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Original research article

When the turbines stop: Unveiling the factors shaping end-of-life decisions of ageing wind infrastructure in Italy

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ABSTRACT

Wind farms reaching their end of technical, or consent life, are increasing. One of the biggest emerging environmental sustainability issues faced by countries globally is what to do with this ageing infrastructure. This is an urgent issue across Europe and a challenge for countries such as Italy, where about 50 % of the country wind capacity is expected to reach end-of-life by 2030. As wind industry actors, governments and academics seek to identify the scale of this problem, this paper investigates the technical, legal, economic, financial, social and environmental challenges that are coalescing in determining when a turbine has reached the end of its productive lifetime. While the standard design lifetime of a turbine is 20–25 years, the timescale under which wind turbines approach the end of their operational lifetime is not uniform. Through an in-depth analysis of secondary documents and expert interviews, we investigate when end-of-life decisions are being undertaken and how these can influence the different options of waste management alternatives to landfill. The 'age' of the wind farm- and its degrading performance- is determined by a number of factors, with end-of-life decision becoming increasingly an ad-hoc strategy for wind assets, ultimately influencing the environmental impact of wind infrastructure.

Key contribution = the range of factors influencing end-of-life decisions of wind infrastructure.

1. Introduction

Expanding generation from renewables provided just over half of the global increase in electricity supply in 2021 [1] with over 570 GW of new onshore wind capacity forecasted to become operational over the 2022–27 period [2]. There are numerous benefits globally from the growth in wind generation. Nevertheless, a pertinent environmental and policy issue in the next decade, currently under researched, is the consideration of the end-of-life (hereafter, EoL) of low carbon infrastructure.

Existing energy infrastructure has a technical and/or economic lifecycle predetermined by the lifetime of certain components [3]. At the end of this lifetime, it is expected that this infrastructure will contribute to an increase in waste mass generation making the decommissioning of wind turbine (WT) a serious waste disposal issue. This calls for ways to tap into the resource potential of the waste generated and minimise the waste management challenges [4]. Decommissioning of onshore wind turbines (WTs) has occurred for several years already. Nevertheless, an increase in installations coupled with the rise of wind farms reaching EoL brings this issue to the fora. Hence there is a need to reconcile the demands of ageing infrastructure alongside environmental sustainability issues and, particularly, what to do with existing turbines. In Europe, 396 MW of wind power was decommissioned in 2021 [5]. Moreover, a significant share of Europe's WT fleet is estimated to come to the end of its projected lifetime within the next 10 to 15 years (for instance, in 2020 alone there were over 34,000 WTs aged over 15 years [6]). Similarly, Cooperman et al. [9] estimates that in the United States more than 190,000 blades will have been in service for at least 20 years by 2040 and that, based on a 20-year lifetime, a total of 235,000 blades will be decommissioned by 2050 [7].

A number of academic contributions have already turned attention to the issue of what to do with ageing onshore renewable energy infrastructure. Some studies specifically focus on the challenges of recyclability of turbine blades [8]. Others have investigated the significant waste stream of solar PVs and the opportunities for critical material recycling and safe disposal [9]. Research has also started to identify the opportunities that circular economy business models [3] can provide in order to reduce the amount of waste directed to landfill. In addition, several countries in Europe have banned the landfilling of composites promoting calls to minimise the waste management challenges via

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recycling or other circular economy solutions. However, the challenge for wind industry actors and governments is not only to identify the scale of the potential environmental problem but also to understand when a turbine has reached the end of its productive lifetime. In other words to consider the instances in the life of a WT in which this waste stream will materialise [10]. This calls for a need to investigate projects from which lessons can be learned [4,11]. Besides, while countries are seeking to quantify the profile of expected onshore wind decommissioning [12,13], which will vary by country, WindEurope [5] recognises that the rate of decommissioning of wind farms in Europe is lower than had been previously expected. This suggests that other factors might influence EoL decision making other than the projected lifetime of a WT.

Currently according to WindEurope [5], in 2021, the most decommissioned capacity took place in Germany (233 MW), Austria (103 MW) and Denmark (26 MW). As decommissioned capacity increases, there will be more opportunities to develop best practice and lessons learnt on how existing infrastructure, specifically the first wave of wind farms around the world, is transitioning towards EoL. To this end, some guidance and best practice around decommissioned projects have been published to aid wind infrastructure developers [6,12]. Furthermore, some academic contributions offer case study analysis and data on current EoL management practices such as life-extension and repowering. For instance, Ziegler et al. [14] analysed EoL options in Germany, Spain, Denmark and the UK. Woo and Whale [15] discussed and compared EoL options in Denmark and Canada. Abadie and Goicoechea [16] investigated the optimal decision making between life-extension and full repowering and Serri et al. [17] discussed repowering opportunities and strategies in Italy. Moreover, Beauson et al. [18] suggested that cost, technical feasibility, legislation, and environmental impacts influenced EOL decisions. These authors contend that there are technical, economic and regulatory aspects that can influence EoL, with different options being often unique to each decommissioning project. Building from these contributions, more research is needed that focusses on providing further empirical evidence on how these key technical, economic and regulatory factors are influencing the management options actors in the wind industry need to consider.

In supporting this research gap, this paper explores the EoL decision-making for onshore wind farms in Italy. A key aim of the paper is to enhance our understanding of the range of different factors that are determining and influencing EoL options for onshore wind in Italy. To do this, we focus our investigation on the question: what factors influence decision making for EoL, drawing from the example of Italy. To address this question, we specified the following objectives: 1. to investigate the challenges and opportunities associated with ageing wind infrastructure setting the scene for the empirical investigation; 2. to identify the factors that might influence the timing of EOL decisions for wind infrastructure and consequently also influence decisions on EoL in Italy; 3. to explore how these factors have influenced decision making of EoL in Italy and 4. to create a typology of EoL management options.

Italy was chosen as the focus of this research as at the end of 2000 Italy was among the five countries with the biggest installed wind capacity and about 1.5 GW of capacity could be decommissioned by 2025, a number five time higher by 2032 [13]. Following Sovacool et al. [19], this study is empirically-novel presenting data that are primarily descriptive and exploratory albeit socially-relevant by design. Although there are some limitations related to the choice of a single case study [20], this study seeks to generate insights for policymakers, actors and practitioners in the wind energy industry dealing with EoL decision making. Focussing on a country that is facing EoL challenges provides opportunities to learn from current practice in EoL management and the challenges faced. According to Woo and Whale [15], countries where the wind farms are relatively young, as in the case of the UK for instance, could draw from the Italian experience to plan, develop and implement EoL management frameworks, paths, policies and regulations for EoL wind infrastructure management.

The key contribution of this article is therefore to provide empirical support and evidence of the key technical, economic and regulatory factors that might influence the timing of EoL decisions for wind infrastructure. This consequently will also influence decisions regarding the future of wind infrastructure sites. The paper shows, that while determining EoL options for wind infrastructure is undoubtedly a decision unique to each project, there are a number of factors that are influencing such decisions. In Italy, technical, legal, economic, financial, social and environmental challenges are coalescing around determining opportunities and barriers to the management of the EoL of onshore wind infrastructure. This is of valuable importance as understanding these factors can shed light on how much waste will be generated in the future and the range of possible options for dealing with that waste.

This paper is structured as follows; we firstly provide an overview of the selected literature that informed the design and the context of this research project (Section 2). We then provide an overview of the methodological approach taken, explaining the choice of Italy as a case study for challenges that are occurring internationally, before introducing the scoping review, interviews and the approach to the analysis (Section 3). Section 4 of the paper provides the results of this exploratory study before conclusions and recommendations for future research are provided.

2. Literature review: setting the scene

This section follows the specific rationale of framing the paper within the contemporary literature that stresses the challenges and opportunities associated with ageing wind infrastructure. It also starts unpacking the complexity around the different options available for wind projects that are reaching their EoL. By doing this, this section sets the scene to support our evaluation of the technical, economic and regulatory factors that are influencing EoL decision making and EoL options in Italy.

2.1. Challenges and opportunities of ageing onshore wind infrastructure

Energy infrastructure, from conventional power generation plants to wind farms, has a technical and/or economic lifecycle predetermined by gradual decreases in performance or conversion efficiency over the infrastructure's lifetime [21]. Attention towards renewable energy infrastructure has predominantly focussed on the planning, design and construction of projects driven by the need to decarbonise the energy sector, while often overlooking the processes required for the management of EoL and the decommissioning options (with the exception of nuclear). Nevertheless, there is agreement that this is an important issue to consider with waste arising from EoL renewable energy infrastructure projected to grow over the next 10 years [22] (see Fig. 1).

While experience with EoL treatment remains limited, emerging scientific and industry literature has started to address questions of the management of EoL and the decommissioning options of renewable infrastructure. These research areas include technical and economic considerations of EoL [16]; EoL business models to increase circular economy approaches [23]; EoL solutions and assessment guidance for EoL options from front-runner countries that are facing the problem of EoL [14]; government regulation of EoL decision-making [24]. Here we draw on some of these selected contributions to point towards some of the main issues raised and their relevance to understanding the EoL moments of on-shore wind infrastructure.

WTs, due to their significant manufacturing resource requirements, are material intensive technologies [23]. According to Jensen [25], although turbine design might differ regarding manufacturer, technology choice and other product parameters, materials and most components in WTs are similar. Materials generally include steel, iron, aluminium, copper, some rare elements (e.g. neodymium), fiberglass and resin [26]. In relation to the materials used for their construction, most components of a WT – the foundation, tower and components in the nacelle – have long established recycling practices, with around 85

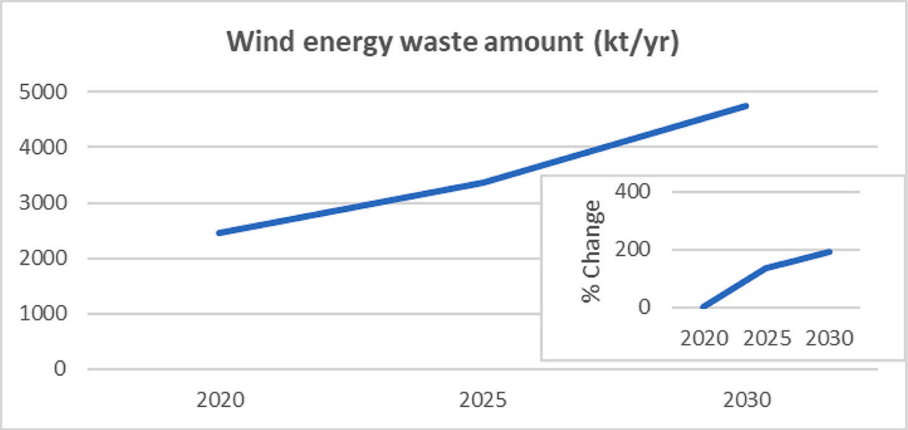


Fig. 1. Expected mass of wind energy waste (based on a 20-year life span of WTs). Source: Authors' re-elaboration from [24].

to 90 % of WTs' total mass being 'in principle' recycled [23].

Despite these high recycling potentials, in reality decommissioned WTs are not always recycled at a high rate due to inefficiency in recycling and metal dissipation [23]. Additionally, from a waste management perspective, the most problematic and concerning materials for the EoL in WTs are i) the rare earth elements used in the permanent magnets in modern generators [27], and ii) the glass or carbon reinforced composites that constitute rotor blades, since there are currently no established recycling routes for composite materials [10]. Research on the former has focussed primarily on the amount of rare earth elements used and future required amounts of these for wind energy expansion [28,29]. The latter emerges from considering the high energy intensity and high value of composite materials which support strong recycling opportunities [30]. However, while various technologies exist for the treatment and recycling of composite materials in blades, such as mechanical grinding and pyrolysis [31,32] there is a recognition that these solutions might not be yet mature enough, widely available at industrial scale and/or cost competitive [6].

In addition to this, the cost of the disposal of WT waste in landfill comes into consideration as this might increase significantly [33]. Besides, as disposing composite waste becomes restricted through legislation, and many European Union countries start to consider a ban to landfilling of composite waste [6], landfilling might not be longer an option for wind operators. Nevertheless, there is a recognition, particularly within the wind industry, that landfill disposal of decommissioned WT blades could be seen as a waste of valuable resources [6]. Hence, the increase in attention by both academics, policy makers and industry in the way in which using circular economy approaches can minimise waste in the wind industry and to identify opportunities to keep WTs, their materials and components in use. Implementing technology design and life cycle management practices, for instance, can provide an opportunity to positively impact upon the availability and sustainability of resource use in the wind industry [34]. Product and system design can also help reduce input resources and waste generation in new wind farm development (see for instance the opportunities introduced by modular approaches and design for deconstruction in energy infrastructure [3]).

Mendoza et al. [23] provide an overview of a number of emerging circular business models with direct application to the wind industry, articulated on the basis of a WT life-cycle stages. Adopting a circular economy principle ensures that the waste generated by wind farm decommissioning can be circulated into continual use of resources. Some of the models suggested include 1) re-use via recondition and refurbishment of the full unit or through using the component parts to extend the life of other installations at a new location [35] and 2) repurpose via the use of the component(s) for novel or bespoke use in different settings as a mechanical or structural element [36]. Another circular opportunity refers to the option of selling used WT in secondary markets. There is a significant portion of decommissioned WTs which are exported for reuse, e.g. to Eastern Europe or outside of Europe, e.g. Latin America [23]. Fig. 2 summarises some of the options available for decommissioned WTs following the waste hierarchy.

Hitherto, there are challenges in the adoption of CE approaches as well as material waste management of EoL of ageing wind infrastructure (see for instance [37,38]). To address these challenges, and to improve the circularity of the wind industry, a number of working groups and task-force groups have emerged (e.g. EU Circular Wind Hub [39] and more recently the EOLO Hubs [40]; the IEA wind task 45 to drive the advancement in the recyclability of blades [41]). These are coupled with a number of networks and projects amid at investigating opportunities for repurposing wind blades. For instance, the Re-Wind project [36] that produced a catalogue of designs and details of structures and products made from EoL repurposed wind turbine blades. One other example is provided by the SuperUse studio [42] that supported the development of the first circular urban playground utilising five decommissioned rotor blades. The IEA wind task 45 for instance identified in 2023 about fifty-three projects currently underway focussing on the following areas: prevention, re-use, re-purpose, recycling, recovery, circular economy and decision support.

However, while there is awareness within the literature that EoL materials management needs to be addressed, there is also a need to identify how decisions around EoL are made and, in particular, what are the determining factors of EoL of WTs. We turn to investigate these in the next section, before investigating how these multifaceted and interdisciplinary challenges are influencing EoL decision making in Italy.

2.2. *Determining the end-of-life of wind turbines: what matters?*

The standard design lifetime of a WT is at least 20 years according to the International Electrotechnical Commission (IEC) standard [43]. However, the timescale under which WTs approach the end of their operational lifetime is not uniform. WTs (like most technology) will be exposed to two forms of ageing: i) loss of performance as a result of physical wear and tear and ii) a relative age when compared to advancement in technological innovation in the market that can affect the profitability of a project (e.g. increased performance and energy output are some of the key benefits of new turbine technology that might influence return on investment- ROI- for a wind farm [25]).

According to Woo et al. [15] towards the end of the operational life of a wind farm, operators must decide on whether to seek to maximise return on investment by extending operations via lifetime-extension and repowering or to decommission the site. We discuss these in turn, highlighting the range of different factors that are determining and

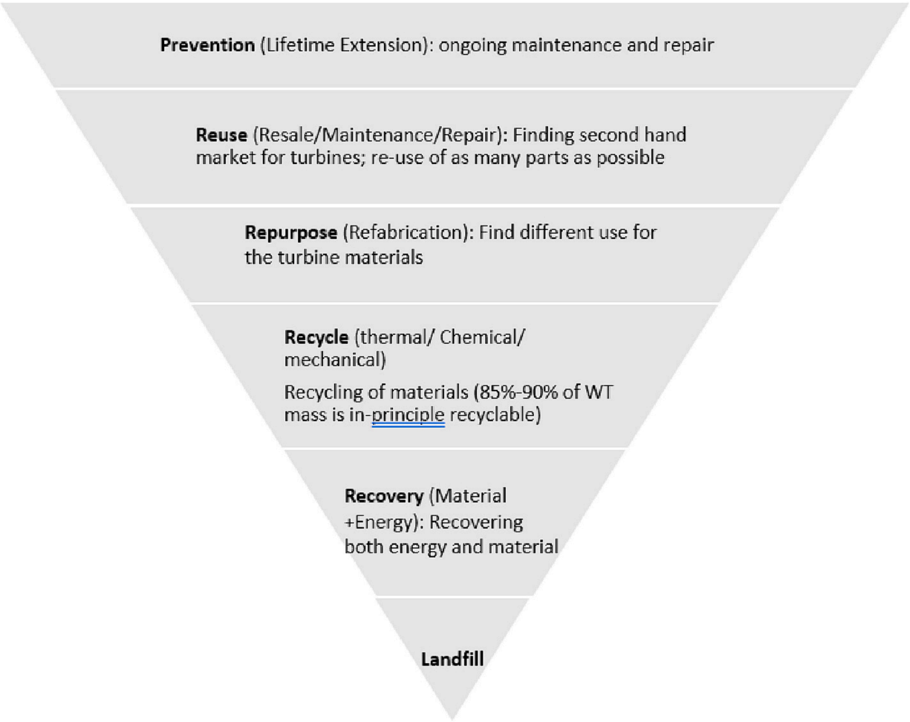


Fig. 2. Circular options following a waste hierarchy for WTs. Source: Authors' re-elaboration following [39].

influencing these EoL options identified in the literature.

Lifetime extension involves extending the operation of wind farm beyond their permitted life. For lifetime-extension, WT must have sufficient life remaining without compromising their safety level. Technical assessments will determine the suitability of a lifetime-extension, including site evaluation to investigate environmental (e.g. wind speed) and operational conditions [14].

While operational data is relevant, decisions on life-extension will also be based on economic factors. Ziegler et al. [14] summaries them in terms of: 1. Type of operators (e.g. small operators with few assets will approach EoL in different ways from large operators); 2. Operational costs (e.g. maintenance contracts and repair expenses); 3. Subsidy schemes (e.g. tariffs and support schemes and their duration) and 4. Legal requirement (e.g. certification and guarantees required for the WT that exceed their design lifetime). During lifetime-extension, major components might be reconditioned or replaced to increase reliability and optimal operation. Operators might develop a life-extension strategy based on individual component analysis, inspection requirements and recommendations [15], aided by industry association reports and decision support tools [6,44–46].

Repowering is a way to increase a wind farm's performance and energy output by replacing old WTs with newer, more efficient technologies and can also involve improved electrical connections to contribute to the stability of the power system. Repowering can be partial, which involves the replacement of certain components to increase the units' lifespan and/or power output. Woo et al. [15] suggest that partial repowering is a relatively recent development, which includes frequently larger rotors and a specific power reduction. While there is not a clear definition of partial repowering, some authors refer to it as revamping [17]. Full repowering, on the other hand, will involve full replacement often with a larger and more productive turbine model. While repowering as an EoL option can reduce maintenance and operation costs, reducing WT failure rates [47] it also requires a specific and stable financial framework to justify the investments [47].

In most cases, repowering will require new planning/permitting approval [48]. Such permitting processes are often similar to new projects in terms of the detail of documentation required (including environmental impact assessment, legal consent and public acceptance [24]). Ziegler et al. [14] and Serri et al. [17] identify a number of advantages of repowering over new sites. Among these are: i) increase of the specific energy production and improved performance; ii) deeper knowledge of the wind, including historical records of wind conditions; iii) better exploitation of the resource in the most windy sites (often these coincide with first-generation of wind plants); iv) reduction of the overall capital costs for the installation of a wind plant in comparison to a new plant (through reusing infrastructure); v) reduced maintenance and operation costs; vi) availability of grid connection. These, in turn, are influencing the repowering decisions of wind sites.

Decommissioning involves removal of WTs and foundations and returning the land to its previous condition. Full decommissioning is usually subject to the necessary legal agreements being in place [49]. Decommissioning may be unavoidable in some circumstances (for example, due to planning permission restrictions and changes in land designation [49]). Nevertheless, removing capacity is often seen as the option of last resort compared to life-extension and repowering [50]. It is also important to consider that decommissioned components will also result from lifetime-extensions and repowering (both partial and full). How these decommissioned components are treated might vary. Some of the options for waste management might include some of the circular approaches highlighted above and in the literature, see for instance [23]. An overview of EOL options is provided in Table 1.

Determining EoL options will undoubtedly be a decision unique to each project. Nonetheless, there will be a number of factors that will also influence EoL decision making and, drawing from the existing international literature on this topic and reviewed here, we listed the main factors in Table 2. In the remainder of the paper, we investigate how these have influenced EoL choices in the Italian context, after summarising the methodological approach used for data collection and analysis.

Table 1
An overview of EoL options for wind farms.

Option	Detail
Life-extension	- Increasing the duration of the existing infrastructure. - This may involve replacing components on a like-for-like basis.
Partial repowering (revamping/ refurbishing/reblading)	- Different forms of partial repowering/ revamping are taking pace. Broadly these involve a replacement of a turbine component.
Repowering	- Removing the existing infrastructure and replacing with new - The new infrastructure is often capable of generating more energy
Decommissioning	- Removing the infrastructure from the site and returning the land to its previous condition.

Table 2
Determinants and factors influencing of EoL decision making options.

Determinant	Examples
Technical	- Design life of the WT components (including the guarantee on components); - Damage to parts may create need for EoL decisions to be taken early; - Parts will wear out more quickly in sites with stronger wind speeds; - Good levels of maintenance may enable turbine components to last longer; - Calculations and assessment regarding life-extension and repowering; - Wind availability
Economic	- Financial incentives that make an EoL option more viable; - Duration of original business model for the wind farm; - Sale of wind farm to a new owner; - Data and best practices availability; - Change in subsidies and decreases in output due to turbine age;
Legislative/ regulatory	- Policies for wind energy/wider energy or climate change targets; - Policy for circular economy; - Country waste management legislation and introduction of landfill band; - Wider policies impacting existing sites e.g. changes in national land designations; - Support for EoL markets (e.g. incentive for repowering projects);
Environmental planning	- Planning/operational licences may require turbine removal at a certain time; - Land use agreement and ability to re-negotiate; - Availability/scarcity of sites for reaching energy targets; - Opposition to repowering or life-extension may impact the decision that is taken;
Business environment	- Industry collaboration; - Wind operators driving action; - Industry push for best-practice.

3. Methodology

3.1. Aim and objectives

This paper draws from a RGS-IBG funded research project aimed to understand EoL solutions for ageing wind infrastructure in Italy. The research design that informs this paper is summarised in Fig. 3. This paper, in particular, addresses the research question of what factors influence decision making for EoL of wind infrastructure, drawing from the example of Italy. This research question is exploratory and inductive in nature [19]. We contend that due to EoL of wind infrastructure being a developing and emerging field, EoL decision making is an emergent process. This process is predictable, to a certain extent, in terms of outcome, e.g. wind infrastructure predicted waste volume, but is largely unpredictable in detail (the why, the how and when this waste will be generated). Therefore, in order to understand EoL decision making, and the factors that influence EoL options for wind infrastructure, the focus needs to be around charting agency [20], thus exploring, via empirical work, the decisions and actions of wind energy actors that are starting to address the EoL challenges and opportunities identified in the literature review presented above.

As highlighted in Fig. 3, a number of objectives were identified to help addressing the research aim of this paper and they stress the intended empirical contribution that the paper wishes to make. The host university ethically approved the research, and all participants were made aware of the project's content and its aim and objectives. All names were removed during data analysis to maintain anonymity.

3.2. Justification of location of the study

Italy was chosen as the location of this study as it provides a clear example of a country that is facing the imminent challenge of ageing WTs.

As Fig. 4 [51,52] shows, in the past decade there has been a rapid development of the wind sector in Italy. Two key issues justify the choice of the Italian case. Firstly, it is estimated that approximately 1.5 GW of wind could be decommissioned by 2025, with expectations that this will be five times higher by 2032 as shown in Fig. 5.

Secondly, there have been concerns that the country could fall short in achieving the following targets:

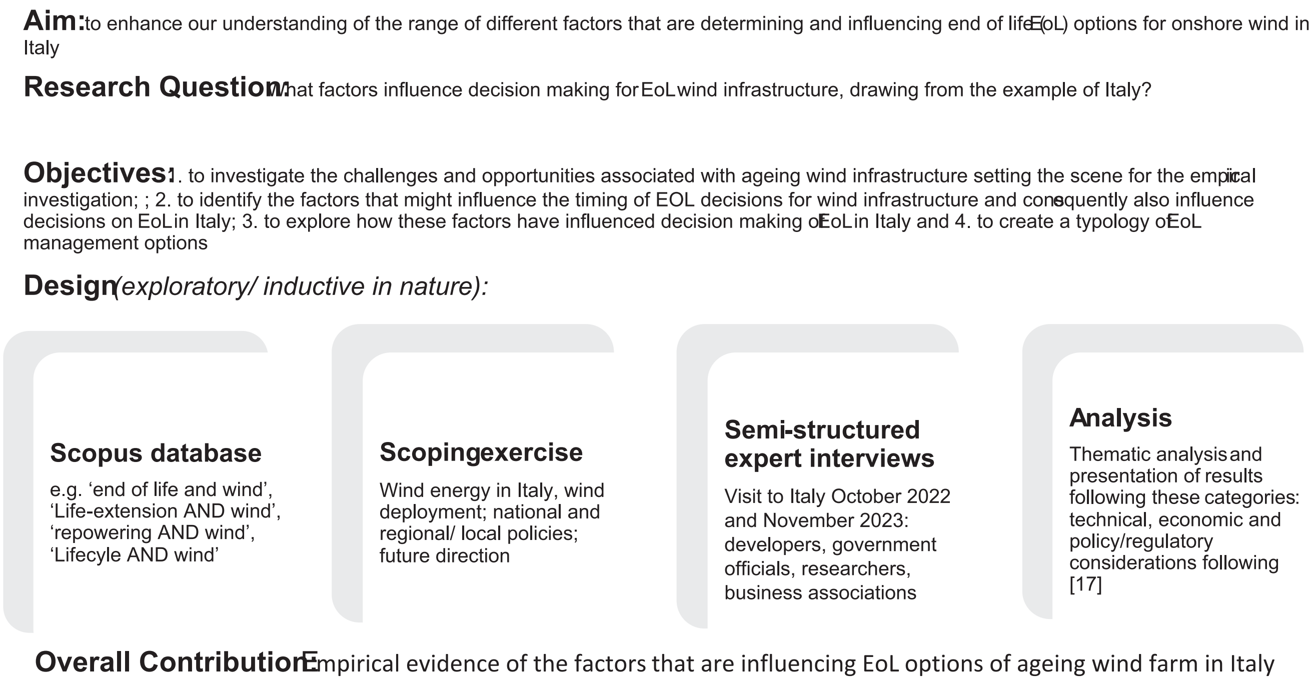
1. 44 GW of renewables by 2030 defined in the final 2030 National Energy and Climate Plan [53] and
2. 40 % of energy demand from renewables and over 70 GW of power from renewables by 2030 (with 72 % of electricity produced by renewables) which represent the Italian contribution to the RePower EU targets.

In other words, Italy will require a steep increase in installed wind power capacity to contribute towards such targets (identified recently from ANEV, the wind energy association, at around 19,000 MW of installed wind capacity by 2030). To achieve such an increase, the National Energy and Climate Plan [53] indicates that repowering of existing wind farms (with fewer more efficient and productive turbines) is key to increasing wind power capacity.

Additionally, wind farms supported with a number of incentives (from CIP6/92, Green Certificates and Feed-in premiums) are also approaching the end of the incentive period: according to Gianni and Benedetti [54], in 2017–2019 about 103 plants for a total of 1.4 GW expired and between 2023 and 2028 about 447 plants (6.1 GW) will also expire. The ending of financial support mechanisms is making the EOL moment for existing wind farms more pertinent. These projects are reaching the end of the funding period, creating challenges for the design of profitable end-of-funding strategies and decommissioning options. More broadly, in recent years Italy has also progressed policy actions towards the adoption of a circular economy, with the wind energy sector seeking to influence end of waste decrees on composite materials [13].

3.3. Scoping exercise

An initial scoping exercise was undertaken in order to explore the EoL of Italian wind farms. The scoping exercise [55] was conducted by analysing a number of secondary-data sources. The aim of this scoping exercise was to 1) investigate and synthetize the range of options for EoL for WT in Italy, 2) to review the policy context and 3) to identify key stakeholders within the wind industry. The first element involved a review of academic and industry literature in order to provide an overview of the different EoL options and challenges for onshore wind farms. The Scopus database was used to search for the following pairs of terms:



Aim: to enhance our understanding of the range of different factors that are determining and influencing end of life (EoL) options for onshore wind in Italy

Research Question: What factors influence decision making for EoL wind infrastructure, drawing from the example of Italy?

Objectives: 1. to investigate the challenges and opportunities associated with ageing wind infrastructure setting the scene for the empirical investigation; ; 2. to identify the factors that might influence the timing of EOL decisions for wind infrastructure and consequently also influence decisions on EoL in Italy; 3. to explore how these factors have influenced decision making of EoL in Italy and 4. to create a typology of EoL management options

Design *(exploratory/ inductive in nature):*

Scopus database
e.g. ‘end of life and wind’, ‘Life-extension AND wind’, ‘repowering AND wind’, ‘Lifecyle AND wind’

Scoping exercise
Wind energy in Italy, wind deployment; national and regional/ local policies; future direction

Semi-structured expert interviews
Visit to Italy October 2022 and November 2023: developers, government officials, researchers, business associations

Analysis
Thematic analysis and presentation of results following these categories: technical, economic and policy/regulatory considerations following [17]

Overall Contribution: Empirical evidence of the factors that are influencing EoL options of ageing wind farm in Italy

Fig. 3. Research design.

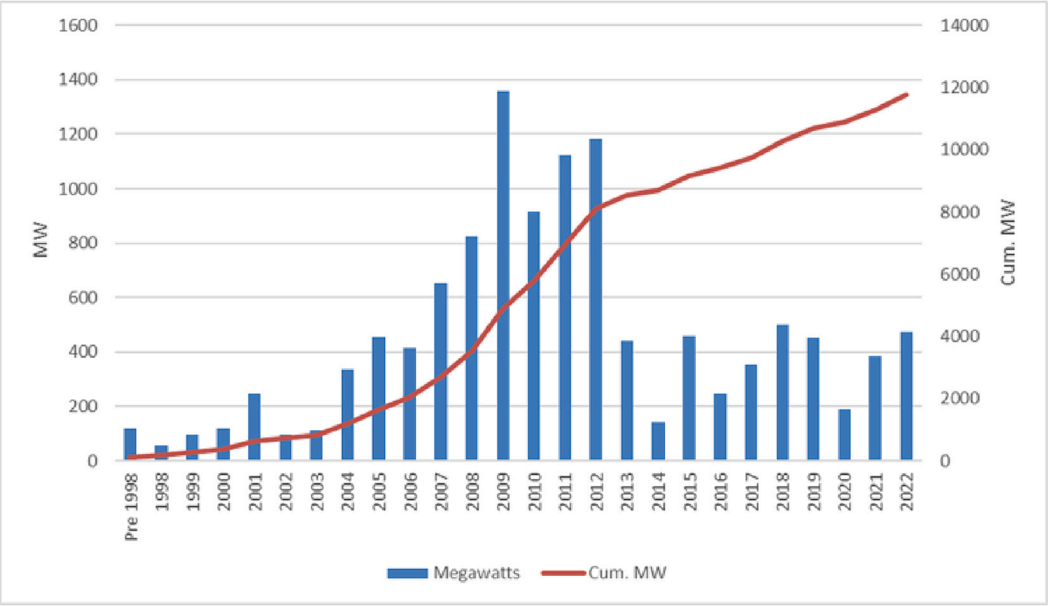


Fig. 4. Wind energy in Italy: Evolution of the number of sites and installed capacity (pre1998–2022). Source: [50]; Data for 2022 from [51].

‘reuse AND wind’, ‘Circular economy AND wind’, ‘Life-extension AND wind’, ‘repowering AND wind’, ‘reconditioning AND wind’, ‘Lifecyle AND wind’, ‘Repurpose AND wind’, ‘decommission AND wind’. A search engine inquiry was then used to search for industry reports on ageing turbines particularly looking for any that mentioned Italy.

The second part of the scoping exercise involved a policy review as energy transition policies and the legislative/regulatory regime have an important role in influencing decision-making for EoL management of wind infrastructure. This involved reviewing the national level policies in Italy for onshore wind development searching for policies on ‘repowering’ ‘revamping’ ‘life-extension’ and ‘decommissioning’. It also involved reviewing Italian policies on the circular economy, particularly looking for mention of composite materials and onshore WTs.

In addition to documentary analysis, the research comprised semi-structured exploratory interviews with expert stakeholders directly involved in EoL wind energy in Italy. This was achieved through an online search of owners and operators of Italian wind farms as well as relevant policymakers and industry organisations. These searches were supported by the experience and knowledge of the researchers and a snow-balling technique where initial key stakeholders pointed out other stakeholders or initiatives in the area that were not covered in the initial scoping exercise.

3.4. Expert interviews

Following the scoping exercise, interviews were organised with a

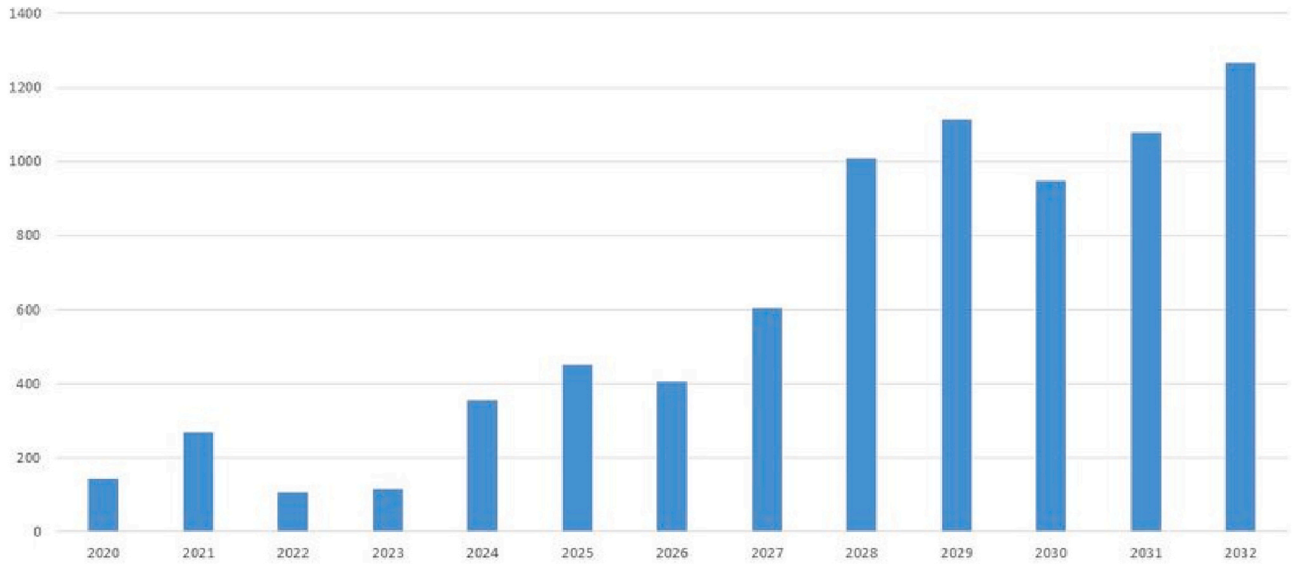


Fig. 5. Wind capacity to be decommissioned in MW (2020–2032). Source: [14].

number of expert stakeholders. These comprised wind farm developers, consultants and policymakers involved in EoL decision making of wind infrastructure in Italy. Participants were contacted via email and were invited to participate in a face-to-face interview in Italy in October 2022. All participants were provided with an information sheet providing an overview of the research in Italian and English. In total 15 interviews were undertaken during this phase, with 7 interviews conducted in person in Italy and 8 online using Microsoft Teams. 12 interviews were recorded following the consent of the interviewees. For the three interviews where recording consent was not provided, detailed notes were taken. The interviews were semi-structured, seeking to understand interviewee perspectives on the regulation of the EoL of wind farms and waste management for turbine materials. A guide of questions was used but the interviewee was also able to converse and provide more details on elements that they felt important. The interview guide (Appendix 1) was designed around thematic blocks (background information, EoL wind energy projects, decommissioning considerations and waste management and circular economy for wind energy). Questions were broad (and exploratory) and were explicitly devised to elucidate understandings of current practices and consideration that are influencing EoL decision making in Italy.

Table 3 summarises the aim and objectives of the paper and how they relate to the methods used to address the research question set in the paper. The table also showcases how the open questions linked with the research question and objectives.

3.5. Thematic analysis

The text of the interview transcripts was subject to thematic analysis. Thematic analysis was used as the preferred method to help in identifying, analysing and reporting patterns (themes) within the dataset [56]. Thematic analysis was chosen over content analysis as the data collected via the semi-structured interviews allowed for follow-up and more probing questions. Thematic analysis also provided a more suitable fit with the research question. For instance, we were not interested in identifying frequency counts or to conduct a quantitative analysis of the data acquired [56,57]. Moreover, the lack of a highly-structured framework for data collection while enhancing the depth of analysis did limited the opportunity to apply other qualitative approaches (e.g. content analysis [19]). In order to identify content and meaning of patterns (themes) in the data, a preliminary list of ideas related to the data was created. This process is visible in Fig. 6. This was followed by the organisation of the data around emerging areas (e.g. projects currently under-consideration, legislative framework etc.). Following Javadi and Zarea [58], themes were identified via an inductive analysis (e.g. the themes identified are related to the data with little relationship with the questions asked from the participants). The themes, applied manually across the whole dataset, aimed at identifying descriptive and narrative accounts of emerging practices around EoL decision making.

Table 3
How aim and objectives relate to the methods used to address the research question set in the paper and interview questions.

Research aim and question	Research objectives	Methods used	Role of methods in the paper
Aim: to enhance our understanding of the range of different factors that are determining and influencing end of life (EoL) options for onshore wind in Italy	To investigate the challenges and opportunities associated with ageing wind infrastructure setting the scene for the empirical investigation	Scoping exercise and documentary analysis	Supported the set-up of the problem to address and categorisation of findings.
Research question: What factors influence decision making for EoL wind infrastructure, drawing from the example of Italy?	To identify the factors that might influence the timing of EOL decisions for wind infrastructure and consequently also influence decisions on EoL in Italy;	Scoping exercise, documentary analysis and semi-structured interviews	Supported set-up of the problem to address and themes identification. From the interview guide: Q3; Q4; Q5; Q6; Q8
	To explore how these factors have influenced decision making of EoL in Italy and	Semi-structured interviews; thematic analysis	From the interview guide: Q3; Q4; Q5; Q6; Q8 Q3; Q4; Q5; Q7; Q9; Q12; Q17;
	To create a typology of EoL management options	Semi-structured interviews; thematic analysis	From the interview guide: Q3; Q4; Q5; Q6; Q8 Q10; Q11; Q13; Q14; Q15; Q16.

Once the themes were identified, these were grouped under the following categories: technical, economic and policy/regulatory considerations following Woo and Whale [15]. A further category was

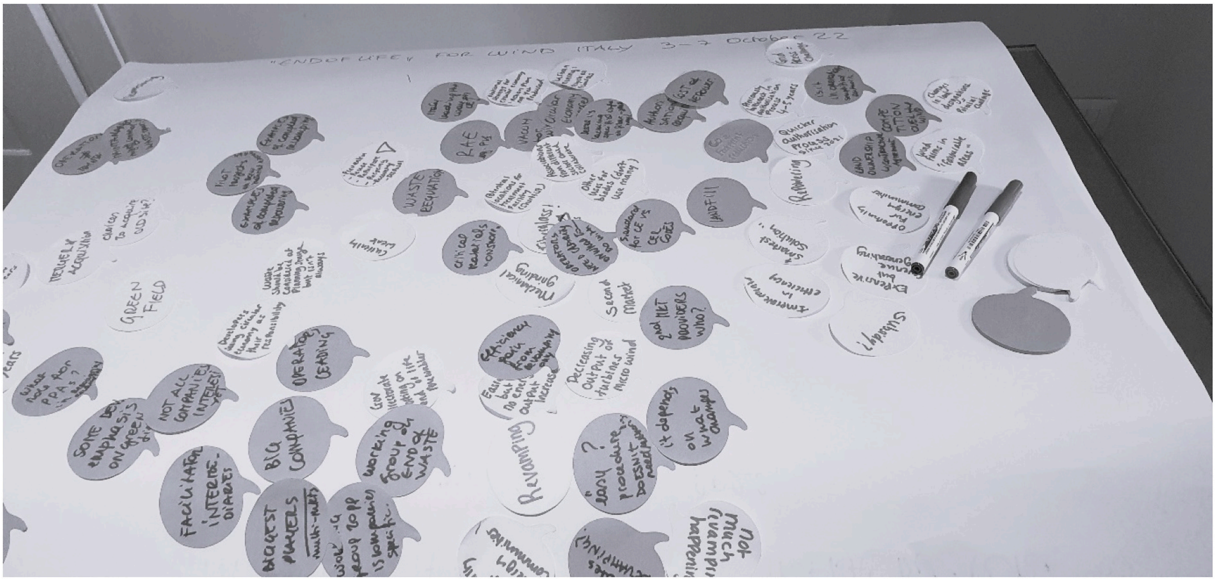


Fig. 6. Preliminary analysis.

added, namely business environment to take into considerations the networks of collaborative nature emerging in EoL experiences in Italy. The analysis followed an interactive process by sharing and discussing interpretations and understanding concerning the data with the involvement of two researchers. A second visit to Italy allowed for follow-up interviews to present preliminary findings.

Table 4 provides some examples of the initial text data, codes, themes and categories created during data analysis.

The descriptive and narrative accounts derived from this analytical process are discussed in the next section. Illustrative quotations from the interviews are used to support the narrative presented. The limitations of the research are dealt with in the concluding section.

4. Results and discussion

The results revealed a range of factors influencing when EoL decisions are taken. These factors have been grouped under the following categories:

- technical and design life
- economic and business models
- legislative and regulatory (including planning)
- business environment.

Table 4
Examples of data analysis.

Data extract from interviews	Codes	Themes	Categories (emerging from literature)
'If there's a strong wind, but it's something very rare and uncommon to have strong wind, or whether it is a let's say milder but constant wind… this has a different effect on the real age'	Wind availability	Site conditions	Technical
'While we have a life-time guarantee on the assets for 20–30 years, our decisions on EOL will be driven by the incentives: one of our wind farm, built in 2012, will benefit of incentives for another 4 years and we have considered the re-blading of the site to cover the cost sooner' (WO 5).	Incentives	Financial models	Economic

The following section discusses these factors showing how they are shaping actual EoL decisions and outcomes. This is followed by a wider discussion of how together the timing of EoL decisions and the consequent decisions regarding the future of the existing turbine materials, involves technical as well as an analytical and political questions.

4.1. Determinants of end- of-life decision making for onshore wind in Italy

a. Technical issues impacting design life of Italian wind farms

Undoubtedly, the design life of a WT- and its components- can impact on when EoL decisions are taken. The standard design lifetime of a WT is 20–25 years, although this can be extended to 35 years with some renovation and repair. According to the design lifetime, a database compiled by ANEV, estimates that there is a total of 1625 MW that has been installed between 1991 and 2005 corresponding to 133 plants and 2083 turbines. The standard design life of these plants, however, is not the only technical factor affecting EoL decision.

The timescale under which WTs approach the end of their operational lifetime is not uniform. Performance and age will, for instance, depend on the wind in the specific sites. The design life of turbines is influenced by site conditions, as different wind speeds and patterns can impact the performance of turbine components, as explained by our research participants:

> '*If there's a strong wind, but it's something very rare and uncommon to have strong wind, or whether it is a let's say milder but constant wind… this has a different effect on the real age*'.
>
> (WO 6)

> '*They are going to degrade their performance, but their performance depends also on the wind and the kind of wind there is in that specific site*'.
>
> (WO 4)

Moreover, parts will wear out more quickly in sites with stronger wind speeds and damage to parts and EoL decisions can be taken earlier if WTs become damaged during the operation life. Such damages can render them unsafe requiring replacement–lightning strikes are a good example of this.

Ongoing maintenance can also impact the design lifespan of components. Some developers discussed how they tried to keep their wind farms working for as long as possible through high quality maintenance - having dedicated maintenance teams, maintenance plans and through replacing parts. However, such replacements to WT components have to be on a like-for-like basis, as the wind farm is authorised to generate a certain amount of power, and thus changing the type of components would require permission. Moreover, a challenge to such replacement is the availability of replacement parts, particularly for older turbines, therefore affecting life-extensions opportunity. In terms of waste, some operators are stockpiling older turbines on site to guarantee a supply of spare parts to prolong WT's life.

The guarantee on the equipment can also influence the timing of EoL decisions. For example, many older WT components in Italy have a 20-year guarantee, requiring parts to be replaced after this point. A strategic approach used from some developers is to seek the extension of the service life of the asset and de-risk life-time extension by working with suppliers to guarantee life certificate extensions and re-certify the assets:

> '*we are working with our supplier to get a certificate of life-time extension*'.
>
> (WO 5)

> '*One of our suppliers does not provide a certificate of life-time extension, therefore we are looking at other options, including a professional certification for the tower that could extend the life of the site*'.
>
> (WO 5)

A recurring theme across the interviews was that often EoL decisions need to be considered as early as the 15th year of the WT:

> *Life extension is often considered the last 3/4 years of the life cycle of a WT to evaluate the status of the mechanical and electrical components, however we have already done it to ensure the economic viability of the site.*
>
> (WO 5)

Moreover, some operators are considering ad-hoc EoL strategies for their wind assets with '*business plans been prepared for the partial and full replacement of some WTs that are only 8–9 years old and 12 years old (e.g. re-blading)*' (WO 5) with the potentially dismissed WTs been sold to secondary markets.

b. Economic factors influencing the end-of-life of Italian wind farms

As with technical considerations, there are many economic factors that can affect EoL management and decision making. Woo and Whale [15] included the following: operation costs, electricity markets, subsidies, incentive schemes and power purchase agreements.

Life-time decisions will differ depending on the economic evaluation of the sites and their performance. These economic evaluations are in turn influenced not only by the site wind conditions but also by the business model associated with the original wind farm's business case.

Interviews with Italian wind farm operators revealed that some original business models were designed for 15 years, even though turbines may last for up to 30 years. Sometimes, developers acquire their wind farms from other companies, that can develop their own strategies regarding EoL options. There have been some instances where companies have chosen to acquire older sites rather than developing on greenfield sites as their business model.

While decisions such as life-extensions or repowering are often based on the oldest working turbines, for EoL options, projects are also prioritised based on the site wind conditions:

> '*when the first wind farms were built the developers selected the best sites with the best anemological conditions*'.
>
> (WO 1)

Key, in the decision-making process, is the real-time information on wind and also the experience and data availability at the existing site:

> '*How much wind there is in in that specific site? If I dismantle and rebuild, what will be the difference? The delta in terms of energy production that the new wind farm will give me? Will this delta allow me to recover my investment?*'.
>
> (WO 4)

Decisions therefore can be affected by how well the site is performing and whether the increase in energy production (e.g. from repowering) is sufficient for the economic sustainability of the investments. Re-blading options (such as changes in the type of blades and increasing the rotor size,) offer an opportunity, without modifying the installed capacity to '*increase production in sites with medium-to-low wind conditions*' *(WO 5)*. Moreover, repowering is currently considered by many wind energy developers as the 'smartest solution' due to the location of existing wind farms in 'favourable areas'.

Furthermore, EoL decision making may be different if there are financial incentives on the existing site,

> '*While we have a life-time guarantee on the assets for 20–30 years, our decisions on EOL will be driven by the incentives: one of our wind farm, built in 2012, will benefit of incentives for another 4 years and we have considered the re-blading of the site to cover the cost sooner*'.
>
> (WO 5)

> '*A wind plant will have a life duration of about 20 years as operators and developers will associate the durability of the plant not with technological obsolescence of the turbines but rather with the termination of the incentives*'.
>
> (GOV 1b)

As discussed above, many operators will be faced with EoL decision-making challenges in the near future. The striking price the wind operators have secured through auctions and power purchase agreements will also have a similar impact on the economic and financial sustainability of EoL options. It is also worth noting that, only recently, in Italy, repowering projects have been admitted to auctions, offering an opportunity to review the economic and financial sustainability of sites.

The decision will also be influenced by waste management options and the cost of waste collection and landfilling related to the dismissed blade:

> '*In the EoL projects we have been involved with we have kept 3 blades for spare; we have re-sold some of the blades to the manufacturers to enter second markets (especially the newer ones- some where only 10 years old) and some have been kept disuse on site awaiting decision on waste treatment*'.
>
> (WO 5)

While there is not currently a legislative ban for dismissed wind blades in Italy, operators are seeking options to minimise blade waste disposal as this comes with not only an environmental cost but also a financial one:

> '*You cannot dispose the blade. You are required to find a solution (…) So we are trying also avoiding the costs because we expect to dismantle many first-generation WTs*'.
>
> (WO 6)

Moreover, developers have to contribute towards a guarantee fund for the decommissioning of the wind farm to the municipalities:

> '*Developers need to contribute a fixed cost of surety to guarantee the municipality for the disposal of the plant (…) the decommissioning requires developers to restore the area, removing the WTs and foundations (up to 10 mt)*'.
>
> (GOV 1b)

Overall, wind farm developers prioritise re-use when disposing of old turbines components (e.g. blades). When it comes to dealing with the older turbines re-selling turbines is the most economically viable approach. If a wind farm is being repowered early, then selling turbines on the second-hand market (or re-selling to manufacturers) provides a viable approach.

> '*The market for second hand turbine is quite vibrant but it follows some market swings- sometimes we store the turbine on site to wait for more favourable second-hand market conditions*'.
>
> (WO 5)

Similarly, the cost of revamping (can keep the same project operational for a lot longer) can include high costs. For example, one interviewee (W0 6) explained that changing the rotor would improve production- but it is very expensive. Likewise, re-blading is considered expensive. Thus, these approaches which may have a significant impact on waste reduction may be prohibited by costs. The cost of re-balding, for instance, will be kept in consideration when deciding an EoL options:

> '*Within 8–9 years we will cover the cost of the partial re-blading of the site, and this together with life-extension, will extend the technical life of the site from 20 to 30 years. Consequently, after 9 years the site will become profitable*'.
>
> (WO 5)

> '*One of the sites we are considering has not got the best wind conditions (wind-production rate) therefore we are evaluating the cost of substituting the current blades with some more powerful turbines and we need to consider whether the investment is worthwhile*'.
>
> (WO 5)

c. Legislative/regulatory environment for wind farms and waste in Italy

Government policy can also influence choices regarding the future of existing windfarms. Here we refer to 1) changes in policy and financial support and how they might lead to EoL decisions being taken earlier than the operational life of a site and 2) to the way in which EoL decisions are also affected by the current authorisation granted to the site.

The first one refers to the way in which repowering and life-extensions can be explicitly supported from governments. In Italy, for instance, the National Energy and Climate Plan (NECP) published in 2020 [59] indicates that repowering of existing wind farms offers a key opportunity to increase wind power capacity to contribute towards the achievement of 2030 targets.

> 'In order to attain the targets on renewables identified for 2030, it will not only be necessary to stimulate new production, but also to preserve existing production and, if possible, actually increase it, by promoting the revamping and repowering of installations. In particular, the opportunity to promote investments in the revamping and repowering of existing wind power plants with more developed and efficient machines, by exploiting the excellent wind conditions at well-known sites that are already being used, will also help to limit the impact on soil consumption'
>
> [59: 68]

Despite the support of repowering and revamping in the NECP, repowering did not receive any specific support measure and the repowering projects – in terms of authorisation procedures and environmental impact assessments- were still treated as a completely new plant. Projects with 'no-relevant modification defined by law' can take advantage of a simplified administrative procedure. However, a definition of what a 'no-relevant modification' consists of was missing. This, to a certain extent, had the effect to discourage operators to undertake repowering interventions (see also [17]). One of the main barriers being the time waited for the authorisation procedure to be granted.

> '*The time for the authorisation procedures for repowering is too long and too onerous*'.
>
> (WO 5)

Nevertheless, more recently, some simplifications in the authorisation procedures have been put in place to support the repowering or revamping of existing wind sites:

> '*There are a number of decrees, published in the past three years that are basically trying to sustain these types of EoL options that are helping to clarify and define what can be considered as a no-relevant modification and can be considered as a substantial change- this simplification can also apply to sites that have been granted authorisation but they have not yet been built and can be modified- via simplified authorisations- to increase the installed capacity*'.
>
> (GOV 1b)

Changes in these authorisations (permitting regulations for modifications, simplification of authorisations and permitting timing) have started to positively influence repowering of some sites. Nevertheless, it is also the changes in the environmental impact analysis, to be undertaken on a differential basis from existing plants, introduced in early 2023 that are expected to contribute to an increase in repowering projects. The adopted principle is that 'for environmental assessments, the intention is to favour an approach that evaluates only the impact of the changes with respect to the situation prior to the revamping or repowering intervention' [53: 180]. Moreover, repowering projects of existing wind farms, that do not include changes to the occupied area and with a total power, following the intervention, of less than 50 MW, are exempt until 30th of June 2024 from the environmental impact assessment. This coupled with repowering projects and green field projects been considered in the same auctions, yet with some tariff reductions, led some commentators to suggest that Italy is becoming de-facto a *fertile* ground for the development of repowering.

As early wind farms development were mainly located in the windier southern regions (Campania, Apulia, Sicily, Molise and Sardinia), some regions are considering the opportunities that some EoL solutions can provide to maintain their role in contributing to national wind energy production and to fulfil their burden sharing targets set up at national level. For instance, Apulia, already in 2020, adopted a regional law to regulate the EoL in order to identify ways in which the current wind sites could be renewed (via further simplification and in respect of national legislation), in particular via revamping the sites without affecting environmental and landscape impact.

> '*Under considerations are also the identification of 'suitable areas' for concentration of renewable energy sites, including for wind energy, that might consider favourably repowering or revamping current sites located in those areas*'.
>
> (GOV 1b)

As discussed, while developers have to pay a guarantee fund to the decommissioning to the municipalities- for instance this in Apulia is fixed to 100 Euro per Kw, such cost is defined at the time of the authorization of the plant. However, there are regions- such as Apulia – that are considering, pushed by developers, to revise this fixed cost by identifying alternative EoL options. For instance, in the phase of authorisation, developers can present an EoL plan for the decommissioning of the WTs which can include the options for WTs to be re-sold (in their entirety or as components) reducing in such way the fixed costs of surety.

Another factor influencing EOL decision-making is permitting in terms of planning/operational licences and land use agreements. In numerous cases in Italy operating licences have been issued for 20 years. If there are no terms for an extension of the licence, then decommissioning might be the only option. Importantly this will also depend on the type of rights the wind farm operators have on the land in which they operate: for instance, the EoL will be determined by the end of land use contracts and if they cannot be extended. Such restrictions can bring forward the date at which the future use of the materials has to be decided upon.

> '*the authorization that we got from the local or national bodies that allowed us to build that wind farm, I mean that in in some cases you have a 20 years authorization to operate that wind farm in other cases, we have 30 years in some other cases you do not have a time limit to operate*'.
>
> (WO 4)

> '*If, at national level, the government will introduce a way to extend the incentives already assigned to projects of revamping, operators and developers might apply for an extension of the planning permits and operational licence*'.
>
> (GOV 1a)

A further issue that is having an impact on the EoL decision-making processes relates to changes that occurred in the land designation since early development ins wind energy. In the Italian context, national guidelines provide the criteria for identifying areas to be excluded from wind energy production. The national guidelines were only published in 2012 [60] and for several plants that are reaching EoL, the new criteria indicate that their locations fall in unsuitable areas.

> '*As these plants have been granted permission prior to the publication of the national guidelines, it is unlikely that they will be dismissed and developers will seek, while extending life duration of the sites, to adopt changes such as substitution of WTs. Different considerations will be given however to unsuitable areas where there are some objective risks (such as hydrological risks). In these circumstances, for instance, WTs of newer generation could be re-located in proximate areas to maximise production and reduce the size of the wind farm. These are considerations that will need to be applied on a case by case once developers present their plans of re-qualification of the site*'.
>
> (GOV 1b)

d. Business environment

Central to progress on the EoL and material recovery for onshore wind in Italy has been the role of industry and industry associations in driving the EoL agenda's forward. Industry efforts in particular have focussed on two main areas:

- pushing for policy change for re-powering;
- exploring opportunities for adopting circular economy models and developing a supply chain for recycling blades.

There is a widespread recognition among wind farm developers that repowering is the 'smartest solution' in terms of enabling increased energy generation from existing sites. As such, wind farm developers have been pushing for an easier and quicker consenting process for repowering. Moreover, such business leadership translated into collaborative work and learning opportunities. In particular, a task force was created for EoL that included operators, developers, wind and renewable energy associations and industry association for composite material. This task force promoted the publication of a Charter of Sustainable Wind Energy [50] aimed at promoting the 'reconstruction and modernization projects of existing plants as well as of those already authorised, but not yet built' [50: 3].

The wind sector in Italy has been collaborating on providing potential responses to the challenge of WT waste materials – in particular the question of what to do with the blades that currently cannot be recycled. Elettricità Futura- the main renewable energy association, ANEV- the wind energy association and Assocompositi- the industry association for composite material- have published a position paper [13] to discuss and ensure the sustainable and circular management of EoL WTs. The position paper resulted from a working group in which over forty companies in the sector participated, coordinated by leading companies in the Italian and global markets- Enel, ERG, Vestas and Enercon- that are pioneers in the adoption of EoL strategies. This supported collaborative learning and sharing of best practice.

There is a recognition that re-use and repurposing are unlikely to be large scale solution given the expected volumes of wind farms that will reach end-of-life, there is also a recognition that blade waste is an increasing problem e.g. in 5–7 years there could be a significant amount of waste fiberglass.

As well as recognising the need to improve the decision-making speed for repowering applications, the Italian wind farm industry has also been at the forefront of the movement to address waste materials. What emerged from our interviews was that many developers saw addressing the challenge of '*what to do with old blades and moving the wind sector to a circular economy as their responsibility*' (WO 1). As such the wind industry has been leading the way both in terms of raising the issue and working to provide potential responses.

While industry efforts have successfully influenced policy change for repowering (e.g. simplification of authorisation and shortening the time allocated for a decision on planning applications and permits), industry actors have highlighted that there is a key gap in national level policy/activities in Italy regarding waste treatment. This relates in particular to fiberglass. Industry actors and associations have identified a need to understand the costs and opportunities for this material. Nevertheless, the opportunity to address a legislative vacuum on wind farm waste through pushing for a policy decision (ASS 2) are yet to be captured. In the meanwhile, the industry is working towards addressing this gap by:

1. identifying the supply chain challenge related to waste management of fiberglass working in collaboration with other sectors. An emerging technology under consideration is grinding of blades – that could be used in the construction industry e.g. for road surfacing. At the moment there is not a value chain to perform proof of concept that grinding blades would be suitable and, the industry is working to develop a pilot project to create a treatment facility to explore these challenges. There are also a range of other innovative projects such as the Re Wind and Superuse-Studio project using turbines for street furniture and other projects using turbines for items such as play-parks. While these projects are currently at a small scale, some Italian wind operators are involved in European and international networks with similar scope, highlighting the importance of networking and collaboration within the industry.
2. seeking collaboration with the national government and the general directorate for the circular economy by proposing the involvement of the wind sector in the working tables on the End of Waste decrees on composite materials [13].

4.2. *Summary of results*

In summary, the above represents examples of the factors that are influencing decision making around EoL. The discussion also shows that these are also affecting options and opportunities around what can be done with the emerging waste. Fig. 7 summarises the discussion, highlighting the decision-making process supporting EoL options and the linkages between these EoL decisions and waste management options. The intention here is not to draw conclusions on which, if any, of the

Fig. 7. End of life decision making strategies.

factors leading to EoL, are the most important. The evidence presented above show the complexity of the decision-making process. Nevertheless, there might be different options (and outcomes) depending on when the decision of EoL is taken. Identifying EoL decision making and assessing consequent waste issues is not straightforward. Besides, the empirical evidence provided here show that when considering waste from EoL, there are a number of key technical, economic and regulatory questions that must be asked before deciding on the most appropriate EoL option. This is an important message and outcome from the research.

Moreover, as part of the research, a return visit to Italy was undertaken. The aim of the second visit was to explore projects currently undergoing decommissioning and either experiencing re-blading or repowering. However, these projects were delayed or altered. A number of reasons were identified to justify such delays. Firstly, the wind industry has suffered from a number of challenges, including inflation in commodity prices and other input costs that have given raise to the price of WTs. These challenges have had the effect of slowing down progress in addressing the sustainability challenge of the industry, despite industry commitment.

Secondly, despite the simplification of the permitting rules, projects have not been granted authorisations at the expected speed (mainly due to undergoing legislative changes in designated areas for wind development) slowing down the uptake of repowering projects. Thirdly, the recent increase in wholesale electricity prices compensated for increased operational costs of old wind turbines. To a certain extent, one can conclude that EoL decisions, while done on a case-by-case basis, will still be affected by most relevant factors such as economic (e.g. wholesale prices and prices of WTs) and legislative (e.g. planning). These issues have not only affected the decommissioning landscape in Italy but have been felt across Europe as highlighted by Wind Europe in their statistics outlook for 2022–2026 [5].

4.3. How these elements come together to influence end-of-life decision making

The paper started with a selected and narrative review that highlighted the emerging evidence surrounding current practices of EoL of wind infrastructure and the multitude of factors that might influence decision making. As mentioned, there is still currently limited information on the current EoL practices and EoL decision making of ageing wind turbines. Some of the literature reviewed suggest that EoL is complex and influenced by a number of factors spanning from cost, technical feasibility, legislation, and environmental impacts [14,15,18]. These contributions highlighted that as few onshore windfarms have been decommissioned, more evidence should be collated on EoL practices and EoL decision making for ageing wind turbines. The data collected from the Italian case study have offered further detail on the decision making related to EoL of wind infrastructure and have explained how the key technical, economic and regulatory questions are influencing the management options actors in the industry need to consider.

Table 5 summarises these factors highlighting how these have influenced EoL decision making in the Italian context. The table shows how the EoL options considered by wind operators might be different depending on which factors promoted their decision to EoL. Indeed, operators that cannot access spare parts or negotiate a certificate of life extension might need to consider full or partial decommissioning with a full or partial repowering of the site. Besides, the economic and business model associated with the wind farm might determine whether operators will opt for life-extension or a full or partial repowering with different consequences for waste and waste treatment. For instance, if

Table 5
Summary of factors influencing end-of-life decision making.

Factor	Examples from Italy	How they influence end-of- life decision
Design life and technical issues	Performance and 'age' will depend on the kind of wind there is in the specific site (e.g. 'experience of the site')	Changes and series data on real-time information on wind condition are useful metrics to investigate EoL options and opportunities.
	Extreme weather effects on wind turbine parts/components Availability of spare parts	Damage to parts and cost (or lack) of maintenance might bring forward end-of-life decisions: partial/full repowering;
	Good levels of maintenance may enable turbine components to last longer	Parts for older models of WTs are increasingly difficult to find: partial decommissioning of the WT affected; operators also consider stockpiling options
	Guarantee on the equipment: e.g. WT certificate of life-time extension	Some manufactures might not offer this with effect of accelerating decommissioning of the WT.
Economic and financial	Incentive regimes about to expire	Financial revenue models need to be re-negotiated at the end of the incentives and this represents an ideal time for considering life/extension and partial/full repowering
	Electricity prices/auctions, PPAs	The striking price the wind operators secure through auctions and power purchase agreements will influence economic and financial sustainability of EoL options; Some countries are including re-powering in new auctions.
	Duration of original business model and operation costs Second-hand markets for dismissed turbines	Fewer turbines will incur in lower operational cost; opportunities for second- hand market and buy-back options; These factors will influence the decision of an operator to proceed with life-extension and partial/full-repowering
	Early sites in the windier southern regions	Knowledge of older sites can support re-powering options (for best sites) or life-extension
Legislative/ regulatory	Operating licences for 20 years/30 years Rights on the land (e.g. end of land use contracts)	The authorisation processes to build the wind farm and land ownership will determine whether options other than decommissioning can be considered.
	Achieving 2030 targets by promoting the revamping and repowering of installations becoming a government priority; Repowering and green field projects in the same auctions (but with some tariff reductions)	Changes in policy and financial support can favour repowering and life-extension of schemes. This is considered a win-win solutions as more renewable generating capacity can be introduced with a lower land footprint.
	Changes in authorisations (permitting regulations for modifications, simplification of authorisations and permitting timing) Changes in Env Impact analysis: on a differential basis from existing plants	Planning policy will influence the choices to be made by favouring life-extension over repowering but also can determine the full decommissioning of the WT (changes in land designation during the operation of the wind site)
Business environment	Stakeholder awareness of EOL 'Charter of sustainable wind energy' Sharing of best practices	Shedding light on what the challenges are EoL can bring to the fora the opportunities that can be captured by keeping the site in used- via life-extension and repowering
	Waste awareness and circular business models opportunities	Managing the EoL of renewable energy projects represents many cross-sectoral challenges requiring the sharing of best practices and active engagement from actors from the renewable energy sector and beyond (including building & construction, electrical & electronics, waste)
	Lessons learnt: a 'task force' for EoL (operators, developers, wind and renewable energy associations, industry Association for composite materials)	Supporting governance that offers collaboration and learning opportunities.

business models were designed for 15 years even though turbines may last for up to 25/30 years, operators will have an opportunity to reconsider those business models and, where appropriate, decide to proceed with life-extension or repowering. If repowering younger sites, certainly there might be an incentive for those operators to consider and explore second market opportunities for their dismissed WTs.

Similarly, a favourable repowering policy landscape that aims at increasing renewable electricity generation and reduce landscape impact might positively contribute to partial and full- repowering. The findings of this research are therefore best viewed as the much-needed empirical evidence of current practices of EoL of wind infrastructure. Understanding these factors can support policymakers, actors and practitioners in the wind energy industry dealing with EoL decision making. Additionally, these factors can represent questions that must be asked before deciding on the most appropriate EoL options as shown in Fig. 7. For instance, if the operating licence (e.g. land use agreement and/or planning permitting) is coming to an end, operators might need to consider the renegotiation of these terms. These might include request for extending the life of the WTs or applying for the re-powering of the site. Some authors suggest that these should also include a re-negotiation of community involvement and engagement with onshore wind assets [48].

5. Conclusions

As wind farms reach EoL the potential challenges associated with waste management and resource recovery requires investigating. Nevertheless, there is also a need to identify how decisions around EoL are made and, in particular, what are the determining factors of EoL of ageing WTs. Emerging literature on the EoL of wind infrastructure suggests that EoL decisions and actions are influenced by a range of technical, economic and regulatory aspects. Yet the empirical evidence from countries that are already facing EoL challenges due to their ageing wind infrastructure is still scant. To address this gap, the paper offers empirical evidence of how these factors are influencing the decisions and actions of Italian wind energy actors that are starting to address the EoL challenges.

The paper shows that the timing of EoL decisions and the consequent decisions regarding the future of existing turbine materials, and waste management opportunities, involves technical as well as analytical and political questions. EoL of wind infrastructure represents both an opportunity and a challenge for industry and government departments. Wind industry operators are willing to showcase the environmental credential of the technology. Government departments are interested in regulating the way in which long-term EoL impacts are governed. The Italian case shows that policy considerations, and the determining regulatory factors for EoL for onshore wind, resides in the opportunities life-extension and repowering offer to reach decarbonisation of the energy sector targets. There is alignment between government's awareness of the opportunities EoL management entails to reach ambitious decarbonisation targets and the industry's interest into the economic opportunities to grasp the advancement in technological innovation in the market, that is favouring life-extension and repowering opportunities.

While discussing the important and emerging issues of managing EoL for wind infrastructure, the paper reveals that identifying EoL instances and the consequent waste issues is not straight forward as it will not always occur at the end of a wind farm's projected life. The paper highlights the importance of distinguishing between the end of standard life and the end of operational life of a wind farm and how much EoL decisions relate to business models and associated economic factors. Expiring incentives, electricity markets, wholesale electricity prices and the cost of EoL management will influence the EoL decisions at times accelerating decisions on life extension and/or repowering. Besides, through using the case study of Italy, the paper reveals the important role of the industry in promoting collaboration between all actors involved. In particular, it shows how managing EoL of renewable energy projects represents many cross-sectoral challenges requiring sharing of best practices and active engagement from actors from the renewable energy sector and beyond (including building and construction, electrical and electronics, waste). Successful collaborative platforms are starting to emerge in Italy to share best practices that can support the management and decommissioning challenges of onshore wind infrastructure.

As shown, there is value in identifying the key technical, economic and regulatory of EoL and these factors raise questions that must be asked before deciding on the most appropriate EoL options. This is important and future research should increasingly focus on the management and decommissioning challenges that European and international contexts might be facing, including the empirical evidence and lessons learnt from the first wave of wind farms that are approaching their EoL. We argue that the findings of this paper provide valuable insights and lessons to be learnt for EoL of wind assets in Italy but also internationally as countries seek to address this emerging environmental sustainability issue and as the industry matures.

Certainly, there are many further avenues for future research to be considered and a number of limitations that have affected the generalizability of the results; something that future research could address. Every research has its intrinsic limitations. Firstly, the research scope has been restricted to a single case study, that of Italy, in a specific context and time. The adoption of a single case study offered some evidence-rich and detailed explanation of the relevant factors affecting EoL in Italy. Yet future research could apply the research questions and methods adopted here to other geographical contexts. Wind Europe [5], for instance, expects Germany to continue being the largest repowering market, followed closely by the Netherlands, Italy, Denmark, and Spain. Looking and comparing other international contexts can enhance and strengthen both the internal and external validity of the research. However, it is important to highlight that most of the interviewees were also involved in multiple international markets (e.g. with wind sites in Spain, the UK and other countries) and, while the discussions focussed on the Italian market specifically, the identified EoL decision making factors are also relevant in other countries. Perhaps one of the main points of difference is how different countries might support EoL via the presence or absence of life-extension and repowering policy incentives. These are certainly playing an important role in the Italian context in mobilising interest around EoL management of wind infrastructure and supporting Italy in its ambition to reach decarbonisation of the energy sector targets.

Secondly, the research is based on a relative low number of interviews conducted. These low numbers were due to the fact that interviewees were selected among wind farm developers, consultants and policymakers involved in EoL decision making of wind infrastructure in Italy. As EoL management is still a relatively new concern, there is a small population of experts to be drawn upon. With time and experiences these numbers can be increased and so are the many lessons that can be learnt from experts in the field.

Despite these limitations, the paper provides an empirical overview of the factors that might influence the EoL of wind infrastructure. Future research could expand on this empirical frame to provide a more detailed investigation to each of these instances, expanding on the number of experts and countries to detail the unique challenges and opportunities that may emerge as EoL of ageing wind infrastructure progresses.

CRediT authorship contribution statement

Carla De Laurentis: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rebecca Windemer:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Carla De Laurentis and Rebecca Windemer reports financial support was provided by Royal Geographical Society.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2024.103536.

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