Technical Note
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Opportunities for the Circular Economy in the Energy Transition in Latin America and the Caribbean

olacde

JUNE 2026

This document was prepared under the direction of

OLACDE: Latin American and Caribbean Energy Organization

(OLACDE)

Andrés Rebolledo Smitmans

Executive Secretary

Prepared by

Fitzgerald Cantero Piali

Director of Studies, Projects and Information

Fabio García Lucero

Katherine Segura González

ASSOCIATE SPECIALISTS IN STUDIES, PROJECTS AND INFORMATION MANAGEMENT INFORMATION

David Delgado Noboa

CONSULTANT OLACDE

With the collaboration of:

Gastón Siroit

TECHNICAL ADVISOR TO THE EXECUTIVE SECRETARY OF OLACDE

and

Patricia Otero Valladares

COORDINATOR OF THE DEGREE IN ELECTRICITY OF THE NATIONAL POLYTECHNIC SCHOOL OF ECUADOR AND MEMBER OF THE SCINERGY RESEARCH GROUP

Quito, Ecuador

June 2026.

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Table of acronyms and acronyms

Acronym/Acronym	*Description*
LAC	Latin America and the Caribbean
FV	Photovoltaic
GHG	Greenhouse gases
g/Wp	Gram per Peak Watt
g/t	Gram per metric ton
GW	Gigawatt
GWh	Gigawatt hour
kt	Metric kiloton
Li	Lithium
t/MW	Metric ton per MW
Wh/kg	Watt hour per kg

Opportunities for the Circular Economy in Energy Transition in Latin America and the Caribbean

1. Introduction

The transition towards the greater use of renewable energy sources, a process in which most Lac countries are immersed, undoubtedly means an important contribution to global efforts to mitigate climate change and is generating tangible benefits in terms of reducing Greenhouse Gases (GHG) from the energy sector. For example, in 2025, 67.4% of the region's electricity generation came from renewable sources, including 44% hydropower, 11% wind, 8% solar, 4% bioenergy, and 0.4% geothermal energy (sieLAC–OLADE, 2025).

However, the technologies used to harness these energy sources may also generate environmental impacts across their entire lifecycle, from construction to end-of-life waste management. This is due to the fact that these energy conversion technologies contain materials that may pose environmental risks, including heavy metals, plastics, and corrosive or toxic substances that can contaminate soil, air, and water.

Although the expansion of non-conventional renewable energy in Latin America and the Caribbean is relatively recent—beginning approximately a decade ago—only a limited number of the energy facilities installed for this purpose have reached the end of their operational life. However, some of the technologies used are discarded prematurely due to equipment failures or technological upgrades. As a result, many countries have begun to develop plans and programs and to adopt regulations for the recycling of reusable materials and the proper management of technological waste from equipment such as solar panels, wind turbines, and batteries.

This Technical Note makes a brief current and prospective inventory of the constituent materials of the technologies related to the energy transition[1], in order to present the opportunities for recycling materials and needs for environmentally responsible disposal of final waste in the region, once the technologies involved in the energy transition exhaust their useful life.

[1] The capacity projections for each technology correspond to the outlookincluded in the latest edition of the Energy Outlook for Latin America and the Caribbean 2025, for an environmentally ambitious scenario that reaches net 0 status for the region by 2050.

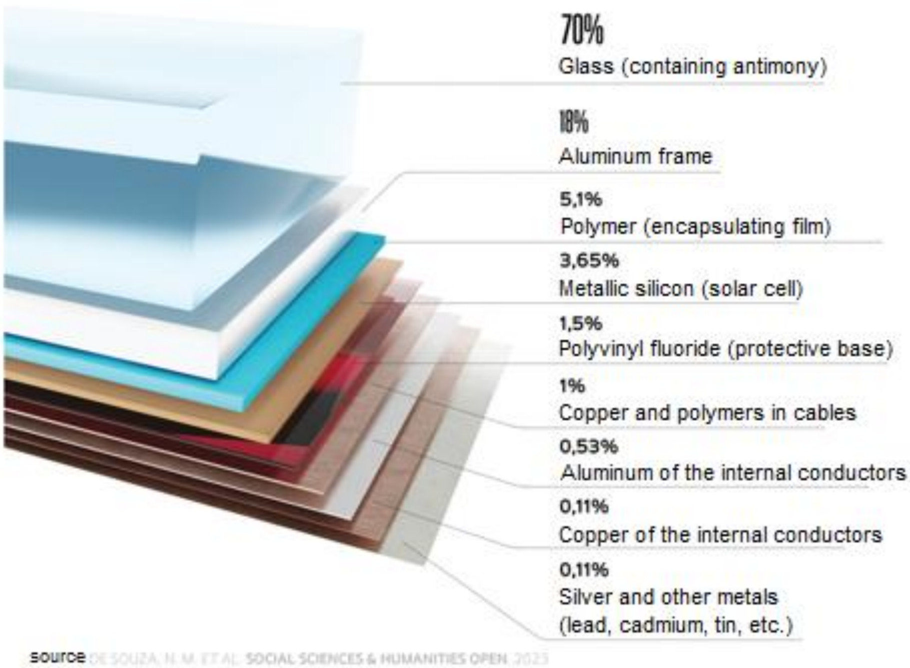
2. Recycling and disposal of waste

2.1. General information on the structure of photovoltaic panels

Crystalline silicon photovoltaic modules are the technology used in practically all photovoltaic plants installed in LAC. These modules are made up of different materials. Glass accounts for approximately 78% of the total weight of monofacial modules and more than 86% of bifacial modules. They also contain metals such as aluminum, lead, silver, cadmium, and copper, as well as various plastic materials and, of course, silicon. While most of these materials are recyclable, the presence of heavy metals such as lead and cadmium, which are soil and water pollutants and harmful to health, requires an appropriate decommissioning procedure. In addition, incomplete recovery of recyclable elements means waste of embedded energy[2] and material and economic resources. It should also be noted that, with current technology, photovoltaic panels can have an operational lifetime of up to 30 years.

In Figure 1. The composition of an average photovoltaic panel is observed as a % of its weight.

Figure 1. Percentage composition by weight of an average photovoltaic panel[3].



[2] Energy embedded in a product is the amount of energy used to make it, counted from the processing of raw materials.
[3] https://revistapesquisa.fapesp.br/es/el-destino-de-los-paneles-solares-al-final-de-su-vida-util/

2.2. Projection of the amount of materials present in photovoltaic panels in LAC[4].

For the projection of materials, the installed and projected photovoltaic capacity for LAC (published in OLACDE's Energy Outlook for LAC 2025) is used as the basis[5] and an average specific weight of the crystalline silicon photovoltaic panels of 50 g/Wp (grams/peak watt) is assumed. Based on these assumptions, the amount of materials contained in the region's photovoltaic fleet is estimated for the coming years, taking into account that, once these facilities reach the end of their operational lifetime, the region will need the capacity to recycle reusable materials and properly manage non-recyclable waste in order to prevent environmental impacts and the loss of valuable resources. The results are shown in Table 1.

Table 1. Quantity of materials contained in the current and projected LAC photovoltaic solar park

	2025	*2035*	*2050*
Capacity (GW)	*90*	*192*	*426*
Aluminium (kt)	833.9	1,778.9	3,946.9
Polymers (kt)	297	633.6	1,405.8
Copper (kt)	50.0	106.6	4.
Glass (kt)	3,150.0	6,720.0	14,910.0
Silver (kt)	5.0	10.6	23.4
Crystalline silicon (kt)	164.3	350.4	777.5
Total (kt)	**4,500.0**	**9,600.0**	**21,300.0**

Source: authors' own work.

2.3. Some processes for recycling and disposition of the component materials of the photovoltaic modules.

Recycling process of a Solar Panel

The patent of Jr Brandhorst et al, of the United States, whose description was published in the document "Technological Surveillance Report – Recycling of Solar Panels and Batteries", of the National Institute of Industrial Property - INAPI of Chile (INAPI, 2024), consists of a clean, safe and efficient process to recycle solar cells and panels, based on thermolysis, to eliminate polluting materials such as fluorine and others, while recovering recyclable materials, converting solar cells and panels into a clean source of combustible gas and coal. The process described in this invention consists of the following steps:

I. Introducing a source of waste solar panels and/or solar cells containing polyfluoroaliphatic compounds into a thermolysis system consisting of a reactor, an oil/water separator, an oil/tar cracker, and a gas scrubber;
II. Depolymerizing and cracking hydrocarbons;

[4] The current installed photovoltaic capacity in the region corresponds to approximately 150 million solar panels with an average peak power of 600 W per unit.
[5] https://www.olade.org/wp-content/uploads/2025/12/PANORAMA_ENERGETICO_DE_ALC_2025.pdf

III. Thermally cleaving the fluorine from the polyfluoroaliphatic compounds;
IV. Capture fluorine in system scrubbers as fluorine hydrogen gas and convert it to fluoride salts for removal;
V. Destroy and/or eliminate toxic compounds present;
VI. Generating a clean combustible gas and coal source that is substantially free of halogenated organic compounds and does not include tars and/or oils; and
VII. Recover recyclable metals and photovoltaic materials and/or silicon.

Recycling process of the glass of the solar modules

This patent by Giovanni Modica et al.,[6] from Italy, whose description was also published in a report by Chile's National Institute of Industrial Property (INAPI), relates to a method for recycling glass waste from end-of-life photovoltaic panels that is substantially free of organic contaminants and lead. The method enables the production of industrial-grade liquid sodium silicates and mixed inorganic silicates that are insoluble in water and alkaline solutions.

The process also relates to soluble and insoluble silicates obtained by said method. According to the patent, the method for recycling glass waste from end-of-life photovoltaic panels comprises the following steps:

I. Supplying end-of-life photovoltaic panels;
II. Obtaining glass waste from the end-of-life photovoltaic panels;
III. Shred glass scraps;
IV. Treat the crushed glasses with an aqueous solution of sodium hydroxide, to obtain a solid fraction and a liquid fraction;
V. Separating the solid fraction from the liquid fraction by filtration; and
VI. Add organic or inorganic chelating agents to the liquid fraction.

Method for recovering valuable materials from solar cell modules

The patent of Masaru Sasai et al of Japan described in the Technology Surveillance Report (INAPI,2024), provides a method for recycling valuable materials from a photovoltaic module, which has a resin back sheet or the like, thereby easily and efficiently recovering these valuable materials and removing the resin components from the photovoltaic module. According to this invention, the method comprises:

I. Loading a photovoltaic module with a resin backsheet and a sealing resin layer onto a heat-resistant porous molded body, with the backsheet facing downward; and
II. A step of heating the load, including the photovoltaic module and the porous molded body in a heating furnace in an oxidizing atmosphere to melt and then burn the resin components.

[6]Prof. Dr. Ing. Giovanni Modica is an Italian senior scientific advisor, industrial chemist and prolific inventor who holds 35 international patents.

In addition to eliminating toxic substances, recyclable materials recovered from photovoltaic panels, such as metals and glass, can serve as raw materials for the manufacture of new panels or various products of the metallurgical and glass industry.

3. Recycling and disposal of lithium-ion battery materials.

3.1. General information on the structure of lithium-ion batteries.

Lithium-ion batteries are currently the predominant technology for energy storage in electric vehicles and with the highest expectations for the storage of electricity, generated by plants that take advantage of intermittent energy sources such as solar and wind, allowing the energy generated to be stored during periods of high renewable production for subsequent dispatch when the electricity system requires it, improving operational flexibility and increasing the integration of variable renewable sources.

Although, due to its high specific cost, the installed capacity in the LAC region of this type of devices for the support of electricity generation systems is still low at around 2 GW, technological improvements in terms of efficiency, load density and useful life have produced a decreasing trend in their costs, so that many countries already consider the implementation of an important component of battery banks in their plans for the expansion of their electricity generation systems.

However, the positive outlook for the advancement of electric mobility and energy storage systems supporting renewable electricity generation also brings challenges related to the management of end-of-life lithium-ion batteries. These batteries contain materials that can be harmful to both the environment and human health if not properly managed at the end of their operational lifetime.

The chemical composition of a lithium battery depends on the use for which it is intended, for example, lithium cobalt oxide ($LiCoO2$) batteries are mainly used in portable electronic equipment, while lithium iron phosphate ($LiFePO4$) batteries are mainly used in electric cars. In general, a lithium-ion battery can contain materials such as Lithium, Nickel, Cobalt, Manganese, Graphite, Iron, Copper and aluminum sheets and the Electrolyte that is normally flammable.

Several of the materials used in lithium-ion batteries, including lithium, nickel, cobalt, copper, and graphite, are considered critical minerals for the global energy transition. Their recovery and recycling therefore represent not only an environmental challenge but also a strategic opportunity to strengthen regional value chains and reduce dependence on imported raw materials.

A typical weight percentage composition of a lithium-ion battery can be seen in Table 2.

Table 2. Typical percentage composition by weight of a lithium-ion battery.

COMPONENT	PERCENTAGE	MAIN FUNCTION
CATHODE (METAL OXIDES)	25% - 35%	It stores lithium ions (the most expensive part).
ANODE (GRAPHITE)	15-20 %	Holds ions when the battery is charged.
CASING AND FRAME (ALUMINUM)	20%-25%	Physical protection and structural support.
COPPER	10–15%	Current collector at the anode.
CATHODE (ALUMINUM)	5% - 10%	Current collector at the cathode.
ELECTROLYTE (LI SALTS AND SOLVENTS)	10–15%	Liquid medium that enables the flow of ions.
POLYMERS AND SEPARATOR	3-5%	Prevents internal short circuits.

Source:https://bateriaslaspalmas.es/blog/56-baterias-de-ion-de-litio-funcionamiento-y-ventajas#:~:text=Componentes%20principales%20%C3%81nodo:%20Generalmente%20hecho%20de%20grafito%2C,de%20litio%20se%20mueven%20durante%20la%20descarga.

3.2. Projection of the amount of materials present in lithium-ion batteries used as a support for the electrical generation system and in electromobility in LAC

Batteries to support electricity generation

Although the gravimetric energy density of a lithium-ion battery is very variable, depending on its type and composition, a lithium-iron-phosphate battery, which is the most commonly used in both electric vehicles and electric generation units, is between 100 and 180 Wh/kg (Lee PAN, 2025), so it can be considered an average value of 140 Wh/kg. With the data in Table 2 and the prospective carried out by OLACDE, the amount of materials present in the lithium batteries specifically intended for the support of the electricity generation system is calculated for the years 2025, 2035 and 2050, for which the region should have recycling capacity and disposal once said devices end their useful life.

It should be noted that for the calculation it is considered that the battery banks are charged and discharged only once a day (with 4 hours of discharge), so their storage capacity is the annual energy provided divided by 365 days in GWh. The results are presented in Table 3.

Table 3. Amount of materials by weight present in lithium-ion battery banks installed as a support for the electrical generation system in LAC

Storage / material cap.	***2025***	***2035***	***2050***
Storage cap. (GWh)	0.67	92.26	359.74
Metal oxides (kt)	1.2	164.7	642.4
Graphite (kt)	0.8	112.0	436.8
Copper (kt)	0.6	82.4	321.2
Aluminum (kt)	1.5	197.7	770.8
Lithium salts and solvents (kt)	0.6	82.4	321.2
Polymers (kt)	0.1	19.8	77.1
Total (kt)	**4.8**	**659.0**	**2,569.5**

Source: authors' own work.

Batteries for Electromobility

Using the data in Table 4, with the projection of the energy consumed by electromobility in LAC, obtained from the OLACDE energy prospective, with the consideration of characteristic parameters of the Lithium-Iron-Phosphate type batteries such as: gravimetric energy density (140 Wh/kg), storage capacity of the batteries in buses and electric cars and the projection of the number of electrified vehicles in circulation in each year of the period 2025 – 2050, the amount by weight of each of the components of the batteries used in electromobility was calculated for the years 2025, 2035 and 2050. It should be noted that for the calculation, only 100% electric light vehicles (BEV) and plug-in hybrids (PHEV) were considered, as well as 100% electric buses, considering that they are the technologies that provide the greatest contribution to the energy transition.

Table 4. Weight-based quantity of materials contained in lithium-ion batteries used for electric mobility in LAC.

Number of batteries / material	***2025***	***2035***	***2050***
Number of batteries (Millions of units)	0.71	21.7	63.6
Metal oxides (kt)	41.0	1,264.0	3,700.0
Graphite (kt)	28.0	860.0	2,516.0
Copper (kt)	21.0	632.0	1,850.0
Aluminum (kt)	49.0	1,517.0	4,440.0
Lithium salts and solvents (kt)	21.0	632.0	1,850.0
Polymers (kt)	5.0	152.0	444.0
Total (kt)	**165.0**	**5,057.0**	**14,800.0**

Source: authors' own work.

Total amount of materials in lithium-ion batteries in LAC

By adding the material quantities presented in Tables 3 and 4, the total amount of materials contained in lithium-ion batteries in LAC is estimated, as shown in Table 5.

Table 5. Total amount of materials by weight present in lithium-ion batteries in LAC.

Material	***2025***	***2035***	***2050***
Metal oxides (kt)	42.2	1,428.7	4,342.4
Graphite (kt)	28.8	972.0	2,952.8
Copper (kt)	21.6	714.4	2,171.2
Aluminum (kt)	50.5	1,714.7	5,210.8
Lithium salts and solvents (kt)	21.6	714.4	2,171.2
Polymers (kt)	5.1	171.8	521.1
Total (kt)	**169.8**	**5,716.0**	**17,369.5**

Source: authors' own work.

According to the above calculations, it is observed that the largest number of lithium-ion batteries and their constituent materials are in the electromobility sector, which added to those corresponding to the electricity generation sector, result in quantities that will grow exponentially over the next 25 years, so the countries of the region must be prepared with environmentally friendly and circular economy programs, once these devices finish their useful life.

3.3. Processes for recycling lithium-ion battery components.

The recycling of lithium-ion batteries is a complex industrial process that consists of two main phases: pretreatment (collection, transport, disassembly and crushing) and treatment or refining, where valuable metals are recovered through processes such as pyrometallurgy and hydrometallurgy. In pyrometallurgy, waste is subjected to high temperature converting waste into gases, slag and metal alloys, although it requires a large amount of energy and subsequent purification, while in hydrometallurgy, waste is treated with aqueous solutions resulting in *black mass*, a mixture rich in lithium, cobalt, nickel and manganese, in addition to other materials, being the preferred method due to its lower energy expenditure, although even in developed countries such as Europe, this treatment is still limited. There is also the direct recycling method, where the cathode and anode materials are recovered without altering their original chemical structure.

Of the materials recovered from the recycling processes of lithium battery components, the main use is made of metal alloys in the metallurgical industry and in the electronics industry.

Second Life Application of Lithium Batteries Used in Electric Mobility

Although the quantity and type of materials that will need to be managed once lithium-ion batteries used in electric vehicles reach the end of their operational lifetime have been previously analyzed, it is important to note that, when these batteries reach a level of degradation that makes them unsuitable for continued use in electric mobility applications, they generally still retain between 70% and 80% of their nominal storage capacity.

This residual capacity is sufficient for reuse in stationary energy storage applications, such as backup systems for power plants based on intermittent renewable sources, such as solar and wind, power grid stabilization systems and uninterruptible power supply (UPS) units. Likewise, these batteries can be used for other forms of electrical transport with lower energy requirements, such as small river boats, for example.

This second life application of lithium batteries contributes to extending their overall lifecycle, postponing the need for end-of-life waste management while also reducing their levelized cost.

Although the useful life of batteries is not measured in years but in the number of charge and discharge cycles, considering a daily cycle, a lithium-ion battery would be degrading between 1 and 3% per year of its nominal capacity (GridX, 2025). If the 2% annual average is taken, it means that in 10 years it would lose 20% of its nominal capacity and this period could be considered as its first useful life for its application in electromobility, although it is a very approximate estimate, because it depends on the different conditions of use of the battery and even on climatic conditions. The remaining time for a second life in stationary systems can be extended until the battery reaches 60% of its nominal capacity, which could represent an additional 10 years.

4. Wind Turbine Waste Management[7]

4.1. General information on the structure of wind turbines.

Wind turbines are the devices in charge of converting the kinetic energy of the wind into electrical energy and are made up of three main components: the turbine or rotor, the nacelle that houses the electrical generator and the tower or support structure. In each of these components approximately 85% to 90% are recyclable materials, such as steel, aluminum and copper, while turbine blades, usually made of fiberglass or carbon and some complex resins, are discarded and sent to landfills. For this reason, wind turbine waste management programs are generally focused on the treatment of blade materials. Research is also being conducted on processes that could make it possible to recycle 100% of the materials contained in a wind turbine in the near future. The useful life of these devices can reach 30 years.

The composition by weight of the materials present in wind turbines is very variable, depending on the height and type of technology, however, steel constitutes between 70% and 80% of the total weight of these machines and that a typical land model of 3 MW capacity can weigh between 250 and 330 tons. In these models the nacelle weighs around 68 tons, the tower between 155 and 235 tons and the turbine or rotor approximately 30 tons. It is also estimated that this type of wind turbines contains between 9 and 12 tons of copper and up to 2% by weight of aluminum.

With this information, it is possible to estimate values per power unit of the main components of a typical *onshore* wind turbine, which are shown in Table 6.

[7] The current installed wind power capacity in the region corresponds to approximately 16,000 wind turbines with an average capacity of 4 MW per unit.

Table 6. Estimated weight composition of an onshore wind turbine, per power unit.

Material	***t/MW***
Steel	90
Copper	4
Aluminum	3
Fiberglass/carbon and resins	10
Total	**107**

Source: own elaboration based on different sources of information

4.2. Projection of the amount of materials present in wind turbines in LAC.

Using the information presented in Table 6 and the wind power installed capacity projections prepared by OLADE through 2050, the quantities of materials contained in the region's wind power fleet are estimated for 2025, 2035, and 2050. The result of this calculation is presented in Table 7.

Table 7. Total Material Quantities in the LAC Wind Power Fleet

Capacity/material	***2025***	***2035***	***2050***
Wind capacity (GW)	63.2	160.8	394.3
Steel (kt)	5,688.2	14,467.7	35,482.7
Copper (kt)	252.8	643.0	1,577.0
Aluminum (kt)	189.6	482.3	1,182.8
Fiberglass/carbon and resins (kt)	632.0	1,607.5	3,942.5
Total (kt)	**6,762.6**	**17,200.5**	**42,185.0**

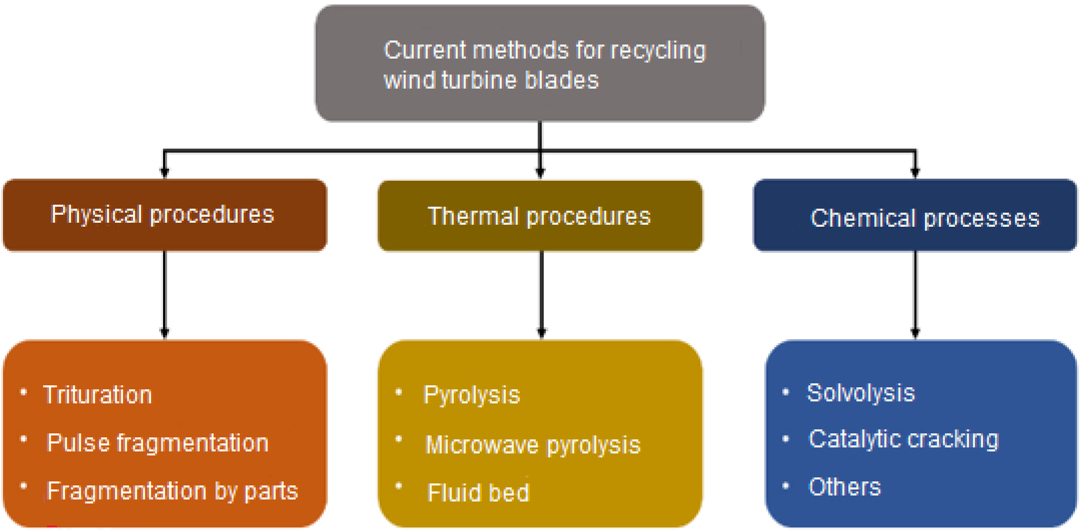
Source: own elaboration

4.3. Processes for the arrangement of wind turbine components.

Most of the materials that make up a wind turbine consist of conventional metals such as steel, copper, and aluminum, for which recycling processes are already well established and widely implemented at the industrial scale. The main challenge, therefore, lies in recycling rotor blades, which are made of glass or carbon fibers and resin composites.

The problem with recycling blade materials is that it involves complex and costly processes and they fail to fully recover such materials. The methods currently used for this partial recovery are illustrated in Figure 2.

Figure 2. Current methods of recycling wind turbine blades.



Source: José Luis Colín Martínez et al, 2024, Review of recycling methods focused on wind turbine blades in Mexico.

5. Methodology for estimating the recoverable economic value of materials from energy transition technologies

The quantification of materials contained in energy transition technologies is a first step to evaluate the opportunities associated with the circular economy. However, the physical presence of materials in photovoltaic panels, lithium-ion batteries, and wind turbines does not imply that all of these materials can be recovered or reincorporated into new value chains.

The processes of collection, disassembly, classification, separation, and recycling involve technical and economic limitations that affect the amount of materials that can be effectively recovered. In addition, the purity of the materials obtained, operating costs and market conditions influence the economic value that can be generated from these secondary resources.

For this reason, in addition to estimating the physical stock of materials contained in energy technologies, it is also useful to assess their potentially recoverable economic value, defined as the value associated with the fraction of materials that could be recovered through circular economy processes under reasonable technical and commercial conditions.

5.1. Difference between theoretical value and recoverable value

The economic value of technological waste is estimated by multiplying the amount of material contained by the international price of raw materials. This approach provides an approximation of the gross value of the resources contained in the equipment, but it does not necessarily reflect the economic value that could be recovered through recycling or recovery processes.

The theoretical value of a material can be expressed as:

$$Vt = M * P$$

where:

(Vt) = theoretical value of the material (USD)

(M) = amount of material contained (tons)

(P) = international price of the material (USD/t)

However, in practice only a fraction of the contained material can be effectively recovered due to losses inherent in the treatment processes.

Therefore, the recoverable economic value can be estimated by:

$$Vr = M * R * P$$

where:

(Vr) = recoverable economic value (USD)

(M) = amount of material contained (tons)

(R) = recovery rate of the material

(P) = international price of the material (USD/t)

Within this framework, the recovery rate should be interpreted as a theoretical parameter that reflects the proportion of the material that could be recovered under ideal technological conditions or in scenarios of development of recycling capacities, without implying specific empirical values.

The conceptual application of this framework allows us to understand that the economic value associated with the materials contained in energy transition technologies does not depend only on their physical presence, but also on the technical and economic possibility of their recovery.

To facilitate the interpretation of the results, the economic valuation of the materials can be understood at three levels:

Level Indicator Interpretation

Level 1. Gross value of material content: theoretical value obtained from the physical content of materials and international reference prices.

Level 2. Potentially recoverable economic value: estimated value considering only the technically recoverable fraction of the materials through circular economy processes.

Level 3. Net recoverable economic value: potential value discounting the costs associated with collection, transport, recycling and refining. This level is not addressed in this Technical Note due to the lack of consistent data across LAC countries.

This classification makes it possible to clearly differentiate the physical potential of resources contained in energy technologies from the economic value that could reasonably be obtained through circular economy strategies.

5.2. Regional value added and circular economy

In addition to the economic value associated with the recovery of materials, the circular economy generates indirect benefits that are not reflected in international prices of raw materials. These include:

- Reduced dependence on virgin raw materials.
- Decrease in imports of strategic materials.
- Generation of employment is associated with collection, classification and recycling activities.
- Development of regional value chains.
- Reduction of environmental impacts associated with mining and primary processing.
- Increased security of supply of critical materials for the energy transition.

In this regard, the potential economic value must be interpreted within a broader framework of benefits associated with the transition to more sustainable production and consumption models.

5.3. Scope and Limitations

This methodological framework has a referential character and provides an analytical tool to measure the economic potential associated with the materials contained in the energy transition technologies. The methodology distinguishes between the gross value of the material content and the potentially recoverable economic value, allowing a more consistent interpretation of the opportunities offered by the circular economy for the use of strategic resources.

Likewise, this methodology does not constitute a financial evaluation of recycling projects or an estimate of economic profitability. Its purpose is to provide a conceptual framework to quantify the potential for material recovery, which can be complemented in future studies by incorporating recovery costs, supply chain analysis, evaluation of secondary markets and specific technological scenarios for LAC countries.

5.4. Quantification of the recoverable economic value of photovoltaic panel materials in LAC by 2050.

Table 8. Potentially Recoverable Economic Value of the Materials Contained in the LAC Photovoltaic Fleet by 2050

	Quantity at 2050 (kt)	Average price (US$/kt)	Recovery Rate (%)	Total (MUS$)
Aluminum	3,947	3,410,000	95%	12,786
Polymers	1,406	1,500,000	50%	1,054
Copper	236	13,684,000	98%	3,170
Glass	14,910	1,000,000	95%	14,165
Silver	23	2,406,401,000	90%	50,679
Crystalline silicon	778	1,750,000	85%	1,157
Total	**21,300**			**83,010**

Source: own elaboration

As shown in Table 8, the quantity of materials contained in the photovoltaic panels projected to be installed in LAC by 2050 would reach 21.3 million metric tons. Based on the current average market prices of these materials (LME, 2026), their estimated value would amount to USD 83 billion, of which 61% would correspond to the value of silver.

5.5. Quantification of the recoverable economic value of lithium battery materials in LAC by 2050.

Table 9. Recoverable economic value of the material present in lithium batteries in LAC by 2050.

	Quantity at 2050 (kt)	Average price (US$/kt)	Recovery Rate (%)	Total (MUS$)
Metallic oxides	4,342	1,000,000	30%	1,303
Graphite	2,953	1,000,000	70%	2,067
Copper	2,171	13,684,000	98%	29,116
Aluminum	5,211	3,410,000	95%	16,880
Lithium salts and solvents	2,171	17,000,000	50%	18,455
Polymers	521	1,500,000	50%	391
Total	**17,370**			**68,213**

Source: own elaboration

Considering the amount of constituent materials of lithium-ion batteries used both to support electrical generation systems and for electromobility, which would exceed 17 million tons with an estimated recoverable economic value of close to 68 billion dollars (LME, 2026), where the value of copper would be the largest share (43%).

5.6. Quantification of the recoverable economic value of photovoltaic panel materials in LAC by 2050.

Table 10. Recoverable economic value of the material present in the wind turbines in LAC by 2050.

	Quantity at 2050 (kt)	***Average price (US$/kt)***	***Recovery Rate (%)***	***Total (MUS$)***
Steel	35,483	938,000	98%	32,617
Copper	1,577	13,684,000	98%	21,148
Aluminum	1,183	3,410,000	95%	3,832
Fiberglass/carbon and resins	3,943	1,400,000	10%	552
Total	**42,185**			**58,149**

Source: own elaboration

With a material availability of around 42 million tons present in the wind turbines installed in the LAC region in 2050, the region would have a recoverable economic value of close to 58 billion dollars in that year, where steel and copper would have the largest share with 56% and 36% respectively. In contrast, the material of the blades, such as fiberglass/carbon and resins, would have the lowest recoverable economic value.

6. Digitalization and Intelligent Data Analysis for the Circular Economy in Energy Technologies

Energy transition involves not only the large-scale deployment of renewable energy technologies such as photovoltaic systems, wind turbines, and lithium-ion batteries, but also the development of strategies to ensure the sustainable management of the materials and waste associated with these technologies throughout their entire lifecycle. In this context, the circular economy emerges as a fundamental approach to maximize the use of resources, reduce the generation of waste and minimize the environmental impacts associated with the production, operation and final disposal of energy devices.

Advanced digital tools, massive data analysis, remote monitoring systems, and predictive technologies are taking on an increasingly relevant role in strengthening the circularity of energy technologies. These solutions allow to optimize the operation of the assets, extend their useful life, reduce premature failures and improve the planning of the reuse, reconditioning and recycling processes.

In addition to contributing to the management of the life cycle of assets, artificial intelligence allows optimizing the operation of energy systems by analyzing large volumes of data in real time. Applications such as renewable generation forecasting, electricity demand forecasting, intelligent energy storage management and dispatch optimization contribute to increasing the operational efficiency of the electricity system, reducing losses and maximizing the use of available energy resources.

In photovoltaic systems, the continuous monitoring of operational variables makes it possible to identify performance losses, detect anomalies and estimate the degradation of the modules. This enables more efficient maintenance planning and helps prevent the premature replacement of equipment that can still operate safely and efficiently.

Similarly, modern wind turbines incorporate monitoring systems capable of analyzing the behavior of critical components such as generators, hydraulic systems and blades. Early detection of wear or potential failures enables timely interventions, reducing operating costs and extending equipment lifetime, which in turn helps minimize premature waste generation.

In this context, the application of artificial intelligence acquires particular relevance in the evaluation processes of lithium-ion batteries destined for a second useful life. Once batteries used in electromobility reach levels of degradation that limit their performance for vehicular applications, they still retain a significant fraction of their storage capacity, which can be exploited in stationary applications.

The main difficulty is accurately determining the status of each battery and estimating its remaining capacity for safe operation. Traditionally, this process requires specialized tests that can be expensive and require long evaluation times.

Artificial intelligence algorithms allow the analysis of historical information related to charge and discharge cycles, operating temperature, depth of discharge, usage patterns and electrical parameters, to more accurately estimate the remaining useful life of each battery.

This ability facilitates the automatic classification of batteries for different destinations: direct reuse, reconditioning, second life in stationary systems or recycling. As a result, the use of the material resources contained in these devices is increased and the generation of waste is reduced.

Additionally, artificial intelligence can be applied to implement advanced predictive maintenance systems for stationary battery storage systems. These systems make it possible to identify anomalous behaviors, detect potential risks of failure, and optimize operating strategies, further extending the useful life of energy storage systems.

In addition, the use of digital battery passports (*Battery Passport*) will allow information on the chemical composition, origin of materials, operation history, status and maintenance interventions of each battery to be recorded throughout the life cycle. By analyzing this information, artificial intelligence can optimize the classification of batteries for reuse, second-life applications or recycling, strengthening the traceability of critical materials and the implementation of circular economy strategies. The combination of reuse, predictive maintenance and smart recycling constitutes one of the most promising applications of the circular economy in the field of energy transition, especially considering the projected growth of electromobility and energy storage in LAC.

These technologies are also transforming material recycling and recovery processes. Automated sorting and separation systems enable more accurate identification of materials such as copper, aluminum, glass, silicon, and other components contained in solar panels, batteries, and electrical equipment. As a result, recovery rates of valuable materials increase, and the efficiency of recovery processes improves.

Likewise, the digital traceability of equipment and materials throughout their life cycle facilitates the identification of components suitable for reuse, reconditioning or recycling, strengthening the implementation of extended producer responsibility schemes and reverse logistics programs.

For LAC, these tools represent an opportunity to strengthen the circular economy chains associated with the energy transition, improve the recovery of strategic materials and develop new industrial capacities linked to the recycling and valorization of technological waste. Its incorporation will allow to maximize the use of resources, reduce environmental impacts and increase the sustainability of the energy systems of the future.

7. Remarkable experiences in LAC countries regarding the disposal of waste from the energy transition.

In LAC, the recycling of energy transition waste is still at an early stage, although some countries have already enacted regulations governing the management of this type of waste, mainly within the framework of environmental protection legislation. Some business initiatives also offer disassembly services for photovoltaic panels and disused wind turbines to recover valuable materials, such as metals and glass.

As for the disposal of lithium batteries, there are initiatives, but only for small-scale ones used in portable devices. The corresponding to large-scale batteries, such as those of electric cars and backup of electric power systems, are still in the research phase.

The following is a brief overview of the status of energy transition waste disposal initiatives in some LAC countries.

Argentina

The disposal of photovoltaic waste in Argentina is based on the management of Waste Electrical and Electronic Equipment (WEEE), focusing on dismantling and recycling, since up to 90% of the panels can be recovered. There are specialized centers, such as Tecnorrae in Buenos Aires, that manage this waste, including the separation of materials such as glass and aluminum, complying with environmental standards.

As for wind turbine waste, including metal towers and foundations, it is managed through conventional recycling, while fiberglass blades present challenges, opting for shredding for use in construction materials or thermal recovery in cement kilns to promote the circular economy.

Brazil

The disposal of photovoltaic waste in Brazil is governed by the National Solid Waste Policy (PNRS), which requires proper disposal to avoid contamination, although specific legislation is still missing. Currently, companies such as SunR recycle more than 80% of the modules, recovering materials such as aluminum and silicon, promoting reverse logistics.

The disposal of wind turbine waste in Brazil, especially fiberglass blades, is evolving towards the circular economy, driven by the need to recycle components at the end of their useful life. Although up to 90% of a wind turbine (steel, copper) is recyclable, the blades represent a greater challenge, looking for alternatives such as shredding for construction materials and energy recovery

Chile

Chile is actively developing infrastructure for the recycling of photovoltaic panels, with a view to managing the more than 120,000 tons of waste projected for 2046.

Companies such as Hidronor (Antofagasta), Solar Recycling, Rodmik and Solek lead the recovery of aluminum, copper and glass, complying with the Extended Producer Responsibility Law (EPR) and promoting the circular economy.

The disposal of wind turbine waste in Chile focuses on recycling approximately 85% of the structure (metals, electrical components). The biggest challenge lies in fiberglass blades, which are currently reused in infrastructure or disposed of in landfills, although the industry is looking for recovery technologies.

Colombia

The disposal of photovoltaic waste in Colombia is at an early stage, characterized by a limited recycling infrastructure and the absence of detailed specific regulations, facing increasing challenges due to the useful life of the first systems installed. Currently, they are managed under the general framework for Waste Electrical and Electronic Equipment (WEEE), which prohibits their incineration or open-air disposal.

The disposal of wind turbine waste in Colombia focuses on the circular economy, allowing up to 90% of the structure to be recycled, mainly steel, copper and aluminum from towers and cables. However, blades (glass fiber/epoxy composites) present a technical challenge, with current approaches relying on shredding for use as construction materials or on energy co-processing in cement kilns.

Ecuador

In Ecuador, regulations governing the disposal of solar panel waste are included within the extended producer responsibility framework for the management of Waste Electrical and Electronic Equipment (WEEE). This framework applies to manufacturers, assemblers, importers, and any natural or legal person placing such equipment on the market (MAATE, 2022). Ecuador is currently working on a roadmap for lithium battery waste management.

Mexico

The disposal of photovoltaic waste in Mexico is at an early stage of development, without specific federal regulation, but with a growing focus on circular economy. An exponential increase in this waste is estimated, promoting the need to recycle components such as aluminum, glass and silicon, recovering up to 96% of the materials. Pioneering initiatives such as the Rafiqui association already operate management programs.

The disposal of wind turbine waste in Mexico focuses on the recycling of 90% of the materials (steel, copper) and the rest of the blades, composed of fiberglass and resin, which usually end up in landfills or be shredded for construction materials. Between 2026 and 2037, more than 1,200 turbines are expected to be decommissioned, prompting companies such as Grupo Sasti to seek reuse solutions.

Uruguay

The disposal of photovoltaic waste in Uruguay is part of the national regulations on waste management and circular economy, focusing on recovery and recycling (up to 90% of materials) to reduce environmental impact, under the responsibility of the generator. Private companies manage components such as glass, aluminum and silicon, ensuring the correct arrangement.

The disposal of wind turbine waste in Uruguay, focused on components such as towers, nacelles and blades at the end of their useful life, prioritizes the recycling of steel and copper (up to 90% of the total). The biggest technical challenge lies in fiberglass blades, for which grinding techniques for construction materials and energy recovery are explored, in line with a circular economy approach.

The Government of Uruguay, through Decree No. 227/025 published on November 5, 2025, issued regulations for the management of battery waste, including batteries used in electric vehicles. Article 3 of the Decree establishes the following:

a. The minimization of battery waste generation will be prioritized, compared to any other alternative, seeking to maximize its useful life, through the application of good management practices, best available technologies for recharging and improvement of the quality and durability of its components. The Ministry of Environment, in coordination with the Ministry of Industry, Energy and Mining, may establish specific requirements to be met to achieve the minimization of the generation of waste from batteries.

b. As a complementary measure, second-life applications, recycling processes, and other forms of battery waste recovery shall be promoted, with priority given in this order.

c. Treatment and final disposal shall be considered measures of last resort, and any environmental impacts arising from them shall be minimized.

d. The different stages of waste management must be executed through formal activities, which have the corresponding authorizations and ensure compliance with the appropriate environmental and health conditions.

e. National recovery will be prioritized, if there are installed capacities authorized by the Ministry of Environment for the type of battery to be managed and provided that this does not generate unequal conditions of competition or serious damage to the national economy.

8. Conclusions

The projections presented in this Technical Note indicate that the quantities of materials expected to be contained in the technological devices involved in the energy transition in LAC—such as photovoltaic panels, lithium-ion batteries, and wind turbines—over the next 25 years will be substantial. It would be about 81 million tons in 2050, of which 36 million tons would be steel, representing 63% of the current annual production of steel in LAC; 4 million tons would be copper equivalent to 40% of the current annual production of copper in this region and 10 million tons would be aluminum, almost triple the current annual production of this metal in LAC, so its recycling will mean significant savings both in the cost of production of these metals and in reducing the environmental impact in mining and industrial processing activities. The remaining 31 million tons of materials correspond to other components such as glass, silicon, silver, graphite, polymers, fiberglass, resins and metal oxides.

Based on the current average market prices of the constituent materials used in the technologies analyzed and their corresponding recovery rates for recycling, the potentially recoverable economic value of these materials is estimated to reach USD 84 billion by 2035 and USD 209 billion by 2050.

Although the useful life of photovoltaic panels and wind turbines is around 30 years, many of these devices are discarded before their useful life ends, due to technological updating and premature breakdowns, so recycling opportunities can occur continuously.

As for the disposal of large-scale lithium batteries in the region, although there is not yet a significant demand, due to the fact that electromobility is a relatively recent issue and the banks of backup batteries of electrical generation systems are in a very early stage, due to the polluting potential of some of their components, strategies must be started to be designed for their disposal.

The management of waste from energy transition technologies should not be viewed solely as an environmental challenge, but also as an opportunity to foster regional circular economy value chains, the recovery of critical minerals, and new industrial capabilities related to the recycling and recovery of strategic materials.

In this context, LAC countries should strengthen specific regulatory frameworks, extended producer responsibility schemes, traceability systems, and reverse logistics programs, while also enhancing regional capacities for the recycling and recovery of materials from energy technologies.

Artificial intelligence can become a key enabler of the circular economy in energy technologies by extending the lifetime of photovoltaic panels, wind turbines, and energy storage systems through intelligent monitoring and predictive maintenance strategies. In addition, the application of digital tools to the reuse, second-life, and recycling of lithium-ion batteries can help maximize the recovery of critical materials, reduce waste generation, and strengthen value chains associated with the energy transition.

The development of regional capacities in digitization, data analysis and artificial intelligence will allow LAC countries to improve the management of technological waste, increase the efficiency of recovery processes and consolidate circular economy models oriented to long-term sustainability.

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olacde

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