

Review

Equity-Oriented Decision-Making for Renewable Energy Investments

Justas Streimikis ^{1,*} and Indre Siksnyte-Butkiene ²

¹ Institute of Economics and Rural Development, Lithuanian Centre for Social Sciences, LT-01108 Vilnius, Lithuania

² Institute of Social Sciences and Applied Informatics, Vilnius University, LT-01513 Vilnius, Lithuania; indre.siksnyte@knf.vu.lt

* Correspondence: justas.streimikis@ekvi.lt

Abstract

Renewable energy investment evaluation continues to rely predominantly on techno-economic and environmental criteria, while equity-related considerations remain weakly embedded within formal decision-support frameworks. Although recent research increasingly acknowledges social impacts, spatial constraints, policy uncertainty, and financing structures, these dimensions are rarely integrated in a systematic and operational manner into investment appraisal. This paper addresses this gap by advancing an equity-oriented conceptual framework for renewable energy investment evaluation. Using an integrative literature review combined with thematic analysis, the study synthesises insights from techno-economic assessment, multi-criteria decision-making, energy justice scholarship, and equity-focused modelling studies. The analysis demonstrates that existing evaluation approaches inadequately capture distributional impacts, accessibility constraints, differentiated vulnerability, and equity-adjusted risk. In response, the proposed framework systematises these equity dimensions and embeds them directly into the core logic of investment evaluation alongside conventional criteria. By consolidating fragmented research insights into a coherent evaluative structure, the study contributes to the literature by clarifying how equity can be operationalised within renewable energy investment decision-making. The framework provides a foundation for future empirical applications and supports more socially responsive and analytically robust investment evaluation.

Keywords: renewable energy investments; investment evaluation; decision-making; social equity; energy justice



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1. Introduction

The global shift toward low-carbon energy systems for climate change mitigation and long-term energy security has advanced in the last ten years. Investing in renewable energy technologies is now a focal point of national strategies for decarbonisation and is receiving increasing amounts of public and private funding. But, even though there are technological improvements and the costs associated with these technologies are lowering, the increased adoption of renewable energy technologies is still taking place unevenly across different geographical areas, sectors, and socio-economic groups. A substantial body of research demonstrates that the benefits of the low-carbon transition—such as improved air quality, lower household energy expenditures, and new employment opportunities—are distributed inequitably, while its burdens disproportionately fall on vulnerable communities [1,2]. The awareness of these disparities and the absence of innovative frameworks

and investments in disadvantaged areas pose serious concerns about the equity in the investments made in renewable energy.

During the past several decades, there have been significant developments in the decision-support tools created for renewable energy investments and their additions in areas such as techno-economics, environmental impacts, spatial analytics, and multi-criteria decision-making (MCDM) [3,4]. These tools are useful for assessing the economic viability of the investments. However, despite methodological progress, existing models remain strongly oriented toward financial and technical performance. They rarely account for distributional outcomes, barriers faced by marginalised groups, or differentiated risk exposures, factors increasingly emphasised by energy justice scholars as critical to assessing who benefits from and who is excluded from the low-carbon transition [1,5]. The standard methodologies for the evaluation of investments, therefore, have the potential of entrenching existing inequalities—economically and spatially.

The growing literature on energy justice and just transitions underscores the importance of integrating distributional, procedural, and recognition justice into energy planning and investment appraisal [6,7]. Scientific literature provides a wide range of methodological approaches for multidimensional assessment of energy equity, including inequality measures such as the Gini coefficient and the Atkinson index [8], generalised entropy indices [9,10], variance-based measures, various fairness indices adapted from other fields [11,12], and different energy poverty or vulnerability indices [13,14]. In addition, case-specific composite indicators (e.g., the Energy Trilemma Index) [15] and context-specific analytical frameworks have been applied in selected empirical settings [16].

However, although general inequality metrics provide insights into distributional fairness, they do not reflect procedural or recognition-based equity dimensions, which are essential for a comprehensive understanding of social equity in energy systems. This limitation persists even when such metrics are combined. While inequality measures and energy poverty indices remain dominant in practice and justice-oriented frameworks offer broader conceptual perspectives, there is currently no widely accepted multidimensional methodology dedicated to social equity assessment in energy systems that can be directly embedded into renewable energy investment appraisal and decision-support models. Therefore, methodological fragmentation remains, as most studies construct their own composite frameworks or “justice indices” tailored to specific research objectives, combining energy justice indicators in varied ways [17,18]. The reliance on multiple data sources and case-specific indicator sets limits the comparability, adaptability, and repeatability of results across studies and empirical contexts. To address these gaps, there is a need to focus on developing transparent, multidimensional, and scalable equity measures that link distributional outcomes with procedural inclusiveness and recognition of social diversity.

This study seeks to develop an equity-oriented conceptual framework for renewable energy investment evaluation. The framework builds on established assessment dimensions—techno-economic, environmental, and social—while introducing three equity-sensitive dimensions derived from energy justice research: distributional equity, accessibility and inclusion, and equity-adjusted risk.

While energy justice scholarship traditionally conceptualises justice in energy systems through three core tenets—distributive, procedural, and recognition-based justice [19–21]—subsequent research has expanded these principles into more detailed typologies and indicator frameworks aimed primarily at policy diagnostics, community-level assessments, and governance evaluation [22]. However, in the context of renewable energy investment appraisal, not all justice dimensions can be directly translated into decision-support criteria without substantial aggregation and methodological reformulation. Investment evaluation

requires indicators that are quantifiable, spatially scalable, and compatible with techno-economic and multi-criteria decision-support models.

Accordingly, this study adopts a selective and investment-oriented translation of energy justice principles, focusing on dimensions that most directly influence capital allocation, benefit distribution, participation capacity, and differentiated exposure to financial, regulatory, and socio-environmental risks. Distributional equity reflects distributive justice concerns related to the allocation of costs and benefits; accessibility and inclusion capture key elements of procedural justice insofar as they affect access to investment benefits; and equity-adjusted risk operationalizes vulnerability relevant for investment feasibility and social outcomes. Other justice dimensions are not conceptually excluded but are not foregrounded where they cannot be meaningfully integrated into investment-level evaluation criteria requiring quantifiable and spatially comparable indicators. Each dimension is operationalized through measurable indicators capturing differentiated outcomes across population groups and regions.

The contribution of this study is threefold. First, it synthesises evidence on inequalities, barriers, and gaps in existing renewable energy investment evaluation frameworks, demonstrating why equity considerations remain insufficiently addressed. Second, it introduces a novel set of nine operationalizable equity-sensitive indicators, filling a major conceptual gap in current decision-support approaches. Third, it proposes a structured conceptual framework positioning these indicators within a holistic decision-making logic, forming a basis for further methodological and practical applications in renewable energy investment evaluation.

The remainder of this article is structured as follows. Section 2 presents the literature review, covering current decision-making approaches, inequalities in the low-carbon transition, barriers influencing renewable energy investments, gaps in existing evaluation models, and the rationale for introducing equity-sensitive criteria. Section 3 outlines the methodological approach. Section 4 develops the equity-sensitive indicators and the conceptual framework. Section 5 provides a discussion of the implications for renewable energy investment evaluation and policy. Section 6 concludes with key insights and directions for future research.

2. Literature Review

This section provides the conceptual background for the study by reviewing the main literature relevant to renewable energy investment evaluation. The discussion begins with an overview of the approaches commonly applied in renewable energy investment decision-making, followed by a summary of the criteria used in project appraisal. The review then considers evidence on inequalities arising in the low-carbon transition and examines the barriers in existing evaluation frameworks. Finally, it outlines the key gaps in existing decision-making models, with particular attention to the limited integration of equity-related aspects. Taken together, these components provide the conceptual groundwork for the study.

2.1. Renewable Energy Investment Decision-Making: Current Approaches

Decision-making on renewable energy investments has become increasingly complex, as it is shaped by interdependent economic, environmental, technological, social, and policy-related factors. Traditional single-criterion financial appraisal is no longer sufficient to capture this complexity, and a broad range of analytical, multi-criteria, and data-driven approaches has emerged to support more robust investment choices in the low-carbon transition [3].

An important exception at the conceptual level is the Energy Trilemma framework, which explicitly includes energy equity alongside energy security and environmental sustainability and has been widely adopted in high-level energy policy and system-level assessments [15], as well as in academic research on energy transitions and investment contexts [23]. However, while the Energy Trilemma provides a valuable normative lens for considering equity, it does not offer an operationalisation of equity into concrete criteria or indicators suitable for renewable energy investment-level evaluation. As a result, its application in investment appraisal remains largely descriptive and insufficient for assessing distributional outcomes, access barriers, and differentiated risk exposure at the project or decision-making level.

A first group of approaches comprises traditional investment appraisal methods, such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP). These methods are still the mainstay of the financing model in the energy industry and are frequently employed to analyse the financial feasibility and profitability of renewable energy projects [24]. NPV assesses projects in terms of expected cash flows at discounted rates, IRR assesses the internal rate of return, and PP relates to the time needed to recoup initial investment expenditures [25]. However, these methods are based on static assumptions concerning price, policy, and technological cost changes and approach uncertainty in a simplistic manner. With renewable energy, where projects are highly capital-intensive, subject to changing market conditions, and diverse policy frameworks, static approaches very often fail to capture long-run risk, managerial flexibility, and path dependence [26]. This has resulted in a recognition, which is showing signs of growth, that traditional metrics should be supplemented with more adaptable and dynamic frameworks.

In response, Real Options Analysis (ROA) has gained prominence as a way to value managerial flexibility under uncertainty. OA views investment possibilities as options that may be exercised, postponed, expanded, or abandoned depending on the state of the market, regulation, or technology [27]. This approach is particularly relevant for renewable energy projects, where investors may face uncertain support schemes, technology learning curves, and evolving climate policies [28]. By modelling flexibility, ROA goes beyond traditional appraisal and provides a more accurate representation of strategic decision-making under uncertainty. Moreover, behavioural economics has shown that decision-makers act outside the parameters of the strictly normative model: bounded rationality, risk and loss aversion, as well as heuristics, can and do affect investment decisions in energy markets [29]. New behavioural decision-making models, therefore, combine normative (NPV-like) evaluation with non-normative approaches to uncertainty.

The second major strand in the literature is concerned with MCDM. This approach has become fundamental in the assessment of renewable energy investments when numerous, frequently contradictory, goals need to be addressed. The Analytic Hierarchy Process (AHP), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), VIKOR, PROMETHEE, ELECTRE, and their fuzzy variations have been used for the ranking of technologies, the selection of project site(s), and the prioritisation of investments [3,30]. These methods aid decision makers in tackling intricate challenges by balancing economic, environmental, technical, and social factors and producing composite scores for each alternative. AHP is widely used for its intuitive hierarchical structure and pairwise comparisons, while TOPSIS and VIKOR are focused on selecting the alternative that is closest to ideal and the one that is furthest from a negative ideal; PROMETHEE and ELECTRE are focused on the outranking relationships of the alternatives [4]. Within the MCDM methods of renewable energy, there is a systematic way of integrating non-financial and economic measures, such as emissions reduction, local environmental consequences, social acceptability, and the employment effects, alongside the traditional economic measures.

A developing area of research focuses on building hybrid and advanced decision-making models that integrate MCDM with different analytical approaches. In particular, several studies combine AHP or other MCDM techniques with fuzzy logic to improve the management of linguistic and subjective uncertainty in expert evaluations [30]. Other studies integrate MCDM with optimisation, multi-objective programming, Monte Carlo simulation, or stochastic programming to jointly tackle trade-offs, risk, and constraints in the system [31,32]. For example, hybrid models have been used to rank and simultaneously optimise the costs and emissions of the renewable energy technologies or sites, assess the risk of overseas renewable energy investments using the expert-elicitation techniques, AHP, and fuzzy methods of aggregation, or assist in the long-term planning of investments in power grids under sustainability constraints [33,34]. The integration of Geographic Information Systems (GISs) with MCDM to facilitate the spatially explicit site selection of wind, solar, and other green energy projects is also common.

Incorporating data analytics, machine learning, and automation into the decision-making processes surrounding renewable energy investments continues the pattern of ongoing technological and digital transformations of processes, systems, and policies. Machine learning systems now draw from vast datasets on resource availability and demand, network conditions, and market prices to locate, optimise, and assess risk for site potential [26]. Several studies discuss the use of machine learning to predict generation, prices, and demand and project patterns to optimise performance and guide investment [35–37]. Operational performance and lifecycle cost predictability and reliability are enhanced by energy digital twins that allow for real-time monitoring and scenario testing [38]. These tools draw from the financial, multi-criteria, and other decision-making paradigms to provide in-depth, granular data on which to base investment decisions.

Lastly, there is a growing body of literature that advocates for participatory and community-focused approaches to decision-making in renewable energy. Energy communities and citizen-led initiatives highlight the importance of stakeholder involvement, social acceptance, and local benefit-sharing in investment processes [39,40]. Stakeholders' preferences, social consequences of the investment, and community-aligned investment are some of the specific issues that are being included in the MCDM and other decision-support frameworks [3,39]. In parallel, there are studies that deal with green finance and innovative and flexible financing that draw attention to public financial institutions, community finance, and blended finance in addressing capital and renewable energy [41,42].

In summary, recent trends in renewable energy investment decision-making have shifted from a singular view of traditional financial appraisals to multidisciplinary approaches that incorporate financial, multi-criteria, data-analytical, and participatory methods. This is a response to the reality of the low-carbon transition, where the investors and decision-makers have to deal with low-carbon technical and economic variables, in addition to environmental, social, and institutional factors [3]. Nevertheless, limitations remain regarding the systematic treatment of equity-related considerations, which are examined in detail in subsequent sections.

The approaches considered revolve around the evaluation of a particular set of criteria encompassing the economic, environmental, and social aspects within a project. That is to say, a framework for analysis can be achieved through methods of decision-making (traditional financial appraisal, ROA, MCDM, data methods); however, the results depend on the criteria on which the various methods focus. As a follow-up to the review of methods, the next section organises the substantive criteria that tend to be used in investment appraisal systematically, providing a richer account of the particular aspects that are measured and given priority in various decision-making situations. This shift in focus

makes it possible to move from examining how decisions are made to analysing which criteria are prioritised within those decisions.

2.2. Criteria Commonly Used in Renewable Energy Investment Evaluation

The assessment of renewable energy investments is predicated upon a comprehensive array of criteria, encompassing financial viability, technical and operational attributes, ecological ramifications, and societal consequences. Given that renewable energy systems are capital- and policy-support-intensive and embedded in particular locations as well as ecological environments, a multi-dimensional set of criteria becomes necessary. These are commonly used criteria for evaluating renewable energy investments. These categories reflect the interdisciplinary nature of renewable energy planning and are commonly accepted in many recent empirical and conceptual studies. Table 1 below systematises the criteria commonly applied in the evaluation of renewable energy investments, grouped into techno-economic, environmental, and social dimensions, which are examined in greater detail in the subsequent subsections.

Table 1. Common criteria in renewable energy investment evaluation. Source: developed by the authors.

Category	Criteria	Typical Indicators/Metrics	Common Methods
Techno-economic	Financial performance	NPV, IRR, MIRR, payback, BCR, discount rate, LCOE, TCO	NPV/IRR analysis, CBA, sensitivity analysis
	Technological performance	Efficiency, capacity factor, maturity, reliability, degradation rate	Techno-economic modelling, performance benchmarking
	Risk and uncertainty	Policy risk, resource risk, regulatory risk, and financial risk	AHP, sensitivity, scenario analysis, ROA
Environmental	Emissions reduction	CO ₂ /GHG reduction potential	LCA, carbon accounting
	Environmental impacts	Land use, biodiversity, water/air quality, noise	EIA, environmental scoring
	Alignment with sustainability goals	SDG contribution, green finance eligibility	ESG/SDG frameworks, green bond criteria
Social and community	Social acceptance	Trust, perceived fairness, conflict potential	Surveys, stakeholder analysis, MCDM
	Socio-economic benefits	Job creation, local economic development, and energy access	Socio-economic assessment
	Equity and justice	Distribution of benefits, inclusion, and impact on vulnerable groups	Distributional analysis, equity frameworks
	Participation and governance	Stakeholder engagement, community ownership	Participatory planning, co-governance models

Notably, while techno-economic and environmental criteria are well-established in most decision-making models, social and equity-oriented criteria remain less consistently integrated, creating potential biases in investment prioritisation [43].

2.2.1. Techno-Economic Criteria

The criteria for profitability when considering the investment in the renewable sector are the most important. Previous research studies show that values such as Net Present Value (NPV), Internal Rate of Return (IRR), Modified Internal Rate of Return (MIRR), Payback Period (PP), and Benefit–Cost Ratio (BCR) are particularly important when differentiating between financially viable and non-viable projects. Most renewable energy studies use a range of 6–11% in discount rates, which affects the MIRR and the overall savings in the life cycle [44,45]. The Levelized Cost of Electricity (LCOE) is also important as it allows for a comparison across the differing technologies on the average lifetime cost

of electricity produced. The values of LCOE that make investments viable are noted in the techno-economic assessments of solar and wind systems [46].

The profitability of renewable energy also brings economic resilience on a national and regional basis. Diversification away from fossil fuels reduces exposure to market volatility and supports energy independence. In the underdeveloped parts of the world, the renewable energy projects improve employment opportunities, energise the local economy, and improve access to energy [38]. They are the primary benefits of the renewable public–private partnerships and community-based projects.

Maturity, reliability, conversion efficiency, and capacity factors are important indicators of the potential overall performance of any energy system and have been found to vary depending on climate and resource availability [47]. Technical long-term feasibility documents must include derating factors in photovoltaic systems, performance degradation of technology, and grid integration [48].

Risks associated with investments (particularly in overseas, large-scale ventures) have become standard practice and include (but are not limited to) political, regulatory, and financial decision-making aspects [49]. Sensitivity analysis is common practice in predicting and assessing the financial robustness of alternative scenarios predicated on changes in capital, operational costs, and energy output [50]. The Total Cost of Ownership (TCO) approach provides a financial outlook on costs associated with a project beyond capital expenditure to include costs of operations, maintenance, replacement, and project lifecycle [51].

2.2.2. Environmental Criteria

The most fundamental aspect when it comes to financing activities that involve renewable energy, in particular the construction of renewable energy facilities, is the degree to which such activities contribute to the decrease in Greenhouse Gas (GHG) emissions. Numerous works of literature point out that there is an inverse relationship between the utilisation of renewable energy and the levels of CO₂ emissions. Therefore, financing the construction of such facilities is consistent with the objectives of climate change mitigation [52,53].

The Environmental Impact Assessment (EIA) process is particularly important for assessing the impacts of renewable energy facilities from an ecological perspective. The potential impacts that an EIA is likely to focus on include the change in the composition and structure of biological communities (biodiversity) and land use, as well as air and water quality and noise pollution. In the context of policy, knowledge of the impacts on the environment allows for trade-offs of ecological risks and economic development activities [54].

An increasing number of renewable energy investments focus on the financing of such investments in relation to the UN Sustainable Development Goals (SDGs). Green finance, represented by financial instruments such as green bonds, is directed to projects that enhance positive environmental outcomes and long-term sustainability [55]. Among its benefits, renewable energy systems promote the achievement of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) and indirectly the achievement of other related SDGs through socio-economic benefits.

Recent advancements in improved efficiency solar cells, design upgrades in wind turbines, and tools integrating digitally for optimisation have sustained impacts on environmental performance. Financial technologies and public–private partnerships have been shown to enhance the environmental sustainability of renewable energy systems in developing countries [56]. The expansion of green credit policies and analogous regulatory

frameworks reinforces the governing institutional structure, thereby promoting the integration of environmental considerations into investment decision-making processes [57].

2.2.3. Social and Community Criteria

There are social and community criteria that affect the investment decisions that are especially focused on community-centred energy systems. Local stakeholder engagement during the planning and governance phases of the project has been shown to improve project acceptance and legitimacy. Community members ensure that renewable energy investments meet the region's needs and that energy generation conflicts are mitigated [58].

There are a number of elements that shape public acceptance of the project, most notably, the perception of fairness, transparency, and community benefits. The presence of a robust engagement framework has been shown to positively influence the level of trust and support for the renewable energy project [58]. Several studies suggest that the social impacts of a project that are likely to be adverse and that are a result of policy neglect should be integrated into the policy framework of the project at the earliest stages of the policymaking process [59,60].

The provision of renewable energy systems and the energy they generate has a number of advantages. There are many benefits, especially socio-economic ones, that are associated with the provision of renewable energy systems. For example, hybrid renewable systems result in emission reductions alongside the attainment of local job creation and economic growth [61]. Evidence shows that economic incentives and growth opportunities often correlate positively with social acceptance [62].

Equitable energy and social justice considerations are paramount when it comes to assessing the long-term sustainability of renewable energy systems. The investments that are made into renewable energy systems should consider the impacts of the system in order to ensure that the benefits from the system are not inequitable and that the system does not reinforce existing inequalities. Participatory governance models in geothermal and other sectors highlight the importance of equity-driven frameworks for social acceptance [63].

Strong institutional frameworks and public-private partnerships enhance the ability of projects to address community needs and ensure social responsibility [49]. Multi-criteria decision-making methods are increasingly incorporating social factors to facilitate comprehensive assessment [64,65].

Overall, renewable energy investment assessment requires the application of a broad set of criteria encompassing techno-economic performance, socio-environmental impacts, and social conditions. These criteria are a function of the interconnected character of energy systems that require assessment of profit, ecosystem health, and social system health to facilitate the low-carbon transition. The next section builds on this to address the extent to which the factors of inequality and equity are disproportionately underdeveloped in current frameworks of decision-making.

2.3. *Inequalities in the Low-Carbon Transition*

While the global low-carbon transition is essential to mitigate climate change, the social and distributional impacts are evident and deeply unequal across socio-economic, regional, and demographic lines. Many countries are developing strategies for fast-tracked decarbonisation. Existing inequalities such as energy poverty, uneven exposure to pollution, and inequitable access to clean technologies are likely to be exacerbated, not alleviated, in this context. In order to address the transition alongside these different inequalities to achieve some degree of justice and inclusion, it is essential to understand the different forms and dimensions of these inequalities.

To begin with, one of the most widely discussed aspects of inequality relates to household-level access to energy and clean technologies. Energy poverty will continue to be one of the most critical issues facing both developing and high-income countries. Numerous studies indicate that most low-income households and residential buildings have disproportionate and massive energy poverty and have little to no ability to implement energy-efficient or low-carbon innovations [2,66]. Territorial energy vulnerability assessments further demonstrate the way socio-cultural and economic barriers influence the quality and affordability of energy services in a region, paying particular attention to the weak socio-cultural and economic aspects of the urbanising areas in low-carbon transition [67]. These disparities are reinforced by cost barriers, financing gaps, and tenure-related constraints that hinder access to renewable energy solutions among marginalised households [68,69].

Furthermore, it is plausible that new decarbonisation regulations, such as carbon pricing, may further increase poverty. Numerous studies have shown that carbon taxes are regressive, as low-income households pay a higher percentage of their income on energy, and thus it is the poorest households that suffer the most [70,71]. Inequalities generated by digitalization are also present, as low digital access households are unable to engage in rapidly expanding smart, decentralised, and digitally governed clean energy systems [6]. Older adults are increasingly recognised as a distinct vulnerable group in the low-carbon transition, facing higher risks of energy poverty, lower adaptive capacity, and digital exclusion that limits their ability to access emerging low-carbon solutions [72].

Beyond household-level inequalities, spatial disparities constitute another critical layer of uneven transition outcomes. Aspects of regional inequality pose considerable structural concerns that still need to be addressed. Research conducted spanning Asia, Europe, and North America shows that the pathways of economic decarbonisation pose net economic benefits to the economically stronger regions, while the lagging or structurally dependent regions bear the greater losses. For example, the regions that historically depended on coal are further vulnerable to losses due to job losses and are also ill-equipped to diversify economically [73,74]. Similarly, studies conducted in Japan and in China indicate that the differing outcomes of national decarbonisation and carbon-neutral policies are due to the uneven regional industrial structures, variances in governance, and differences in technological capacity [75,76].

If not adjusted to socio-economic and institutional contexts, decarbonisation policies are likely to exacerbate regional inequalities. Empirical studies highlight substantial differences across regions in the impacts of climate and energy policies, reflecting variations in industrial structures, technological capacity, and governance arrangements [77,78]. Even within individual countries, significant subnational variation in emission reduction and carbon intensity has been observed over time, partly due to differences in development levels and local capacity for policy implementation [79]. As a result, uniform decarbonisation approaches—such as carbon pricing or technology mandates—often fail to deliver equitable outcomes, particularly in structurally disadvantaged regions.

A further dimension of inequality arises from environmental justice and broader social impacts associated with transition policies. The low-carbon transition relates to issues of environmental justice and social inequities. Research on pollution burdens shows that Black, Indigenous, and low-income communities are more severely impacted by decarbonisation air pollution exposures, both historically and in some future decarbonisation scenarios [66]. This illustrates the importance of transition strategies that eliminate rather than reproduce unequal environmental burdens.

Energy justice scholars argue that historical injustices and systemic discrimination create the current inequities in vulnerabilities—who is more likely to be exposed to harmful

pollutants, who lacks access to clean energy, and who is excluded from energy decision-making [5,80]. Procedural justice is characterised by the top-down paradigm of decision-making, which forecloses trust and legitimacy of the transition policies [81].

The impacts from the social and labour dimensions are also unequally distributed. Research suggests that shifts in the green labour market may unintentionally benefit higher-skilled workers and displace lower-skilled workers unless policies are designed to avoid such outcomes [82]. Moreover, the social and labour dimensions of large-scale transition policies (e.g., the U.S. Inflation Reduction Act) are likely to disproportionately benefit corporations rather than frontline communities—unless equity provisions are integrated by design [83].

Taken together, these forms of inequality reveal that social and regional disparities are not peripheral but structurally embedded within low-carbon transitions. The evidence from different global regions, socio-economic classes, as well as different energy infrastructures points to the fact that disparities in the system are not further to the margins but are core to the functioning of low-carbon transitions. This includes the different levels of access to clean technologies, the inequitable environmental burdens created, the different economic impacts of the transitions, and the lack of equitable participation in the processes. Building on this, the following sections examine how barriers and drivers shape renewable energy investments and where existing decision-making models fall short. This, in turn, motivates the subsequent development of equity-sensitive criteria as an integral component of renewable energy investment evaluation.

2.4. Barriers Influencing Renewable Energy Investments

Investments in green energy are influenced by a diverse set of factors, comprising economic, institutional, infrastructural, social, and political aspects that either facilitate or impede the flow of capital. Although the transition to a low-carbon economy offers great prospects, such elements do not function in a uniform manner. They often replicate or worsen the inequalities discussed in Section 2.3 by enabling some areas and social groups to attract capital more easily than others.

The first set of barriers has to do with the economy and finances. Continuing high initial investment costs and extended payback durations are still some of the most common barriers to renewables investment, especially in contexts with constrained capital [42]. Market failures, weak financial systems, and high perceived risks negatively impact the cost of capital and access to finance, as is the case in developing (emerging) areas and smaller-scale investors [84]. Financial innovations like green bonds and impact investing, however, can serve as important enablers by lowering risk and opening new avenues for capital. Nonetheless, empirical evidence suggests that these tools are still more accessible in some countries and to some types of investors than others [85].

Infrastructure and spatial factors affect the geography of investment. Insufficient grid capacity, unreliable electric networks, and the lack of transport infrastructure add to operational risks and costs, thus dissuading the diffusion of renewable energy across multiple regions [42]. Geographical limitations and conflicts concerning land use can prolong the duration of a project and heighten opposition to the project in its location, which is the case when a project is situated in a populated area or an area that is ecologically important [86]. Conversely, targeted infrastructure upgrades, public–private partnerships, and the use of spatial planning tools such as GIS can mitigate some of these barriers and improve the bankability of projects in underserved territories [87].

Social, behavioural, and institutional factors create another layer of barriers. Limited public awareness, misconceptions about the reliability of renewables, and cultural attachment to conventional energy sources can weaken social acceptance and create resistance

to projects [88]. Administrative inefficiencies, fragmented regulatory frameworks, and unstable or opaque policy environments further undermine investor confidence, as permitting delays and regulatory reversals increase perceived risk [89]. In contrast, clear and predictable policy frameworks, well-designed incentive schemes, and long-term strategic commitments—often supported by international climate agreements—can act as powerful drivers of investment [90,91]. Social values, climate awareness and associated health benefits, community energy/grassroots initiatives, and mobilisation also positively impacted the social acceptance of the renewable project [92].

Finally, there is risk and uncertainty intersecting with all the aforementioned elements. Volatility in energy prices, shocks to the macroeconomy, and fluctuations in policies all make the investments in renewables riskier. This is particularly the case in weaker governance jurisdictions, where the cost of capital is raised the most. Political will and credible, long-term regulation can mitigate this to some degree by stabilising expectations and demonstrating support for low-carbon investments. However, these policies are also, unevenly, themselves the most lacking [91].

The combination of the constraints and the enabling factors indicates that the investment environment for renewables is not homogenous but highly compartmentalised, and is deeply connected to the structural inequalities discussed in Section 2.3. Economic and infrastructural limitations, insufficient institutional capacities, and uneven risk exposure are the factors that impact the most on the lagging regions and the most vulnerable populations, while nascent policy frameworks and financial support tend to be allocated geographically to the high-capacity regions. However, most existing policy frameworks on investment appraisal do not capture these distributional elements of social equity, focusing instead on techno-economic efficiency. This explains why the next section will discuss the social equity gaps in current investment appraisal frameworks in order to provide justification for introducing equity-sensitive elements as an additional dimension for evaluating investments in renewables.

2.5. Gaps in Existing Decision-Making Models

Despite the growing number of methods available for techno-economic, environmental, and social assessments in the renewable energy sector, there are still extensive and interlinked gaps to be addressed in existing investment decision-making models. These gaps constrain the ability of existing frameworks to respond to the multidimensional challenges of the low-carbon transition and limit their capacity to support equitable and socially responsive investment outcomes.

First, most decision-support models continue to rely heavily on techno-economic criteria and financial optimisation, giving substantially less weight to social, environmental, and distributional aspects. This disproportionate focus narrows the analysis and overlooks community impacts, social acceptance, and varying degrees of vulnerability in both affected regions and population groups. As pointed out in the recent reviews, traditional frameworks ignore inclusion within the dimensions of equity, such as energy poverty and affordability, and even the lack of these dimensions is crucial in determining social acceptance of low-carbon transitions [93,94].

Second, the complexity of factors like policy, regulations, and market uncertainties, which are of great relevance to investing in renewable energy, is not fully accounted for in current models. Policy uncertainty, the lack of a regional governance framework, and uneven policy governance have, for decades, been incorporated into models in investment risk analysis, and without a doubt, resulted in risk perception changes and capital allocation distortions [95]. Consequently, investment decision support systems do not consider the

actual investment constraint and thus have a tendency to overestimate the potential of the investment in a policy-unstable environment [42].

Third, these frameworks do not incorporate spatial and land-use sensitivities into their assessments. This disjointed approach results in the examination of site-level ecological risks, land-use conflicts, and interactions with local biodiversity and livelihoods in isolation from the economic and technological assessments. Such fragmented evaluations not only lead to suboptimal siting decisions, but they can also produce social opposition and ecological tensions, which outcomes can be mitigated through integrated spatial-risk modelling and differentiated land-use planning, systems theory [84].

Fourth, current models demonstrate a limited ability to incorporate innovative financing tools and new forms of green finance. There is evidence that green bonds, concessional and blended financing, and community finance can reduce perceived risks, fill financing voids, and direct funds to the most neglected areas. Despite this, the aforementioned finance models are still largely absent from mainstream decision-making frameworks [42,96]. The failure to include such innovative finance within models constrains the ability to capture the equity-augmenting investment opportunities that such models ought to be addressing.

Finally, perhaps most drastically, there are no equity-sensitive criteria that systematically influence how renewable energy investments are evaluated. Equity and justice concerns are present in energy justice literature, but they are poorly integrated within the framework of investment decision models. Most existing MCDM, cost–benefit, and risk assessment frameworks do not feature distributional accessibility and risk exposure for vulnerable groups [1]. Without these criteria, current models will perpetuate socio-economic disparities instead of facilitating the necessary socio-economic equity within a low-carbon transition.

The existing models exhibit significant limitations, including an overreliance on techno-economic metrics, an insufficient treatment of uncertainty and spatial constraints, and an inadequate incorporation of innovative finance and equity considerations. These shortcomings of existing models also provide the motivation for the development of equity-sensitive model criteria and a novel conceptual model framework, which aims at integrating the principles of distributive, procedural, and recognition justice in the evaluation of investments in renewable energy.

Figure 1 presents a conceptual timeline of key research directions in renewable energy investment evaluation. The horizontal orientation of the arrow symbolises a forward-moving trajectory, emphasising how the literature has expanded from a narrow techno-economic focus toward a broader understanding of social, spatial, financial, and equity-related dimensions of renewable energy investment evaluation. This representation highlights the evolving nature of decision-making in the energy sector, where each emerging research strand builds upon and extends earlier analytical approaches. Moreover, the figure underscores the conceptual gaps identified in the recent literature, which justify the development of an equity-oriented framework.

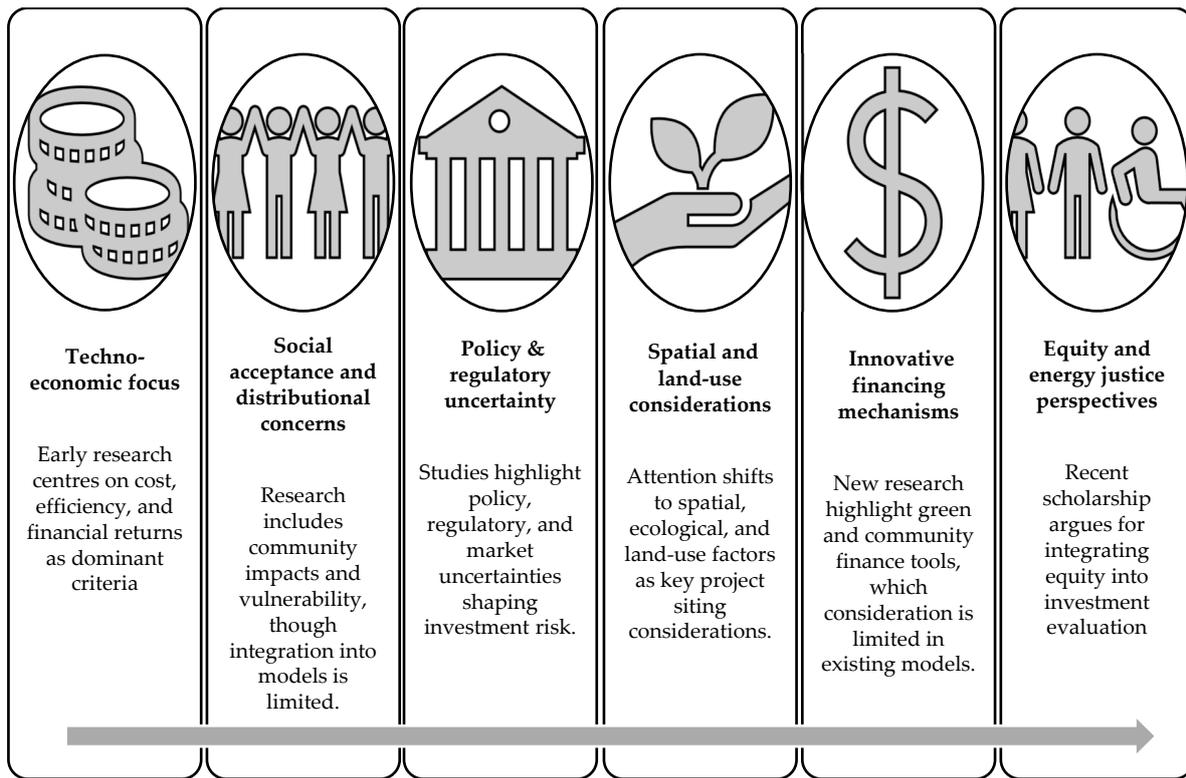


Figure 1. Conceptual timeline of research developments in renewable energy investment evaluation. Source: developed by the authors.

3. Methodology

This study employs a conceptual research design aimed at developing an equity-oriented framework for renewable energy investment evaluation. Given that existing decision-support models insufficiently integrate equity considerations, the methodology is structured to facilitate the systematic identification of gaps and the formulation of equity-sensitive criteria. The process consists of three interrelated stages (Figure 2). These stages were implemented sequentially, with each step informing and constraining the subsequent phase of analysis.

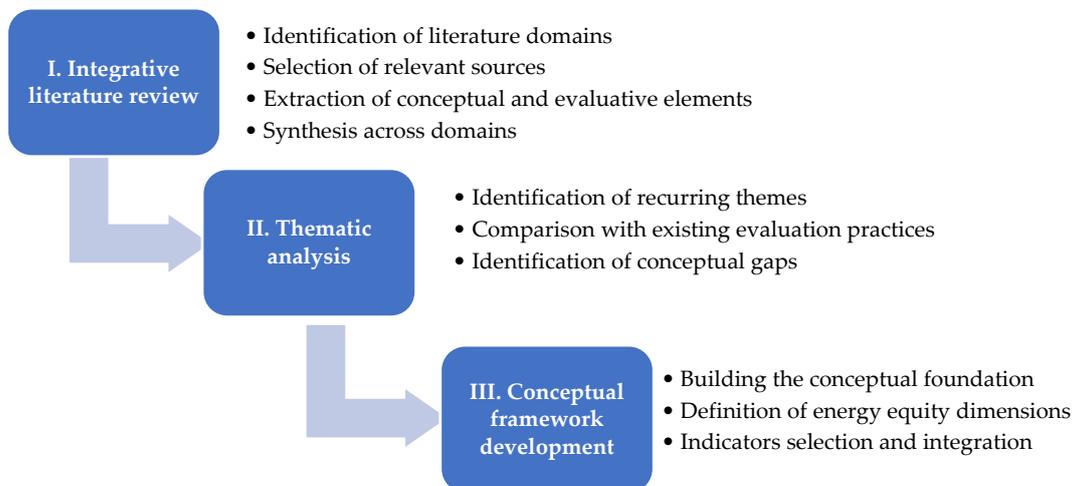


Figure 2. Research design of the study. Source: developed by the authors.

The integrative literature review followed a structured three-step process designed to support transparent framework development. First, relevant literature was identified across three analytical domains using predefined keyword combinations. Second, studies were screened and selected based on explicit inclusion and exclusion criteria to ensure relevance for renewable energy investment evaluation and equity considerations. Third, the selected literature was thematically coded and synthesised to identify recurring patterns related to investment decision-making gaps, inequality mechanisms, and equity-sensitive dimensions. While the review does not follow a systematic review protocol, this structured synthesis ensures analytical coherence and methodological transparency consistent with integrative review standards.

The first stage, the integrative literature review, established the knowledge base for the framework development [97,98]. The integrative literature review approach was selected because it is well-suited to examining emerging topics where existing conceptualizations are limited. In such contexts, the objective is to develop initial or preliminary theoretical models rather than to reassess established ones. This type of review does not require the exhaustive collection of all published studies but instead seeks to synthesise perspectives and insights drawn from different fields and research traditions, allowing for a more comprehensive understanding of fragmented knowledge areas [99]. The review began with the identification of three core literature domains: (1) renewable energy investment decision-making approaches, (2) criteria commonly used in investment appraisal, and (3) empirical evidence on inequalities arising in the low-carbon transition.

Literature was identified through keyword-based searches in Google Scholar and targeted screening of leading journals within the three analytical domains defined above. Search strings combined terms related to renewable energy investment and decision-making (such as: “renewable energy investment evaluation”, “energy project appraisal”, “multi-criteria decision-making in energy”), investment appraisal and decision-support methods (such as: “sustainability assessment of renewable energy”, “energy planning evaluation frameworks”), and social equity and justice in energy transitions (such as: “energy justice and renewable investments”, “distributional impacts of renewable energy”, “social equity and renewable infrastructure”). The temporal scope emphasised literature published from the mid-2000s to 2025, reflecting the period in which renewable energy investment frameworks and energy justice research have developed most intensively, while earlier seminal contributions were included where necessary to establish conceptual grounding.

Studies were included if they (1) addressed renewable energy investment decision-making or evaluation, (2) proposed or applied social, equity, or justice-related analytical dimensions, or (3) provided empirical evidence on distributional impacts, participation barriers, or differentiated vulnerabilities in low-carbon transitions. Only original peer-reviewed journal articles published in English were included in the synthesis. Studies focusing exclusively on technical optimisation or market modelling without social or distributive considerations were excluded from the synthesis used for framework development. Relevant literature sources were selected based on their contribution to these domains. This allowed the extraction of key conceptual and evaluative elements, including assessment criteria, methodological assumptions, and decision-making practices.

The second stage involved a thematic analysis of the reviewed literature. Recurring themes were identified in relation to structural inequalities and the various barriers that shape renewable energy investment contexts. Examining these themes alongside existing evaluation practices made it possible to assess the extent to which current decision-making models reflect the social realities of the low-carbon transition. This comparison revealed several conceptual gaps, which provided both the justification and the direction

for developing a more comprehensive, equity-oriented approach to renewable energy investment evaluation.

In the third stage, a conceptual framework integrating equity considerations into renewable energy investment evaluation was developed. The framework reflects the main elements that shape investment contexts, including the broader transition pressures, the traditional criteria commonly applied in evaluation, and the constraints created by structural inequalities and investment-related barriers. Positioning these elements together made it possible to clarify how current decision-making models are organised and where important analytical gaps arise.

Given the conceptual nature of this study, the methodological approach is designed to support theory development rather than empirical testing. The integrative literature review enables the synthesis of fragmented insights across multiple research streams, including renewable energy investment evaluation, energy justice, and equity-oriented modelling. The subsequent thematic analysis serves to identify recurring patterns related to inequality, access barriers, and differentiated risk exposure that are not systematically captured in existing decision-support frameworks. Together, these methodological steps inform the development of the proposed conceptual framework and equity-sensitive indicators, which represent the main analytical outcomes of this conceptual study. The literature included in the analysis was selected based on its relevance to renewable energy investment evaluation, equity and justice considerations in energy transitions, and the identification of investment-related barriers and distributional outcomes. Studies focusing exclusively on technical optimisation without socio-economic or distributional implications were not prioritised, as they fall outside the scope of the proposed equity-oriented framework.

Building on this foundation, equity was incorporated as an explicit evaluation dimension in the framework. The development process focused on ensuring that equity considerations could be systematically integrated rather than treated as supplementary or external to conventional evaluation logic. The indicators were chosen based on their relevance to the equity dimensions identified and their grounding in empirical literature. Their integration within the framework establishes a structured basis for evaluating renewable energy investments in a way that reflects both traditional performance criteria and the wider social implications of the low-carbon transition.

The need for this methodological approach is reinforced by recent modelling research showing that equity dimensions remain largely absent from power system and energy planning optimisation models used to inform investment and policy decisions, strengthening the rationale for developing a conceptual framework capable of integrating equity directly into investment evaluation [100].

4. Framework Development and Key Conceptual Outcomes

While techno-economic, environmental, and social indicators form the backbone of conventional renewable energy investment evaluation, growing attention is given to the equity implications of the low-carbon transition. This may include equity-sensitive criteria that consider the distribution of benefits and risks as well as the costs of investments in renewable energy across social, geographic, and relational silos. These criteria are inspired by energy justice literature, which is concerned with the distributional, procedural, and recognitional aspects of justice. As there is widespread evidence that, relative to the energy transition, there is a pronounced lack of energy services, unequal exposure to adverse environmental impacts, and significant disparities in civic engagement, vulnerable groups will be disproportionately affected [1]. Accordingly, equity-sensitive criteria become essential for assessing how inclusive and just renewable energy investments are within the proposed framework.

Within the proposed framework, equity-sensitive dimensions are not treated as descriptive labels but as evaluative lenses that are systematically integrated into renewable energy investment decision-making. Each dimension is operationalised through specific criteria and indicators that can be incorporated into existing appraisal and decision-support processes alongside conventional techno-economic and environmental metrics. In this way, the framework enables the structured comparison of investment alternatives in terms of distributional outcomes, access and inclusion constraints, and differentiated risk exposure.

The analytical outcomes of the study correspond directly to the three phases of the methodological approach. The first phase (integrative literature review) resulted in the identification of key limitations and gaps in existing renewable energy investment evaluation frameworks, particularly with respect to equity, access, and distributional outcomes. The second phase (thematic analysis) synthesised recurring patterns related to structural inequalities, investment barriers, and differentiated risk exposure, providing the conceptual basis for defining equity-sensitive evaluation dimensions. The third phase produced the main analytical contribution of the study: the development of an equity-oriented conceptual framework and a corresponding set of operationalisable indicators designed to integrate equity considerations into renewable energy investment evaluation.

This recognition also responds directly to the gaps identified in Section 2.5, where current decision-making frameworks were shown to insufficiently address distributional outcomes, accessibility barriers, and differentiated risk exposure. Therefore, equity-sensitive criteria are introduced not as optional extensions but as necessary components of a comprehensive and fair investment evaluation model.

4.1. Conceptual Framework

To integrate these justice-driven considerations into renewable energy investment evaluation, this study proposes a conceptual framework that positions equity-sensitive criteria as a systematic extension to established assessment dimensions (Figure 3). At the top of the framework, the low-carbon transition is depicted as the overarching systemic driver, reflecting climate policy commitments, decarbonisation targets, technological progress, and global energy trends. This transition sets the overall direction of change in energy systems and creates the need for large-scale renewable energy investments.

As the transition unfolds, it is mediated by traditional investment criteria—techno-economic, environmental, and social—which still form the core of most decision-support tools. These criteria are indispensable for assessing project performance and feasibility, yet they are largely blind to how benefits and burdens are distributed across different social groups and territories. At the same time, two sets of contextual constraints operate laterally within the framework: structural inequalities (such as income disparities, regional imbalances, energy poverty, and social vulnerability) and barriers (economic and financial, infrastructural and territorial, social and institutional, and policy-, risk-, and uncertainty-related). Together, these constraints shape who can participate in and benefit from the transition and where investments are likely to be concentrated.

The interaction between traditional criteria, structural inequalities, and contextual barriers generates gaps in existing decision models, represented in the framework as a separate layer of “missing equity dimensions”. These gaps capture the absence of explicit attention to distributional outcomes, accessibility for vulnerable groups, and differentiated risk exposure in most current appraisal practices. In response, the framework (Figure 3) introduces three groups of equity-sensitive criteria—(1) distributional equity, (2) accessibility and inclusion, and (3) equity-adjusted risk—each operationalised through a set of measurable indicators that reflect who gains, who can participate, and who bears the risks associated with renewable energy investments.

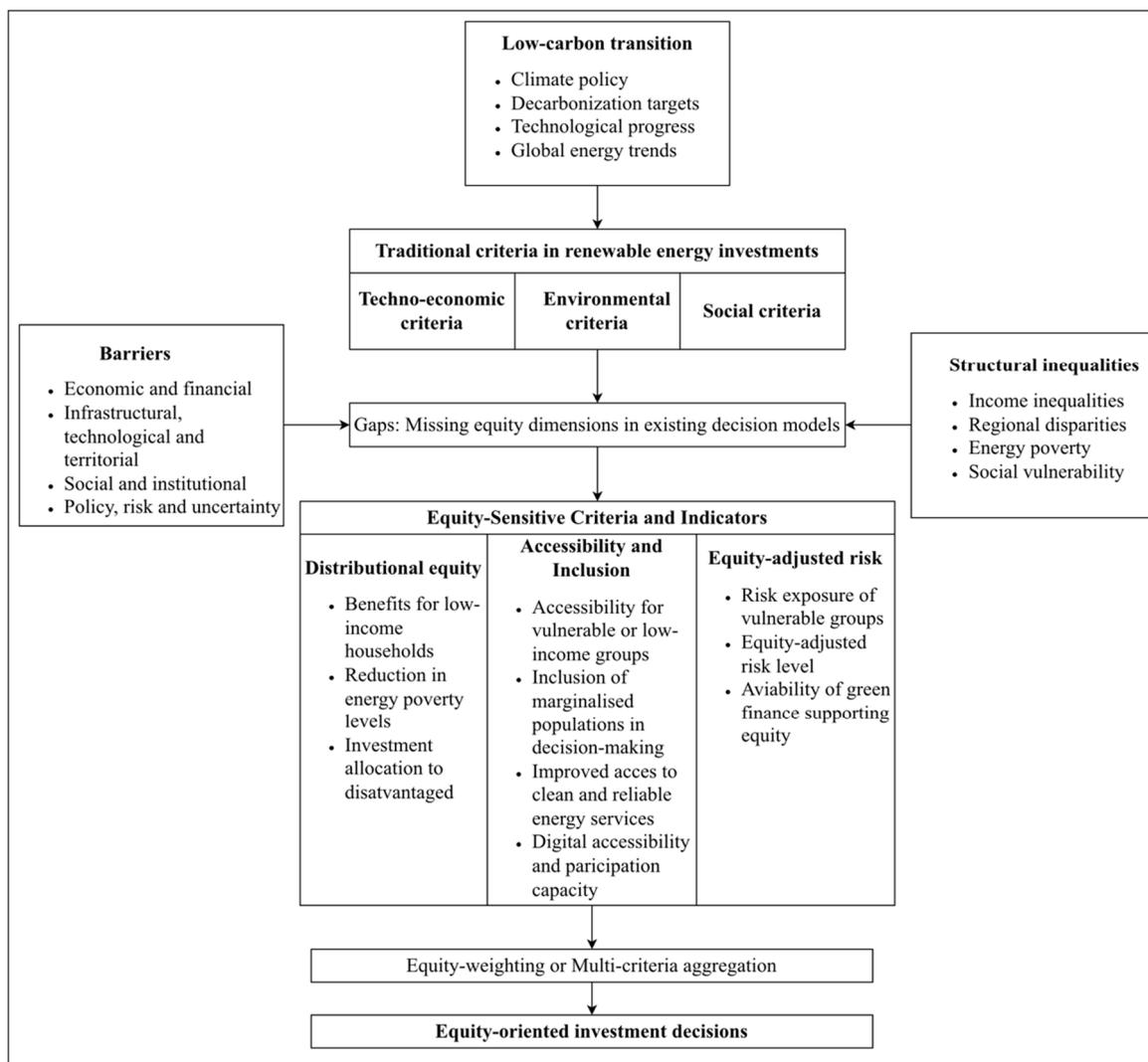


Figure 3. Conceptual framework integrating equity indicators in renewable energy investments. Source: developed by the authors.

At the bottom of the framework, these equity-sensitive indicators are designed to feed into equity-weighting or multi-criteria aggregation procedures, alongside traditional techno-economic, environmental, and social criteria. This allows decision-makers to incorporate equity considerations directly into investment evaluation and to move towards equity-oriented investment decisions rather than purely efficiency-driven ones. The conceptual structure thereby provides the theoretical grounding for integrating equity-sensitive criteria into renewable energy investment evaluation frameworks.

4.2. Proposed Equity-Sensitive Criteria and Indicators

The selection of equity-sensitive dimensions and indicators was guided by three criteria: their relevance for renewable energy investment decision-making, their conceptual grounding in energy justice and inequality literature, and their potential to be operationalised within evaluation frameworks. Accordingly, the proposed indicators focus on distributional outcomes, access and participation constraints, and differentiated risk exposure, as these dimensions consistently emerge in both empirical and conceptual studies on just and inclusive energy transitions.

In addition, the indicators were prioritised based on the availability of harmonised statistical data and their applicability across different territorial scales, allowing implemen-

tation using routinely collected household, regional, and administrative datasets rather than case-specific surveys. This supports both comparative analysis and adaptation to different national and regional data infrastructures.

Table 2 summarises the equity-sensitive criteria and indicators identified in the scientific literature and proposed for inclusion in renewable energy investment evaluation. These indicators are described in more detail in the following subsections.

Table 2. Equity-sensitive indicators for renewable energy investment evaluation. Source: developed by the authors.

Dimension	Indicator	Definition	Key References
Distributional Equity	Benefits for low-income households	Extent to which the project reduces energy costs or improves access to clean, affordable energy for income-poor households.	[71,101]
	Reduction in energy poverty levels	Expected decrease in the number or share of households experiencing energy poverty as a result of the project's implementation.	[71,101]
	Investment allocation to disadvantaged regions	Share of total investment directed toward economically lagging, structurally vulnerable, or peripheral regions.	[102]
Accessibility and Inclusion	Accessibility for vulnerable or low-income groups	Degree to which project design, subsidies, or financing schemes enable participation among disadvantaged households.	[68,69]
	Inclusion of marginalised populations in decision-making	Extent to which vulnerable social groups are represented in planning, consultation, or governance processes.	[101,103]
	Improved access to clean and reliable energy services	Extent to which the project expands access to modern, reliable, and clean energy services for underserved communities.	[101,103]
	Digital accessibility for energy participation	Degree to which communities have adequate digital access (infrastructure, literacy, affordability) required to benefit from digitalised renewable energy systems.	[6,68]
Equity-Adjusted Risk	Risk exposure of vulnerable groups	Extent to which marginalised groups are disproportionately exposed to financial, regulatory, or environmental risks related to the project.	[71,104]
	Equity-adjusted investment risk level	Degree to which investment risk assessments incorporate distributional impacts and vulnerabilities of different social groups.	[101,105]
	Availability of green or concessional finance supporting equity	Presence and adequacy of concessional loans, green bonds, or blended finance mechanisms targeted at vulnerable communities.	[106]

Distributional Equity

Distributional equity considers the socio-economic and geographical distribution of the benefits of renewable energy and its economic and environmental advantages, such as job creation, reduced energy costs, and better air quality. The literature underscores that the deployment of renewable energy can positively impact regional development as well as job creation in economically lagging regions [107]. Similarly, studies on energy poverty confirm that the risk of energy deprivation is highest among the economically disadvantaged and that this risk can be mitigated through the provision of reliable, affordable, and clean energy [101,108]. These insights underscore the need to evaluate how renewable energy investments affect income-poor households, energy poverty levels, and investment flows toward marginalised regions.

Proposed indicators:

- Benefits for low-income households—extent to which a project reduces energy costs or improves access to clean energy services [101,108].
- Reduction in energy poverty levels—expected decrease in households experiencing energy poverty [101].
- Investment allocation to disadvantaged regions—share of project investment directed to economically or geographically vulnerable areas [102].

Accessibility and Inclusion

Accessibility and inclusion criteria assess whether vulnerable and marginalised populations can meaningfully participate in and benefit from renewable energy investments. Studies demonstrate that low-income households face substantial structural barriers, including high upfront costs, limited financing opportunities, policy gaps, and unstable housing tenure [68,69]. Procedural justice—ensuring that communities are involved early and meaningfully in project planning—has been shown to increase trust, legitimacy, and acceptance of renewable energy projects [109,110]. In addition, digital exclusion is emerging as a critical barrier, as households and communities with limited digital access or skills are less able to engage with smart, decentralised, and digitally governed energy systems [6]. The focus here is on assessing the extent to which renewable energy investments reduce participation barriers and extend the benefits of modern energy services.

Proposed indicators:

- Accessibility for vulnerable or low-income groups—the degree to which project design, subsidies, or financing schemes enable participation among disadvantaged groups [68,69].
- Inclusion of marginalised populations in decision-making—representation of vulnerable social groups in planning and governance processes [101,102].
- Improved access to clean and reliable energy services—extent to which renewable projects expand access to reliable and clean energy for underserved communities [68,111].
- Digital accessibility and participation capacity—extent to which households and communities have sufficient digital access, connectivity, and skills to participate in smart, decentralised and digitally governed low-carbon energy systems [6,68].

Equity-Adjusted Risk

Equity-adjusted risk acknowledges that financial, regulatory, and socio-environmental risks are unevenly distributed across communities. Vulnerable populations face heightened exposure to energy price volatility, regulatory instability, or environmental hazards [104,108]. Moreover, socio-economic structures influence investor risk perceptions, which can systematically disadvantage already underserved regions [101,105]. Meanwhile, concessional finance, blended finance, and green bonds can redirect capital towards vulnerable communities by reducing perceived risks [106].

Proposed indicators:

- Risk exposure of vulnerable groups—extent to which marginalised groups are disproportionately affected by financial, environmental, or policy risks [104,108].
- Equity-adjusted investment risk level—degree to which risk assessments incorporate vulnerability and distributional impacts [101,105].
- Availability of green or concessional finance supporting equity—existence of financial instruments that directly support disadvantaged populations [106].

Taken together, equity-sensitive criteria broaden the scope of traditional investment appraisal frameworks with an additional focus on justice concerning who profits, who participates, and who bears risks during the energy transition. The proposed conceptual framework illustrates how these indicators can be systematically incorporated into decision-support tools; however, the specific design of equity-weighting schemes is beyond the scope of this conceptual study. In this way, the framework provides a structured foundation

for integrating equity-sensitive indicators into investment evaluation and highlights their relevance for future empirical applications.

While several equity dimensions are inherently complex and context-dependent, many of the underlying mechanisms shaping unequal investment outcomes can be approximated through harmonised socio-economic, energy, and territorial indicators routinely collected by statistical authorities. To demonstrate the empirical feasibility of the proposed equity-sensitive indicators framework and clarify how these concepts can be operationalised using commonly available statistical data, Table 3 summarises indicative measurement approaches and typical data sources corresponding to each equity-sensitive indicator.

Table 3. Indicative data sources and statistical proxies for equity-sensitive indicators in renewable energy investment evaluation. Source: developed by the authors.

Indicator	Scale	Indicative Measurement Approach	Typical Data Sources
Benefits for low-income households	Household; regional	Change in energy expenditure share of disposable income (energy burden) by income quintile; change in average energy expenditures	EU-SILC; household budget surveys; national statistics offices
Reduction in energy poverty levels	Regional; national	Change in population share below national/regional energy poverty thresholds (e.g., arrears, inability to keep home warm, housing quality indicators)	EU-SILC; national statistics offices
Investment allocation to disadvantaged regions	Regional	Share of renewable capacity; investment per capita in less developed regions; subsidy flows in lagging regions	Eurostat database; national statistics offices; cohesion policy indicators
Accessibility for vulnerable or low-income groups	Household; regional	Share of households unable to afford energy efficiency improvements or clean heating; uptake rate of support schemes among low-income households	EU-SILC; housing budget and condition surveys
Inclusion of marginalised populations in decision-making	Regional	Existence and depth of consultation mechanisms; participation rates in local governance; civil society or community activities	Eurostat database; national statistics offices; national social participation surveys; qualitative stakeholder surveys
Improved access to clean and reliable energy services	Regional; national	Share of population connected to gas/electricity networks; electricity supply reliability indicators; change in connection rates; service reliability indices; decentralised generation access	Eurostat database; national regulators' statistics; national statistics offices
Digital accessibility for energy participation	Regional	Broadband coverage, share of households with internet access, and digital skills levels	Eurostat database; national statistics offices; household surveys data
Risk exposure of vulnerable groups	Regional	Composite index combining socio-economic vulnerability and territorial exposure to energy-related land-use change	EU-SILC; Eurostat regional statistics; national statistics offices
Equity-adjusted investment risk level	Regional; national	Composite index of labour instability, income inequality, demographic pressure, and energy expenditure volatility	Eurostat regional statistics; national statistics offices
Availability of green or concessional finance supporting equity	National; regional	Share of public climate funding in total energy investment; cohesion fund allocations; share of public and EU funds directed to renewable deployment and energy renovation in disadvantaged regions	Eurostat database; EU cohesion databases; national budgets; national statistics offices

As shown in Table 3, the proposed equity-sensitive indicators can be operationalised using commonly available official statistics, including household surveys, regional socio-

economic and demographic data, energy infrastructure and service quality indicators, as well as public expenditure and investment statistics. Although internationally harmonised datasets are cited for illustrative purposes, comparable indicators are routinely collected by national statistical offices, energy regulators, and international organisations in both high-income and emerging economies. This supports the general applicability of the framework across different institutional and geographic contexts and indicates that the indicators can be readily adapted to regional data systems and planning practices, facilitating their integration into policy-oriented investment evaluation and decision-support tools.

5. Discussion

The findings of this study indicate that renewable energy investment evaluation continues to be dominated by techno-economic optimisation logics. This persists despite substantial evidence that renewable energy investment and deployment processes generate differentiated social, spatial, and distributional effects. Although research increasingly acknowledges issues such as community acceptance, energy burden, vulnerability, spatial constraints, policy risk, and innovative finance, these aspects remain only partially integrated into formal modelling and evaluation tools. As a result, investment decisions are still primarily assessed through aggregated performance metrics that inadequately capture the heterogeneity of needs, capacities, and risk exposures across population groups and regions.

Recent modelling studies reinforce these limitations by demonstrating that equity considerations can materially alter renewable energy investment outcomes when they are incorporated into decision-support tools. Sifuentes et al. [112] provide a quantitative illustration of this effect by showing how embedding equity objectives within investment optimisation reshapes renewable energy allocation patterns. Their Equity and Climate Outcomes of Community Energy model demonstrates that equity-driven allocation of community solar investments can simultaneously reduce energy burdens for low-income households and support decarbonisation goals, while also revealing trade-offs between emissions maximisation and energy affordability.

Related insights are provided by Heleno et al. [113], whose linear programming analysis shows that the optimal allocation of energy-efficiency measures, rooftop solar, and community-scale renewable resources changes once energy burden and vulnerability indicators are explicitly incorporated. Their findings indicate that interventions that appear cost-effective at an aggregated level do not necessarily deliver proportional benefits across socio-demographic groups and may fail to alleviate energy insecurity without targeted equity considerations.

Taken together with other equity-oriented modelling studies, this evidence underscores that investment strategies assessed solely through aggregate efficiency metrics risk obscuring distributional effects that are critical for socially inclusive low-carbon transition outcomes.

Evidence from power-system modelling research further demonstrates that these limitations are not confined to individual models or case studies but are embedded in dominant planning paradigms. Drawing on a systematic review of 99 studies, Goforth et al. [100] show that equity and energy justice considerations are rarely incorporated endogenously into electricity-system models used to inform planning and investment decisions. Instead, these models continue to rely on least-cost optimisation logics, with equity-related dimensions typically addressed, if at all, through ex-post analyses rather than integrated into objective functions or constraints. The review identifies persistent shortcomings across multiple modelling domains, including reliability planning, distributed energy resource adoption, spatial siting, retail pricing, emissions allocation, and economic impact

assessment. These findings indicate that the marginalisation of equity is not incidental but structural, reinforcing the need for evaluation frameworks capable of integrating demographic characteristics, vulnerability profiles, and distributional impacts directly into the core logic of renewable energy investment decision-making.

The need for explicit equity criteria is further underscored by recent efforts to systematise equity metrics within energy planning and policy analysis. The review performed by Tarekegne et al. [114] demonstrates that existing equity indicators remain fragmented and are often limited in their ability to capture distributional outcomes, identify disadvantaged populations, or reflect social heterogeneity at appropriate spatial scales. While the review does not focus explicitly on investment decision-making, it highlights important measurement gaps that constrain the integration of equity considerations into planning and evaluation processes more broadly. These limitations are directly relevant for renewable energy investment evaluation, as they restrict the capacity of decision-support frameworks to assess how investments redistribute benefits and burdens across social and territorial contexts. Earlier multi-criteria decision-making research similarly acknowledges the relevance of social and environmental criteria in sustainable energy planning; however, these dimensions are commonly treated as secondary or qualitatively weighted factors rather than systematically embedded equity constructs [115,116]. Consequently, conventional investment appraisal tools remain limited in their ability to capture differentiated vulnerability and distributional effects in a consistent and transparent manner.

The limitations of prevailing investment and evaluation frameworks become more evident when examined through the lens of energy justice theory. Normative analyses of energy justice provide an essential foundation for understanding why equity considerations cannot be separated from renewable energy decision-making. Belleflamme [117] examines renewable energy transitions through the lenses of distributive, procedural, and recognition-based justice, demonstrating that the deployment of renewable technologies can generate localised burdens, affordability pressures, and governance exclusions when justice principles are not systematically embedded. The analysis makes clear that renewable energy transitions are not socially neutral processes but are shaped by decision-making structures that determine whose interests are prioritised and whose burdens are amplified. This insight offers a strong conceptual justification for embedding equity considerations within renewable energy investment evaluation itself, rather than treating them as peripheral or corrective concerns. Foundational energy justice scholarship further clarifies that distributive, procedural, and recognition-based justice are analytically inseparable from energy system decision-making [19,118], underscoring that equity concerns are structural features of investment choices rather than external normative considerations.

These strands of literature collectively reveal a persistent conceptual and methodological gap in renewable energy investment evaluation: prevailing models continue to inadequately capture differentiated social impacts, territorial disparities, and uneven risk exposure associated with renewable energy investment and deployment. While techno-economic performance and financial feasibility remain indispensable components of investment appraisal, they offer only a partial representation of investment outcomes when assessed in isolation. In the absence of explicitly articulated equity-sensitive dimensions—such as distributional effects, accessibility constraints, and differential vulnerability—evaluation frameworks may contribute to the persistence of socio-economic inequalities and weaken the inclusiveness and legitimacy of transition pathways.

The conceptual framework developed in this study responds directly to these shortcomings by embedding equity within the core logic of investment evaluation rather than treating it as an ancillary or corrective consideration. Drawing on insights from techno-economic assessment, spatial analysis, governance and institutional studies, energy justice

scholarship, and equity-oriented optimisation research, the framework advances a multidimensional evaluative structure that reflects the socio-technical nature of renewable energy investments. Spatially oriented research further supports this approach by demonstrating that investment outcomes are shaped by uneven territorial contexts, where siting decisions interact with land-use conflicts, local livelihoods, and regional development trajectories [119], reinforcing the need for evaluation frameworks that move beyond aggregate performance indicators. By foregrounding distributional equity, accessibility, and equity-adjusted risk, it provides a coherent basis for assessing how investment decisions interact with heterogeneous social conditions and regional contexts. It also highlights that policy instruments prioritising market efficiency, in the absence of systematic distributional assessment, may contribute to uneven social and territorial outcomes.

6. Conclusions and Future Research Directions

This study shows that renewable energy investment evaluation remains dominated by techno-economic optimisation, with equity-related considerations only weakly and inconsistently incorporated into formal decision-support frameworks. While existing approaches provide valuable insights into cost efficiency and environmental performance, they offer a limited representation of investment outcomes by insufficiently accounting for distributional impacts, accessibility constraints, spatial heterogeneity, financing structures, and structural inequalities. As a result, current evaluation practices are poorly equipped to capture differentiated vulnerabilities, uneven risk exposure, and the heterogeneous capacity of social groups and regions to benefit from renewable energy investments.

To address these limitations, the study develops a conceptual framework that embeds equity directly into the logic of renewable energy investment evaluation. By foregrounding distributional equity, accessibility, and equity-adjusted risk, the framework extends conventional appraisal approaches and provides a multidimensional basis for assessing investment outcomes under diverse social and territorial conditions. Rather than replacing established techno-economic methods, it complements them by expanding the evaluative scope to include dimensions that are essential for socially responsive and robust investment decision-making.

Future research should focus on the empirical operationalisation of the proposed framework. This includes the development of measurable and context-sensitive indicators for equity dimensions, their integration into quantitative investment appraisal and decision-support tools, and systematic testing across different institutional, socio-economic, and geographical contexts. Further work is also needed to examine how equity-oriented evaluation interacts with financing instruments, governance arrangements, and participation mechanisms in renewable energy investment processes. Such research will be critical for advancing evaluation practices that support both effective renewable energy deployment and more equitable investment outcomes.

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