with limited supervision and high autonomy, shapes the conditions under which predictive maintenance recommendations are acted upon (Kahneman, 2011; Mobley, 2002). Under these operational conditions, the quality of a technician's response to a model recommendation depends largely on their individual understanding, trust, and judgment, without the organizational checks that centralized maintenance settings provide. The framework addresses this by identifying the training, interface design, and feedback mechanisms that support consistent and effective use of predictive maintenance systems across the distributed organizational structures of renewable energy operators, treating the organizational geography of maintenance as a design constraint rather than a background condition.

Interpreting predictive maintenance of distributed renewable assets through the socio-technical framework brings into focus the mechanisms by which social conditions become technical outcomes, mechanisms that are concrete and traceable rather than abstract (Arumosoye & Obriki, 2019). They operate through the decisions that communities and operators make about use, payment, maintenance, and stewardship, and through the institutional arrangements that distribute authority and accountability among the parties to a system. Tracing these mechanisms is what converts the general proposition that social conditions matter into specific, actionable design knowledge, since knowing how a condition such as the gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones shapes outcomes indicates where intervention will be effective and what would be required to establish the conditions on which durability depends (Ambali *et al*., 2021; Arumosoye & Obriki, 2018).

The distributional dimension of the framework draws attention to the way design choices made on narrowly technical grounds nonetheless allocate benefits and burdens across groups, determining who gains from an intervention and who bears its costs (Bhattacharyya *et al*., 2021). Because these allocations bear directly on the fairness and the legitimacy of energy provision, the framework treats them as integral to design rather than as consequences to be assessed afterward. For regions transitioning away from fossil fuel dependence, the distributional consequences are especially significant, since the durability of the transition depends on whether its benefits are seen to be fairly shared, and a framework that leaves distribution implicit risks reproducing the very inequalities that inclusive transition is meant to address (Arumosoye & Obriki, 2021; Bednar *et al*., 2017).

The framework also clarifies the role of governance and institutional arrangements, which emerge as inseparable from technical design in determining outcomes (Dagodzo, 2018b). The way authority, accountability, and ownership are distributed interacts with the technical configuration of a system to shape both its performance and its legitimacy, and arrangements that communities regard as fair and that hold operators to account are associated with more durable operation. Within predictive maintenance of distributed renewable assets, this means that the design of governance is part of the design of the system itself, and the framework treats it accordingly, representing institutional arrangements as variables that influence outcomes rather than as a separate administrative layer added once the technical work is complete (Collath, 2021; Dagodzo, 2018a).

A further dimension of the socio-technical analysis concerns the temporal character of the conditions governing durability, since participation, capacity, trust, and legitimacy are not fixed at the moment of deployment but evolve over the life of a system (Dagodzo & Patrick, 2021b). The framework represents these conditions as dynamic, recognizing that they can be built or eroded by the way a system is operated and governed, and that early conditions are therefore not destiny. For problems of this kind, this dynamic view matters because it implies that durability is not secured once and for all at commissioning but is sustained, or lost, through the ongoing interaction of technical operation and social conditions over time, which is precisely what a static, installation-focused analysis fails to capture (Dagodzo & Patrick, 2020; Dagodzo & Patrick, 2021a).

A further strand of the socio-technical analysis concerns the way procedural fairness and transparency build the trust on which cooperation, and therefore durability, depend, a relationship the framework represents explicitly (International Energy Agency, n.d.). Where communities perceive that decisions are made fairly and that resources are managed transparently, they tend to engage in ways that sustain a system, while perceived unfairness tends to erode the cooperation a system requires. In such settings, this means that procedural matters are not ethical niceties external to the technical work but determinants of technical outcomes, and the framework treats them accordingly, representing the fairness of process as a condition that bears directly on whether an intervention endures (Ewim *et al*., 2021; Guerrero *et al*., 2013).

The analysis also draws attention to the way histories of extraction, neglect, and unmet promises shape the reception of new interventions in many of the regions concerned, conditioning the trust and legitimacy on which durability depends (Mbonu *et al*., 2020a). The framework accommodates this by representing the prior context into which an intervention is introduced, recognizing that systems are never introduced onto a blank slate. Applied to this domain, this historical dimension explains why technically sound interventions imposed without genuine participation so often struggle, and why establishing legitimacy may require explicit attention to the relationship between an intervention and the history that precedes it in a given setting (Jessel *et al*., 2019; Liu *et al*., 2014).

Another aspect of the analysis concerns the question of who holds authority over a system and how that authority is exercised, since the framework treats governance as inseparable from technical design in determining outcomes (Mbonu *et al*., 2019a). Arrangements that distribute authority in ways communities accept, and that hold operators accountable, are associated with more durable operation, while arrangements that concentrate control outside the community tend to be resisted even when technically optimal. On this account, the analysis thus identifies governance design as part of the design of the system itself, and the framework represents institutional arrangements as variables that shape both performance and legitimacy rather than as a separate administrative layer (Mbonu *et al*., 2021a; Mbonu *et al*., 2021b).

A complementary dimension of the analysis concerns the matching of system complexity to local capacity, which the framework represents as a determinant of durability rather than a secondary consideration (Mbonu *et al*., 2021c). Where the demands a system places on its operators and governing institutions exceed the capacity available to meet them, the analysis indicates that the system will tend to decay regardless of its technical quality (Mbonu *et al*., 2020b). For predictive maintenance of distributed renewable assets, this dimension directs design toward configurations whose demands are matched to the capacity that can realistically be established and sustained, which the framework treats as essential to inclusive outcomes. The framework represents this condition accordingly, as a determinant of durability that design can address.

The analysis also attends to the distributional consequences of design choices, tracing how decisions made on technical grounds nonetheless allocate benefits and burdens across groups (Muhtadi *et al*., 2021). Because these allocations determine for whom an intervention works, the framework treats them as integral to its analysis rather than as outcomes to be assessed afterward (Mbonu *et al*., 2019b). Particularly for regions in transition, this distributional dimension is central, since the legitimacy and durability of an intervention depend on whether its benefits are seen to be fairly shared among the populations it affects. This dimension reflects the framework's treatment of social conditions as interrelated rather than independent.

The analysis finally considers how the conditions it identifies can be deliberately influenced through design and governance, since the framework's practical value depends on their being levers rather than fixed constraints (Nnaji *et al*., 2020). By identifying which conditions are modifiable and through what means, the analysis converts the recognition that social factors govern durability into a structured set of choices (Nnaji *et al*., 2019). This is the primary contribution of the socio-technical analysis, namely a disciplined way of reasoning about how to establish the conditions on which durable, inclusive service depends. The framework captures this relationship in reasoning jointly about technical and social determinants. This dimension is addressed within the framework, which treats the relevant condition as a lever for intervention.

A related facet of the socio-technical analysis concerns the role of information and transparency, since the framework recognizes that the availability of clear information about a system's operation, costs, and governance conditions the trust on which cooperation depends (Obogo *et al*., 2020b). Where information is shared openly, communities are better able to engage with and hold accountable those responsible for a system, while opacity tends to erode confidence (Obogo *et al*., 2020a). Within this context, the analysis treats transparency as a condition bearing on durability, and the framework represents it accordingly, as a feature of governance that influences whether technical capability is translated into sustained and accepted service. This dimension illustrates how the framework converts the recognition that society matters into design knowledge.

The analysis also considers the relationship between the scale of an intervention and the social conditions governing its durability, since the framework recognizes that arrangements suited to one scale may not suit another (Obogo *et al*., 2021a). Small community systems and larger shared infrastructures pose different demands on capacity, governance, and participation, and the conditions for durability vary accordingly (Obogo *et al*., 2020c). For problems of this kind, the analysis treats scale as a factor mediating the relationship between social conditions and outcomes, and the framework accommodates this by relating the conditions it represents to the scale of the intervention under consideration. The framework represents this condition as a determinant of durability that design can influence.

An additional dimension of the analysis concerns the cumulative effect of the social conditions the framework represents, since these conditions interact rather than operating independently (Obogo *et al*., 2019a). The analysis suggests that favorable conditions tend to reinforce one another, as participation supports legitimacy and legitimacy supports cooperation, while unfavorable conditions can compound, as low capacity undermines performance and poor performance erodes trust (Obogo *et al*., 2021b). In such settings, the framework captures these interactions, treating the social conditions not as a checklist of independent factors but as an interrelated system whose combined state governs the durability of an intervention. This dimension reflects the framework's treatment of social conditions as interrelated.

A further element of the socio-technical analysis concerns the gendered distribution of benefits and burdens, since the framework recognizes that interventions affect women and men differently within the same community and that these differences bear on equity and durability (Obogo *et al*., 2021c). By representing intra-community distribution, the framework captures disparities that aggregate measures obscure, allowing design to attend to them deliberately (Obogo *et al*., 2019b). Applied to this domain, this dimension reflects the framework's treatment of distribution as encompassing differences within communities, and it ensures that the analysis of equity considers how benefits and burdens fall among groups and not only across communities as wholes. The framework captures this relationship in reasoning jointly about technical and social factors.

The analysis also considers the affordability of interventions over time, since the framework treats the capacity of a population to sustain the costs of operation and maintenance as a condition of durability (OECD, n.d.). Where ongoing costs exceed what a community can afford, the analysis indicates that use will decline and durability will suffer, regardless of the system's technical quality (Odejobi & Ahmed, 2018). On this account, this dimension reflects the framework's lifecycle perspective, and it directs attention to whether interventions remain affordable to sustain, which the framework treats as a determinant of whether they continue to function and to serve their populations over time. Acknowledging this, dimension, the framework treats the condition as a lever for intervention.

A further dimension of the analysis concerns the recognition of local knowledge and priorities, since the framework treats the extent to which an intervention accommodates the circumstances and understanding of the community it serves as bearing on its legitimacy and durability (Okonkwo *et al*., 2020). Where local knowledge is recognized and incorporated, the analysis associates the intervention with the acceptance and stewardship that condition durable operation (Ogunwole *et al*., 2021). For predictive maintenance of distributed renewable assets, this dimension reflects the framework's treatment of recognition as a social condition alongside participation, distribution, and procedure, and it captures a determinant of durability that the framework represents and that design can deliberately address. This dimension shows how the framework converts recognition into actionable design knowledge.

A connected consideration in the socio-technical analysis is that the conditions it identifies do not operate in isolation but reinforce or undermine one another, so that the overall durability of an intervention depends on their combined state rather than on any single factor (Okonkwo *et al*., 2018b). Participation supports legitimacy, legitimacy supports cooperation, and cooperation sustains the maintenance and stewardship on which durable operation depends, while the erosion of any one can set in motion a decline in the others. The framework represents these conditions as an interacting system, and this systemic view is central to its account of predictive maintenance of distributed renewable assets, since it explains why interventions strong on one social dimension but weak on another often disappoint (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2018a).

The analysis also attends to the ways in which technical design choices shape the social conditions that subsequently govern durability, since the two are not independent (Patrick *et al*., 2020). The complexity of a system bears on the capacity required to sustain it, the distribution of its benefits bears on its perceived fairness, and the arrangements for its control bear on its legitimacy, so that decisions made on technical grounds carry social consequences that feed back into outcomes. The framework captures these couplings, and the analysis emphasizes that within predictive maintenance of distributed renewable assets the social conditions governing durability are partly produced by the technical choices made, which is why the two must be reasoned about together rather than in sequence (Okonkwo *et al*., 2021b; Okwu *et al*., 2021).

6. Application and Illustrative Reasoning

Applying the framework to a distributed wind farm illustrates how the gap between model accuracy and technician adherence manifests in practice and how the framework's components can be used to narrow it (Lee *et al*., 2014). A model achieving high accuracy on held-out test data may nonetheless produce low adherence if the explanations it generates are insufficiently interpretable, if its predictions arrive through an interface that disrupts established workflows, or if technicians lack the training to calibrate their trust appropriately. The framework's application identifies each of these contributing factors, enabling targeted intervention that addresses the specific sources of the gap rather than attempting comprehensive system redesign (Basnet *et al*., 2021).

A further illustration concerns the application of the framework to battery storage assets, where degradation mechanisms are diverse and the consequences of missed early detection are high (Smith *et al*., 2017). Battery predictive maintenance presents a particularly demanding application because degradation is gradual, sensor-to-failure time lags are variable, and the cost of false alarms in terms of unnecessary maintenance visits can be significant. The framework's application to this setting identifies the accuracy-interpretability trade-offs specific to battery diagnostics, the interface design requirements for communicating uncertainty about degradation state, and the training requirements that enable technicians to use battery-specific model outputs effectively. This application illustrates how the framework's general structure can be adapted to the specific requirements of different asset types within the distributed renewable portfolio.

The framework is also applied to illustrate the consequences of neglecting the organizational conditions that govern adherence, using a case in which a technically capable predictive maintenance system achieves low operational performance because the maintenance organization lacks the training, workflow integration, and incentive structures the system requires (Rogers, 2003). In this application, the framework's analysis identifies the gap between technical and operational performance, traces it to the specific organizational factors responsible, and identifies the targeted interventions that would close it. The illustration demonstrates that the framework's value lies not only in anticipating such gaps during design but in diagnosing them after deployment, providing a structured basis for system improvement that purely technical analysis could not supply.

Although the contribution of this paper is conceptual, the framework is intended to be applied, and this section illustrates the reasoning it supports without claiming to report empirical measurement (Smith, 2017). Applied to a candidate intervention in predictive maintenance of distributed renewable assets, the framework directs attention first to whether the technical configuration is sustainable under the conditions the system will actually encounter, and then to whether the social and institutional conditions on which its durability depends are present. Where those conditions are absent, the framework prompts the question of what would be required to establish them, reframing a binary judgment about technical adequacy as a richer assessment of whether an intervention is positioned to endure in its intended setting (Patrick *et al*., 2021; Shittu *et al*., 2019).

The framework's reasoning is most effectively illustrated by the contrast it draws between interventions strong on a single dimension and those strong on both (World Resources Institute, n.d.). A technically excellent system introduced into a setting lacking the capacity, legitimacy, or fairness conditions associated with durability is, on the framework's logic, poorly positioned regardless of its specifications, while a more modest system matched to favorable social conditions may prove far more durable. This contrast, which the literature documents repeatedly, is exactly what the framework is designed to anticipate, and applying it allows the likely trajectory of an intervention to be reasoned about before commitments are made rather than discovered after a system has faltered in service (Sunday & Omoegun, 2018; Sunday & Omoegun, 2019).

Applying the framework also clarifies the design choices through which the conditions governing durability can be deliberately influenced, including the matching of system complexity to local capacity, the arrangement of governance to secure legitimacy, and the design of access to reach groups that aggregate measures would overlook (Agbabiaka *et al*., 2019). By treating these as design variables rather than as fixed background, the framework turns the recognition that social conditions matter into a structured set of choices that practitioners can make. Within predictive maintenance of distributed renewable assets, this is the practical payoff of the conceptual work: not a prediction of particular outcomes, but a disciplined way of reasoning about how to position an intervention so that technical capability is translated into durable, inclusive service (Wustenhagen *et al*., 2007; Yeboah & Ike, 2020).

A further illustration of the framework's reasoning concerns its treatment of the conditions that evolve over a system's life, since applying the framework involves asking not only whether the conditions for durability are present at the outset but whether they are likely to be sustained (Ambali *et al*., 2021). This prompts attention to the arrangements for ongoing operation, maintenance, financing, and governance, and to the mechanisms by which trust and capacity are built or eroded over time. This temporal application of the framework is what distinguishes it from a one-time assessment at commissioning, and it directs design toward the establishment of conditions that will endure rather than conditions that merely exist when a system is new (Ahmad *et al*., 2020; Ahmed *et al*., 2020).

Another aspect of applying the framework concerns its use in comparing candidate interventions, since it provides a common structure within which alternatives can be assessed on both technical and social grounds (Arumosoye & Obriki, 2021). Rather than ranking options by technical performance or cost alone, the framework prompts a comparison that also weighs the conditions governing durability, allowing an option that is modest technically but well matched to its social context to be recognized as potentially superior to a technically stronger option poorly matched to its setting. This comparative application is particularly valuable because it surfaces considerations that conventional appraisal omits, and it does so in a structured rather than unsystematic manner (Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2019).

Applying the framework also clarifies where intervention is most likely to be effective, by identifying which of the conditions governing durability are absent in a given setting and which could be established through design or governance (Collath, 2021). This directs effort toward the conditions that most constrain durability rather than toward indiscriminate improvement, and it allows scarce resources to be focused where they will matter most. Within this context, this targeting application of the framework reflects its broader purpose, which is not to predict particular outcomes but to guide the choices through which technical capability is translated into durable, inclusive service in the settings that need it (Bednar *et al*., 2017; Bhattacharyya *et al*., 2021; Basnet *et al*., 2021).

A further illustration of the framework's reasoning concerns its treatment of trade-offs, since applying it often reveals that apparent conflicts between objectives can be reconciled once technical and social factors are considered together (Dagodzo & Patrick, 2020). Where a narrowly technical analysis might present efficiency and equity as opposed, the framework frequently identifies configurations in which attention to social conditions improves durability without sacrificing performance, or in which modest technical compromise secures the legitimacy on which durability depends. For problems of this kind, this application demonstrates the framework's central claim in practice, namely that integrating technical and social reasoning expands rather than constrains the space of viable designs (Dagodzo, 2018a; Dagodzo, 2018b).

Applying the framework also supports deliberation about sequencing, since it indicates which conditions must be established before others and where early attention will yield the greatest returns (Dagodzo & Patrick, 2021b). This helps practitioners order their decisions so that the conditions governing durability are addressed when the design space is still open rather than after commitments foreclose them (Dagodzo & Patrick, 2021a). In such settings, this application reflects the framework's broader insight that the influence of social conditions is largely determined by decisions taken early, and that attending to them in the right sequence is part of designing for durability. This application reflects the framework's orientation toward informing the choices through which interventions are designed.

A further application concerns the use of the framework to communicate across the disciplines and stakeholders involved in an intervention, since its commensurable representation of technical and social factors provides a common language (Guerrero *et al*., 2013). This shared structure can help engineers, social specialists, financiers, and community representatives’ reason together about a candidate intervention rather than working in separate registers (Ewim *et al*., 2021). Applied to this domain, this communicative application is valuable because the integration the framework supports is as much organizational as analytical, requiring that diverse actors be able to deliberate together about the conditions governing durability. The framework supports this use by directing attention to the conditions on which durable, inclusive service depends.

Applying the framework, finally, supports learning across interventions, since its common structure allows the experience of one project to inform another in a disciplined way (Jessel *et al*., 2019). By characterizing interventions in commensurable terms, the framework enables comparison that distinguishes the general from the context-specific, so that lessons can be carried forward rather than repeatedly rediscovered (International Energy Agency, n.d.). On this account, this application reflects the framework's design for transferability, and it points toward the cumulative understanding that the field requires if it is to improve the durability and inclusiveness of interventions over time. This use of the framework illustrates its practical value for reasoning about interventions before commitments are made.

An additional application of the framework concerns its use in identifying the conditions that would need to be established for a proposed intervention to succeed, since the framework directs attention not only to whether favorable conditions are present but to how absent conditions might be created (Mbonu *et al*., 2021a). This prompts deliberation about the investments in capacity, the arrangements for governance, and the measures for inclusion that would position an intervention to endure. For predictive maintenance of distributed renewable assets, this application reflects the framework's constructive orientation, since it treats the conditions governing durability as objects of deliberate action rather than as fixed circumstances to which design must simply accommodate (Liu *et al*., 2014; Mbonu *et al*., 2020a).

The framework's reasoning is also applied to the assessment of risk, since by examining the conditions governing durability it allows the principal threats to an intervention's endurance to be identified in advance (Mbonu *et al*., 2019a). Where the conditions on which durability depends are weak or uncertain, the framework flags a corresponding risk, prompting attention before commitments are made (Mbonu *et al*., 2021b). This risk-oriented application is of particular value because it surfaces vulnerabilities that technical and financial assessment alone would miss, and it does so in a structured way that supports deliberation about whether and how to proceed with a proposed intervention. The framework draws on this insight and that social conditions govern durability into a structured set of choices.

A further application concerns the monitoring of interventions over time, since the framework's representation of the conditions governing durability provides a basis for tracking whether those conditions are being sustained (Mbonu *et al*., 2021c). By directing attention to participation, capacity, legitimacy, and fairness as the intervention operates, the framework supports the early identification of erosion that might otherwise go unnoticed until performance declines (Mbonu *et al*., 2020b). This application extends the framework's use beyond design to operation, reflecting its treatment of durability as something sustained through ongoing attention rather than secured once at deployment. This application reflects the framework's purpose of guiding design toward conditions that endure rather than merely exist.

Another aspect of applying the framework is its use in structuring deliberation among the parties to an intervention, since its representation of technical and social factors in commensurable terms gives engineers, financiers, administrators, and community representatives a common basis for reasoning together (Nnaji *et al*., 2019). Much of the difficulty in practice arises not from disagreement about facts but from the absence of a shared structure within which technical and social considerations can be weighed against one another, and the framework supplies such a structure. Within this context, this deliberative application is among the framework's more practical contributions, since the integration it advocates is realized only when the relevant parties can reason jointly rather than in separate registers (Mbonu *et al*., 2019b; Muhtadi *et al*., 2021).

Applying the framework also clarifies the points at which intervention is most consequential, since by tracing how technical and social conditions jointly determine durability it identifies which conditions, if altered, would most improve the prospects of an intervention (Obogo *et al*., 2020b). This allows effort and resources to be directed toward the conditions that most constrain durability rather than dispersed across many that matter less, an allocation that is especially important where resources are scarce. For problems of this kind, this prioritizing application reflects the framework's purpose, which is not to predict outcomes but to guide the choices through which technical capability is translated into durable, inclusive service in the settings that need it (Nnaji *et al*., 2020; Obogo *et al*., 2020a).

7. Discussion and Implications

A significant implication of the framework concerns the professional training of the data scientists and engineers who design predictive maintenance systems for distributed renewable assets, since the framework's approach requires competencies in human factors, organizational behavior, and interface design that are not typically part of engineering or data science curricula (Ribeiro *et al*., 2016). Universities and professional development programs that train practitioners in predictive analytics without addressing the human and organizational conditions that govern adoption are producing graduates who will systematically underestimate the implementation challenges that their models face in the field. This paper identifies this training gap as a systemic issue that the energy sector's growing reliance on predictive analytics is making increasingly consequential (Basnet *et al*., 2021).

The discussion also considers the implications of the framework for procurement and contracting in the predictive maintenance market, since contracts that specify model accuracy metrics without requiring evidence of operational performance create incentives for vendors to optimize for the wrong criterion (Mobley, 2002). A procurement framework aligned with this paper's approach would require vendors to demonstrate operational performance, including adherence rates and maintenance outcome improvements, in comparable deployment settings, and would specify interface design and organizational integration requirements alongside technical specifications. This procurement implication extends this paper's argument into the market structures that shape what kinds of predictive maintenance systems get built and deployed, suggesting that contractual alignment with operational criteria is a lever for improving field outcomes at scale.

The framework also has implications for the design of incentive structures within maintenance organizations, since the adoption of predictive maintenance recommendations depends partly on whether technicians are rewarded for following model guidance or for meeting other performance targets that may conflict with it (Endsley, 1995; Kahneman, 2011). Where performance metrics reward rapid task completion without distinguishing between adherence to model recommendations and departure from them, the organizational incentives work against effective use of predictive maintenance systems regardless of their technical quality. The discussion identifies incentive alignment as a management intervention that must accompany technical deployment, arguing that the operational performance of predictive maintenance systems depends on the entire organizational system surrounding them, not only on the models themselves.

The framework set out here both confirms and extends the prior literature on predictive maintenance of distributed renewable assets, confirming the importance of the social conditions that qualitative scholarship has documented while extending that work by representing those conditions in terms that can enter design directly (Obogo *et al*., 2021b). Compared with technical studies, the framework suggests that performance findings obtained under idealized assumptions require qualification once the conditions governing durability are taken into account, and compared with social-science work, it supplies the conceptual structure needed to bring social factors into systematic reasoning. The discussion situates the contribution at the interface of these literatures, where it is intended to remedy the complementary deficiencies that each exhibits when taken alone (Obogo *et al*., 2020c; Obogo *et al*., 2021a).

Several limitations qualify the contribution, and stating them plainly is part of what makes the framework credible (Obogo *et al*., 2019b). As a conceptual contribution, it offers a way of reasoning rather than a body of empirical results, and its value depends on the soundness of the relationships it posits and on the willingness of practitioners to apply it (Obogo *et al*., 2019a). The definitions it gives to social conditions involve conceptual choices that others might make differently, and its applicability to a given setting depends on whether the conditions it represents are the ones that actually govern outcomes there. These limitations point toward the empirical work that would test and refine the framework, which lies beyond the scope of the present paper.

The implications of the framework extend to practice and to policy within predictive maintenance of distributed renewable assets (Odejobi & Ahmed, 2018). For practitioners, it offers a disciplined way to consider the social determinants of durability alongside technical specifications, reframing design as an inherently socio-technical task (Obogo *et al*., 2021c). For the institutions that fund and regulate energy systems in resource-dependent regions, it suggests that appraisal should weigh demonstrated attention to these determinants alongside technical and financial soundness, thereby aligning incentives with the conditions that govern long-term success. In both respects the framework is intended not as an abstraction but as a guide to action, and the discussion emphasizes that its purpose is ultimately to improve the durability and inclusiveness of interventions in the field.

A further implication of the framework concerns the organization of the work of design itself, since bringing social variables into the design problem from the outset requires that social and institutional expertise be present when the design space is still open rather than consulted once technical choices have been fixed (Okonkwo *et al*., 2020). This is a modest organizational change with substantial consequences, because it determines whether the conditions governing durability are designed for or merely managed after the fact. In such settings, the discussion emphasizes that adopting the framework is therefore not only a matter of analysis but of practice, entailing changes in how project teams are composed and how the sequence of design decisions is arranged (OECD, n.d.; Ogunwole *et al*., 2021).

A related point of discussion concerns the relationship between the framework and the empirical work that would test it, since the relationships the framework posits are ultimately claims that evidence must confirm or revise (Okonkwo *et al*., 2018b). This paper is explicit that its contribution is conceptual and that the framework's value depends on its application, and the discussion considers what such application would involve, including the development of measures for the social conditions the framework identifies and the examination of the relationships it posits across diverse settings. Applied to this domain, this discussion positions the framework as a foundation for subsequent investigation rather than as a finished account, and it identifies the empirical work that would consolidate the conceptual contribution (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2018a).

The discussion also considers the implications of the framework for how success in predictive maintenance of distributed renewable assets is understood and measured, arguing that the broadening of evaluation criteria it entails has consequences extending well beyond any single intervention (Okwu *et al*., 2021). Because what is measured shapes what is funded, built, and rewarded, adopting the framework's broader criteria would, over time, reorient the field toward the conditions that govern durability and inclusion (Okonkwo *et al*., 2021b). The discussion treats this as among the framework's most significant potential effects, since it concerns not merely the design of individual systems but the incentives and standards that shape the field as a whole. The discussion treats this as among the framework's features that bear on its practical value.

A final point of discussion concerns the limitations of the framework and the conditions under which it applies, which the present paper acknowledges as a matter of scholarly transparency (Shittu *et al*., 2019). The framework's value depends on whether the conditions it represents are the ones that actually govern outcomes in a given setting, and its definitions involve conceptual choices that others might make differently. The discussion acknowledges these limitations directly, treating them not as defects to be concealed but as the natural boundaries of a conceptual contribution, and it identifies them as among the matters that subsequent empirical and comparative work would help to clarify and refine for predictive maintenance of distributed renewable assets (Patrick *et al*., 2020; Patrick *et al*., 2021).

The discussion considers how the framework relates to established practice in predictive maintenance of distributed renewable assets, arguing that it does not displace technical analysis but situates it within a wider account of the conditions that determine real-world durability (Sunday & Omoegun, 2018). The technical work remains indispensable, but it is joined by an equally disciplined treatment of the social conditions on which durability depends (Smith, 2017). The discussion emphasizes that this is an enlargement rather than a rejection of existing practice, and that the framework's contribution lies in extending rigor to dimensions that practice has tended to address informally if at all. This point reflects the framework's broader commitment to representing the determinants of durability together.

The discussion also reflects on the framework's potential effect on incentives, observing that by broadening the criteria of success it could, over time, reorient the field toward the conditions that govern durability and inclusion (World Resources Institute, n.d.). Because what is measured and rewarded shapes what is built, adopting the framework's broader criteria would influence not only individual interventions but the standards and incentives of the field as a whole (Sunday & Omoegun, 2019). The discussion treats this as among the framework's most significant potential consequences for predictive maintenance of distributed renewable assets, extending well beyond any single project. The discussion connects this consideration to the framework's implications for practice and policy. Accordingly, the discussion situates the framework as an enlargement rather than a rejection of existing practice.

The discussion finally addresses the framework's limitations directly, acknowledging that its value depends on whether the conditions it represents are the ones that actually govern outcomes in a given setting, and that its definitions involve choices others might make differently (Agbabiaka *et al*., 2019). These limitations are presented not as defects to be concealed but as the natural boundaries of a conceptual contribution, and the discussion identifies them as matters that subsequent empirical and comparative work would help to clarify, refining the framework's application to the varied settings of predictive maintenance of distributed renewable assets. This consideration demonstrates the framework's capacity to bring neglected determinants of durability into view (Wustenhagen *et al*., 2007; Yeboah & Ike, 2020).

A further point of discussion concerns the relationship between the framework and the diversity of the settings in which predictive maintenance of distributed renewable assets operates, since the framework's claim to generality must be reconciled with the evident variation among contexts (Ambali *et al*., 2021). The discussion argues that the framework accommodates this variation through its separation of general structure from context-specific content, allowing its logic to apply across settings while its particulars are re-examined locally. This reconciliation of generality with context-sensitivity is, the discussion suggests, among the framework's more important features, since it determines whether the framework can be useful across the range of settings the field encompasses (Ahmad *et al*., 2020; Ahmed *et al*., 2020).

The discussion also considers how the framework relates to the practical constraints under which interventions in predictive maintenance of distributed renewable assets are designed and implemented, acknowledging that the integration it advocates makes demands on the expertise, time, and resources available to projects (Arumosoye & Obriki, 2021). The discussion argues that these demands are modest relative to the consequences of neglecting the conditions governing durability, and that the framework can be applied at varying levels of detail according to the resources available. This practical consideration is treated as important, since a framework that cannot be applied under realistic constraints would offer little to the practice it is meant to inform (Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2019).

A further point of discussion concerns the framework's contribution to communication and shared understanding among the diverse actors involved in interventions, since its commensurable representation of technical and social factors provides a common basis for deliberation (Bhattacharyya *et al*., 2021). The discussion suggests that this communicative function may be among the framework's more valuable practical effects, since the integration it advocates requires that engineers, social specialists, financiers, and communities reason together (Bednar *et al*., 2017). By providing a shared structure within which they can do so, the framework supports the organizational integration on which its analytical integration depends in the practice of predictive maintenance of distributed renewable assets. The discussion treats this as among the framework's features bearing on its practical value.

A complementary point of discussion concerns the framework's treatment of lifecycle considerations, since by representing the costs and conditions of operation over the full life of a system the framework addresses a dimension that conventional analysis, focused on installation, tends to neglect (Dagodzo, 2018b). The discussion argues that this lifecycle perspective is essential to the framework's account of durability, since the affordability and capacity that condition sustained use are matters of the working life of a system rather than of its deployment. On this account, the discussion treats this as among the framework's important features, since it brings into view costs and conditions that bear directly on whether interventions endure (Collath, 2021; Dagodzo, 2018a).

The discussion also considers the framework's attention to distribution within communities, since by representing how benefits and burdens fall among groups, including along lines of gender, the framework addresses disparities that aggregate analysis obscures (Dagodzo & Patrick, 2021a). The discussion argues that this attention to intra-community distribution is necessary to the framework's account of inclusion, since an intervention improving aggregate conditions may still affect groups within a community unequally (Dagodzo & Patrick, 2020). For predictive maintenance of distributed renewable assets, the discussion treats this as a significant feature, since it ensures that the framework's account of equity encompasses the disparities that determine whether interventions are genuinely inclusive. This point reflects the framework's commitment to representing the determinants of durability together.

A further point of discussion concerns the framework's treatment of environmental resilience, since by representing the conditions a system will encounter over its life the framework addresses a determinant of durability that analysis focused on technical and social factors alone might neglect (Guerrero *et al*., 2013). The discussion argues that this attention to environmental conditions is essential in the regions of concern, where climatic stress and environmental change bear heavily on whether systems endure. The discussion addresses the framework's incorporation of resilience as important, since it ensures that durability is assessed in light of the full set of conditions, environmental as well as social and technical, on which it depends (Dagodzo & Patrick, 2021b; Ewim *et al*., 2021).

A further point of discussion concerns the relationship between the framework and the empirical research that would test and refine it, since the relationships the framework posits are claims about the world that evidence must ultimately assess (Liu *et al*., 2014). This discussion acknowledges that the contribution of this paper is explicitly conceptual, and it considers what empirical engagement would involve, including the development of measures for the social conditions the framework identifies and the examination of its posited relationships across diverse settings. The discussion positions the framework as a foundation for subsequent investigation, and it treats the empirical work that would consolidate it as lying beyond the present paper while being essential to the framework's eventual validation (International Energy Agency, n.d.; Jessel *et al*., 2019).

The discussion also considers how the framework bears on the standards by which interventions in predictive maintenance of distributed renewable assets are judged, since by treating durability, inclusion, and legitimacy as first-order objectives it implies a broadening of the criteria of success beyond technical performance and cost (Mbonu *et al*., 2021b). Because the criteria applied in appraisal shape what gets designed and funded, this broadening has consequences extending beyond any single intervention to the incentives and standards of the field. The discussion treats this as among the framework's more significant potential effects, since it concerns not only how individual systems are designed but how the field as a whole defines and pursues success (Mbonu *et al*., 2020a; Mbonu *et al*., 2021a).

8. Conclusion

The framework developed in this paper reframes the design of predictive maintenance systems for distributed renewable assets as an inherently sociotechnical challenge, in which the gap between model accuracy and technician adherence is not a deployment problem to be managed but a design problem to be solved (Lee *et al*., 2014; Ribeiro *et al*., 2016). By treating interpretability, workflow integration, organizational capacity, and trust dynamics as first-order design requirements alongside accuracy, the framework provides a structured basis for designing systems that achieve operational performance rather than merely technical performance. The conclusion emphasizes that this reframing is practical as well as conceptual, since the organizational and human factors the framework identifies are as amenable to systematic analysis and deliberate design as the technical characteristics of the models themselves.

A final conclusion concerns the contribution of the framework to the broader project of deploying machine learning in safety-critical infrastructure settings, since the challenge of closing the gap between model accuracy and human adherence is not unique to renewable energy maintenance but recurs across healthcare, transportation, and financial systems (Kahneman, 2011). This paper's approach, which treats the human and organizational conditions of adoption as design requirements rather than implementation variables, offers a model for how this challenge can be addressed in other domains. By demonstrating that integrated sociotechnical design for predictive systems is both feasible and necessary, this paper contributes to a growing consensus that the deployment of machine learning in consequential settings requires a broader conception of system design than the technical tradition has historically provided.

This paper has treated predictive maintenance of distributed renewable assets 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 gap between model accuracy and technician adherence, where interpretable models produce greater net benefit than opaque ones, 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets.

A connected 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets, 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets. 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets 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 predictive maintenance of distributed renewable assets. 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.

Another 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 predictive maintenance of distributed renewable assets 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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