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Powering the Future: An Integrated Framework for Clean Renewable Energy Transition

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Powering the Future: An Integrated Framework for Clean Renewable Energy Transition

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Abstract: Transition to renewable energy has been recognized as a crucial step to addressing climate change and achieving greenhouse gas reduction targets, but it can also cause energy sprawl if not planned properly. Clean renewable energy communities (CREC) are emerging globally as an approach for decentralized energy systems and an alternative to traditional centralized energy systems. CREC aims to lower the energy carbon footprint, enhance local energy resilience, and improve the quality of life of residents. Through a comprehensive literature review, this study reviews metrics that can assess the impact of energy transition plans and support decision-making to select technologies that create efficient, reliable, and accessible energy systems. It classifies these metrics into a five-dimensional sustainability approach: environmental, technical, social, economic, political and institutional. The paper proposes a conceptual framework to guide decision-makers in recognizing the role of sustainable land development, sustainable energy planning, and resiliency as an integrated approach to energy transition planning. This framework stresses mapping the place-based potential for clean renewable energy at various scales, highlights the importance of resilience in energy planning, and addresses challenges associated with energy source selection, built environment efficiency, and energy trade. While the framework can serve as a starting point for evaluating energy transition plans, further work is needed to address the limitations of existing metrics and identify additional evaluations for energy mixed land use that are critical to managing energy sprawl on ecosystem services and other land uses.

Keywords: energy transition; Clean renewable energy communities; metrics; sustainable land use; energy planning; sustainability; resilience

1. Introduction

Energy is one of the major sources of carbon emissions, contributing 20.7 $GtCO_{2e}$ to global net anthropogenic emissions in 2021 (Minx, 2021). As global concerns about climate change grow, so does the movement toward renewable energy as a primary energy source, to mitigate climate change (Bogdanov, 2021). The current global economy is driven by fossil fuels (Bhattarai U, Maraseni, T, Apan, A, 2022), and energy is the fundamental block that simulates modern societies (Adedoyin, F, Bekun, F, Alola, A, 2020). Therefore, it is crucial to understand the performance of such a system at multiple levels to ensure its reliability, efficiency, and accessibility (Adedoyin, F, Bekun, F, Alola, A, 2020). However, there is no universal agreed-upon method or set of metrics for measuring or estimating the impact of plans to address uncertainties accompanied by variable supply of renewables, energy sprawl that could affect other built environment and ecological services, and the system reliability and accessibility (Shandiz, 2020).

Land is a competitive source (Smith et al., 2010). With the growing demand for renewables, and an estimated population of 10 billion by 2050 (UN, 2022), the built environment and energy sprawl will increase to meet the demands of the growing population (Becker, J and Kaza, N., 2022). The relationship between energy and land has become necessary, especially when developing long-term plans (Horner, R, Clark, C, 2013). To avoid negative environmental, ecological, economic, and social impacts, decision-makers may need to understand the trade-offs of their policies before proceeding with the transition (Omri, E., Nouri Chtourou, N., Bazin, D., 2022). A complete energy transition from

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finite fossil fuel resources to renewable and low-carbon resources is an essential breakthrough in combating the effects of GHG emissions on climate change. This transition should also consider various aspects that affect sustainability and emission reduction targets, such as energy efficiency generation, demand reduction, environmental impact, and socioeconomic factors (Rosen M. , 2009).

As countries strive to meet their climate goals, understanding the metrics that drive effective planning and decision-making becomes paramount. Despite the extensive body of literature on studying the impact of renewable energy transition and energy resilience, the majority of studies focus on one area such as evaluating energy equity (Kime, S et al, 2023), resilience (Mar, A., Pereira, P., Martins, J.), and social, economic, and environmental sustainability (Akella, A. K., Saini, R., and Sharma, M., 2009). A limited number of studies have focused on reviewing the impact of a complete transition plan that replaced fossil fuels with hybrid systems. The principal goal of this article is to move beyond theories toward practical application of planning for a complete energy transition. It does this by developing a conceptual framework that allows evaluating the performance of the main elements that deliver reliable, efficient, and accessible renewable energy sources. The conceptual framework relies on, (i) developing a conceptual framework that can assist energy planners, spatial planners, community, policymakers, and stakeholders in planning and decision making, (ii) conducting a comprehensive review of the metrics used to evaluate the plan, projects, and scenario of energy transition used in the literature; (ii) evaluate and select metrics based on the overall objectives of the framework that can measure the impact of energy transition for communities.

2. Background

Traditionally communities relied mostly on large-scale power plants powered by fossil fuels, gas, and nuclear, at a central location and transmitting electricity over long distances to end users (Kabeyi M, Olanrewaju O, 2022). These systems are dominant in most counties (Kabeyi M, Olanrewaju O, 2022), where energy planning favors centralized systems because of their cost-effectiveness and ability to satisfy energy demand (Andrews, 2008). However, centralized energy systems are explicitly dependent on finite, nonrenewable resources such as fossil fuels and gas, which are major contributors to climate change through greenhouse gas emissions. In addition, coal mining and drilling of oil and gas, which are essential to operate these systems, cause land degradation, water pollution, and biodiversity loss. (Holechek, J, Geli, H et al., 2022). Clean renewable energy communities (CREC) are a bottom-up transition approach that relies on citizen engagement to create a niche that can influence transition in the energy system (Kirkman, 2009). However, these communities face barriers in implementing their initiatives. In this section, CREC is defined in the context of this study and how metrics can guide communities planning to transition to clean renewable energy.

2.1. Clean Renewable Energy Community Transition Dynamics

There are multiple definitions of energy communities, these definitions rise from the definitions of communities. According to the sociological definition of community by Fuller and Scott (1999), communities can be defined based on their living situation, as residential or nonresidential communities; or based on shared activity, that is not limited to work, or sports, and covers other areas of life; or based on a shared collective action of common interest; or sharing a common identity. Communities can also be defined based on a place or geographical area that binds a group of people (Fisher, 2017). Accordingly, energy communities' definition can be summarized as communities that have a social relation, involved in decision-making for a common local benefit of living in a specific geographical area (Moroni, S et al., 2017).

The European Union has given communities legal identification and defined two types of communities, renewable energy communities (RECs) and citizen energy communities (CECs). REC can be defined as a legal entity, controlled by members located in proximity to a renewable energy project and have environmental and social benefits from the projects, while the CEC is a legal entity directly engaged in all aspects of generation, supply, consumption, storage and charging for Electric Vehicles (Spasova D, Braungardt S, 2022). Another common definition of REC by Walker and Devine-

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Write (2008), a group of people who collectively own, operate, and benefit directly from a renewable energy project, is defined as a group of people who collectively own, operate, and benefit from renewable energy systems, such as solar, wind, geothermal, and biomass. Walker and Devine-Write also argued that the broad meaning of REC allowed the innovation and testing of different social, technological, and economic models.

In the context of this study, CREC refers to communities residing in a common geographical area that are engaged in the production, consumption, distribution, and local policy advocacy of clean renewable energy. These communities place their residents at the center of the energy transition, creating local economic and social benefits and environmental preservation across the area (Seyfang, G., Haxeltine, A., 2012). Globally, many community transition initiatives have been implemented, using several energy production and storage technologies, and sharing approaches covering partially or fully the energy demand. The grassroots initiative used different socio-economic models to develop, manage, and operate community energy projects. Communities utilized different business strategies, cooperative participation models, and public-private participation to facilitate community energy transition (Schoor, T., Scholtens, B., 2015). Their primary goals are to address climate change, decarbonize the energy system, and achieve net zero GHG emissions by implementing long-term strategies to create cleaner and more sustainable solutions (Henderson, J, Sen, A., 2021). However, this transition involves multilayered challenges and requires innovative energy planning approaches that mix different energy resources, land use reforms, development of energy policies aligned with decarbonization, and environmental preservation (Saraji, M, Streimikiene, D, 2023).

2.2. Role of Dimensions, Indicators, and Metrics in Energy Transition

The energy transition is a multi-dimensional issue, and effective planning to shift completely from fossil fuel centralized systems to decentralized clean renewable energy systems can face multiple challenges (Saraji, M, Streimikiene, D, 2023). To overcome these challenges, Iddrisu and Bhattacharyya (2015) proposed a five-dimensional model to assess sustainable energy, comprising environmental, social, technical, economic, and institutional dimensions. To capture tangible results indicators are used to provide a measurement or value that benchmarks progress toward transition goals (Meadows, 1998). Since energy transition is a complex development issue, there is no single indicator that can capture the components of each dimension (Iddrisu, I, Bhattacharyya, S, 2015). In this case, metrics provide an efficient method to evaluate plans and provide essential information to evaluate trade-offs and ensure alignment with the overall goals (Shandiz, 2020).

Energy resilience (ER) has gained traction during the last two decades (Jing W, 2019). Multiple definitions of ER have expanded over the last 20 years (Afzal, S, Mokhlis, H et al., 2021). Panteli (2017) defined ER based on the ability to meet energy demand during natural and manmade disasters, adapt, recover, and prepare for energy disturbances while focusing on system reliability, security, and stability in terms of the ability to supply energy during contingencies and remain stable (Panteli, M, Mancarella, P, 2017). The changing nature of energy from fossil-fuel centralized to decentralized systems of clean renewable sources gives CREC a pivotal role in the global energy landscape (Gui, E, MacGil, I, 2018). However, the risks associated with using variable energy sources that have uncertainties require resilience planning to prevent energy shortage (Kiehbadroudinezhad, M. et al., 2023), along with other disruptions that face power systems (Sharifi, A., Yamagata, Y., 2016). To provide resilience, metrics should be incorporated into community transition plans to ensure system reliability (Panteli, 2017). Thus, a clear definition of metrics and evaluation methods for resilient systems is crucial at the planning stage (Linkov, 2014).

The research on sustainable energy transition is a growing field covering multiple theories and methodologies from different dimensions (Bhowmik, C, Bhowmik, S, Ray, A, 2020). On the other hand, sustainability in energy transition poses questions of trade-off and margin of losses. What technologies should be adopted? What resources are needed? Answering these questions requires an overlook over multiple dimensions and establishing a balance between the variables encompassing each dimension (Köhler, J. et al., 2019). The complexity of sustainability transition requires unpacking

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the dimensions into variables that allow answering these questions in a nuanced manner. It is also important to know when and how to answer them (Lv Y, 2023). Thus, the identification of metrics that reflect the impact of different plans, and provides a way to understand the trade-off of different scenarios over time before developing decisions and implementing actions is crucial (Zhang W, Li B, Xue R, Wang C, Cao W, 2021).

Examining energy transition has gone from being fundamentally studied as a techno-economic transition to being examined now in both space and time (Bridge, G et al., 2013). This broader analysis allows for determining how land can be used based on the capacity and potential of energy generation (Cagle, A, Shephers, M et al., 2023). Understanding the spatiality of energy transition can help address the sustainability dimensions of energy transition as well, and overcome the challenges associated with energy sprawl and land use choice (Bridge, G et al., 2013). Selecting metrics that assess land use can provide insight into the interaction between land development choices and their impact on the economic, social, technical, environmental, and institutional dimensions.

Table 1. Summary of the energy transition adopted terminology.

Term	Definition
Dimension	Factors that affect or are affected by the transition from fossil fuels to clean renewable energy sources. The dimensions are: environmental, social, technical, economic, political and institutional.
Indicator	Quantitative or qualitative measurement or value that describes the current or forecasted trend of sustainability dimensions and objectives.
Metric	Ways to measure the progress and impact of the transition from fossil fuels to low-carbon renewable sources, including combinations of one or more methods, and values that reflect changes in energy supply, demand, efficiency, reliability, emissions, and economics over time.

3. Methodology

This study is based on a literature review of renewable energy transition, sustainable and resilient energy scholars, and methods and metrics that quantify the impact of energy transition plans on the goals of shifting towards decentralized renewable clean energy systems. The literature review supports the development of a conceptual framework that can guide research, stakeholders, communities, and decision-makers in transition plan development. The research is then extended to integrate the main concepts of the framework with indicators and metrics that guide decision-makers to assess the performance of transition plans to manage energy sprawl and synthesize complex and interconnect challenges facing the shift from fossil-based energy systems.

3.1. Literature Review

A combination of standard literature review methodology and a focused review on wide-ranging disciplines to compile articles from different scholars, including urban planning, energy policy and planning, resilience studies, and sustainability sciences. The literature review focused on studies that quantitatively assess the transition to renewable energy systems across different scales-communities, regions, and countries. The aim is to provide a comprehensive overview of the different methodologies, metrics, and indicators used that guide research in measuring the decision-making and progress of the transition to renewable energy and its impact on different aspects, sectors, and dimensions.

A thematic review was conducted to cover the five dimensions of sustainability (social, technical, environmental, economic, political, and institutional) and the different metrics and indicators used to assess the transition to clean renewable sources. The review process included several steps. First, it identified the metrics and indicators used to evaluate the transition to renewable energy plans, processes, and approaches. Second, it examined how these metrics vary across the different dimensions of sustainability. Finally, it assessed the strengths and limitations of these metrics in

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terms of measuring system efficiency, reliability, and accessibility. This information was then used to support the analysis of the metrics that guide the objective of the framework developed in this study.

To ensure the coverage of a wide range of literature among studies conducted, the research used the Web of Science database and Google Scholar search engine to obtain the studies that measure and analyze the transition to renewable energy from different aspects. The search was filtered to include only studies published between 2005 and 2023. Sustainability is a very broad theme, that includes multiple sub-themes and was used in different disciplines (Rosen M. , 2020). Therefore, the search was narrowed by using specific keywords related to the energy transition. These included 'renewable energy transition metrics', 'renewable energy transition dimensions', 'renewable energy transition indicators', 'renewable energy transition planning', 'renewable energy transition analysis', and 'renewable energy transition assessment'. The search was then targeted towards metrics that measure one or more of the five sustainability dimensions. In addition to that, the search examined the transition from specific disciplines such as urban planning, resilience planning, development studies, and environmental sciences and conservation, and using different tools, such as temporal modeling, spatial modeling, and techno-economic modeling. The review of the articles took a narrative approach to synthesize literature across the transition to renewable energy through territorial planning, resilience planning, and sustainable planning and develop a conceptual framework to guide the decision-making pathway.

The initial assessment of the identified papers was based on the title and the abstract. Papers that met specific inclusion criteria were then selected for a comprehensive review. The inclusion criteria included: (1) the paper uses a qualitative or quantitative metric; (2) proposes an assessment method for transition to renewable energy; (3) evaluates one or more dimensions of sustainability; (3) evaluates the impact of energy across one or more of the selected disciplines; (4) it can be case study, scenario modeling or literature review; (5) written in English. Papers that did not meet these criteria were excluded from the comprehensive review.

3.2. Conceptual Framework

Planning for community energy transition is more than just economic feasibility, renewable resource selection, and infrastructure development. It requires a comprehensive approach that encompasses energy sustainability, land development, and system resiliency. This integration requires changes in policies, regulations, and land use at multiple scales to support decentralized systems. The proposed framework for community energy transition, integrates the principles of Sustainable Land Use (SLU), Sustainable Energy Planning (SEP), and Resilient Energy Planning (REP). This study provides a comprehensive approach to studying the impact of sustainable land use on the transition to a reliable, efficient, and accessible energy system.

Mapping place-based potential for clean renewable energy at various scales (community, town, or area) is crucial, this framework includes a land-based planning strategy to ensure growth and improve energy efficiency at the building and area levels while committing to environmental and biodiversity protection and societal well-being. It also highlights the importance of resilience in energy planning to ensure a reliable energy supply that is not disrupted by variable energy output. To integrate sustainability, resilience, and sustainable land use principles, we designed this conceptual framework (Figure 1) that was inspired by the triple bottom line principle to integrate interdisciplinary energy planning, policy changes, and land use strategies needed for community energy transition. This also assists in addressing the challenges associated with energy source selection, built environment efficiency, and energy trade.

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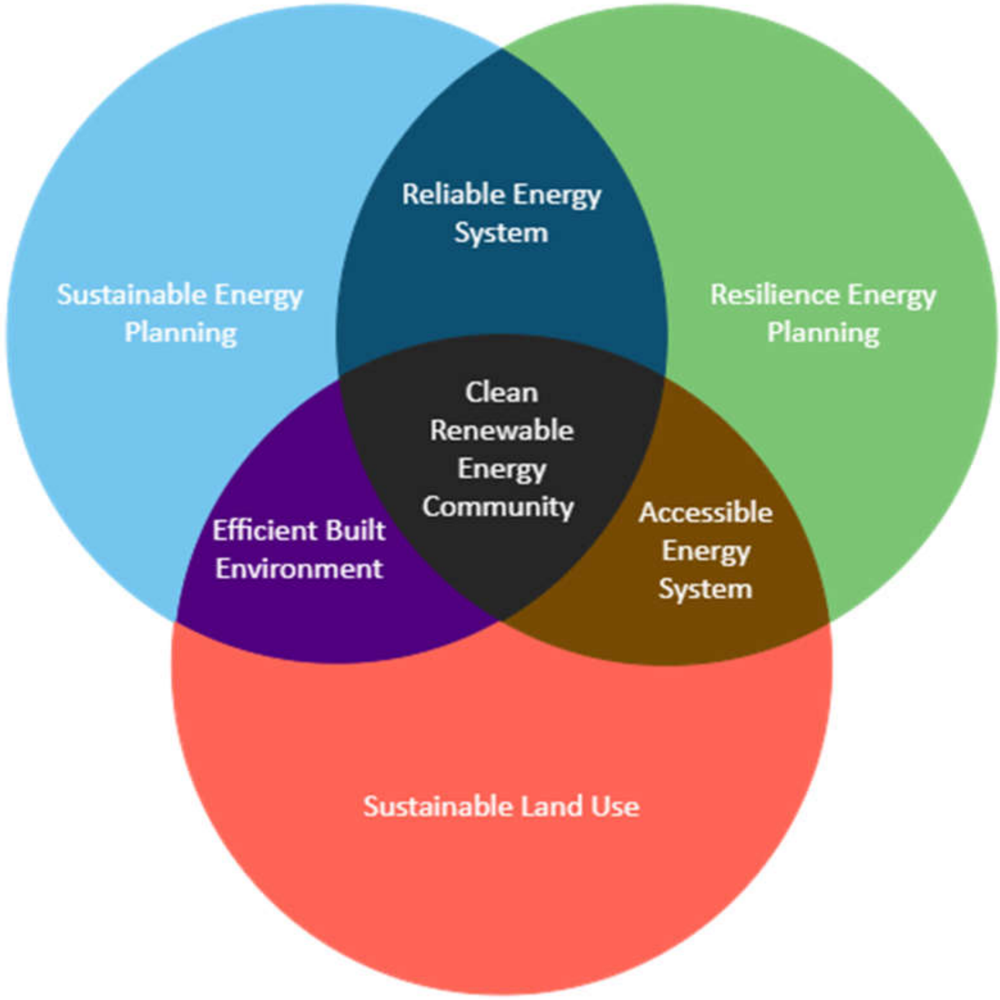

Figure 1. Clean renewable energy community transition framework.

The framework also serves as a simplified practical tool.to identify indicators and metrics that crosscut between the three elements of SLU, REP, and, SEP, and use the five-dimensional approach of sustainability adopted from Kabeyi and Olanrewaju (2021) to analyze energy sustainability.

Table 2. Sustainable energy dimensions**.**

Sustainable dimensions	**Description**
Environmental	Deals with ecological health, biodiversity, and climate resilience
Technical	Focuses on infrastructure, technology, and resource efficiency.
Social	Addresses community well-being, equity, and quality of life.
Economic	Considers economic viability, job creation, and affordability.
Political and Institutional	Involves governance, policies, and stakeholder engagement.

3.2.1. Efficient Built Environment:

The core principles of sustainable land development can offer communities greater opportunities to decentralize their energy system through clean renewable energy resources because energy is central to economic growth, compact urban form, efficient land use, and infrastructure, mixed-use principles and recognition of community participation creates opportunities for communities to plan for transition (Thrän, 2020). However, this is not independent of the need for complementary policies that create financial and regulatory incentives to support the transition (Becker, J, Kaza, N., 2022).

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Sustainable land use planning allows planners and guide energy plans for wise placement to larger-scale renewable energy projects while managing energy sprawl and mitigating environmental impacts to ensure sustainability of energy transition (Lovering J, 2022). This can be combined with energy generated within the mixed-use development through rooftop PV (Hachem-Vermette, 2020) and dual land use with farmlands, commercial buildings, and parking lots (de Boer, 2015). Allowing for decentralized energy systems through local generation and distribution, additionally reducing energy loss through long transmission lines, where most of the energy is generated and used locally through microgrids (Si, S, Sun, W, Wang, Y, 2024). This also contributes to economic vitality, social equity, environmental quality, energy accessibility, and energy efficiency (Della Valle, N. and Bertoldi P. , 2022). Several studies have assessed the impact of sustainable land use planning, such as smart growth on energy efficiency. For example, a study in Porto- Portugal by Silva et al. (2018), concluded that smart growth plans have also been linked to reduced energy consumption for heating and combating the symptoms of urban sprawl. Additionally, transit-oriented development through increased compactness and densification scenarios was studied in Dallas, TX to understand the impact on energy consumption in residential and commercial buildings. It was concluded that this form of sustainable land planning decreased the energy demand in both residential and commercial (Trepci, E, Maghelal, P, Azar, E, 2020). Another study in Toronto by O'Brien & Kennedy (2010) found that mixed energy land use combined with energy efficiency building measures in high-density areas, with low-rise, large-area storage buildings, and markets, can generate renewable energy that exceeds local demand.

3.2.2. Reliable Energy System

The resilient energy planning aims to create a robust energy system that withstands shock events, such as climate events and variable energy supply (Amini, 2023) . The reliable objective of the proposed framework is rooted in several aspects. It aims to ensure reliable access to communities through diversifying energy supply through hybrid energy systems, that combine renewable sources such as wind, solar, and hydro, and clean low-carbon sources as secondary sources, such as bioenergy from agricultural waste, incinerators, or peer-to-peer energy trading (Afzal, S, Mokhlis, H et al., 2021). Hosseinzadeh-Bandbafha (2023) suggested that adopting mixed energy sources, including renewables, can ensure long-term energy security and can be more sustainable, unlike the short-term security provided by fossil fuels.

Achieving reliable energy systems aligns with sustainability dimensions in several ways. The reduction of greenhouse gas emissions through the adoption of renewables, hence reducing the environmental impact is one aspect. The stability of energy prices through reducing the reliance on fossil fuels that are affected by price fluctuation is another aspect. Furthermore, it creates social resilience through enhancing energy security and provides an efficient renewable energy system.

3.2.3. Accessible Energy System

Accessibility of the energy systems not only ensures that the energy system is available but also reachable and useable by all members of the community (Singh, S, Ru, J, 2022). Access to renewable energy also requires proximity between where energy is generated and used to reduce the reliance on long transmission lines, which are vulnerable to disruptions such as heat waves, and reduce energy loss through transmission lines (Hoffacker MK and Hernandez RR, 2020). This requires planning not only for technology selections but also for how these technologies are integrated into communities and landscapes (Anvari-Moghaddam, 2019).

Accessibility of the energy system is also related to its affordability, which is also factored in resilience energy planning (Anderson, K. et al., 2021). However, this requires policies that incentivize renewable energy use, provide subsidies for renewable energy infrastructure that enables the accessibility objective (Tryndina N, 2022), and renewable energy siting (Thrän, D., Gawel, E., Fiedler, D., 2020). Thus, considering renewable energy transition as a key component of land use planning and community development is essential for a successful energy transition.

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4. Review of Renewable Energy Transition Metrics

The literature review focused on five main aspects of measuring energy transition: decision-making, planning, modeling, deployment, and scenario analysis for fossil fuel energy source replacement. This review provides an overview of the most used metrics in studies that included analysis or assessment of transition scenarios, to renewable energy. The metrics were categorized into five main dimensions: environmental, technical, social, economic, and political and institutional, which are associated with the sustainability element of the conceptual framework. The indicators reflect how to measure performance against resilient and smart growth planning. The environmental dimension, represented by carbon emissions, technical dimension through system performance. and economic impact through return on investment. These metrics are the most used in the studies that assess energy transition projects, covered in the review. The studies review covered a lot of metrics that can be summarized in the following table.

Table 3. Summary of the Environmental dimension metrics for renewable energy transition.

Dimensions	Indicators	Metrics	Definition	References
Environmental	GHG Emission	Total emissions	The total emission quantifies the direct and indirect emissions of energy.	(Turney, A, Fthenakis,V, 2011)
		Carbon Intensity	The amount of greenhouse gases emitted per unit of energy produced.	(Chen, C et al., 2019), (Wen, Y., Bin Cai, B., Xinxin Yang, X., Yusheng Xue, Y., 2020) (Mehedi, T, Gemechu, E, Kumar, A, 2022) (Kapila, S., Oni, A.O., Gemechu, E.D., Kumar, A., 2019)
	Waste Generated	Waste Footprint Component	The quantity of waste generated during energy production and consumption activities.	(Hammond, G., Howard, H., Hanumant, R., 2019)
	Water consumption	Water Footprint Component	The amount of water used in energy production processes, often expressed as a water footprint.	(Hammond, G., Howard, H., Hanumant, R., 2019)
	Natural Resources	Natural resources depletion or Abiotic depletion	Used to assess the impact of resources depletion in life cycle assessment	(Davidsson, S., Höök, M. & Wall, G., 2012)
	Land Use	Land Use Energy Intensity	The energy required to transform land for energy production, often measured per unit area.	(Cagle, A, Shephers, M et al., 2023)
		Absolute Area of land converted	The total land area required to supply energy needs and offset carbon emissions.	(Cagle, A, Shephers, M et al., 2023)
		Annual Land Transformation	The extent of land converted for energy production purposes on an annual basis.	(Cagle, A, Shephers, M et al., 2023)
		Lifetime Land Transformation	The duration over which transformed land returns to its original state after energy use.	(Cagle, A, Shephers, M et al., 2023)
		Land-Use Efficiency	The capacity of energy in land area occupied	(Cagle, A, Shephers, M et al., 2023)
		Energy Footprint	It is the land needed to supply energy and land needed to offset CO2 by plantation	(Tran, T, Egermann, M., 2022)
		Land Occupation Metric	The area of transformed land and the time needed for full recovery to its original state.	(Rej, S. and Nag, B. , 2021)
	Ecological Footprint	Carbon sequestration	the global biological system through biological process affects the world carbon cycle	(Hammond, G., Howard, H., Hanumant, R., 2019)

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Table 4. Summary of the Technical dimension metrics for renewable energy transition.

Dimensions	Indicators	Metrics	Definition	References
Technical	Renewable Energy Share	Renewable Energy fraction	The percentage of energy derived from renewable sources compared to total energy consumption.	(Gul, E.; Baldinelli, G.; Bartocci, P., 2022)
	System Generation	Residual Load Range	The expected number of hours per year when system demand exceeds generating capacity.	(Saarinen, L. & Tokimatsi, K., 2021)
		Surplus Energy	The expected number of days per year when available generation exceeds daily peak demand.	(Olowosejeje, S. et al., 2020)
		Power system flexibility	The system power ability to cope with uncertainty not to affect reliability and economy	(Guo, Z., et al., 2020)
		Insufficient ramping resource expectation (IRRE)	A metric used to measure the system flexibility for long term planning	(Lannoye, E, Flynn, D, O'Malley, M., 2012)
	System Efficiency	Energy Efficiency	The average efficiency of energy conversion and utilization processes within the system.	(Kraan, O. et al., 2019)
		Total Final Consumption (TFC)	The consumption of energy carriers such as solid, liquid, or gaseous fuels and electricity to fulfil this service demand.	(Kraan, O. et al., 2019)
		Total Primary Energy (TPE)	the primary energy required to produce these energy carriers	(Kraan, O. et al., 2019)
		LPSP Loss of power supply probability	The metric is used to assess system reliability through measuring the risk of inadequate power supply to load requirement	(Elkadeem, et.al, 2021)
		Energy Intensity	The total final renewable energy consumption per unit of economic output.	(Kraan, O. et al., 2019)
	System Security	Full Load Hours of Generation	The time needed to produce total energy under full load conditions, representing utilization.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
	System performance	Net Energy ratio NER	Measures the ratio of total energy output to total energy input of the system	(Mehedi, T, Gemechu, E, Kumar, A, 2022) (Kapila, S., Oni, A.O., Gemechu, E.D., Kumar, A., 2019)
	Adequacy	Loss-of-Load Hours (LOLH)	Loss-of-Load Hours (LOLH): The expected number of hours per year when system demand exceeds generating capacity1.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
		Loss of Load Expectancy	Loss of Load Expectancy: The average frequency of power supply interruptions1.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
		Loss of Load Probability	Loss of Load Probability: The probability of system peak or hourly demand exceeding generating capacity1.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
		Loss of Load Events	Loss of Load Events: The number of events where system load is not served due to capacity deficiency in a year1.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
	Reliability	Expected Unserved Energy (EUE)	Expected Unserved Energy (EUE): The expected total energy not supplied to any load buses, regardless of cause or location1.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
		Expected Energy Not Supplied	The expected total energy not supplied to any load buses, regardless of cause or location.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
		Energy Index of Unreliability (EIU)	Energy Index of Unreliability (EIU): The expected total energy not	(Heylen, E., Deconinck, G., Hertem, D., 2018)

			supplied divided by the total energy demand1.	
		Energy Index of Reliability (EIR)	Energy Index of Reliability (EIR): The ratio of the total energy supplied to the total energy demand1.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
		System Minutes	The total duration of system-wide interruptions in energy supply over a specified period.	(Heylen, E., Deconinck, G., Hertem, D., 2018)
		Average Interruption Time (AIT)	The average duration of system-wide interruptions in energy supply over a specified period.	(Heylen, E., Deconinck, G., Hertem, D., 2018)

Table 5. Summary of the Social dimension metrics for renewable energy transition.

Dimensions	**Indicators**	**Metrics**	**Definition**	**References**
Social	Equitable	Changes in Energy Expenditures	Percentage of household income spent on energy bills, indicating the affordability of energy.	(Kime, S et al, 2023)
	Secure	Energy Burden	The percentage of household income spent on energy bills, indicating the energy cost burden.	(Kontokosta, C. Reina,V., & Bartosz Bonczak, B., 2019)
	Accessible	Energy Access	The availability and affordability of energy services to meet basic needs, such as lighting, cooking, heating, cooling, etc.	(Kime, S et al, 2023)
	Acceptable	Community Acceptance	The level of public support and acceptance for renewable energy projects in local communities	(Lennon, B, Dunphy, N, Sanvicente, E, 2019)
	Health Impacts and Pollutant Exposure	Occupational Pollutant Concentration	Concentration of pollutants in workplaces associated with energy production activities.	(Kime, S et al, 2023)
		Proximity to Resource Extraction	Distance from residential areas to resource extraction sites, indicating environmental impact.	(Kime, S et al, 2023)

Table 6. Summary of the Economic dimension metrics for renewable energy transition.

Dimensions	**Indicators**	**Metrics**	**Definition**	**References**
Economic	Energy Affordability	Levelized Cost of Energy (LCOE)	The average cost of energy production over the lifetime of a project, excluding subsidies.	(Gulagi, A et al., 2020) (Abdin, Z, Mérida, W, 2019)
		Cost of Valued Energy (COVE)	Improved valuation metric that accounts for time-dependent electricity prices.	(Gulagi, A et al., 2020)
	Resource Cost	Real Gross Domestic Product (RGDP)	The total value of goods and services produced within a country, adjusted for inflation.	(Somoye, O, Ozdeser, H, Seraj, M, 2022)
	Employment	Jobs created per installed capacity	The number of jobs created by renewable energy projects measured based on the energy capacity, including direct, indirect, and induced job	(Lui, G et al., 2023)
	Financial viability over time	EPBT Energy payback time	time required to generate the same amount of energy that has been invested into the system over the entire lifecycle as primary energy.	(Mehedi, T, Gemechu, E, Kumar, A, 2022)
		Energy Return on Energy Investment (EROI)	The ratio of energy delivered by an energy source to the energy required to extract it.	(Capellan-Perez, I, Castro, C, Gonzalez, L., 2019)
		Total net present cost	It assesses the component costs over lifetime	(Tsai C, Beza TM, Molla EM, Kuo C., 2020)
	Cost Effectiveness	Cost per Unit of Energy Saved	- The cost of implementing a renewable energy project divided by the amount of energy saved	(IRENA, 2016)

Table 7. Summary of the Political and Institutional dimension metrics for renewable energy transition.

Dimensions	Indicators	Metrics	Definition	References
Political and Institutional	Participation	Public Participation in Energy Planning	The involvement and influence of stakeholders, such as consumers, communities, civil society, etc., in energy planning and management	(Zhang W, Li B, Xue R, Wang C, Cao W, 2021)
	Policy support	Renewable Energy Policies	The presence and effectiveness of policies that support renewable energy development, such as feed-in tariffs, tax incentives, etc.	(Zhang W, Li B, Xue R, Wang C, Cao W, 2021) (Breetz, H., Mildenberger, M., Stokes, L., 2018)
		Regulatory Certainty	The stability and predictability of the regulatory environment for renewable energy projects	(Zhang W, Li B, Xue R, Wang C, Cao W, 2021) (De Laurentis, C., Pearson, P.J.G., 2021)
	Institutional Capacity	Institutional Capacity for Renewable Energy -	The ability of institutions to plan, implement, and manage renewable energy projects.	(Zhang W, Li B, Xue R, Wang C, Cao W, 2021) (Breetz, H., Mildenberger, M., Stokes, L., 2018)

5. Discussion:

In this section, we discuss the gaps and challenges associated with the metrics used in literature to evaluate the transition to renewable energy and will then identify how to select metrics and indicators that align with the proposed conceptual framework presented in (Figure 1) section 4.

5.1. Challenges Associated with Metrics Identification:

The review highlights many issues in identifying metrics that can be used to study the impact of renewable energy transition. One common issue is the standardization of metrics as highlighted by Ahi, et al. (2016), the study identified metrics relevant to the supply chain in energy-related projects. However, they identified more than 100 metrics, and only three metrics were common. Another issue is the subjectivity of selecting metrics. Kime et al. (2023) in their study, aiming to review metrics addressing equity in energy transition highlighted that this may cause ignoring important metrics while studying one of the dimensions. Whether it was unintentional or not, this may affect decision-making and reduce transparency. A third issue is the inconsistency of using these metrics and the units that misguide the result analysis. Cagle & Shephers (2023) highlighted this issue and the need for dissemination of findings across different disciplines contributing to this field. They also suggested the need to classify these metrics for easy use and selection. A fourth issue is the data sources and assumptions that also affect the selection of some metrics (Turney, A, Fthenakis,V, 2011). A fifth issue is the methodology to calculate the emission (Mehedi, T, Gemechu, E, Kumar, A, 2022). A sixth issue is a contextual reference that may vary among regions and societies, where there is a need for metrics that measure the range of access and quality (Engel-Cox, J, Chapman, A, 2023).

Additionally, the choice of metrics is often associated with the assessment method, which is highly related to the tools used and their resulting data (Buytaert, V et al., 2011). For example, the techno-economic modeling tools usually provide an overview of the system efficiency either by providing the unmet hours or the energy supply (Jumare et al. , 2020). That also includes economic output, such as net present value or return on investment. This is also another reason why these metrics are more common than other metrics. Also, with the increase in interest in justice, and equitable issues as well (Barlow, J, Tapio, R, Tarekegne, B, 2022), more metrics have been used in studies to assess the social impact, some of these metrics require qualitative tools to be measured, this has increased the share of social metrics used (Kime, S et al, 2023).

5.2. Evaluating Metrics for CREC Transition:

To evaluate the energy transition plan, metrics can provide data information on specific indicators to make the assessment and decision-making easier. The selection of the metrics depends

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on the overall goal and the context of the transition. Multiple metrics for one indicator can be used to provide a clear understanding of the impact of the plan and can also be analyzed through multiple disciplinary perspectives. To understand how planning for sustainable land use can be integrated with resilience and sustainable energy planning to transition communities to renewable energy, metrics should reflect the desired objectives. For this purpose, the study aims to utilize metrics that comprehensively evaluate energy transition plans for communities from a multidisciplinary approach. The attributes developed can assist in selecting the proper metrics that provide a better understanding of the impact of transition plans. These attributes are developed based on the gaps and challenges identified in the review of metrics and can be summarized in the following table.

Table 8. Metrics evaluation attributes for CREC transition framework.

Attributes	Definition
Relevance	It must be associated with one or more of the dimensions of the framework. It must reflect at least one of the indicators.
Ease of application	It has a clear tool, methodology, or approach to measure energy transition performance.
Input Data availability and quality	The required input is clear. Input data is accessible through a clear approach. The quality of data is. Accurate, complete, and reliable.
Reliable	The output results can be interpreted. Ability of the output data to reflect desired objectives. The metric provides accurate and truthful output.
Comparable	Can be tracked over time. Allows detecting changes or differences in the phenomenon being measured.

These attributes were used to select the metrics that can assist in measuring the performance and impact of the community energy transition plan. Each metric identified in the literature was reviewed based on its use and the reviews in previous studies and their alignment with the developed attributes. The metrics were then scored high, moderate, and low accordingly. Then, the metrics that scored the highest in each category were selected to be used as a guiding measure for each dimension. The result of the analysis was captured in a sunburst diagram integrated with a heatmap, the lighter colors for each dimension represent the lower scores among each attribute, while the darkest shades represent the higher scores. A total of 18 metrics were selected, among these metrics, 8 can be used to measure the technical dimension of energy transition. This integrated diagram provides valuable insight into the areas where most metrics have been extensively developed and can be effectively utilized in the study. And, allowing to identify areas that require more focus and additional metrics to measure the impact across these dimensions.

Figure 2. Sunburst chart for metrics evaluation that can guide the performance of clean renewable energy community transition based on their relevance to the framework, ease of application of the metrics, the availability and quality of metrics input data, reliability of the metrics output, and ability to compare outcomes over time or across different decisions.

The CREC framework focuses on three main objectives: Efficiency, Reliability, and Accessibility. Each of these objectives contains several key aspects, as outlined in the table below:

Table 9. CREC transition main objectives and aspects according to the framework.

Objectives	Aspects	Description
Efficiency	Operational Efficiency	Refers to optimizing processes, minimizing waste, and achieving maximum output while considering social, economic, and environmental aspects.
	Resource Efficiency	Focuses on using resources (Land, energy, materials, financial, etc.) effectively to transition communities to clean renewable energy.
	Productivity	Indicates how efficiently resources including land and energy potential are transformed into valuable outputs.
Reliability	Dependability	Reflects the reliability and predictability of energy services.

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	Continuity	Addresses uninterrupted energy supply and consistent performance.
Accessibility	Equitable Access	Highlights fair and inclusive availability of energy services for all, regardless of socioeconomic factors, through energy distribution and policy development that facilitates and supports energy transition.
	Affordability	Considers the financial accessibility of energy services.

These objectives were used to further classify the 18 metrics that were selected based on the evaluation criteria and were presented in the sunburst diagram that is crucial to each aspect of CREC. To better understand the relevance of each metric to the objective the following matrix was developed as a guidance tool.

Table 10. Matrix of metrics categorized based on CREC transition framework objectives.

Metric / Objectives	**Carbon Intensity**	**Waste Footprint Component**	**Land Use Energy Intensity**	**Land-Use Efficiency**	**Renewable Energy fraction**	**Residual Load Range**	**Energy Efficiency**	**Total Primary Energy**	**Loss of power supply probability**	**Full Load Hours of Generation**	**Net Energy ratio**	**Expected Unserved Energy**	**Energy Access**	**Occupational Pollutant Concentration**	**Cost of Valued Energy**	**Energy Return on Energy Investment**	**Cost per Unit of Energy Saved**	**Renewable Energy Policies**
Efficiency	×	×	×	×	×		×								×	×	×	
Reliability					×	×	×	×	×	×	×	×						
Accessibility					×						×	×	×	×	×		×	×

4. Future research and Limitations:

The study relies on a thematic literature review method, which may be critiqued with bias and subjectivity in the selection and interpretation of sources. While there are many tools used to assess the impact of energy transition, however, there is no single tool that can cover the different impacts and thus the choice requires a guiding framework that supports the decision-making process (Curran, 2013). The study focuses on categorizing the metrics from a sustainability perspective dimension. However, it doesn't address the important aspects of assessing the infrastructure capacities through grid integration, energy management through smart systems, and behavioral change. These aspects also have an impact on evaluating the transition to renewable energy. Additionally, while the interpretation of the metrics was based on the developed framework earlier in the study and the diagrams developed were aimed to simplify the complex process, however, the interpretation remains subjective, and the metrics selected may have not fully covered the complexity of the energy transition.

To overcome this limitation, future research should include a systematic review to cover all metrics used across multiple disciplines to measure the impact of renewable energy transition. This can enhance the validity and reliability of the finding. It can also assist in understanding which metrics are more commonly used, and what types of tools and methodologies are better suited to aid decision-making in transition planning to renewable energy. Future research should also cover a broader impact on the transition by identifying the stages of energy transition and the decisions required during each stage. This will help in identifying suitable metrics that can guide decisions rather than measuring the performance at irrelevant times of the transition pathways. Future research in this area should aim to deepen our understanding of the relationships between various variables that contribute to the efficiency, accessibility, and reliability of the energy system in the built environment. This involves analyzing how sustainable land use practices can facilitate the transition to renewable energy and contribute to the resilience of energy systems.

5. Conclusion

As the transition to low carbon spreads, policymakers, planners, and other stakeholders are increasingly faced with decisions that will affect the future landscape and transition pathway. Each pathway will have a different impact on the environmental, human, economic, and future development at the local, regional, and global levels. While this is recognized as a common problem, the spread of the transition requires measuring the performance of each pathway from a multidisciplinary approach. To support these efforts, this review has identified several metrics that have been used to evaluate transition from multiple perspectives, either used individually or together to give a broader understanding. These metrics were categorized based on the sustainability dimensions that guide the framework developed in this study.

Evaluating community energy transition plans, particularly those aiming to shift completely from centralized fossil fuel systems to decentralized renewable sources, is a complex process that requires a multidisciplinary approach to analyze the plans. The framework developed in this study can guide the selection of metrics during scenario development for the transition pathway and can inform the long-term planning decisions that affect land use, economic growth, selection of technologies, and energy sources that can provide reliable supply to ensure system resiliency. It can also support stakeholders, communities, and policymakers to consider energy transition as a key element in land development. With thoughtful planning, the potential conflict between renewable energy and preservation of other built environment land uses, farmland, and natural areas can be mitigated. Planners can integrate the transition to decarbonize the energy section as an integral part of the future.

Annex 1

Metrics Evaluation for analysis

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