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Auteur 1

Prénom / First name	Marina
Nom / Last name	Frolova
Titre / Title	Hidden dimensions of the energy transition
Institution / Institution	University of Granada
Domaine de compétence scientifique / Field of scientific expertise	Geography
Adresse postale / Postal address	Acera de San Ildefonso 24, 1, 18010 Granada, Espagne
E-Mail / Email	mfrolova@ugr.es
Auteur / Authorship	☐ Premier auteur / First author ☐ Co-premier auteur / Co-first author (max. 2) ☒ Auteur ☐ Dernier auteur / Last author
Auteur correspondant / Corresponding author	☒ Oui / Yes

HIDDEN DIMENSIONS OF THE ENERGY TRANSITION

LES DIMENSIONS CACHEES DE LA TRANSITION ENERGETIQUE

Abstract

The transition to renewable energy systems is central to addressing climate change, yet its implications extend far beyond merely reducing carbon (CO2) emissions. While renewable energy projects significantly lower operational CO_2 emissions, they can also result in substantial environmental, territorial, and socioeconomic impacts. This paper critically examines the hidden dimensions of the energy transition, focusing on overlooked consequences such as biodiversity loss, land-use conflicts, and resource depletion. Furthermore, it explores the challenges associated with the end-of-life of renewable technologies and the growing issue of waste management. By expanding the scope of impact assessments beyond CO_2 metrics, this paper highlights the importance of incorporating life-cycle, social, and territorial assessments to ensure a fair and sustainable energy transition.

Keywords

Energy transition; Renewable energy systems; Environmental impacts; Territorial planning; Social justice; End-of-life management; Life-cycle assessment; Carbon emissions assessment

Résumé

La transition vers les énergies renouvelables est essentielle pour lutter contre le changement climatique, mais ses implications vont au-delà de la réduction des émissions de carbone $(CO)_2$. Si les projets d’énergie renouvelable réduisent les émissions opérationnelles, ils engendrent aussi des répercussions environnementales, territoriales et socio-économiques. Cet article analyse les dimensions cachées de la transition énergétique, telles que la perte de biodiversité, les conflits d’usage des sols et l’épuisement des ressources. Il aborde également les défis liés à la fin de vie des technologies renouvelables et à la gestion des déchets. En élargissant les évaluations d’impact au-delà des émissions de CO_2, l’article souligne l’importance d’inclure des évaluations du cycle de vie, sociales et territoriales pour garantir une transition énergétique durable et équitable.

Mots-clés

Transition énergétique; Systèmes d'énergie renouvelable; Impacts environnementaux; Planification territoriale; Justice sociale; Gestion de la fin de vie; Évaluation du cycle de vie; Évaluation des émissions de carbone

INTRODUCTION

The transition to renewable energy systems (RES) has been widely presented as a fundamental strategy for mitigating climate change, reducing dependency on fossil fuels, and fostering long-term sustainability. The European Union (EU) has taken a leading role in this transition through its ambitious policies, in particular the European Green Deal, which aims to make the EU the first climate-neutral continent by 2050 (EC, 2021). To achieve this, the EU initially set a binding target for 2030 that at least 32% of its total energy mix should be obtained from renewable sources. Progress towards this goal has been fast and this figure has recently been revised upwards to a minimum of 42.5%, with an indicative target of 45% (IEA, 2024). However, the energy transition is often viewed simplistically as a straightforward replacement of fossil fuels, which overlooks the complex nature of socio-territorial dynamics and the implications of large-scale renewable installations (Windemer and Cowell, 2021; Ertelt & Carlborg, 2024). These targets emphasize the political and economic commitment to decarbonization, while ignoring the challenges inherent in the large-scale deployment of RES across Europe (Ertelt & Carlborg, 2024).

The main metric used to evaluate the effectiveness of RES in mitigating climate change is CO_2 emissions. While measuring emissions is essential, this metric alone fails to capture the full spectrum of environmental and socioeconomic consequences associated with renewable energy (RE) expansion (Gayen et al., 2023). Large-scale wind, solar, and hydroelectric projects often require extensive occupation of land, leading to biodiversity loss, habitat fragmentation, and conflicts over land use (Senyapar & Bayindir, 2023; Sayed et al., 2020). Furthermore, while renewable energy systems cut operational emissions, they may increase other environmental impacts, such as resource depletion and toxic waste, because of the materials required in their construction (Hertwich et al., 2014; Gibon et al., 2017). Moreover, the accuracy of CO_2-based assessments varies depending on the technology, the geographical region, and the methodology employed. Renewable technologies such as wind, solar, and hydro dramatically reduce operational carbon dioxide emissions compared to fossil fuels, but the manufacture and decommissioning of RES often involve significant emissions that are overlooked in mainstream assessments (Pehl et al., 2017). The life cycle of renewable technologies involves raw material extraction, energy-intensive manufacturing, and complex waste management challenges, all of which can exarcebate environmental degradation in ways that are often not taken into consideration in CO_2-centric assessments (Piotrowska et al., 2022; Mahmud et al., 2018; Quek et al., 2019; Ertelt & Carlborg, 2024).

Another important issue in the territorial dimension of the energy transition is the competition for land resources. Unlike fossil-fuel power plants, which have a relatively compact footprint, RES installations—particularly solar and wind farms—require large areas of land to achieve significant energy output (Frolova et al., 2019; Ouro et al., 2024). In densely populated regions such as Europe, this expansion frequently encroaches on agricultural land, conservation areas, and urban developments, leading to spatial conflicts and social opposition (Doukas et al., 2022). Studies have shown that while smaller RES projects can coexist with agricultural activities through dual land-use strategies such as agrivoltaics, large-scale plants can displace local farming and disrupt rural economies (Senyapar & Bayindir, 2023). Moreover, the transformations caused by RE infrastructure can alter the aesthetic and cultural value of the landscape, affecting tourism and heritage conservation in the local area (Diego et al., 2022; Romov & Teschner, 2022).

Apart from environmental and territorial concerns, energy justice, i.e. the fair distribution of both the benefits and burdens associated with energy systems, has emerged as a crucial yet often overlooked aspect of the energy transition (van Bommel, & Höffken, 2021). The rollout of large-scale RE projects often has disproportionate negative effects on marginalized communities, particularly in rural areas where land is more readily available for infrastructure expansion (Buechler & Martínez-Molina, 2021; Martínez, 2023). Research has highlighted cases where wind and solar farms have been installed without sufficient community consultation, leading to rejection and social conflicts (Poggi et al., 2018). This raises ethical questions about the governance of the energy transition and the mechanisms in place to ensure that the communities affected by it have a voice in decision-making processes.

The purpose of this article is to critically examine the hidden dimensions of the energy transition in Europe, with a particular focus on the environmental, territorial, and socioeconomic consequences that are often ignored in mainstream assessments. By integrating insights from recent academic and grey literature, this review will explore the limitations of CO_2-based assessments, the broader environmental repercussions of RES, and the role of life cycle assessment (LCA) in capturing the full range of sustainability challenges. It will also emphasize the importance of spatial planning and policy adjustments to ensure a fair and balanced transition to renewable energy. Understanding the many and varied challenges we are facing is essential for developing an energy transition strategy that not only meets climate targets but also respects ecological integrity, social equity, and long-term economic viability.

I. CO_2-BASED ESTIMATIONS AND THEIR INSUFFICIENCY

The current discourse on energy transition is limited by its excessive reliance on assessments based on CO_2 emissions, the main metric used to evaluate the effectiveness of RES in mitigating climate change. While numerous studies demonstrate that RES significantly reduce CO_2 emissions compared to fossil fuels, highlighting their critical role in meeting national and international climate targets (Beltrami et al., 2021; Sharif et al., 2021; Kulpa et al., 2022), an exclusive focus on CO_2 risks oversimplifying the broader environmental implications of renewable energy deployment. The accuracy of CO_2-based assessments is often compromised by methodological inconsistencies, regional disparities, limited data availability, and insufficient attention to emerging technologies, which collectively hinder a comprehensive understanding of RES impacts.

The effectiveness of RES in reducing CO_2 emissions varies considerably across regions. In Europe and Central Asia, renewables have been relatively successful in curbing emissions, whereas in East Asia and the Pacific, investments in RES have been insufficient to offset rising emissions (Jia et al., 2021). In Africa, the impact of renewables on emissions remains negligible due to limited investment, underscoring significant regional disparities (Nathaniel & Iheonu, 2019). Furthermore, research tends to disproportionately focus on developed regions, leaving gaps in our understanding of the global effects of RES and their potential in less-studied areas (Kang et al., 2020).

Another critical limitation is the failure of many studies to account for interdependencies between countries, which are essential for analysing emissions in interconnected regions (Inglesi-Lotz & Dogan, 2018). Additionally, inconsistencies in methodologies for estimating CO_2 emissions savings from RES complicate validation efforts and hinder comparability across studies (Anke et al., 2021). While technologies such as solar and wind have been extensively researched, emerging systems like hydrogen energy and waste-to-energy remain underexplored, despite their potential to contribute significantly to emissions reduction (Kang et al., 2020).

A further challenge lies in accurately calculating emissions across the entire life cycle of RES, from construction to decommissioning. Key issues include accounting for upstream emissions, such as those generated during the manufacturing and transportation of materials used in RES. This is exacerbated by a scarcity of primary data, forcing researchers to rely on secondary sources that may lack accuracy or fail to reflect current conditions (Pehl et al., 2017; Chambile, 2024).

Some authors argue that, in the case of solar PV systems, often promoted as key ingredients in the RE transition, CO_2 emissions over their life cycle appear to have been underestimated by earlier research (Chandrasekharam & Ranjith Pathegama, 2020). For instance, Grbes (2016) reported emissions of 267,293 kg of CO_2, translating to 439 kg of CO_2 per 1 MWh of power consumed. However, more recent assessments indicate that manufacturing a single solar PV cell capable of generating 1 MWe emits up to 4 million tons of CO_2. This suggests that under a sustainable development policy scenario, solar PV emissions in 2040 will significantly exceed earlier estimations, so calling into question its claim to be a "clean energy" source (Chandrasekharam & Ranjith Pathegama, 2020).

In addition to CO_2 emissions from manufacturing, the end-of-life (EoL) stage of solar PV introduces further environmental concerns. The management of solar PV waste, including panels, components, and storage batteries, is a growing issue that has often been overlooked in prior sustainability assessments.

According to projections by the International Renewable Energy Agency (IRENA, 2016), the global volume of solar PV panel waste is expected to rise significantly by 2050. When emissions from waste disposal are taken into account, it is evident that solar PV cannot be regarded as fully renewable or environmentally friendly (Chandrasekharam & Ranjith Pathegama, 2020). Similarly, in the case of wind farms, energy consumption and metalwork during manufacture are responsible in some cases for over 98% of total lifetime CO2 emissions, due to the large amounts of material consumed and the high emission factors (Eang & Sun, 2012).

Secondly, different renewable technologies have different life-cycle emissions, which are not always consistently assessed. For instance, several studies have shown that the life-cycle emissions of RES, particularly wind and solar power, are significantly lower than those of conventional energy systems (Nugent & Sovacool, 2014; Wang et al., 2019), while geothermal, bioenergy, and hydropower produce higher, more uncertain operational emissions (Pehl et al., 2017; Mello et al., 2020; Hertwich et al., 2014). Compared to solar PV, however, geothermal energy offers the advantage that its life-cycle CO_2 emissions are naturally occurring and significantly lower (Chandrasekharam & Ranjith Pathegama, 2020).

Finally, the transportation and decommissioning of renewable energy systems makes a significant contribution to CO2 emissions. This stage is often overlooked or underestimated in life-cycle assessments (Mello et al., 2020). Several research studies have highlighted that there is a need for better integration of life-cycle assessments with energy system models, so as to ensure that the contribution made by each stage of their life-cycle is accurately assessed and to evaluate their full environmental impact (Junne et al., 2021; Blanco et al., 2020). A more comprehensive data collection system is also essential to address these gaps and improve the accuracy of emissions assessments.

II. IMPACTS OF RENEWABLE ENERGY SYSTEMS

The transition to RES is often addressed as a critical step in addressing climate change, yet it brings with it a range of environmental, territorial, landscape, and social challenges. Despite its undeniable environmental benefits, the deployment of RES involves a complex array of impacts that require careful, rigorous assessment to ensure that the benefits exceed the downsides. This section explores the positive and negative consequences of RES development, focusing on the controversies and debates surrounding their environmental, territorial, landscape, and social impacts.

A. Environmental Impacts

The most significant environmental advantage of RES is that they can help mitigate climate change by significantly reducing greenhouse gas emissions. Unlike fossil fuels, RE sources such as wind, solar, and hydropower generate little or no direct carbon emissions during their operational phase. The deployment of RES can also improve air quality by reducing the levels of harmful air pollutants, such as sulphur dioxide (SO_2) and particulate matter (PM_{10}), which contribute to respiratory and cardiovascular diseases (Bodziacki et al., 2024).

However, not all the environmental impacts of RES are positive. Renewable energy systems, such as wind, hydro, biomass, geothermal, and solar, have negative effects on the environment at various stages of their lifecycle. The ecological footprint of RE technologies is a serious concern. Large areas of land are required for many renewable technologies, in particular hydropower, concentrated solar power, and geothermal systems, and this can lead to habitat destruction, biodiversity loss, and ecosystem fragmentation, particularly in ecologically sensitive areas (Senyapar & Bayindir, 2023). For example, solar PV systems have been linked to substantial land-use changes, particularly in arid regions, where large areas of land are converted to energy production. This can lead to a decrease in biodiversity and the fragmentation of habitats (Senyapar & Bayindir, 2023). Similarly, Mahmud et al. (2020) show that offshore wind farms and hydropower projects can cause damage to marine and freshwater ecosystems, threatening aquatic species and disrupting water flow patterns. In general, offshore wind farms have higher environmental costs and higher CO2 emission per kWh than onshore farms due to the additional efforts required in construction, such as boat landing platforms, external sea cables and offshore transformer stations (Eang & Sun, 2012).

Life-cycle assessments of RES reveal that significant environmental problems can arise during their production and disposal phases. These include the use of scarce or limited resources, emissions during manufacturing, transportation, and waste generation at the end of their useful life (Sayed et al., 2020; Rabaia et al., 2020; Mahmud et al., 2020).

The extraction of raw materials for RE technologies has profound environmental implications, particularly in resource-rich regions of Africa, South America, and Asia. The demand for critical materials, such as lithium, cobalt, and rare-earth elements, required for the manufacturing of wind turbines, solar panels, and batteries is surging as a result of the global shift to renewables (Arshi et al., 2018). However, this demand comes with significant environmental costs. Mining and refining these materials are energy-intensive processes that increase greenhouse gas emissions and environmental degradation, exacerbating climate change (Dutta et al., 2016; Langkau & Erdmann, 2020; Pell et al., 2021; Gallo et al., 2022).

Apart from these climate impacts, the extraction of raw materials also poses severe risks to biodiversity and land use. In regions with rich ecosystems, such as parts of Africa and South America, mining activities frequently result in habitat destruction and biodiversity loss. They can also lead to significant land-use changes, often displacing local communities and disrupting ecological balances (Olivetti & Cullen, 2018). The long-term implications of these changes highlight the need for more sustainable resource extraction practices.

Resource depletion is another important challenge associated with RES. The rapid increase in material extraction is straining the availability of critical resources, raising questions about the long-term viability of current RE supply chains (Shahsavari & Akbari, 2018). This issue is particularly evident in developing regions, where regulatory frameworks may be weaker, so enabling unsustainable practices to persist (Olivetti & Cullen, 2018).

The environmental costs of raw material extraction extend to water and energy use. Mining and processing activities require substantial amounts of water and energy, often contributing to resource scarcity in regions already facing significant environmental stress (Czajka et al., 2022). In areas where water is scarce, this can intensify local resource conflicts, creating additional social and ecological dilemmas (Gallo et al., 2022).

Finally, the disposal of decommissioned RES infrastructure—such as solar panels and wind turbine blades—presents significant waste management challenges, and the environmental costs, although lower than those of fossil fuel systems, should not be underestimated. If not properly recycled, these materials can contribute to soil and water contamination (Shah et al., 2021).

B. Territorial and landscape impacts

The territorial implications of RES go far beyond ecological concerns. Land use is one of the most contentious issues, as large-scale RE projects generally require larger areas of land than conventional forms of energy to produce the same amount of power (Van Zalk & Behrens, 2019). Their relative visual impact per MWh can also be higher (Wolsink, 2007). Such transformations mean that landscape quality has become central to the debate on RE development in Europe, with local opposition linked to landscape issues often limiting the growth of the renewable sector (Devine-Wright & Batel, 2017). Rapid technological advances and evolving policy frameworks—especially at the EU level—reveal the need for robust energy planning practices to prevent the degradation of the landscape (Frolova et al., 2019).

Large-scale renewable projects require a great deal of space, frequently in areas of high ecological or cultural value. This can lead to territorial disputes, especially when projects overlap with or encroach on areas of high ecological or cultural value (Frantál et al., 2023; Senyapar & Bayindir, 2023). The expansion of RES into previously undeveloped areas can create tensions between the need for RE and the desire to preserve agricultural land and cultural heritage sites. The construction of RE infrastructure, such as roads, substations and transmission lines, can fragment landscapes and interfere with local land-use patterns. Owing to the generally lower power density of many RE systems, land occupation can be extensive (Van Zalk & Behrens, 2019), leading to a phenomenon often referred to as "energy sprawl"

(Trainor et al., 2016). For example, wind energy, despite its smaller direct footprint, may have broader indirect impacts due to infrastructure sprawl, while large-scale solar developments can visually dominate rural areas with uniform arrays of panels.

The conversion of large strips of land for RES installations can result in territorial and landscape fragmentation, in which previously continuous landscapes are divided into smaller ones. This fragmentation can diminish the ecological and aesthetic coherence of landscapes, potentially affecting local communities' sense of place and identity (Saganeiti et al., 2020). Moreover, the land-use competition between RE installations and other critical land functions, such as agriculture and conservation, further complicates the landscape dynamics of RE expansion.

Additionally, RE projects can have a profound visual impact on landscapes, altering their public perception. The large-scale infrastructure required for energy generation can transform rural landscapes, particularly in protected areas, affecting both the aesthetic and cultural values of natural environments (Cialdea & Mastronardi, 2016; Frolova et al., 2019). Wind turbines, with their towering presence and rotating blades, can dramatically change the visual landscape. In regions where wind farms are installed, the height of the turbines—often over 100 meters tall—can be in stark contrast to the surrounding environment. This visual impact has triggered substantial opposition in certain areas, especially where the landscape has high cultural or scenic value for local communities (Schwenkenbecher, 2017; Pasqualetti et al., 2002). Similarly, solar PV farms, which cover vast areas of land, can create large, uniform fields made up of countless rows of panels that alter the visual aesthetics of rural areas (Frolova et al., 2019). The integration of these renewable technologies into existing landscapes requires careful consideration of their aesthetic impact so as to ensure local acceptance.

Dynamic factors, such as the stroboscopic effect caused by the rotating blades of wind turbines or the reflective glare from solar panels, can exacerbate these visual concerns. These effects can be particularly problematic for nearby residents, leading to increased resistance to RES projects (Kil, 2011). As RE technologies become more widespread, these landscape impacts are expected to grow, intensifying debates around their visual impact and the need for mitigation strategies.

The impact of RE developments depends heavily on their scale and context. While smaller projects generally have less pronounced impacts, the cumulative effect of numerous small-scale installations may exceed that of a single large project. Conversely, larger projects risk creating dramatic visual transformations and ongoing land-use conflicts. This tension between scale and cumulative impacts is evident in the literature, so emphasizing the need for careful siting and planning strategies (Frolova et al., 2019). The use of "brownfield" sites or agricultural residues can sometimes mitigate these effects by avoiding prime farmland or natural habitats (Trainor et al., 2016).

C. Social impacts

The social implications of RES deployment are varied and can be both positive and negative. On the plus side, RE projects can stimulate local economies, create jobs, and promote energy independence. However, the large-scale implementation of renewable technologies can also lead to displacement of the local population, social conflicts, and economic disruption.

The most frequently cited social benefit of RES is job creation. RE projects can generate both direct employment in the energy sector and indirect employment in related industries such as manufacturing, construction, and maintenance (Mu et al., 2018). In regions where unemployment rates are high, the expansion of RES can provide much-needed economic opportunities and boost social welfare (Omri & Bélaïd, 2020). Community-based RE initiatives, such as local wind or solar farms, can also enhance social cohesion by fostering a sense of local ownership and empowerment (Rogers et al., 2012).

Despite the economic end environmental benefits, the development of RES can also lead to social problems. Renewable energy development has led to social conflicts and land grabbing in various parts of the world. In Japan, conflicts arose over landscape changes due to solar power installations (Akita et al., 2020). The Isthmus of Tehuantepec in Mexico experienced opposition to wind farms, with land rent being a key driver of conflicts (Alonso Serna, 2021). Similar issues occurred in Brazil with palm oil production for biodiesel (Backhouse & Lehmann, 2020). Large-scale RE projects, particularly those involving land acquisition, can displace local communities, causing tensions between energy developers and affected populations, as happens for example when entire towns and villages are flooded to make way for a new reservoir and hydropower plant (Senyapar & Bayindir, 2023). This displacement can result in the loss of livelihoods, homes, and cultural heritage, particularly in rural areas. Furthermore, the disruption of local economies due to the repurposing of land for RE can exacerbate social inequalities, particularly when there is insufficient community involvement in the decision-making processes (Terrapon-Pfaff et al., 2019).

In addition to displacement, RES projects and in particular wind farms can lead to noise pollution, which can disturb nearby residents. This can become another source of social unrest and opposition to further developments (Senyapar & Bayindir, 2023).

Another important challenge that must be overcome is the lack of formal methodologies for assessing social impacts, as existing assessments tend to focus on the quantitative socioeconomic repercussions of RES rather than on qualitative social changes in community cohesion and social capital (Karytsas et al., 2020; Colvin et al., 2019).

III. END OF LIFE ISSUES AND (IR)REVERSIBILITY OF THE IMPACTS OF RE SYSTEMS

A. Challenges involved in the end of life of RE systems

A core challenge is the absence of a clear definition of the end-of-life phase in renewable infrastructure. De Laurentis and Windemer (2024) describe two forms of aging affecting RE technologies: (i) physical wear and tear that diminishes performance, and (ii) relative aging, wherein newer innovations render older plants economically uncompetitive. Delaney et al. (2023) identify a range of EoL scenarios for wind turbines—Design, Functional, Location, Economic, Stockpiled, and Abandonment—highlighting varied reasons for decommissioning or continued operation. Although many turbines are designed for 20 years of service, some can remain in use for 25–30 years (Majewski et al., 2022). In reality, repowering may occur much sooner, driven by market incentives, policy changes, or equipment failures (Lantz et al., 2013).

One mechanism for shaping how RE infrastructure is deployed and removed is time-limited permissions. In theory, such regulatory approaches prevent facilities that need not be permanent from becoming so, ensuring a point of reconsideration of the plant's viability when the permit expires. In practice, however, this notion of reversibility is complex. Windemer (2019) highlights that while wind turbines are often promoted as easy to decommission, the wide range of EoL options—such as repowering, extending operational consent, or outright abandonment—introduces uncertainties regarding how and when infrastructure is ultimately removed.

RES, particularly wind and solar technologies, pose significant EoL challenges, primarily due to the increasing volume of waste generated as installations reach decommissioning. By 2050, global wind energy waste is projected to exceed 43 million tons, with the majority generated by China (40%) and Europe (25%) (Beauson et al., 2022). Similarly, the accumulation of solar photovoltaic (PV) waste is estimated to surpass 78 million tons globally, with regions like the EU and Latin America expected to experience significant waste surges due to early adoption (IRENA & IEA-PVPS, 2016; Chowdhury et al., 2020). While some wind turbines are decommissioned or repowered annually, data gaps on dismantling practices and instances of incomplete removal raise concerns about site restoration (Delaney et al., 2023). As Windemer (2019) notes, the presumed "temporariness" of wind power infrastructure is frequently constrained by the economic interests of developers, the limits of recycling markets, and the efficacy of legal enforcement.

The presumption that decommissioning will restore the site to pre-project conditions is complicated by potential abandonment, varied aging scenarios, and the willingness—or capacity—of developers to remove the infrastructure (Ferrell & DeVuyst, 2013; Windemer, 2019). Some carefully drafted leases do specify the removal of substantial above-ground equipment and site restoration, yet bankruptcies and lax enforcement can leave sites partially reclaimed or even deserted (Conaway, 2017; Delaney et al., 2023).

Problems may appear when older RE plants with minimal decommissioning requirements are situated on landscapes that cannot readily be reverted to their prior state. Although RES are often promoted as temporary due to the purported ease of dismantling, real-world outcomes hinge on economic drivers and legal frameworks (Windemer & Cowell, 2021). For instance, in some cases, wind turbines are allowed to run to fail and then abandoned, reflecting a Functional or Economic EoL, prolonging the impacts of infrastructure in ways that undermine claims of reversibility (Delaney et al., 2023).

The question of the reversibility or otherwise of the impacts of RES is central to understanding the long-term consequences of the energy transition. While RES are often perceived as more environmentally-friendly alternatives to fossil fuels, their deployment can lead to both reversible and irreversible changes in the environment, territory, society, and landscape. The degree to which these impacts can be reversed depends on several factors, including the type of technology, the characteristics of the site, and the planning and regulatory frameworks in place.

The waste materials generated when installations reach decommissioning include wind turbine blades and PV panels, which are difficult to recycle and contain hazardous substances, so posing risks to the environment if not properly managed. Recycling frameworks and circular economy principles remain underdeveloped with the result that a substantial portion of the waste ends up in landfills. While we know that large numbers of older wind turbines are decommissioned or repowered every year, the lack of precise data on decommissioning and the premature abandonment of facilities further complicates waste management (Delaney et al., 2023).

Addressing these challenges requires urgent advances in recycling technologies and robust regulatory frameworks to ensure sustainable EoL practices and mitigate the long-term environmental impacts of RES.

B. Reversibility of environmental impacts

The environmental impacts of RES are not always reversible and some may persist long after the RE projects have been decommissioned. One of the most contentious issues in terms of environmental reversibility is land use. Large-scale RE installations, such as wind and solar farms, often require the conversion of natural or agricultural land into energy production sites. While some land-use changes, such as the reclamation of land for agricultural purposes after the decommissioning of a solar farm, can be reversible, the destruction of habitats and ecosystems may have long-term effects that are difficult to undo. Habitat loss, for example, can lead to the permanent extinction of local wildlife species, making the environmental damage irreversible (Senyapar & Bayindir, 2023).

Another area where impacts may be irreversible is in the extraction of large amounts of scarce resources for the production of RE technologies, such as the mining of rare earth metals for wind turbines and solar panels. The extraction process can cause significant environmental degradation, including soil erosion, water contamination, and loss of biodiversity (Schwenkenbecher, 2017; Zapp et al., 2022). These impacts are often long-lasting, and restoration of the affected areas can take decades, if not centuries, making the environmental consequences largely irreversible.

The installation of offshore wind farms can have lasting impacts on marine and coastal ecosystems, in that marine biodiversity and water quality may not be fully restored during decommissioning of these projects (Ouro et al., 2024). Similarly, land-based wind and solar farms can fragment habitats, leading to permanent ecological alterations that are difficult to reverse. Even if the infrastructure is later removed, the ecosystem may struggle to recover its original state due to long-term disruption of soil, water, and plant life (Senyapar & Bayindir, 2023).

The disposal of RE technologies at the end of their life cycle, such as the recycling of wind turbine blades or solar panels, can also result in permanent environmental costs. The materials used in these technologies are often difficult to recycle and can cause environmental harm if not properly managed. The majority of wind turbine blades are made of non-biodegradable fibre-reinforced polymers and either end up in landfills or are incinerated, both of which are unsustainable and environmentally harmful methods of disposal (Paulsen & Enevoldsen, 2021; Delaney et al., 2023). The disposal of wind turbine blades can also lead to the formation of microplastics, with their ensuing risks to ecosystems and human health (Tayebi et al., 2024). Solar panels, especially those made from cadmium telluride (CdTe), contain toxic materials that could endanger the environment if not properly disposed of (Vellini et al., 2017; Lisperguer et al., 2020).

C. Reversibility of territorial and landscape impacts

The territorial and landscape impacts of RES, particularly in rural or ecologically sensitive areas, can also be irreversible. The construction of wind farms, solar arrays, and other RE infrastructure often leads to changes in land use and territorial fragmentation, which are difficult to reverse. While it is possible to restore some aspects of the land, for example by replanting vegetation after the removal of wind turbines, the long-term alteration of landscape aesthetics and the displacement of local communities is often irreversible. RE infrastructure planning tends to be guided by two key assumptions. Firstly, that the impacts of RE power plants are reversible and secondly, that landscape dynamics are only affected by the implementation and EoL phases of RE projects. However, both assumptions are increasingly being called into question.

The reversibility of RE landscapes, linked to the presumed ease of removing RES, is far more complex and costly than previously assumed. Windemer and Cowell (2021) highlight that while developers may attempt to maintain their reputations as being environmentally aware, they often seek to limit their responsibilities for the long-term impacts of their facilities. The efforts they make to decommission their plants depend on several factors, including developer accountability, the existence of material recovery markets, and legal enforcement mechanisms (Ferrell & DeVuyst, 2013; Windemer, 2019). In practice, some leases stipulate that above-ground and some underground equipment must be removed and the area restored, but these agreements are not always honoured, particularly when companies go bankrupt before reaching the EoL phase (Conaway, 2017; Delaney et al., 2023).

RE infrastructures can therefore cause permanent alterations to landscapes, creating new dynamics that continue even after decommissioning. This poses risks of "industrializing" formerly rural areas, an issue highlighted by Fast and Mabee (2015), Pasqualetti et al. (2002), and Windemer and Cowell (2021), so challenging the notion of landscape reversibility.

The second assumption, namely that the EoL of RE infrastructures is a predictable process, is undermined by instances of abandonment or premature dismantling. Developers may abandon projects due to inefficiency, social conflicts, or financial difficulties. In the Tehachapi Pass region of California, for instance, approximately 4,500 turbines were abandoned after they became unprofitable. These turbines and their associated infrastructure were not removed due to insufficient regulations requiring developer accountability (Stripling, 2016). Concerns about improper decommissioning are widespread, as landowners worry that their land will not be restored to its original condition once the projects have been abandoned (Ferrell & DeVuyst, 2013; Smith et al., 2011). Additionally, some wind companies allow turbines to "run to fail," operating without maintenance until repair costs exceed revenues (Delaney et al., 2023; Lacal-Arántegui et al., 2020). These changes can lead to ongoing tensions and conflicts over land use and landscapes, particularly in areas with strong cultural or historical ties to the land.

D. Reversibility of social impacts

The reversibility of social impacts of RES is also a key consideration when evaluating RE projects, in particular, when they involve the displacement of the local population and the disruption of their community. In some cases, to enable the installation of large-scale RE developments, such as hydropower, whole towns and villages have had to be abandoned and their population relocated with permanent consequences that are difficult or impossible to reverse. When communities are relocated, their social structures and local networks are severely altered, leading to the loss of livelihoods and cultural connections (Terrapon-Pfaff et al., 2019).

In addition, while RE projects can generate jobs and stimulate local economies, these positive impacts are often temporary. For instance, the jobs created during the construction and installation phases of RE projects may disappear once the infrastructure is operational, leading to long-term economic disruption if alternative employment opportunities are not available (Mu et al., 2018). In regions where RES projects are developed without adequate community engagement or compensation, the social and economic consequences can be irreversible, leaving lasting scars on local populations.

Therefore, the reversibility of the impacts of RES is a complex issue that depends on the type of impact, the characteristics of the site, and the impact mitigation strategies employed. While some negative consequences can be attenuated or reversed with careful planning and management, others may result in irreparable changes that cannot be undone. It is therefore essential that policymakers, developers, and communities carefully consider all potentially irreversible impacts when planning RE projects. By incorporating robust impact assessments, taking long-term sustainability into account, and engaging in community-based decision-making processes, it is possible to minimize irreversible damage and ensure that the energy transition is both environmentally and socially responsible. While RES are essential for reducing our dependence on fossil fuels, they are not without their drawbacks. These systems can negatively impact the environment, economy, and society, particularly through resource depletion, habitat disruption, and social displacement. Addressing these issues requires careful planning and mitigation strategies so as to ensure a truly sustainable energy transition.

IV. INSTRUMENTS FOR THE ASSESSMENT OF RES IMPACTS IN ADDITION TO CO2 EMISSION-BASED METRICS

Since the RES development is linked to multiple environmental, territorial, and social impacts that extend far beyond their capacity to reduce CO_2 emissions, comprehensive assessment frameworks should be introduced. Some of the most advanced instruments for impact evaluation are LCA, spatial decision support systems (SDSS), Ecosystem Services (ES) assessment, Social life-cycle assessment (SLCA) and multi-criteria decision-making (MCDM).

A. Life-Cycle and End-of-Life Assessments

LCA remains a key methodology for understanding the full environmental footprint of RES. By examining the entire lifecycle from raw material extraction to decommissioning, LCA provides critical insights into emissions, resource consumption, and waste generation. For example, the manufacture of solar PV systems, often lauded for their operational carbon neutrality, produces significant emissions due to energy-intensive processes and the extraction of materials such as silicon and cadmium telluride (Vellini et al., 2017). The case of wind turbines is similar, in that although they generate low levels of operational emissions, their construction relies on rare-earth elements, such as neodymium, praseodymium, dysprosium and terbium, which are used to make important components such as the neodymium–iron–boron (NdFeB) permanent magnets used in the turbines' generators. Apart from the over-exploitation of these scarce resources, their mining contributes to soil degradation and water contamination.

Despite its usefulness, LCA is not without limitations. Many assessments rely on secondary data, which are often outdated or overly general, leading to inaccuracies (Pehl et al., 2017). Furthermore, LCAs often fail to capture regional variations in impacts. For instance, the energy mix used for manufacturing RES varies significantly between countries, such that the overall environmental footprint of these technologies can also differ widely (Piotrowska et al., 2022). Improved integration of site-specific data and harmonized methodologies across regions could address these gaps.

EoL assessments are increasingly critical as the first generation of RES technologies approaches decommissioning. The numerous challenges involved in disposing of wind turbine blades, composed of non-recyclable composites, exemplify the inadequacies of current waste management systems (Paulsen & Enevoldsen, 2021). By contrast, solar PV waste—projected to exceed 78 million metric tons by 2050—poses risks of heavy metal leaching if not properly handled (Chowdhury et al., 2020). Circular economy frameworks, which emphasize reuse and recycling, offer promising pathways but remain underdeveloped due to a lack of robust regulatory support and recycling infrastructure (Delaney et al., 2023).

B. Spatial and territorial planning tools

Spatial planning tools are vital for mitigating land-use conflicts and ensuring the harmonious integration of RES into diverse landscapes. Unlike fossil fuel plants with relatively compact footprints, RES installations such as solar farms and wind turbines often require large tracts of land, leading to competition with agricultural, conservation, and urban land uses (Senyapar & Bayindir, 2023).

One advanced approach is to use SDSS like LANDIS-II. These tools process data on ecosystem conditions, land-use patterns, and climate scenarios to guide decision-making (Povak et al., 2024). For instance, SDSS can simulate the long-term ecological impacts of RES projects, aiding policymakers to select sites that minimize habitat disruption.

Ecosystem services frameworks also play a crucial role in assessing the trade-offs associated with RES development (Busch et al, 2011). By quantifying changes in ecosystem functions—such as pollination, water filtration, and carbon sequestration—ES models provide a holistic overview of the environmental costs and benefits of RES deployment (Cervelli et al., 2020). However, the effectiveness of these tools is often hampered by limited data on baseline ecosystem conditions, particularly in regions with high biodiversity (Pătru-Stupariu et al., 2020).

Quantitative methodologies like landscape metrics further enhance our understanding of the spatial impacts of RES. These metrics analyse changes in landscape configuration, connectivity, and fragmentation, providing insights into the ecological consequences of land-use changes (Ioannidis & Koutsoyiannis, 2020). While these methods offer precise measurements, they often overlook qualitative aspects, such as the cultural significance of landscapes, so underscoring the need for integrated approaches.

C. Social impact and justice frameworks

The rollout of RES is increasingly being scrutinized from the perspective of energy justice, which seeks to ensure the equitable distribution of benefits and burdens. SLCA extends the principles of LCA by evaluating the social implications of RES projects, including labour practices, community displacement, and access to energy (Di Cesare et al., 2018). For example, research has highlighted how large-scale wind farms in rural areas can lead to social fragmentation and strong opposition when local communities are excluded from decision-making processes (Poggi et al., 2018).

Stakeholder engagement methodologies, such as participatory mapping and community workshops, are instrumental in addressing these challenges. By involving local people in the planning and evaluation phases, these methods foster social acceptance and reduce conflicts (Brunet et al., 2020). Multi-criteria decision-making (MCDM) tools further enhance stakeholder engagement by integrating diverse perspectives into project evaluations. These tools allow for the simultaneous consideration of environmental, economic and social criteria, so ensuring balanced decision-making (Katre & Tozzi, 2018).

Qualitative methodologies, including visual and aesthetic impact assessments, address the often-overlooked cultural dimensions of RES deployment. Within participatory frameworks, tools like GIS-based visualization and 3D modelling can help local people and other stakeholders understand the visual impacts of renewable infrastructure, such as wind turbines and solar panels, on the landscape (Sargentis et al., 2019). These assessments are particularly valuable in regions where tourism and cultural heritage are key drivers of the local economy.

D. Addressing methodological gaps

Despite significant advances, critical gaps remain in the methodologies used to assess RES impacts. One major limitation is that the quantitative and qualitative data on which they are based are not sufficiently well integrated. While tools like LCA and ES provide rigorous quantitative insights, they often fail to capture the social and cultural dimensions that influence local acceptance (Campos-Guzman et al., 2019). Conversely, qualitative methods, while rich in context, lack the precision needed for large-scale policy applications.

The time and spatial scales applied are also very important. Many assessments focus on short-term impacts, neglecting the cumulative effects of RES projects over decades (Pătru-Stupariu et al., 2020). Additionally, the spatial focus of existing tools often overlooks dependencies between regions and countries, such as the global supply chains of critical materials.

To address these gaps, researchers recommend the adoption of hybrid methodologies that combine the strengths of various tools. For instance, integrating LCA with MCDM and participatory approaches can provide a broader-based evaluation of RES impacts, balancing technical precision with social relevance (Campos-Guzman et al., 2019).

Expanding the scope of RES impact assessments is essential for aligning RE development with the principles of sustainability and justice. Instruments such as LCA, SLCA, spatial decision support models, and participatory planning frameworks offer valuable insights, but they must be continuously refined and updated to ensure their effectiveness.

By adopting a multidimensional approach that considers environmental integrity, social equity, and cultural heritage, policymakers and stakeholders can ensure that the energy transition is not only effective in reducing emissions but also equitable and inclusive. This broader perspective is crucial for fostering public trust and achieving long-term sustainability in the global shift to RE.

CONCLUSION

The transition to RE systems represents a fundamental change in the way we address global climate issues, yet it is fraught with complexities that extend far beyond CO_2 reduction. This review has emphasized the multiple impacts of RES deployment—on the environment, territory, landscapes, and societies—highlighting the urgent need for a complete overhaul of how these systems are planned, assessed, and implemented. A more integrative approach, grounded in spatial and temporal planning, can help mitigate the negative consequences often overlooked or ignored in traditional frameworks.

A. Summary of analysis

The analysis reveals that while RES significantly reduce operational greenhouse gas emissions, they have lifecycle impacts on the environment that must be taken into consideration. Manufacturing processes, the extraction of critical raw materials, transport, and the management of end-of-life waste can have substantial ecological costs. These include habitat destruction, biodiversity loss, and pollution, particularly in resource-rich but vulnerable regions like Africa and South America. These issues are further compounded by the absence of robust recycling systems and circular economy frameworks, which leaves vast amounts of poorly managed decommissioned infrastructure—such as wind turbine blades and solar panels— that can damage the environment.

The territorial and landscape implications of RES are equally pressing. Unlike conventional fossil fuel plants, RES installations require large areas of land, often encroaching on agricultural land, conservation zones, and areas of cultural or heritage value. This land use competition not only disrupts ecological functions but also fragments landscapes, altering their aesthetic and cultural values, often acquired over many generations. These impacts are especially controversial in regions where the local economy relies heavily on tourism or agriculture and can lead to social conflicts and opposition.

The social dimensions of the energy transition are another critical area of concern. While RES projects promise job creation and economic revitalization, these benefits are often temporary and unevenly distributed. Large-scale installations in rural areas can displace communities, disrupt livelihoods, and exacerbate existing inequalities. Moreover, the lack of meaningful community engagement in decision-making processes frequently results in social opposition, undermining the potential for an inclusive, fair energy transition.

In addition to these challenges, there are also gaps in the methodologies used to assess the full impact of RES. Existing tools often operate in closed silos, focusing on specific dimensions while neglecting the broader picture. For example, LCA provides valuable data on emissions and resource use, but fails to account for social and cultural implications. Similarly, many assessments are conducted over an excessively short timescale to enable the long-term and cumulative effects of the rollout of RES to be accurately calculated. These gaps highlight the need for more integrated and adaptive methodologies that can capture the many, varied impacts of RES over their entire life cycle.

B. Recommendations for future energy policies and practices

Addressing the challenges posed by RES requires a fundamental change in energy policies, moving beyond simplistic CO_2 reduction targets toward much more comprehensive sustainability goals. Central to this transition is the recognition that careful planning, rather than narrowly defined emissions metrics, must guide the rollout of RE systems.

Long-term spatial planning must become the basis of RES strategies. Effective spatial planning can identify optimal siting for RE projects, minimizing conflicts with other land uses and protecting ecologically sensitive areas. Tools such as ecosystem services modelling, spatial decision support systems, and landscape metrics can provide critical insights into the trade-offs involved, enabling more informed and balanced decisions. These decisions must be taken with a long-term perspective so as to help spread resource demands over time, mitigating ecological disruption and allowing for adaptive management in response to emerging challenges.

The integration of community perspectives into planning and assessment processes is equally important. Significant stakeholder engagement, facilitated through participatory methods such as workshops, mapping, and consultations, will ensure that local concerns are addressed and that the benefits of RES are distributed equitably. This approach not only enhances social acceptance but also reduces the probability of conflicts, so paving the way towards a more inclusive energy transition.

Policymakers must also prioritize the development of regulatory frameworks that address the end-of-life challenges of RES infrastructure. These frameworks must be based on the principles of the circular economy in order to promote recycling and reuse and so reduce the environmental footprint of decommissioned materials.

It is also clear that the methodologies used to assess RES impacts need significant refinement. Hybrid approaches that combine quantitative tools like LCA with qualitative methods such as SLCA and visual impact assessments can provide a more comprehensive understanding of RES impacts. Integrating these tools into planning processes will ensure that decisions are informed by a multidimensional outlook that balances environmental, social, and economic considerations.

Finally, energy policies must adopt a regional, context-specific approach. The impacts of RES vary widely depending on geographic, cultural, and ecological contexts, and strategies must be tailored accordingly. For instance, land-scarce regions may benefit from dual-use strategies like agrivoltaics, while resource-rich areas should focus on sustainable extraction practices and community-driven projects.

The energy transition involves a great deal more than the technical challenge of reducing emissions; it is a far-reaching social, territorial, and ecological process that requires careful and inclusive planning. Fixating on CO_2 reduction targets without considering the broader impacts of RES risks perpetuating significant environmental degradation, social inequalities, and territorial conflicts. By placing long-term spatial planning at the heart of energy policies, and by including the voices of all stakeholders, we can ensure that the RE transition is not only effective in combating climate change but also equitable, sustainable, and respectful of the diverse landscapes and communities it affects.

Therefore, the energy transition must evolve beyond its current narrow focus to embrace a holistic vision of sustainability. Only through thoughtful planning, comprehensive assessments, and inclusive policies can we balance the urgent need for RE with the imperative to safeguard our environment, territories, and societies for future generations.

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