Energy for Sustainable Development 85 (2025) 101676

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Abandoning renewable energy projects in Europe and South America: An emerging consideration in the recycling of energy landscapes

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ARTICLE INFO

Keywords:
Recycling
Energy
Landscapes
Wind
Decommissioning

ABSTRACT

Landscape legacies of conventional energy development are vast. Mines, well fields, power plants, sub-stations, refineries, and disposal sites have been accumulating for more than a century. We know these energy landscapes exist, but we are uncertain what to do with them once their initial function is completed. Can they be used for any future purpose; that is, can they be "recycled"? As we gradually shift to renewable energy resources for all the benefits they promise, we are becoming aware that we will be facing similar end-of-life questions about the unique landscapes they are creating. What is their landscape legacy? This paper expands on growing attention to recycling *conventional* energy landscapes by introducing the circumstances regarding *renewable* energy landscapes. It addresses the first stages in consideration of these questions as they pertain to the abandonment of renewable energy infrastructures in Europe and South America. Based on reconstructive and comparative analysis of examples of abandoned wind farms, we found that there are barriers to formal decommissioning of these facilities, leaving recycling options as open questions. The main conclusion is that abandoned wind farms are consequences of gaps and weaknesses in the regulations on decommissioning of renewable energy infrastructures, in particular in case of installations abandoned before reaching their operational end-of-life. The need to improve those regulations will be crucial to ensure the restoration and recycling of renewable energy landscapes going forward.

Introduction

Climate change, increasing political instability in oil-rich countries, and worries about public risks of nuclear power, have triggered an unprecedented growth in renewable energy (RE) development worldwide. Its rapid expansion is largely due to (1) favorable national policies that are mainly based on quantitative targets and economic incentives; (2) advantageous social, institutional and political conditions (Küpers & Batel, 2023); and (3) the plummeting costs of some RE technologies, such as wind power and solar photovoltaic (PV) (Xiao et al., 2021). However, it has also introduced complex challenges, particularly concerning the end-of-life (EoL) phase of RE infrastructures and their impact on landscape reversibility.

The concept of landscape reversibility pertains to the ability to restore – or recycle – landscapes for some subsequent use following the decommissioning of RE infrastructures (Windemer & Cowell, 2021). It expands on the previous work of Pasqualetti and Smardon (2025) and Frantál et al. (2024) that emphasized conventional energy landscapes. This issue is critical, as the physical footprint of RE technologies—such as wind turbines, solar panels, and hydroelectric facilities—can lead to long-term alterations in land use and visual aesthetics (Spielhofer et al., 2021). Several studies have highlighted that RE systems often require more surface area compared to conventional energy sources due to their lower energy densities, thereby intensifying their visual and spatial impact on landscapes (Frolova et al., 2019; Ioannidis & Koutsoyiannis, 2020; van Zalk & Behrens, 2018; Wolsink, 2007).

Fig. 1 illustrate global growth of renewable energy capacity for generating electricity, showing that wind power and solar PV are the dominant technologies in the market. Global cumulative wind power capacity passed the first 1,017,199 MW milestone in 2023, with significant participation from the European Union (EU) (with 218,766 MW) and South America (with its almost 40,000 MW) (GWEC, 2024; IRENA, 2024). Almost 74,000 MW of this global capacity were installed before 2006, with Europe a frontrunner in wind energy development with a

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https://doi.org/10.1016/j.esd.2025.101676
Received 15 October 2024; Received in revised form 12 February 2025; Accepted 13 February 2025

total of 48,279 MW, while South America had only 286 MW (IRENA, 2015). While only 6060 of solar PV MW were installed before 2006 (3318 MW in Europe and only 1 MW in South America) (IRENA, 2015), its cumulative installed capacity worldwide has grown dramatically up to 1,418,969 MW in 2023, outranking Europe with its 288,122 MW (with 257,057 MW at EU27) and South America with 48,921 MW (IRENA, 2024).

By 2050, the annual waste generated from wind energy alone is projected to reach 2 million tons globally (Liu & Barlow, 2017), with Europe set to experience some of the earliest impacts due to its early adoption of wind energy technologies (Beauson et al., 2022; WindEurope, 2019; WindEurope, 2020a). At the same time, it is projected that by 2050 up to 78,000,000 metric tons of solar panels will reach the end of their useful life, without taking into account learning to reduce premature losses and repowering of PV plants (IRENA and IEA-PVPS, 2016). In some regions, waste volumes from solar PV are anticipated to rise exponentially by 2030 as early installations approach their operational limits. While research on waste management and decommissioning strategies has grown, significant gaps remain in understanding how existing regulatory frameworks address—or fail to address—these challenges. Therefore, it becomes crucial that we understand whether there are suitable regulations for addressing the EoL of RE infrastructures as we consider how we might recycle the landscapes they were to occupy.

When RE infrastructures are aging, they have new specific impacts that are likely to continue to affect the local environment and communities (Küpers & Batel, 2023; Windemer, 2019; Windemer and Cowell, 2021). The reversibility of landscapes is further complicated by the integration of RE infrastructures into existing ecosystems and land uses. For instance, the installation of RE technologies can disrupt local ecosystems and alter the provision of ecosystem services, such as food production and cultural values (Picchi et al., 2019).

When the assets approach the end of their operational life and initial planning RE farms become time-expired, project owner have several options: decommissioning, repowering, extending the planning consent while making no material changes, run to fail or abandonment of the equipment in-place or abandonment (Lacal-Arántegui et al., 2020; Windemer, 2019). All these options are related to the problems of reversibility of the RE facilities' impacts on landscape and the recycling of energy landscapes.

In future scenarios, with a largely decarbonized electricity system, van de Ven et al. (2021) estimated that with solar energy accounting for 25 to 80% of the electricity mix, land occupation by utility-scale solar energy will range from 0.5 to 2.8% of the total territory in the EU.

There are, however, several caveats to this general statement. First, wind and solar development avoid such stages in the fuel cycle as fuel recovery, fuel processing, and centralized power operation. Avoiding the land requirements of these stages brings the total land necessities into rough approximation with conventional power sources in many cases (Pasqualetti and Miller, 1984). Second, RE landscapes can often accommodate multi-purpose land use and thereby reducing their required land commitment. Examples of such dual use include agriculture and grazing (Apostol et al., 2017) (Fig. 2). The landscape impacts of RE facilities have often been a source of tension (Pasqualetti, 2011, 2013; Pasqualetti & Stremke, 2018) (Fig. 3).

Finally, abandonment or dismantlement of disused or ill-planned RE landscapes is becoming an important challenge for sustainable energy transitions all over the world (Fugleberg, 2014). Even though in general a number of abandoned RE infrastructures has been fairly small so far, the experience with the latter in the countries with intensive exploitation of these resources shows us that it could become an important issue for future landscape planning as the equipment ages. For example, in China, the rapid growth in installed capacity of solar PV plants and wind farms has led to significant abandonment issues. According to estimations of Ge et al. (2018), in 2016, the abandoned wind power reached 49.6 billion kWh. As for solar power, the total solar power generation abandoned amounts to 7.3 billion kWh, being the average rate of solar power abandoned in China was about 16%, but in some regions such as Gansu and Province Xinjiang Uygur Autonomous Region, it reached about 31% and 26% respectively (Li et al., 2017). The mismatch between power generation locations and consumption areas, and inadequate transmission infrastructure have contributed to this problem (Li et al., 2017).

The USA too has striking examples of the impacts of abandoned energy facilities. For example, Ferrell and DeVuyst (2013) estimated approximately 57,064 abandoned oil and gas wells awaiting decommissioning through state funds. The authors claimed that although this number is a relatively small 6.9% of the over 800,000 active oil and gas wells in the U.S., it has posed national policy issues and became important problem for the landowners impacted by these wells.

Up to this moment, there are no reliable estimations regarding abandoned RE facilities in Europe and South America; however, but due to the growing intensity of RE resources deployment, thousands of abandoned turbines and solar panels can soon be accumulated all over the world and generate new land use conflicts.

While there have been studies of the conflicts during the development and functioning of RE facilities (see Frantál et al., 2023), interest in problems derived from RE landscape impacts that extend beyond the early stages of their development is relatively recent (Jensen, 2019; Küpers & Batel, 2023; Windemer & Cowell, 2021). Nor has there been any attention to the empty sites that are being created after the abandonment of RE equipment such as turbine blades (Mercer, 2024).

The aim of this paper is to take a first step in filling this gap by highlighting the complexity of the issues related to abandoned RE projects. This study highlights an underexplored dimension of the energy transition: the legacy and decommissioning challenges posed by aging

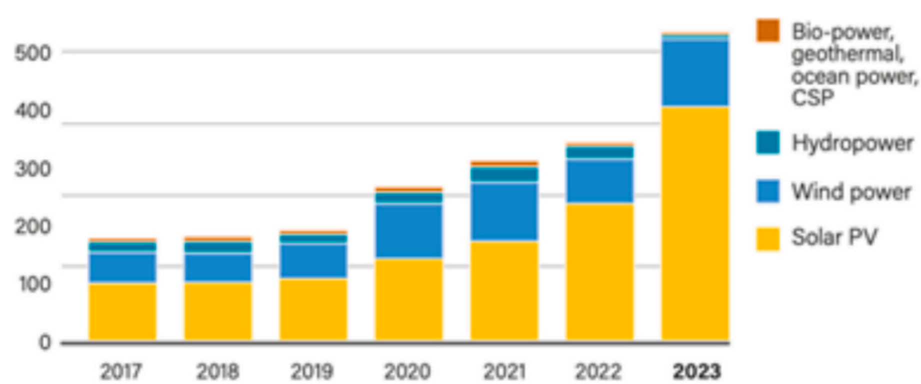

Fig. 1. Global annual additions of renewable power capacity in GW, by technology, from 2017 to 2023.
Source: (REN21, 2024).

Fig. 2. Wind farm within agricultural field, west of Cologne, Germany; solar PV and sheep grazing, near Saarbrucken, Germany. Photos: M.J. Pasqualetti.

Fig. 3. Windfarm Hell. English translation: "We have seen far too many images of white wind turbines on a backdrop of blue skies and green pastures, with smiling babies and animals at pasture. Is this what we want to continue to believe?" Poster produced by Rocco Lombardi for Edizioni Montaonda and "dedicated to all people worldwide who are in the fight against wind turbine speculation." (from: en.friends-against-wind.org) Public Domain.

RE facilities. By examining abandoned RE power plants in Europe and South America, we will elaborate a typology of the reasons for abandonment, explore common patterns, and examine the regulatory aspects associated with this issue and identify barriers to effective EoL management.

Finally, we will highlight opportunities for policy interventions to foster recycling and repurposing of energy landscapes. The findings carry implications that extend beyond academic interest. The insights presented here underscore the pressing need for policymakers to anticipate and address the negative consequences of RE deployment as part of the broader energy transition agenda. This research not only contributes to filling a critical knowledge gap but also provides actionable recommendations for enhancing the sustainability of RE infrastructures, offering a pathway to mitigate the socio-environmental impacts of the energy transition.

This paper is structured as follows. The next section addresses a theoretical background on the end-of-life of RE infrastructures and their landscape impacts. Methodology Section presents the methodology used to perform the analysis related to RE power plant abandonment. Results Section describes the results associated with the reasons, patterns, and regulatory aspects of abandonment. These results are discussed in Discussion Section. Finally, Conclusions Section provides conclusions and recommendations.

Theoretical background

End-of-life of RE power plants and reversibility of their effects

The EoL of RE infrastructures poses critical challenges in terms of landscape reversibility, waste management, and regulatory oversight. Traditionally, RE projects have been framed within a linear model—development, operation, and eventual decommissioning—assuming that their environmental impacts are temporary and reversible. However, emerging research highlights that this assumption may be flawed, as energy landscapes often undergo transformations that make full restoration to their pre-development state complex, costly, or even unfeasible (Fast & Mabee, 2015; Pasqualetti et al., 2002; Pasqualetti & Smardon, 2025; Sayan, 2019; Windemer & Cowell, 2021; Woods, 2003).

Several conceptualizations of EoL exist in the literature, each offering a different perspective on how RE infrastructures reach obsolescence. Delaney et al. (2023) distinguish between Design EoL, Functional EoL, Economic EoL, and Abandonment EoL, each driven by different technical, financial, and regulatory considerations. These differences in the EoL scenarios create several difficulties for RE facilities planning. In fact, today RE infrastructure planning is conditioned by two presumptions: that the impacts of RE power plants are reversible and that RE landscape dynamics are determined by project development phases—implementation and EoL.

Yet, both of these presumptions are questionable. First, while the reversibility of the RE landscape, linked to the ability of RE systems to be easily removed, has often been taken for granted, potential problems surrounding EoL issues could be very complex and costly. Thus, Windemer and Cowell (2021) have pointed out that although RE power plant developers may wish to maintain their environmentally conscious image, the industry may still seek to limit the temporal, spatial and substantive scope of responsibility for the impacts generated by their facilities. Ensuring decommissioning in practice depends on a number of assumptions: that developers choose to be responsible, that a market exists to justify material recovery, or that decommissioning can be legally enforced (Ferrell & DeVuyst, 2013; Windemer, 2019). While conscientiously written leases state that after decommissioning at least substantial above-ground equipment (and some underground equipment) should be removed and the surrounding area should be restored to its pre-construction condition, these were not always respected as some companies declared bankruptcy before decommissioning was reached (Conaway, 2017; Delaney et al., 2023; Ferrell & DeVuyst, 2013).

The second premise may be distorted by the abandonment of RE plants before (or after) the planned EoL phase or by the developer's desire to legitimize further RE expansions. This way, it does not consider the possibility of dismantling or abandoning these infrastructures before initial planning equipment becomes time-expired due to its inefficiency, bad planning, social conflicts, etc. Already in the early 2010s American landowners attending public meetings frequently expressed concerns about the impact on the property if the project is not properly maintained, is completely abandoned or will be properly "decommissioned" after its EoL, i.e., whether the equipment will be removed and the area restored as closely to it pre-project conditions practicable (Ferrell & DeVuyst, 2013; Smith et al., 2011). These concerns were, in fact, well justified since up to 4500 turbines have been abandoned in the Tehachapi Pass region of California, USA, because of a lack of laws and regulations requiring developers to assume responsibility (Stripling, 2016). Moreover, in cases of some wind farms, turbines are run to fail, that is, they are allowed to operate with little maintenance until maintenance costs are higher than revenues for their owner (Delaney et al., 2023; Lacal-Arántegui et al., 2020; Madlener et al., 2019).

Therefore, while the reversibility of RE infrastructures is often assumed, research suggests that the landscape legacies of these projects may persist even after decommissioning. The decommissioning process itself can create new environmental and social impacts, particularly when restoration efforts are incomplete or when economic pressures favor continued land occupation for repowered installations (Pasqualetti & Smardon, 2025; Windemer & Cowell, 2021).

Circular economy and the need for a meta-framework on recycling energy landscapes

A sound conceptual approach to managing RE EoL should involve integrating circular economy (CE) principles and sustainability frameworks. The CE model emphasizes minimizing waste, maximizing resource efficiency, and extending the life cycle of materials used in energy systems (Velenturf & Purnell, 2021). In this respect, Pasqualetti and Smardon (2025) advocate for replacing the traditional "create-use-abandon" model with a meta-framework of "create-use-recycle", which would better align with sustainability objectives.

The CE approach in RE landscapes requires not only material recycling but also functional repurposing of sites. Research has identified several pathways for repurposing former energy landscapes (Frantál et al., 2024; Pasqualetti & Smardon, 2025), including:

- Repowering existing infrastructure to extend operational life.
- Reintegrating decommissioned sites into natural ecosystems, in particular in cases where restoration is ecologically viable.
- Reusing sites for new energy purposes, such as converting decommissioned coal mines into solar farms or using former wind farm sites for energy storage.

Pasqualetti and Smardon (2025) suggest that recycling RE landscapes must be considered from the outset, rather than being an afterthought once infrastructures become obsolete. This requires stronger regulatory mechanisms, economic incentives for developers to invest in decommissioning, and a clearer integration of landscape sustainability into energy policy frameworks.

Contrasting regulatory and contextual differences between Europe and South America

The regulatory frameworks governing the EoL of RE infrastructures differ significantly between Europe and South America, reflecting divergent policy priorities, financial mechanisms, and governance structures. While both regions face regulatory gaps in decommissioning and site restoration, the nature of these gaps varies, influencing the potential for landscape reversibility and the risks of abandoned infrastructure.

European regulatory frameworks have begun to integrate EoL considerations into RE policies, particularly for offshore wind and PV projects. However, despite these advances, existing measures remain fragmented and inconsistent, particularly in terms of financial security mechanisms and long-term site restoration strategies. There are important financial gaps in decommissioning. The EU has implemented extended producer responsibility schemes that require manufacturers to handle PV panel waste, but financial mechanisms ensuring the dismantling of large-scale solar farms remain insufficient (Franz & Piringer, 2020). Without clear financial provisions, project developers are not always held accountable for full site restoration, leading to concerns about abandoned sites.

In addition, some European countries, like Spain exemplify how incomplete environmental impact assessment (EIA) can hinder effective EoL planning (Salvador et al., 2018). The lack of long-term monitoring frameworks means that cumulative environmental impacts of multiple decommissioned projects are not always considered, complicating future site rehabilitation. In other countries, such as UK financial guarantees for decommissioning remain weak, raising the risk of infrastructure abandonment. The absence of strong security deposits can result in public funds being used to dismantle obsolete RE installations, shifting financial responsibility from developers to taxpayers (Mackie & Velenturf, 2021).

While European policies increasingly recognize the importance of EoL management, regulatory gaps persist in enforcing decommissioning obligations and ensuring financial responsibility. The lack of standardized repurposing guidelines further complicates site rehabilitation, increasing the likelihood of long-term landscape impacts.

Regulatory shortcomings in the management of legacy and decommissioning processes for wind and solar energy installations in South Africa are mainly characterized by the absence of holistic frameworks that encompass the full lifecycle of these projects, with a particular focus on the decommissioning stage.

The regulatory shortcomings in the post-operational management of wind farms in South America, particularly in Brazil, are substantial and complex. These gaps arise primarily from incomplete legal frameworks, limited community engagement, and difficulties in managing environmental impacts. Despite the region's rapid deployment of RE, decommissioning considerations are notably absent from national energy policies. This regulatory deficiency has resulted in an increasing number of inactive and abandoned RE installations.

In contrast to countries like Denmark, where decommissioning plans are mandatory from the project's inception, Brazil, Argentina, and Venezuela lack such requirements for developers (González et al., 2020; Vidal et al., 2023). Consequently, when RE facilities reach the end of their operational life, their removal and site restoration are often contingent on unpredictable political and economic conditions, heightening the risk of abandonment.

Furthermore, there is a notable absence of robust mechanisms for community involvement in decision-making processes. This exclusion frequently leads to resistance from local communities, who feel marginalized and derive little benefit from wind farm projects (Araujo et al., 2020; Gorayeb et al., 2018). The lack of tangible benefits for local populations has fueled conflicts, particularly in indigenous territories, raising concerns about the long-term governance of RE landscapes.

Additionally, many South American countries have inadequate environmental licensing requirements, often neglecting post-operational impact assessments (Araujo et al., 2020). This regulatory gap has resulted in unintended consequences, such as biodiversity loss (Agudelo et al., 2021) and disputes over land privatization (Araujo et al., 2020) in regions with concentrated RE developments. In Brazil, the high costs associated with decommissioning offshore wind farms present further challenges, as the lack of state-backed financial guarantees leaves developers without the resources needed to dismantle aging infrastructure.

Despite regional variations, both Europe and South America face obstacles in ensuring that RE infrastructure does not become a permanent fixture in the landscape. In Europe, financial and procedural uncertainties hinder effective site restoration, while in South America, the absence of legal mandates for decommissioning has led to a growing accumulation of inactive facilities.

A critical priority for policymakers is to integrate end-of-life strategies with circular economy principles, ensuring that site rehabilitation, material recovery, and repurposing opportunities are incorporated into RE planning from the outset. Strengthening financial accountability measures—such as security deposits and legally binding restoration plans—will be essential in preventing abandoned RE landscapes and promoting the long-term sustainability of RE developments.

However, while regulatory and policy challenges underscore the structural barriers to effective decommissioning, there remains a significant gap in empirical evidence regarding how these processes are implemented in practice. A systematic investigation is needed to understand the extent to which abandoned RE infrastructures shape landscapes over time, the factors contributing to decommissioning delays, and the potential for repurposing or recycling these sites.

To address these questions, the following section outlines the methodological approach adopted in this study, detailing the criteria for case study selection, the sources of data used to analyze decommissioned and abandoned RE facilities, and the framework applied to assess regulatory effectiveness and landscape reversibility.

Methodology

The methodology used in this paper was performed in three stages. Firstly, we conducted a search of scientific literature and media reports on examples of abandoned RE power plants in Europe and South America. The Google Scholar, Web of Science, and Scopus databases were used to find articles with the following terms (July 15th, 2024): "abandonment" AND "renewable energy" or "abandonment" AND "wind" or "abandonment" AND "solar photovoltaic" or "recycling" AND "renewable energy" or "decommissioning" AND "renewable energy". As can be seen in Fig. 4 (left side), we selected several examples of abandoned RE projects in Europe and South America based on national media articles with information on reasons of abandonment and the stage of these facilities at the time of abandonment (such as before operation and during operation). Then, a typology of the identified reasons for abandonment was developed through a reconstructive analysis of the selected examples, serving as a framework to study the EoL of RE projects. The typology was defined based on technical, economic, managerial, and other factors leading to abandonment.

Secondly, we selected the examples with more available information as case studies for further analysis, following the process show in Fig. 4 (right). In addition to information on the reasons for abandonment and the stage at which abandonment occurred, we selected examples that included at least data on installed capacity, distance from urban areas, and year of abandonment. Thus, five cases of abandonment from Italy, Spain, Venezuela and Argentina, were further analyzed. We described each case study focusing on aspects such as the year construction started, the year and duration of abandonment, the reasons for abandonment, and subsequent developments such as decommissioning the infrastructures and/or the recycling of RE landscapes. A comparative analysis was then performed to identify common patterns among the cases. To identify common patterns among the case studies, we applied a framework that integrates both quantitative and qualitative approaches. The quantitative data analyzed included the year construction started, the year of abandonment, installed capacity, and distance from urban areas. The qualitative aspects examined were the typology of abandonment, the stage at the time of abandonment, the decommissioning status, and the state of recycling of the RE landscape.

Finally, we conducted a review of the regulations of the countries involved in the case studies. This review aimed to identify and compare regulatory aspects regarding the abandonment and decommissioning of RE infrastructures among the countries.

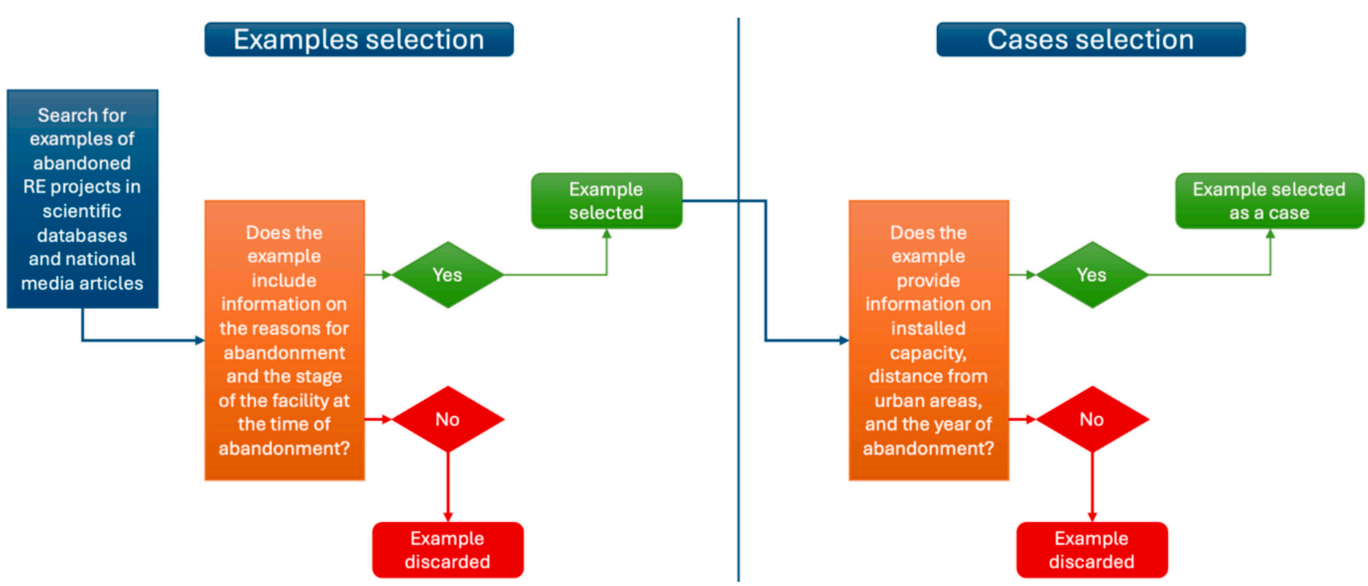

Fig. 4. Flowchart illustrating the selection process of the examples (left) and case studies (right) of abandonment RE projects.

Results

The results are presented in the following structure: Examples of abandoned RE power plants Section provides general information about the collected examples of RE power plants, focusing on the main reasons for abandonment. Case studies of abandonment Section addresses the cases of abandonment selected for further analysis. Finally, Gaps in regulations on decommissioning of abandoned RE power plants in Europe and South America Section presents a comparison of regulation aspects regarding the abandonment of RE power plants in the countries of the selected cases.

Examples of abandoned RE power plants

Table 1 presents examples of RE infrastructure from both Europe and South America that were abandoned. The examples are grouped by the stage at the moment of abandonment: before operation (when a power plant was in the construction stage but finally not connected to the grid) and during operation. For each example, in addition to the general information about the RE facilities (name of power plant, technology, and country), a brief description of the main reasons behind the abandonment is provided.

In general terms, three RE power plants were abandoned before operation and six during operation. Most of these examples (89%) are wind power technology. Within the RE infrastructures abandoned during operation, three were deactivated and three are still injecting electricity into the grid. In Europe, the abandoned RE facilities are in Italy and Spain. In South America, the abandoned RE power plants are in Venezuela and Argentina.

On the other hand, based on the examples shown in Table 1, the identified reasons for abandonment can be grouped into the following topologies: poor planning, lack of management, economic issues, technological issues, and other interests. However, beyond that, there are different reasons for abandonment; the identified RE infrastructures have not been formally dismantled. Although still injecting electricity into the grid—but less than a third of the full capacity—could be a justification for not ordering a formal dismantling of some RE power plants, the question of why they have not been decommissioned yet is open. This is even more unclear for those examples that do not inject electricity into the grid.

In fact, unsuccessful decommissioning has occurred not only for abandoned RE facilities but also for those RE infrastructures that have formally required their decommissioning. This is the case of Keyenberg (Germany) and Jepírachi (Colombia) wind power plants and Núñez de Balboa (Spain) solar PV power plant. Regarding Keynberg, the authorities have urged the owners to stop dismantling the wind farm to make way for an open-pit mine, after activists said the move symbolized a rollback of the government's climate protection plans (The Guardian, 2022; Vujasin, 2022). In the case of Jepírachi, the company has since submitted a decommissioning plan and is currently awaiting the environmental authority's formal declaration to commence the dismantling phase (Hernández, 2023; ReviewEnergy, 2023). Regarding Núñez de Balboa, the court ordered the company to dismantle this PV plant, the largest in Europe, and return the 500 ha of land on which it is located to its owner, considering that they were illegally expropriated, although it is not legally required to restore landscape in its pre-project state. However, this solar plant is still in operation while the company is appealing to the court (EFE, 2022).

In the following section, five selected cases of RE infrastructures that were abandoned will be addressed for further analysis.

Case studies of abandonment

Information on the abandonment of RE projects is slim, so we have been limited to five case studies with more available information for further analysis, based on the references cited in Table 1. The first two wind power plants (Butera and La Guajira) were abandoned before operation, meaning they were never connected to the grid. The other three wind power plants (Montaña Mina, Monte Arci, and Jorge Romanutti) were abandoned during operation.

Butera wind power plants, Italy

According to (Il Mattino di Sicilia, 2016; Janni & Morabito, 2016), this RE power plant, located in south-central Sicily, was abandoned because the necessary expropriations for constructing the electrical substations were not undertaken by the Municipality. Consequently, the connections to the grid from the cabins and facilities needed to provide electricity to Butera's customers were not made. Although the existence of a road to transport the necessary equipment to the wind turbine installation site was highlighted, that road was not actually there. Today, only a single wind turbine is visible (see Fig. 5). In fact, the wind farm was not completed and has not worked. The landscape is similar to what was there before, except for the abandoned turbine, but the feeling is desolate for the people who look at the landscape and see the money

Table 1
Examples of RE power plants that were abandoned in Europe and South America.

Stage at the time of abandonment	Name of RE power plant	RE Technology	Country	Reasons for abandonment	References
Before operation	Butera	Wind power	Italy	Abandoned due to the necessary expropriations for constructing the electrical substations were not undertaken by the Municipality.	(Il Mattino di Sicilia, 2016; Janni & Morabito, 2016)
Before operation	La Guajira	Wind power	Venezuela	The main reason for abandonment is unclear. It seems to be that insufficient coordination and planning impeded the project's integration into the electrical grid.	(EFE, 2023; Rivero, 2024)
Before operation	Vinapoló	Solar photovoltaic	Spain	Abandoned due to the energy injection was not allowed due to an excess of the initially agreed-installed power capacity.	(Pérez, 2023)
During operation	Montaña Mina	Wind power	Spain	Abandoned because of the bankruptcy of the company that was managing this wind farm.	(Gobiernocanarias, 2024; Lancelotdigital, 2023)
During operation	Monte Arci	Wind power	Italy	Abandoned after a few months of operation because the turbines were technologically obsolete.	(EC, 2022; Schiaroli, 2019)
During operation	Corral Nuevo	Wind power	Spain	Abandoned for economic issues: non-payments by the generating company to suppliers or companies that carried out the maintenance, control, and tuning of the wind farm.	(Diario de Burgos, 2021)
During operation	Jorge Romanutti	Wind power	Argentina	Abandoned due to the lack of management and administration by the municipal efforts in charge of the wind farm.	(Runrúnenergético, 2022; TiempoSur, 2022)
During operation	Paraguaná	Wind power	Venezuela	The main reason for abandonment is unclear. It seems that there was no continuity after the change of government.	(TalCual, 2024, 2019)
During operation	de Gorgoglione	Wind power	Italy	The main reason for abandonment is unclear. It seems that there was more interest in incentives, contributions, and the sale of permits and plants than in the production of clean energy.	(Basilicata24, 2021)

Fig. 5. Abandoned wind turbine in Sicily (Italy).
Source: (Janni & Morabito, 2016).

that was stolen from them.

The construction of this wind farm began in 2004 and was intended to produce electricity and economic benefits for citizens. However, it resulted in a waste of public money amounting to three million euros. Twelve years after the work began, thirteen people were reported to the Court of Auditors on charges of fiscal damage. The investigation refers to a tender by the municipality of Butera in the province of Nisseno for constructing a wind farm, financed with regional funds. It was found that the contracting firm did not complete the work, and the Municipality of Butera, as the "contracting station", failed to supervise adequately to prevent the squandering of public money. Additionally, the Region of Sicily—Department of Industry—did not fulfill its supervisory and control duties or initiate procedures to recover the financed sums as required by current regulations.

This is an example of poor planning and lack of management, but it also appears to be a case of vested interest (or even corruption). Finally, there is no information about any use of the landscape after abandonment, indicating that this RE landscape has not been recycled, nor has

Fig. 6. Abandoned wind farm in Zulia (Venezuela).
Source: (Rivero, 2024).

there been any attempt to decommission the wind turbine formally.

La Guajira wind power plant, Venezuela

According to (EFE, 2023; Rivero, 2024), the construction of this RE power plant, with a government budget of US$225 million to be installed in western Zulia state, started in 2011 but was never completed. Although the first stage of the project was developed, it was soon abandoned and is totally inoperative (see Fig. 6). It appears that insufficient coordination and planning impeded the project's integration into the electrical grid due to the interconnection infrastructure and substations remaining unfinished. In 2018, the then Minister of Electric Energy, when attempting to resume the construction of this wind farm, announced that 80% of the wind farm's "strategic material" had been vandalized. The wind turbines had been stripped, with the rotors (the part of the wind turbine that rests on the top of the tower) disassembled and all parts removed, and two machines even fell to the ground and later sold as scrap.

Carrying out these acts of vandalism requires a level of expertise not typical of common crime. The assembly of the wind turbines required the use of an 800-ton crane, which was also left on site awaiting the start-up of the second stage of the project and was vandalized. Moreover, the informal dismantling took place while the wind farm was under surveillance. Although residents remain fearful to speak freely on the subject, the abandonment and dismantling of this project are described as a crime that some attribute to the interest in fossil fuels, which are abundant in Venezuela. In any case, responsibilities for the abandonment and informal dismantling of the project have not yet been established. In short, this project was dismantled by vandals before it was operational, there are grooves in the ground from removing the cables and remains of blades and parts of the rotor lying where the wind farm should have been. It is an abandoned landscape that people talk about as something strange to avoid because there was a section of the army safeguarding the windmills and yet it was dismantled and almost all the parts were taken away. It is not recognized as having any further use. Possible new projects in the area have not been realized.

In parallel, local people have reused some parts of the wind turbines. For instance, parts of the "nose" of the wind turbine are used as boats to navigate the lagoons formed by rains (see Fig. 7, left). Additionally, as shown in Fig. 7 (right), part of the fiberglass from the wind turbine propellers was used for the roof of a house.

In any case, this is another example of poor planning and lack of management, but it also appears to be a vested interest (or even corruption) case. And similarly to the Butera wind power plant, there is no information about any use of the landscape after abandonment, indicating that this RE landscape has not been recycled, nor has there been any attempt to decommission this RE project formally.

Montaña Mina wind power plant, Spain

According to (Gobiernocanarias, 2024; Lancelotdigital, 2023), this RE power plant, located in San Bartolomé (Canary Islands), came into operation in 1992. The wind farm was abandoned in 2014 due to the bankruptcy of the company managing it and has been inoperative since 2017. Currently, the wind turbines are damaged and obsolete (see Fig. 8).

This RE power plant reached its useful life (25 years) in 2017, but because the owner company was bankrupt, the decommissioning works were not carried out. An attempt to repower the wind farm in 2018 was not approved, as local authorities did not believe it was necessary and wanted to reclaim that part of the mountain. Although the decommissioning of this wind farm has been requested thrice, the formal dismantling has not been materialized because this implied a high cost that the municipality does not want to assume, arguing that it is not its responsibility. Finally, in January 2024 the resolution was signed for the ex officio initiation of the procedure to dismantle this wind farm and restore the landscape given the inadequate maintenance of the facilities, which poses 'a danger' to people, flora, fauna, property and the environment. However, during a meeting of a parliamentary committee on May 10, 2024, the Councillor for Ecological Transition and Energy of Spain expressed his concern that the dismantling of the Montaña Mina wind farm and restoration of its landscape will require considerable time due to the intricate nature of the process and the fact that it is the first of its kind to be undertaken in the Canary Islands (La Voz de Lanzarote, 2024).

The municipal government is still fighting the regional government to dismantle the abandoned wind farm and restore the land on which it stands. This landscape with collapsed and ruined windmills is an unsafe place that cannot be used by the population for walking and has also led to problems with the electricity supply (El Diario, 2024). It is a place that has fallen into disrepair and has been lost to the population.

Similarly to previous cases, there is no information about any use of the landscape after abandonment, indicating that this RE landscape have not been recycled. This case also reveals a regulatory gap in the decommissioning process and complexity of the process of wind farm landscape recycling.

Monte Arci wind power plant, Italy

According to (EC, 2022; Schiaroli, 2019), this RE power plant was installed on the top of Monte Arci in the province of Oristano on Sardinia (Fig. 9). The area, known since prehistoric times for its obsidian deposits, was declared a World Heritage Site by UNESCO due to the significance of obsidian extraction and ancient oak trees of the Natural Park located in this area.

The wind farm with 34 turbines was inaugurated in 2000 but operated for only a few months before being deactivated. It was abandoned because the turbines became technologically obsolete, turning into a

Fig. 7. Parts of the wind turbine are used as boats (left) and part of the fiberglass from the wind turbine propellers was used for the roof of a house (right). Source: (Rivero, 2024).

Fig. 8. Abandoned wind farm in San Bartolomé (Spain).
Source: (Lancelotdigital, 2023).

Fig. 9. Abandoned wind farm in Monte Arci (Italy).
Source: (Schiaroli, 2019).

pile of scrap metal within a few years. Numerous letters, warnings, appeals, and an eviction order were issued, but little action was taken until 2010, when the owner company was contacted to clear and restore the site. Partial compliance occurred, but a request for an environmental impact assessment to restore the plant was blocked by the region, leading to an appeal to the Regional Administrative Court.

Years passed, and in December 2013, the Morgongiori City Council issued an order to vacate the site and restore it, aiming to protect the environment and the area. This effort was unsuccessful. It took another four years until December 2018—which represent the turning point—, when, following the services conference requested by the municipal administrations and with the approval of Enel, the decision was taken to dismantle the area which, despite protests, complaints and legal battles, was for years a dumping ground for rusty scrap metal (La Nuova, 2020).

After more than two decades of struggle, dismantlement of the wind turbines and landscape restoration work has finally begun in 2020, but it was not completely restored: the access roads to the wind turbines remain part of the Natural Park. Now, there is a need to verify subsoil pollution and determine compensatory works for the damage suffered. Local authorities are seeking compensatory works rather than monetary compensation to restore the area. Finally, Monte Arci is free again. The mountain has been reclaimed after 30 years and the locals do not want any more such projects.

Although the wind turbines were finally decommissioned, similarly to the previous case studies, the Monte Arci case suggests a regulatory weakness in the decommissioning process.

Jorge Romanutti wind power plant, Argentina

According to (Runrúnenergético, 2022; TiempoSur, 2022), this wind farm (see Fig. 10), located in cold and desertic landscape of the

Fig. 10. Abandoned wind farm in Pico Truncado (Argentina).
Source: (TiempoSur, 2022).

Patagonian plains, in the municipality of Pico Truncado, with its 10 mills of 100 KW capacity each, was one of the largest projects in Latin America. It came into operation in 2003, generating 30 % of the electricity demanded by the city. However, it was abandoned after a few years due to the lack of management and administration by the municipality in charge.

Despite efforts by the municipality at both the national and provincial levels to restore the wind turbines to operation, years of neglect prevented this from happening, and the wind farm was never decommissioned. Some sources attribute this neglect to the new municipal administration. Notably, this is the only abandoned wind farm in the entire area of Pico Truncado. It has not been dismantled, although it has been plundered, so that walking through the area generates a desolate sensation, in the cabin that was installed everything is disarranged and damaged by vandalism and the passage of time. Everything that could be removed was stolen.

This case, where the owner is the municipality, reveals management deficiencies. As in cases of other abandoned wind farms mentioned earlier, there is no information about any use of the landscape after abandonment, indicating that this RE landscape have not been recycled, nor has there been any formal attempt to its decommission.

Patterns

Table 2 summarizes the main aspects of the five study cases. Some patterns can be identified. For instance, a common pattern is that all wind farms were abandoned before reaching the technical EoL (operational lifetime of 20–25 years). The wind farms were located between 4 and 10 km from an urban area. In addition, four of the five cases began construction at least 20 years ago, with only the La Guajira wind power plant starting in 2011. Additionally, four of these RE power plants exhibited a lack of management, which, in some instances, may be related to vested interests.

Moreover, cases of abandonment encounter complications with formal decommissioning. Finally, another common pattern is the absence of action towards recycling energy landscapes.

With the exception of Monte Arci, which has been completely dismantled, in the rest of the cases, these are abandoned landscapes with elements that can generate risk for people and generate distrust, uprooting or even insecurity, without any alternative use and, of course, without any tourist use.

The tourist use of abandoned wind farms or not, seems to be a one-off or relatively rare occurrence in areas where there is a lot of tourism and almost any tourist idea works (e.g. Brenta Dolomites) and/or where the other elements of the environment are conducive to a quality tourist experience.

All these issues highlight gaps and weaknesses in the current regulations concerning the EoL of these facilities in the respective countries and reveals complexity of the process of wind farm landscape recycling.

Gaps in regulations on decommissioning of abandoned RE power plants in Europe and South America

Table 3 presents a comparison of regulations among Italy, Spain, Venezuela and Argentina. In the case of the EU-27, decommissioning at EoL or after the installation has ceased to operate is not regulated. This depends on the regulations of each country, with some countries requiring a specific fund or insurance payment to guarantee decommissioning prior to project approval and others that have not developed specific regulations in this respect. In the case of Spain, decommissioning depends on what is included in the *Environmental Impact Assessment* (EIA), and in the case of Italy according to the Guidelines for the authorization of plants powered by renewable sources (Ministero dello Sviluppo Economico, 2010) municipalities are obliged to establish a guarantee fund for decommissioning, although promoters are using different strategies in order to renegotiate the initial security deposit: to sell wind turbines to other countries, to extend operational phase, etc. (De Laurentis & Windemer, 2024). In the case of South America, and in particular Argentina and Venezuela, there is neither specific regulation on the decommissioning of renewable energy installations, no reference

Table 2
Summary of main aspects related to the study cases of abandonment.

Name of wind power plant	Year of construction or operation (distance from urban area)	Year of abandonment (installed capacity)	Stage at the time of abandonment	Typology of abandonment	Decommissioning situation	State of recycling of RE landscape
Butera	2004 (10 km)	2006 (Not available)	Before operation	Poor planning, lack of management and other interests.	There is no information about any attempt to dismantle the wind turbine formally.	Not recycled.
La Guajira	2011 (7 km)	2013 (76 MW)	Before operation	Poor planning, lack of management and other interests.	There is no information about any attempt to dismantle the wind farm formally.	Not recycled.
Montaña Mina	1992 (5 km)	2014 (1.1 MW)	During operation	Economic issues.	The decommissioning of this wind farm has been requested three times. However, the decommissioning has not materialized.	Not recycled.
Monte Arci	2000 (10 km)	2000 (30 MW)	During operation	Technical issues and lack of management.	After several efforts spanning a couple of decades, the wind farm will finally be decommissioned.	After partial restoration landscape is used as a part of the Natural Park.
Jorge Romanutti	2003 (4 km)	2005 (2.4 MW)	During operation	Lack of management.	There is no information about any attempt to dismantle the wind farm formally.	Not recycled.

Table 3
Comparison of regulations of decommissioning of abandoned RE infrastructures.

Region/ Country	EoL decommissioning Regulation	Observations
EU-27		
Italy	Decommissioning of wind turbines is regulated by the Ministerial Decree of 10 September 2010 "Guidelines for the authorization of plants powered by renewable sources".	Developers must pay a guarantee fund to the municipalities for decommissioning. The operating time granted varies from project to project. Repowering is encouraged.
Spain	Any decommissioning requirements are included in the Environmental Impact Assessment for each project.	There are regulations on waste management and circular economy and incentives for repowering, but there is no specific regulation to guarantee the decommissioning of projects.
South America		
Argentina	Law 26,190 "National Promotion Regime for the use of Renewable Energy Sources for the Production of Electrical Energy. Modification" of October 15, 2015.	There is no specific regulation which guarantees decommissioning and on EoL, circularity, waste.
Venezuela	Draft Law Renewable and Alternative Energy declares renewable energy projects to be of public interest and strategic character for the nation.	There is no specific regulation which guarantees decommissioning and on EoL, circularity, waste.

on EoL, circularity or waste in the legislation.

Discussion

This work, on the one side, presents a typology of the reasons for the abandonment of RE power plants in Europe and South America and identifies common patterns in cases of abandoned wind farms. On the other side, this research reveals gaps and weaknesses in the current regulations associated with the abandonment of RE infrastructure in the countries of study cases (Italy, Spain, Venezuela and Argentina). This lack of suitable regulation directly affects the decommissioning of RE facilities. In turn, this results in limiting or precluding recycling the RE landscapes.

Reasons for abandonment

Abandonment happens not only when some of the older, first-generation (1970s and 1980s) wind farms are no longer functioning and are abandoned in place (Delaney et al., 2023), but also due to a set of other factors. De Laurentis and Windemer (2024) suggest that several factors can influence EoL decision-making, such as design life and technical issues, economic and financial, legislative/regulatory, and business environment. Our study shows that similar factors (or a combination of them) can be a reason for the abandonment of RE infrastructures, but these are associated with RE facilities that were abandoned before reaching the technical EoL (operational lifetime of 20–25 years, also called *Design EoL* by Delaney et al. (2023)).

Specifically, we have classified reasons for abandonment into five types: poor planning, lack of management, economic issues, technological issues, and other interests. Some of these reasons for abandonment are also in line with the EoL definitions provided by Delaney et al. (2023), such as *Functional EoL* (which includes technical issues) and *Economic EoL* (which involves economic issues).

However, Delaney et al. (2023) definition of *Abandonment EoL* only refers to older wind farms that are no longer functioning—like the cases of Tehachapi and Altamont in the United States (Fugleberg, 2014). Therefore, in this study we have found reasons for the abandonment of RE infrastructure in the early stage of a RE project. While there are studies that typify the possible reasons for the abandonment of energy facilities in Italy (De Laurentis & Windemer, 2024) or the problems related to the economic competitiveness of some energy cooperatives that led to the abandonment of wind facilities in Argentina (Clementi, 2019), no in-depth analysis of the causes of project abandonment before the end of their operational phase has been found in the literature.

Patterns

All RE power plants addressed by our case studies and examples were abandoned before reaching technical EoL. Beyond the various reasons for the RE facility's abandonment (and requests for formal dismantlement in some cases), there have not been actions for recycling the energy landscape, and there have been complications for wind farms decommissioning. In fact, as we mentioned in Examples of abandoned RE power plants Section, the unsuccessful decommissioning has occurred not only for abandoned RE power plants, but for those RE power plants where dismantlement has been formally required too (EFE, 2022; Hernández, 2023; ReviewEnergy, 2023; The Guardian, 2022; Vujasin, 2022).

Furthermore, according to Ferrell and DeVuyst (2013), based on the case of the United States, economic analysis of turbine decommissioning is complicated by a lack of operational experience, as few projects have been decommissioned—leading to a lack of data regarding decommissioning costs. Windemer (2019) highlights limited attention to decommissioning in the case of the UK too. In fact, considerations on RE infrastructure has predominantly focused on the planning, design and construction of projects driven by the need to decarbonize the energy sector, while often overlooking the processes required for the management of EoL and the decommissioning options (De Laurentis & Windemer, 2024).

Actually, the rate of decommissioning of wind farms in Europe is lower than had been previously expected (De Laurentis & Windemer, 2024). Full decommissioning depends on the necessary legal agreements being in place (Windemer & Cowell, 2021). According to Delaney et al. (2023), complications with decommissioning is likely to result from the lack of laws and regulations requiring owners, companies, and developers to take responsibility. This is aligned with what we found after examining regulations associated with abandonment and decommissioning in the countries of the study cases.

Regulations related to abandonment and decommissioning

This research shows that none of the countries where the energy projects in question are located had a specific regulation when these projects were authorized that considered the recovery of the environment and landscape and waste management of abandoned projects or those that had reached the end of their operational phase. In Italy, the two case studies were built prior to the approval in 2010 of the RD regulating their decommissioning. In Spain, EoL actions continue to depend on whether or not any criteria have been included in the EIA and, in any case, no deposit or insurance is required to guarantee compliance with any criteria that may have been established. There are no criteria regarding the formal dismantling and recovery of the affected environments in the Argentine and Venezuelan cases. Common landscape regulatory framework in each of these continents give any guidance on this important issue. This shows how the lack of regulation can cause projects to perpetuate themselves in the environment, resulting in permanent modifications which are manifested as territorial traces of the different energy transitions as indicated by Windemer and Cowell (2021) and Clementi (2019) with the regulatory framework being a constraint that needs to be resolved on both sides of the Atlantic.

Although countries such as France, the United Kingdom, Germany and Italy have already regulated the decommissioning of wind farms by incorporating guarantee deposits or insurance to cover decommissioning, they do not specify the liability for the event when the wind farm stops operating before the end of its technical operational phase. Only Denmark has specifically included in its legislation a statement that decommissioning must start one year after the wind farm has stopped operating at the latest (WindEurope, 2020b). In the United Kingdom, the old projects did not establish sufficient guidelines for recovering the territories on which they were established, which in some cases resulted in the extension of the authorizations in exchange for incorporating more criteria that could ensure the complete recovery of the sites (Windemer & Cowell, 2021).

The fact related to gaps and weaknesses of regulation on abandoned RE power plants across continents has not been reported in the scientific literature, particularly, associated with decommissioning a RE facility after being abandoned.

Another aspect related to the decommissioning of RE infrastructures is the management of waste from these facilities. As far as wind turbine waste is concerned, most EU members have voted in favor of legislation banning the landfilling of these materials' sustainable solutions for waste management to promote a circular economy as shown by EU Circular Economy Action Plan (European Commission, 2020) and the European Strategy for Plastics in a Circular Economy (European Commission, 2018). For some product categories including photovoltaic panels the principle of Extended Producer Responsibility (EPR) as set out in the Waste Electrical and Electronic Equipment Directive (2012/19/EC) has been applied. This is one of the proposals being put forward to manage wind turbine blade waste, although there is still nothing regulated in this respect in Europe (Elettricità futura, 2021).

The findings of this study align closely with the theoretical framework outlined in Theoretical background Section, particularly regarding the challenges of landscape reversibility and the integration of circular economy principles into RE decommissioning. As discussed in the theoretical background, the assumption that RE impacts are temporary and reversible is often flawed, as evidenced by the cases of abandoned wind farms in Europe and South America. These cases highlight the persistent landscape legacies of RE infrastructures, even after decommissioning, which complicates the restoration of ecosystems, landscapes and land uses. Furthermore, the lack of robust regulatory frameworks for decommissioning, as identified in the theoretical background, is reflected in the empirical findings, where gaps in legal and financial mechanisms have led to the accumulation of inactive and abandoned RE installations. The integration of CE principles, as advocated by Pasqualetti and Smardon (2025), remains largely absent in the studied regions, underscoring the need for policies that prioritize material recovery, site repurposing, and long-term landscape sustainability from the outset of RE projects. This study thus reinforces the theoretical argument that a shift from a linear "create-use-abandon" model to a circular "create-use-recycle" framework is essential for addressing the end-of-life challenges of RE infrastructures and ensuring the sustainable recycling of energy landscapes.

Conclusions

In this paper, we have presented an analysis of abandoned renewable energy (RE) power plants in Europe and South America. Thus, a typology of the reasons for abandonment was elaborated, common patterns of abandoned wind farms were explored, and the regulatory aspects associated with the abandonment and decommissioning of RE facilities in the country's study cases were examined.

The typology of the reason for abandonment of RE infrastructure before reaching the technical end-of-life (20–25 years) was classified as follows: poor planning, lack of management, economic issues, technological issues, and other interests.

The main pattern that we identify is related to complications with decommissioning abandoned wind farms in Italy, Spain, Venezuela and Argentina due to gaps and weaknesses in regulations for decommissioning of abandoned RE facilities in the countries of study cases.

In conclusion, addressing the reversibility of landscapes affected by RE infrastructures necessitates a comprehensive understanding of the interplay between technological deployment, ecosystem services, and regulatory frameworks. Future research should focus on developing efficient methods and spatial reference systems that accommodate both cultural and regulating ecosystem services, as well as on elaborating landscape design principles that ensure the sustainable integration and eventual decommissioning of RE infrastructures.

The absence of any issues related to the potential abandonment of RE infrastructure in rural areas at the time of ratification of the European Landscape Convention in 2000—due to the incipient development of RE projects at that time—meant that aspects of the specific regulation for this type of landscapes' transformation was not contemplated in Europe. This oversight is also present in the Latin American Landscape Convention, ratified in 2022, which does not clearly address the issue either. However, the regulation depends on the policy which is carrying it out. For example, on the EU level, it was shown that the development of RE which lacks multi-scalar planning and management responds to business interests that are not always aligned with the common benefit that are especially protected by the REPowerEU plan and the EU Directive 2023/2413 (Diaz-Cuevas et al., 2023).

In short, steps should be taken to ensure the full restoration of territories after dismantling of RE facilities. In this regard, we recommend that policymakers and decision-makers consider adopting regulatory frameworks similar to those in countries such as Denmark, where decommissioning planning is mandated even before projects reach the end of their technical operational phase. Since every RE project subject to environmental evaluation must include a decommissioning phase, the issue is not a lack of its importance but rather that current regulations do not require this phase to be executed. Therefore, it is crucial that policies emphasize the establishment of regulations and guarantees covering the entire life cycle of RE projects to ensure their true sustainability.

We believe it is no longer acceptable to allow energy development to affect landscapes permanently. Due to the insufficient regulation on restoring RE landscapes, recycling them emerges as a simpler and more cost-effective alternative that must be considered, given the complexity of decommissioning infrastructure and restoring energy landscapes.

While until recently, the issue of abandonment of RE infrastructure seemed like a remote contingency, due to the pace of deployment of RE in the world nowadays problems related to it could take extreme importance. Addressing the issue early and learning from the first examples of abandoned RE facilities (and from the experiences of the mature conventional energy sources industry) can help avoid the problems of abandoned or improperly decommissioned RE infrastructures and, therefore, permanently transform landscapes. The need to advance regulation on the decommissioning of RE power plants, particularly when they are abandoned, as well as promoting the recycling of RE landscapes, will be crucial to ensure the future sustainability of these infrastructures.

CRediT authorship contribution statement

Marina Frolova: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Juan Carlos Osorio-Aravena:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Belén Pérez-Pérez:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Martin J. Pasqualetti:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Osorio-Aravena thanks the support by the SERC Chile FONDAP/ANID 1523A0006 and by the Juan de la Cierva Grant JDC2023-051647-I.

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