Atti del V Convegno Internazionale

RECYCLING

Proceedings of the 5th International Conference

a cura di / edited by

Adolfo F. L. Baratta
Laura Calcagnini
Antonio Magarò

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ROMA TRE
UNIVERSITÀ DEGLI STUDI
DIPARTIMENTO DI ARCHITETTURA

Atti del V Convegno Internazionale
Il valore della materia nella transizione ecologica del settore delle costruzioni

Proceedings of the 5th International Conference
The value of building materials in the ecological transition of the construction sector

Acta de el V Congreso Internacional
El valor de la materia en la transición ecológica en el sector de las construcciones

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Adolfo F. L. Baratta
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Lost in transition.
The burden of material resources for renewable energy sources

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Summary

Although wind and photovoltaic (PV) systems will inevitably be the cornerstone of the European ecological transition, being the more advanced and widespread technologies, some issues about the related material supply chain and End of Life management must be addressed. Considering the future pervasive presence of these renewable energy sources, questions on how sustainability patterns can merge energy and material resources preservation arise.
The contribution depicts the current obstacles emerging in the wind and PV systems material demand and waste management, highlights the related main criticalities, and outlines an overview of current studies and research that aim at overcoming such known issues.
At first, it will identify the materials required in both the supply chain and production of renewables systems, with a focus on critical raw ones and rare earth elements. It will later examine the current waste management patterns, to highlight the technical, economic, and environmental obstacles which reveal how the sustainable management of wind and PV systems should be significantly improved.
Three main areas of interest for future implementation will then be identified, and suggestions for sustainable improvements through both existing and missing lines of research are discussed. These latter addresses design strategies, material efficiency, and policy.

Renewables, Material supply, Recycling,
Wind technologies, Solar panels

Introduction

The European targets concerning a carbon-neutral economy, aiming at reducing emissions to net zero by 2050 [EP, 2021], dictate a substantial shift towards the use of renewable energy. An increase in wind energy and photovoltaic systems (PV), which will achieve 58% of total production, has been estimated (Figure 1).

This circumstance strongly influences the future building sector and urban systems. To meet these demands building-scale energy production will become fundamental. The targets will concern both private and public constructions, involving a significant building stock, and will likely foster small-scale production by Renewable Energy Communities (RECs). Hence, both small wind turbines and PV systems installations will experience a major spread [IRENA, 2019].

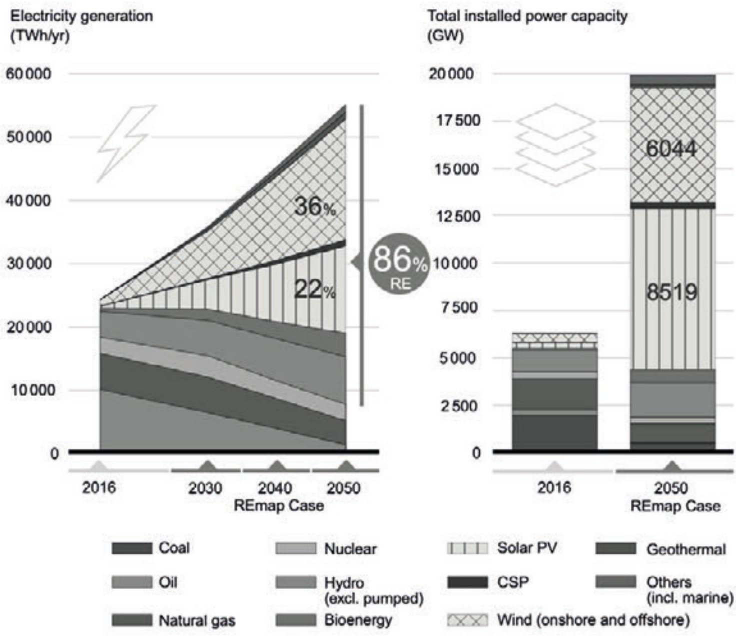

Figure 1. Electricity generation mix, and installed power capacity by source [adapted from IRENA, 2019].

Although such a shift in energy production represents the leading means to deliver the ecological transition, its supply and waste management impacts must be investigated.

On the one hand, since the EU largely depends on imports, the material supply for both PV systems and wind turbines installation will inevitably increase [Carrara et al., 2020], raising further doubts about both the social and environmental effects of mining activities [Bolger et al., 2021] which impact mainly low-income countries where the extraction sites are located (Africa, Asia, and South America). On the other hand, in front of a predictable growing amount of waste, tackling the End of Life (EoL) of renewable installations appears essential [Deng et al., 2019] also to avoid the movement of discarded materials to African landfills.

Although EU WEEE norms [EP, 2012] establish an 85% recovery target, PV systems are complex to manage according to circular principles [Farrell et al., 2020], and many of their components are made of non-recyclable materials.

At the same time, most wind turbine components can be easily recycled, but elements such as rotor blades are difficult to handle due to their size and composite materials [Jensen, 2019].

Starting from these assumptions, more research is required to avoid problem-shifting events - from the energy perspective to the material one.

Aims and methods

The contribution aims to outline the additional stress that the future diffusion of wind turbines and PV systems, driven by the ecological transition, could induce on the material supply and waste management. It will therefore: i) investigate the raw materials required for manufacturing these systems and the potential consequences in terms of waste production and management; ii) analyse the lack of efficiency in current EoL patterns; and iii) will identify potential lines of research.

The first part of the contribution describes the characteristics of current wind turbines and PV systems, focusing on the materials required for their manufacturing and production. The second part outlines current EoL patterns, highlighting the existing technical and economic barriers to their more efficient and sustainable management. The third part then discusses future research opportunities, while the fourth part draws conclusions.

The material supply for wind turbines and PV systems

Wind turbines

The main materials used in the wind turbines supply chain (Figure 2) are aluminium, steel, concrete, carbon fibre and fibreglass, and Rare Earth Elements (REE), included in the list of Critical Raw Materials (CRM) [EC, 2020], such as neodymium, dysprosium, and copper. Concerning REE, in the EU clean energy technologies account for different shares of the total demand due to the elements used in PMG (permanent magnets technology) generators: wind turbines account for 7% of the overall demand of neodymium, while, in the case of dysprosium, for nearly 37% [Alves Dias et al., 2020].

In a scenario that foresees a 64% reduction in greenhouse gas emissions by 2050, the use of REE for clean energy technologies corresponds approximately to 5–20% of the global supply. With the aim of a complete decarbonization of the EU by 2050, a larger share of the supply would be needed at the current state of technology use, and the request for dysprosium would significantly exceed the global supply threshold. Components linked to the production of the nacelle, rotor hub, and tower, which are made of steel and iron, are recyclable, and make up approximately 85% of the structure

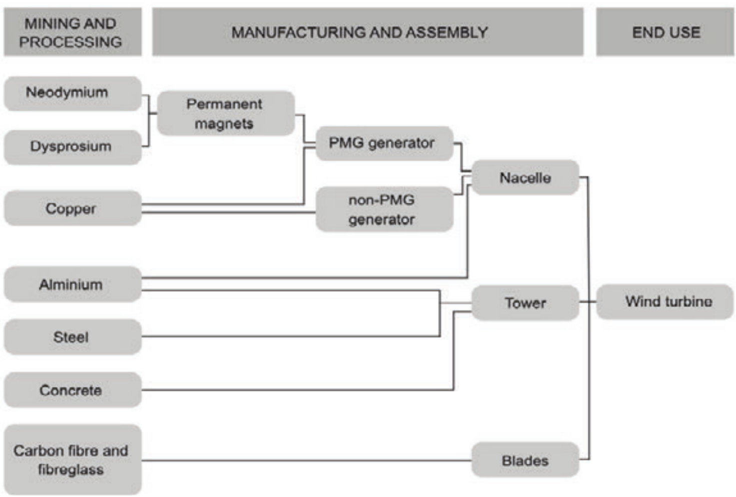

Figure 2. Wind turbines supply chain [adapted from Carrara et al., 2020].

(Figure 3). Since the remaining components are hardly recyclable – PMG generators require the use of REE and blades are made of Fibre Reinforced Polymers (FRP), current research is investigating how to substitute the first [Pavel et al., 2017] and how to dismantle and reuse the second [Jensen et al., 2018].

PV systems

As recent research highlights [Fraunhofer ISE, 2022] silicon wafer-based (c-Si) technology dominates European current PV energy production by accounting for more than 95% of the total, and monocrystalline modules represent the vast majority of this share.

In fact, thin-film modules are currently settled at around 5% of both energy production and market share. The semiconductor used in these technologies can be cadmium telluride (CdTe), copper indium gallium (di)selenide (CIGS), or amorphous Silicon (a-Si). Other emerging technologies account for a minimal part of the market [Yu et al., 2022], and will not be taken into account. Figure 4 depicts the differences in the composition of both c-Si and thin-film modules. Recent studies [Carrara et al., 2020; Deng et al., 2019; Farrell et al., 2020; Yu et al., 2022] examined the material composition of PV systems to discuss both future supply and improvements in their EoL. Besides the different semiconductors, many materials recur in the different technologies (Figure 5), such as aluminium (mainly included in the frame),

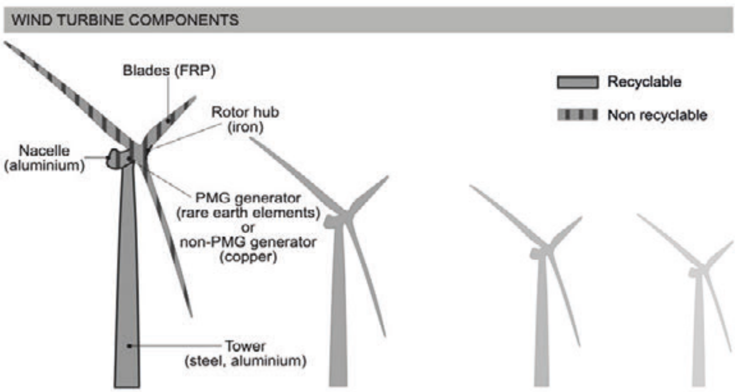

Figure 3. Wind turbine components [adapted from Jensen, 2019].

Ethylene Vinyl-Acetate (EVA) as sealing film, and copper for wiring, cabling, and heat exchange.

A glass layer is used in most cases, while the substrate can be made of metal, plastic, or glass. Common elements in solar cells are silver, magnesium, and germanium.

Current End-of-Life management barriers

Due to technical and economic reasons, several obstacles arise for the circular management at End-of-Life both for wind turbines and PV systems. Even though technological and financial challenges differ, the environmental aspects to be tackled by both the systems are the same Figure 6

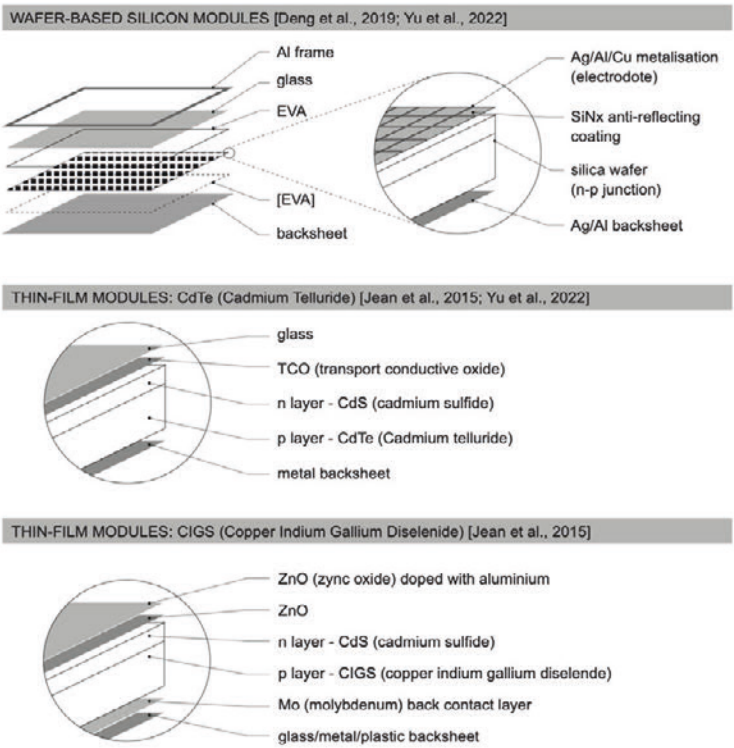

Figure 4. Detail of materials used in c-Si and thin-film modules [Authors].

summarises these obstacles, which are further described in the following sub-sections.

Wind turbines

Wind turbines' expected life is of 20-25 years, and EoL established practices include the disassembly of the structure to reduce it to smaller pieces for recycling or disposal [Jensen, 2019]. The blades are the main non-recyclable components, and 10% of the total FRP waste in Europe stems from them [Schmid et al., 2020]. Since their recycling process is complex, requires a high amount of energy, and is costly, they are shredded and either incinerated or used as concrete aggregate [Topham et al., 2019], but the most common practice is landfilling; to discourage this non-virtuous procedure some countries are banning it. Examples of towers and blades upcycling were recently implemented in European urban areas; however,

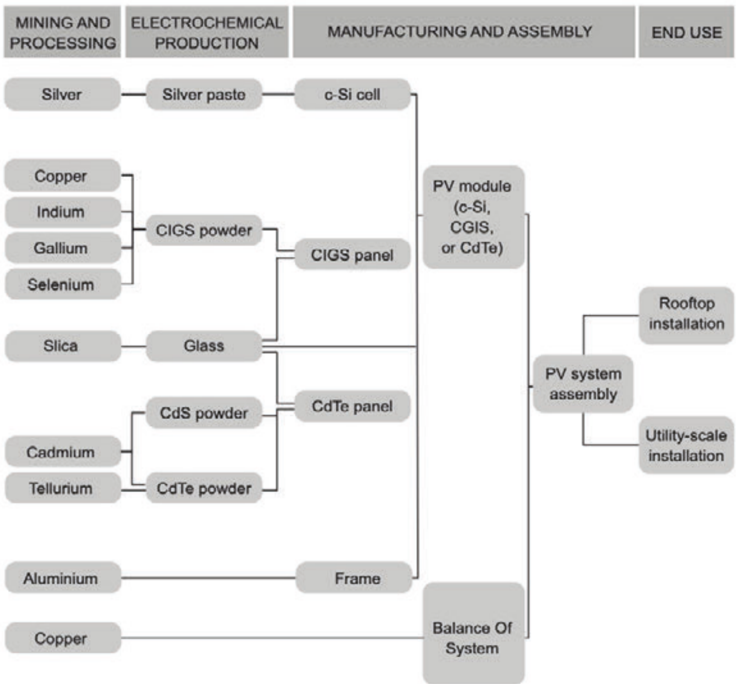

Figure 5. PV modules supply chain [adapted from Carrara et al., 2020].

although representing a creative and efficient management by reuse, this cannot be considered a solution to be applied on a larger scale and able to compensate for a growing throughput. On the other hand, Topham et al. (2019) analysed how the high quantities of metal that are used in most of the structures can be sold after the dismantling, and it could cover approximately only 18% of the decommissioning costs. But financial challenges persist, since the chemical processes to separate REE within permanent magnets are still not cost-effective and produce toxic emissions.

PV systems

Effective recovery patterns for PV modules could allow the preservation of gallium, germanium, and indium, included in the Critical Raw Materials, as well as scarce elements such as cadmium and tellurium [Deng et al., 2019]. Also, precious metals (i.e., silver) and other conventional resources (i.e., aluminium, copper, glass) could be recovered, easing the environmental pressure of the solar panels' life cycle. In particular, individual solar cells recycling encounters several difficulties. Mechanical treatment, a cheaper and low-energy option enabling high throughput, does not allow for the separately recover of valuable elements included in the cells [Deng et al.,

OBSTACLES TO THE RENEWABLE ENERGY SOURCES CIRCULAR MANAGEMENT AT END OF LIFE			
	TECHNOLOGICAL CHALLENGES	FINANCIAL CHALLENGES	ENVIRONMENTAL CHALLENGES
WIND	• difficulties in separating blades' FRP components; • complexity of separate recovery of rare earth elements from permanent magnets.	• metal recovered from dismantling covers for 18% of the decommissioning cost; • low disposal costs compared to recycling.	• energy input required for recycling operations; • toxic emissions (chemical processes); • transportation emissions.
PHOTOVOLTAIC	• delamination of encapsulant layer; • difficulties in recovering the c-Si wafers without damage; • complexity of separate recovery of the materials included in the cells; • lack of purity of the recovered materials for their reuse.	• low economic value of recovered materials due to lack of purity; • uncertain value of recovered cells; • insuffcent waste volume to justify costs of collection, transports and treatment processes; • low disposal costs compared to recycling; • low cost of new moules production.	• energy input required for recycling operations; • toxic emissions (both thermal and chemical delamination); • transportation emissions.

Figure 6. Challenges on wind turbines and PV systems recycling [adapted from Yu et al., 2022].

2019; Farrell et al., 2020]. Chemical and thermal delamination can be quite effective in removing the EVA film from the wafer but are way more energy and carbon-intensive, producing hazardous emissions [Yu et al., 2022; Farrell et al., 2020]. Since silicon wafers got increasingly thinner over time, they are difficult to recover without damage [Deng et al., 2019], and the silica cannot be recycled for another use in solar cells due to the lack of purity [Yu et al., 2022]. Manufacturing affordability makes recycling unappealing, and the PV panels' waste volume is still low to justify its operational costs [Deng et al., 2019].

Preserving the value of materials

This overview highlights that, to improve the sustainable management of renewables EoL, three main fields must be addressed: (i) design strategies, (ii) material efficiency, and (iii) policy. To foster waste prevention, research in Design for Disassembly (DfD) should be encouraged. This is particularly challenging for PV systems, due to the need to protect their components from external events. The design of wind turbines, which need to be assembled on site due to their dimension, inherently includes the principles of DfD, but work is still required for the reuse or recycling of the blades that are made of FRP. Material efficiency can be reached by both improving recycling patterns and replacing the materials currently used. On the waste management side, both wind turbines and PV systems recycling patterns should be investigated to improve their cost-effectiveness. In the first case, the recycling of REE for use in permanent magnets is possible and could be economically viable but is still being tested. Other studies are focusing on either finding possible substitutes or developing new materials. In the long term, recycling could supply nearly one-third of the materials needed for the production of clean energy technologies in general. Concerning PV systems EoL, recovering the whole c-Si wafer could lead to its potential reuse, although research is needed to assess the related performance, and the operations to separately retrieve the valuable elements included in solar cells would benefit further studies as well. Both wind turbines and PV systems would benefit from studies of more effective pyrolysis systems, which would help in the decommissioning of existing wind turbines since most of their blades are made of Glass Fibre Reinforced Polymers (GFRP) and would avoid the EVA film incineration in the delamination of solar cells.

Regarding replacing materials, solutions for 100% recyclable wind turbine blades are researched; the main areas of focus are towards new resins that, when immersed into a heated mild acidic solution, will separate from other components, and blades composed of a reusable fabric. Further research is addressing the metal structures to reduce the production phase impact, and towers made of laminated veneer lumber are being tested. PV systems' environmental impacts could be reduced by replacing the rare and/or valuable materials used in the cells with other ones. The presence of regulations to discourage, or even ban, landfill would both reduce environmental impacts and spur producers to invest in the research towards effective chemical processes to recycle composite materials for both wind turbines and PV systems. In conclusion, to reach the goal of decarbonising the EU before 2050, renewable energy sources such as wind turbines and PV systems are fundamental. Nevertheless, some issues should be addressed to implement the energy transition without forgetting the ecological one, preserving landscapes and ecosystems. The first topic concerns the reduction in the use of critical raw materials extracted from undeveloped countries, which could be handled by finding alternatives to REE in wind turbines, and correct ways of recovering precious raw materials from PV panels. Researchers are already working on both issues, but the results appear not enough cost-effective yet. The second topic concerns the non-recyclable components of renewable technologies, and the current low cost of landfill options: further research is necessary to avoid the prolonged use of low-income countries as dumping grounds for developed countries, thus making them pay the price for the European energy transition.

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Il V Convegno Internazionale Recycling, dedicato a "Il valore della materia nella transizione ecologica del settore delle costruzioni" si è tenuto a Roma il 26 maggio 2023, confermandosi come uno dei principali luoghi di confronto tra accademici e *stakeholders*. Il Comitato Scientifico, composto da docenti ed esperti provenienti da 24 Atenei internazionali, distribuiti su 4 Paesi e 3 continenti, ha selezionato i migliori contributi tra quelli pervenuti secondo la procedura *double blind peer review*. Come di consuetudine, i contributi sono stati suddivisi nelle tre sezioni del Convegno Internazionale: "Saggi", "Ricerche" e "Architettura". La raccolta degli atti ha come obiettivo la definizione dello stato dell'arte del riciclaggio nel settore delle costruzioni, oltre a fotografare la direzione verso la quale il mondo della ricerca scientifica si sta orientando. La moltitudine di punti di vista che caratterizza il presente volume è, probabilmente, il suo maggiore valore, restituendo un profilo innovativo e creativo sul tema.

The 5th International Conference Recycling, dedicated to "The value of building materials in the ecological transition of the construction sector" was held in Rome on May 26, 2023 confirming its status as one of the main venues for dialogue between academics and stakeholders. The Scientific Committee, consisting of professors and experts from 24 international universities, spread over 4 countries and 3 continents, selected the best papers among the ones received according to the double blind peer review. As usually, the papers were divided into the three sections of the International Conference: 'Essays', 'Research' and 'Architecture'. The aim of the proceedings is to define the state of the art of recycling in the construction sector, as well as to take a framework of the direction in which the world of scientific research is heading. The multitude of viewpoints that characterises this volume is probably its greatest value, providing an innovative and creative profile on the subject.

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