



RE-CYCLING

VII INTERNATIONAL CONFERENCE

Luis Palmero
Graziella Bernardo
Stefania De Gregorio

EDITORS

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RE-CYCLING

VII INTERNATIONAL CONFERENCE

**ECOLOGICAL INTELLIGENCE FOR A CIRCULAR
AND TRANSFORMATIVE ARCHITECTURE**

Luis Palmero
Graziella Bernardo
Stefania De Gregorio
(Eds.)



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Circular and Transformative Architecture

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TABLE OF CONTENTS

Introduction

Ecological intelligence for circular and transformative architecture	xv
Luis Palmero, Graziella Bernardo, Stefania De Gregorio	

Closing the loop: circular materials, recycling and upcycling strategies

Recycling as a design and technological practice: limits, and perspective of the six “Re-Cycling” conferences	3
Adolfo F.L. Baratta, Laura Calcagnini	
Circularidad material en la arquitectura popular del Cabanyal: reutilización estética y ambiental	17
<i>Material circularity in the popular architecture of Cabanyal: aesthetic and environmental reuse</i>	
Graziella Bernardo, Luis Manuel Palmero Iglesias	
From fragmentation to integration: the building as a circularity connector between tangible and intangible dimensions	33
Cinzia Maria Luisa Talamo, Noelia Huanca Coacalla, Nazly Atta, Giancarlo Paganin	
Diseño Circular en Acción: a design-build lab for circular living wall systems	59
Carlotta Fasano, Pablo Luis Palmero-Sánchez	
Campus mining: progettare e prototipare con gli scarti del Politecnico di Torino	71
<i>Campus mining: designing and prototyping with waste materials from the Politecnico di Torino</i>	
Nicolò Di Prima, Angela Lacirignola, Elena Montacchini, Silvia Tedesco	

End-of-Life of building materials: innovative upcycling experiment for brick recovery	83
Jacopo Andreotti	
Riciclo delle macerie edilizie: dal QT8 di Milano all'Ucraina di oggi	97
<i>Construction Debris Recycling: from QT8 Milan to Contemporary Ukraine</i>	
Matteo Ocone	
Upcycling dell'architettura industrializzata del secondo novecento: dall'inventario alle strategie di riuso delle componenti in acciaio	107
<i>Upcycling of industrialized architecture from the second half of the 20th century: from inventory to reuse strategies for steel components</i>	
Cristian Tolù, Stefania Mornati, Ilaria Giannetti	
Increasing circularity of small-scale wind turbines: the PANORAMA vertical axis prototype	119
Massimiliano Condotta, Tommaso Morbiato, Chiara Scanagatta, Elisa Zatta	
Nano-silica engineered cementitious matrices for sustainable construction: coupling mechanical strength with reduced thermal conductivity	133
Andres Salas-Montoya	
Analisi FT-IR di materiali alcalino-attivati ottenuti da fanghi di segazione	147
<i>FT-IR analysis of alkali-activated materials produced from sawing sludge waste</i>	
Antonio D'Angelo, Roberto Simonelli, Michelina Catauro, Sara Fasana, Marco Zerbinatti, Luigi Mollo	
Digital Twin e Material Passports per la valutazione dell'effetto serra degli edifici: un focus sulla fase di fine vita	157
<i>Digital Twins and Material Passports for assessing buildings' global warming potential: a focus on the end-of-life stage</i>	
Roberto Giordano, Federica Gallina, Benedetta Quaglio	
Il passaporto digitale per la tracciabilità della circolarità dei prodotti edili	169
<i>The Digital Passport for the traceability of the circularity of building products</i>	
Adriana S. Sferra, Giuseppe Piras, Francesco Muzi	

Hyperlocal architecture in regeneration strategies for the Abruzzo region	179
Donatella Radogna, Luciana Mastrodonardo, Maria Chiara Capasso, Valeria Lualdi	
Hyper-Local Self-Built Infrastructures for Slow Tourism	195
Matteo Clementi, Tae Han Kim, Jae Young Lee	
Designing and self-constructing in mountain contexts: prototyping for the Abruzzo inner areas (Italy)	209
Antonio Vasapollo, Stefania De Gregorio, Miju Kim	
 Living territory: adaptive reuse and circular urban transformations	
Costruire per il riuso. Pionierismi italiani per l'abitare provvisorio(1936-1945)	223
<i>Costruire per il riuso. Pionierismi italiani per l'abitare provvisorio (1936-1945)</i> Laura Greco, Francesco Spada	
Riuso eco-orientato del patrimonio produttivo del Mediterraneo. La Tonnara di Avola	235
<i>Eco-friendly reuse of the Mediterranean's productive heritage.</i> <i>The Tonnara di Avola</i> Rosa Maria Giusto, Mario Buono	
Riuso adattivo e riciclo: una rilettura dei processi di trasformazione urbana di Campo Santa Maria ad Amiternum	247
<i>Adaptive reuse and recycling: re-reading urban transformation processes at Campo Santa Maria ad Amiternum</i> Mariangela De Vita, Alfonso Forgione	
The superuse of urban warehouses to activate built environment stock	255
Jacopo Gasparotto	
Urban circularity and circular development: governance, infrastructure and limits of the ecological transition	267
Pablo Altaba Tena	

Monte de' Cocci in Rome. The testimonial value of historical waste, between Italy and Spain	277
Adolfo F.L. Baratta, Francesca Romana Stabile, Antonio Magarò, Massimo Mariani	
Regenerative approaches to industrial heritage: circular adaptive reuse toward culture	291
Gaia Garofali, Paola Altamura, Serena Baiani	
Riuso e memoria: gli elementi della Certosa nel tessuto urbano di Serra San Bruno	305
<i>Reuse and memory: Charterhouse elements in Serra San Bruno's urban fabric</i>	
Lorenzo Russo, Giuseppe Fortunato	
Facciate prefabbricate in pannelli di calcestruzzo. Strategie di riqualificazione	317
<i>Prefabricated concrete panel façades. Renovation strategies</i>	
Francesco Spada, Laura Greco	
El Análisis de Ciclo de Vida como herramienta estratégica en la rehabilitación del patrimonio edificado	331
<i>Life Cycle Assessment as a strategic tool in the rehabilitation of built heritage</i>	
Pablo Ariel Escudero, Isabela Cristina de Assis Berg	
 Bio-intelligent futures: ecological design and learning environments	
Inteligencia ecológica y Sistemas de Información Geográfica (SIG) en la gestión de riesgos hidrometeorológicos para la regeneración del territorio en el Puerto de Veracruz	341
<i>Ecological intelligence and Geographic Information Systems (GIS) in the management of hydrometeorological risks for the regeneration of the territory in the Port of Veracruz</i>	
María del Carmen Ixtepan Turrent, Fabiola Colmenero Fonseca, Juan Francisco Palomino Bernal, Ángela Sánchez Aldana, Ramiro Rodríguez Pérez	
Decoding Venice: An Erasmus laboratory for ecological intelligence in architecture	353
Maria Antonia Barucco, Benu Berk	

Metodología e inteligencia ecológica aplicada a la vivienda de interés social en Guanajuato con GIS, BIM y ACV	365
<i>Methodology and ecological intelligence applied to social housing in Guanajuato with GIS, BIM, and LCA</i>	
Fabiola Colmenero Fonseca, Ángela Sánchez Aldana, Juan Francisco Palomino Bernal, Ramiro Rodríguez Pérez, Javier Cárcel-Carrasco	
La stampa 3D/4D per materiali bio-eco ispirati in architettura	381
<i>3D/4D printing for bio-eco materials inspired by architecture</i>	
Alessandra Cernaro, Ornella Fiandaca	
Bio-based materials for the energy-efficient retrofitting of buildings	403
Agostino Catalano	
Learning from Bee's Ecological Intelligence: Biomaterials and honeycomb architecture	413
Stefania De Gregorio	
Recycling as a pedagogical strategy: the educational building as a sustainability laboratory. Architecture that teaches sustainability: the building as a learning tool	425
Pilar Rodrigo-Catalán, Carla De-Juan-Ripoll	

Increasing circularity of small-scale wind turbines: the PANORAMA vertical axis prototype

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Abstract: despite the extensive research to optimise the performance of large- and small-scale wind turbines, little research has been conducted on design choices to improve the circularity of their components. Considering the relatively short life expectancy of these systems and, above all, their prospected contribution in increasing the sustainability of built and natural environments through diffused networks, this matter crucially shifts their impacts from the energy dimension to the material resources one.

Starting from this premise, the Interreg project PANORAMA tackled the issue by designing and producing a prototype of a vertical axis micro-wind turbine which implements recyclable, renewable and reused materials in a fully reversible assembly system. The exploration of alternative materials and reversible connections also allowed expanding the investigation to another domain of the project: the landscape integration of renewable energy production systems, including site restoration. The investigation resulted in improving the material efficiency of a renewable energy production system in a life-cycle perspective while preserving its performance, that will soon be field-tested.

The article frames the research by presenting the state of the art on large- and small-scale wind turbines, illustrating their difficult circular management despite current technological improvements. It then introduces the prototype and the theoretical framework behind its design, describing its technical features and the design choices on materials and assembly systems. The potential of implementing

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reversibility, recyclable content, material substitution, and upcycling in these systems will then be described, in light of both their ecological relevance and the prospected diffused integration within urban and landscape contexts.

Keywords: micro-wind turbines, reversible installation, recyclable materials, renewable materials, upcycling.

1. Introduction

Renewables play a central role in the European strategy supporting a sustainable and just transition, a position recently upheld by the 2023 revision of the Renewable Energy Directive, raising the EU's binding target for the share of renewable energy to a minimum of 42.5 % by 2030 (European Parliament, 2023). Besides large-scale production plants, this framework also relies on prosumers and Renewable Energy Communities (RECs) to support small-scale green energy systems – photovoltaic (PV), wind and hydropower ones (Corasaniti et al., 2025). Intended as distributed and community-based, these elements could become widespread in future European urban and natural contexts. Nevertheless, the devices most used in these installations currently fail to comply with circular principles due to technological, financial and environmental challenges (Condotta et al., 2023). As in the coming decades these systems will be increasingly produced – and discarded, addressing their impacts across the entire life cycle is therefore essential. This will enable their full contribution to sustainable consumption and production patterns in the built environment.

Focusing on wind turbines (WTs), technological advancements further intensify this trend (Liu & Barlow, 2017) by shortening their average lifespan through increased repowering opportunities (Jadali et al., 2021) and the replacement of old components and models with more efficient ones (Jensen and Skelton, 2018). At the end of their life, even components that fall outside the scope of the Waste Electrical and Electronic Equipment Directive (WEEE) are difficult to manage through circular patterns due to complex assembly systems and used materials.

Although modular, WTs are generally not designed for disassembly. This also applies to small-scale devices implemented in RECs (micro- and mini-WTs), which differ from large-scale units in configuration: the former ones employ a vertical axis system (VAWTs) rather than a horizontal one (HAWTs) (Table 1). Concerning materials, two modules in both HAWTs and VAWTs involve downcycling or even less suited processes once decommissioned: the foundations or base, realised in reinforced concrete, and the wind turbine blades (WTBs), usually made of glass fiber-reinforced plastics composites (GFRP), which are difficult to dispose of and often landfilled (Firoozi et al., 2024). To mitigate this drawback, current research explores the repurposing of decommissioned durable GFRP blades as structural components, promoting circularity within the construction industry (André et al., 2024) (Ramaswamy et al., 2025). On the other hand, the tower module is typically made from steel or aluminium alloys, ensuring higher recyclability rates.

Table 1. Different modules composing HAWTs and VAWTs. [source: authors].

HAWTs: main modules	
Module	Function
Tower	Elevates rotor to stronger winds, carries loads to the foundation
Nacelle	Houses gearbox, generator, brake and turbine control systems
Rotor	Converts wind energy into rotational mechanical torque
Blades (WTBs)	Capture wind and produce lift to spin the rotor
Foundations	Anchors the tower, transfers loads to the ground
VAWTs: main modules	
Module	Function
Structure	Holds rotor and shaft while resisting wind loads
Generator	Converts shaft rotation into electrical power
Central shaft	Vertical axis transmitting torque from blades to generator
Blades (WTBs)	Extract energy from wind flows
Bearings/base	Support shaft rotation, transfers loads to ground/structure

While issues related to assembly systems and materials concern both large- and small-scale WT's, the latter appears a more dynamic field of study as the scale factor encourages experimentation. Nonetheless, current research primarily focuses on efficiency improvements, such as aerodynamic optimization in the blades design (Yossri et al., 2021) or modular features easing WT's adaptation and resizing (Muñoz-Palomeque et al., 2025). Few studies address circular design, either by proposing material substitution strategies (Firoozi et al., 2024) or design for reuse (Gast et al., 2024); none suggest alternatives to their perceived permanent nature – a circumstance hindering WT's social acceptance, whereas a careful landscape integration should be fostered (Bianchini et al., 2022).

2. Aim and methods

This contribution illustrates a specific experimental study carried out as part of the Interreg project PANORAMA.¹ The project's aim is to support decision-making processes for the development of RECs through the installation of photovoltaic and wind systems, based on (i) local climate conditions, (ii) technical-economic feasibility, and (iii) landscape or urban integration. Within the research, a micro-VAWT prototype was designed and developed considering these three points and two key criteria: full reversibility and a low material footprint compared to current practice.

The paper presents the design of the prototype, detailing its technical features. It then examines strategies informed by circular principles and reduced material footprint across three modules of the WT: the base (reversibility), the structure (renewable material), and the blades (recyclable material, upcycling).

¹ The Interreg VI-A Italy-Austria 2021-2027 project PANORAMA "PIAnificazione di cOmunità eneRgetiche AMbientalmente e pAesaggisticamente sostenibili - PIAnung von umweltschOnenden und landschaftlich gerechten eRneuerbAren" (2023-2026) involves 7 partners: Università degli Studi di Udine, Research Studios Austria mbH, Università Iuav di Venezia, Consorzio BIM Piave, CML S.r.l., Consorzio NIP, Ökostrombörse Salzburg.

3. The prototype

3.1. General features and components

The prototype is an innovative small-scale H-rotor vertical axis wind turbine based on a Passive Variable-Geometry (PVG) technology, designed by the project partner CML srl.² Its dynamic functioning relies on an automatic wind-driven adjustment mechanism (passive) that regulates the blades configuration (variable geometry) in both radius (850 to 1050 mm) and pitch (max +/-20°), with no electronic input required. This allows to optimize the efficiency of the WT also in small-scale installations, leveraging the changing wind conditions at different elevations within urban and natural environments, and allowing an optimal efficiency also in case of turbulence. The prototype was designed to be readily integrated with PV systems and to operate entirely off grid.

Table 2 specifies the features of the prototype, while Figure 1 shows a digital mock-up which studies the proper WT integration in a natural context consistent with the project pilot areas (pre-alpine sites in the Italian and Austrian territory).

Table 2. Features of the prototype.

Module	Features
Structure	Three GL24h glulam beams of variable length, approx. 300 cm (consistent with the shaft positioning, 235 cm from the base)
Generator	IV Class, IEC 61400-2
Central shaft	Aluminium alloy extrusion EN AW-6063 T5, additive manufacturing PA12
Blades	Three elements, 1900 x 250 x 50 mm each
Bearings/base	External radius of the three beams at the base up to 90 cm
Foundation	Steel screw piles supporting a prefab concrete base

² CML co-founded Windcity srl, startup that develops small-scale wind turbines designed for urban and suburban environments.



Figure 1. Render of the prototype. [Source: authors, courtesy of Ivan Del Ponte].

Geographical and climate features of the pilot areas influenced the prototype dimensions, as its design was based on the local pattern of wind flows. Landscape integration was addressed minimising the base plinth and choosing finishings suited with the specific environment.

3.2. Materials and assembly systems

In terms of circularity, the modules were devised to be completely disassembled thanks to the use of mechanical connections, up to the reversible foundations.

Besides strictly mechanical and electric components, research maximised the use of recyclable, renewable, or upcycled content in the modules to enhance sustainability compared to current practice:

- The WT base must ensure the transfer of wind and shaft rotation loads to the ground; therefore, the foundation reversibility must be carefully balanced with the need of a device safely performing. The research group opted for a system of small steel helical anchors that can be screwed/unscrewed to the ground (Figure 2), linked by steel rods to a prefabricated concrete block providing the structure footing.

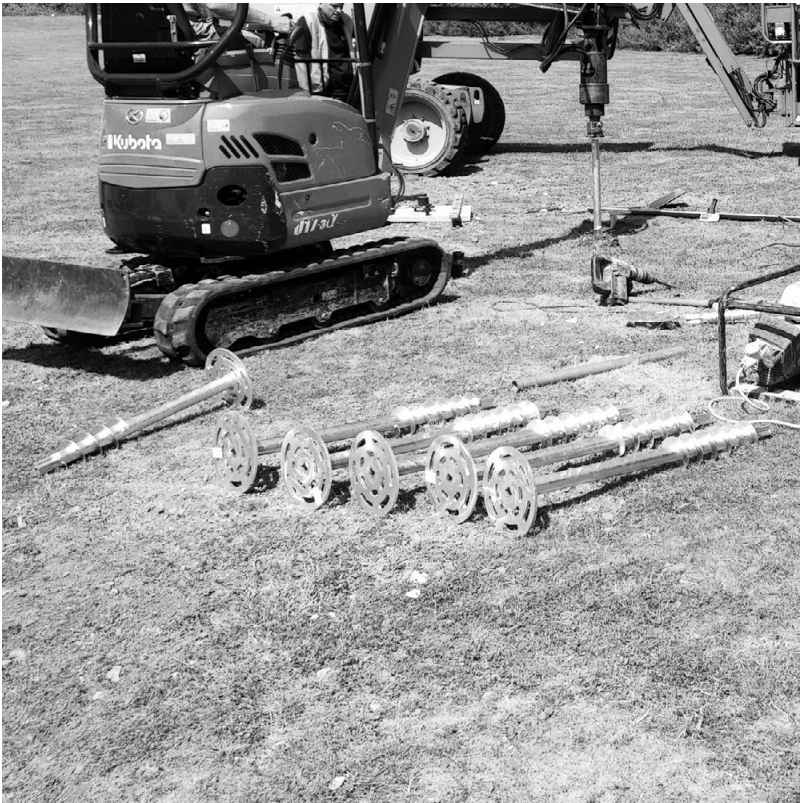


Figure 2. Reversible foundation system (screw piles). [Source: Tommaso Morbiato].

- The support structure consists of four glulam beams. All connections are reversible: flat and T-shaped steel plates are inserted in the beams' width to ensure the connection with the rotor and the concrete base respectively. While the steel plates are welded to the shaft, beams-plates fastening is achieved by through-hole bolts (Figure 3); the connection to the concrete base uses steel rods (Figure 4).



Figure 3. Connection of the glulam structure to the shaft.
[Source: authors, courtesy of Ivan Del Ponte].



Figure 4. Connection of the glulam structure to the prefabricated concrete base [source: authors, courtesy of Ivan Del Ponte].

- The blades design is the most complex part of a micro-VAWT: they must be lightweight while ensuring high resistance. Since the recycled content in GFRP blades is limited to 10 % to ensure the necessary mechanical strength, a material substitution strategy was adopted. The innovative design features a thin aluminium 'hull' structure, defining the geometric shape of the blade, enclosed by PVC sheets reclaimed from lorry tarpaulins (Figures 5 and 6).

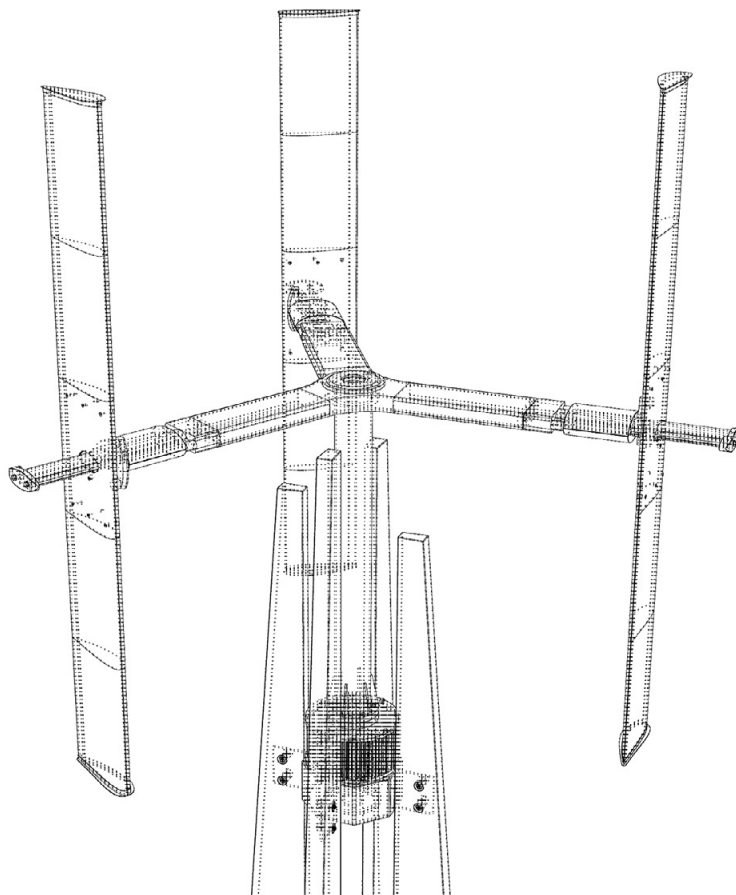


Figure 5. Micro-VAWT blades' technical drawing: detail.
[Source: authors, courtesy of Ivan Del Ponte].

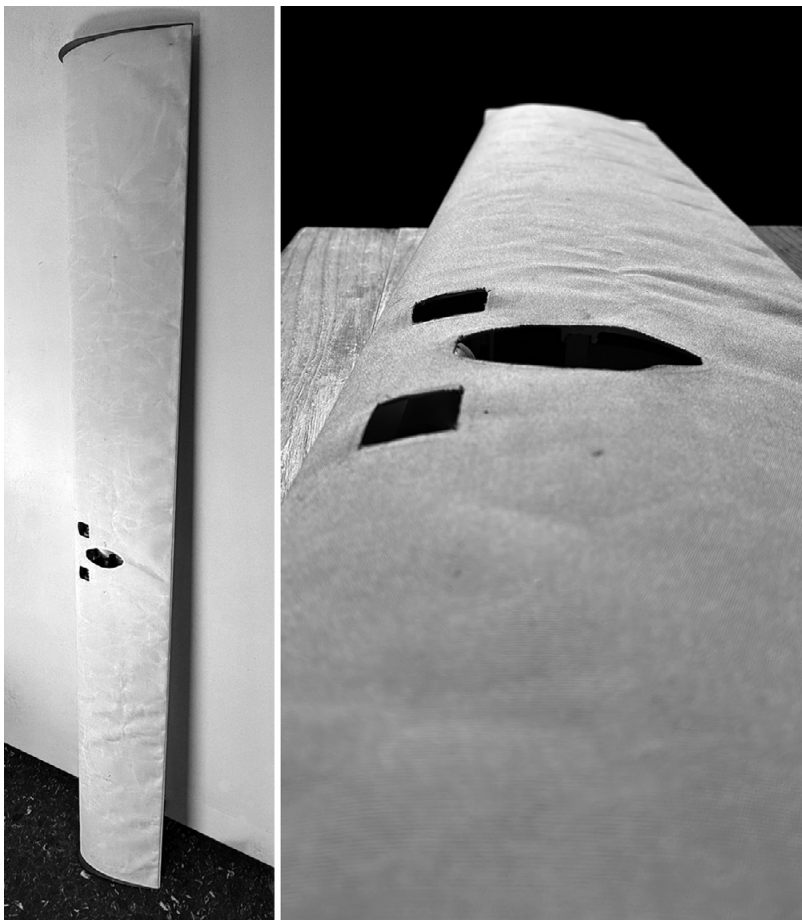


Figure 6. First prototype of the upcycled PVC blade envelope. [Source: CML srl].

The system assembly of the prototype is fully reversible, ensuring operational stability. Structural needs also informed the selection of the concrete base: although not an inherently circular material, the reversible connections to the screw piles enable full disassembly and reuse, in addition to site restoration. The structure design employs a renewable and less energy-intensive material compared to common alternatives: glulam. Albeit less durable and generally downcycled, the research group opted for it

to comply with the landscape integration criteria. While material choices for the base and structure remain subject to further investigation, the fully recyclable aluminium blades, also integrating upcycled PVC elements, represent the most innovative feature of the micro-WT design in terms of circularity.

The prototype was realised and it is expected to be installed in the pilot area in summer 2026, to validate the aluminium and PVC efficiency for the blades and the overall turbine aerodynamic performance, as well as the glulam durability.

4. Conclusion: circular strategies for micro-wind turbines

The research investigated circular improvements in the assembly systems and material footprint for micro-wind turbines, supported by the design and production of a prototype. Reversible connections were implemented in the whole WT, including a removable and reusable foundation system enabling full disassembly and site restoration. The devised blades, engineered using recyclable materials and upcycled elements, provide valuable insight into alternatives to the environmentally critical GFRP composites. The wood-based structure, designed to enhance integration within natural contexts, will be tested for durability and functionality once the prototype is installed.

The research is a first step in filling the state-of-the-art gaps in the circular design of wind turbines. By addressing both the necessary increase in renewable energy production and the lack of circularity of related devices, it supports the significant role of diffused small-scale installations in future sustainable built environments. The illustrated approach implements four strategies – reversibility, recyclable content, material substitution and upcycling, to reduce both material footprint and the degradation of natural or anthropogenic landscapes, also supporting increased acceptance of these technologies.

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