Connecting the Raw Materials Transition and the Energy Transition

Improving the Circular Economy in the Renewable Energy Sector

PowerShift


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Contents

This study highlights the urgent need for a more sustainable and equitable approach to the global energy transition. It emphasizes the importance of using metals more modestly and creating a circular economy to protect both the environment and human rights.

Executive Summary

Five key findings are presented in this study:

1 Metals are crucial for the energy transition. The shift towards renewable energy sources such as photovoltaic (PV) panels and wind turbines necessitates the use of various metals. The prior PowerShift study “Metals for the energy transition”[1] showed, that a large share of common demand projections is caused by the automobile industry, and that renewable energy production is not generally more metal intensive than fossil energy production. Nevertheless, there is no doubt that we will need a substantial amount of metals for the transition to renewable energy production.

2 Mining projects often have negative consequences. The extraction of metals for renewable energy technologies frequently leads to human rights violations and environmental degradation. This underscores the need for a more modest approach to metal usage in order to reduce the negative impacts of mining.

3 In the coming years a large amount of wind turbines and PV modules in Germany will drop out of the EEG subsidy program and will be replaced by newer, more efficient models. The old ones need to be kept in the loop through secondary use or recycling, rather than becoming waste, i.e. lost material.

4 To address this, the study advocates for further development of a circular economy. This approach involves rethinking, reducing, reusing, repairing, and recycling materials, minimizing waste, and extending the life cycle of products. Future PV modules and wind turbines should be designed to be more durable, modular, and repairable. Additionally, finding secondary use options or recycling PV modules and wind turbines at the end of their life cycle will help keep metals in the loop, reducing the demand for new mining projects.

5 Sufficiency and demand reduction as a key component: The study highlights the need for sufficiency measures to reduce overall demand for resources. By promoting energy-efficiency, lifestyle changes, and sustainable consumption patterns, we can alleviate pressure on the environment and natural resources.

To achieve these objectives, the study puts forth several political demands:

1 Implement strict regulations and standards for mining projects, metal, PV and wind turbine production to protect human rights and the environment, such as the EU battery regulation with its recycling and recycling-input rates as well as the forthcoming EU Due Diligence Act.

2 Encourage and support research and development of more durable, repairable and modular renewable energy technologies as well as finding ways of reusing old components.

3 Establish policies that promote the circular economy, including incentives for businesses that prioritize circular design, reduction, reuse, repair, and recycling.

4 Improve the collection, refurbishing and recycling infrastructure, in order to be ready to process the expected growing amounts of outranged PV modules and wind turbines. Create decentral collection where possible and scalable recycling options where needed.

5 Implement sufficiency measures and policies to reduce demand for resources, such as the transformation of other sectors, such as mobility and construction, promoting energy efficiency, sustainable consumption, and behavioral changes.

In conclusion, the study highlights the critical need for more a resource sufficient economic approach that aims at a reduction of the overall material demand in order to secure raw materials needed for the energy transition. It shows how both the energy transition and the raw material transition (i.e. the overall reduction of material demands outlined in the study “12 arguments for a raw materials transition”)[2] can be supported by adopting circular economy principles. This will not only help protect the environment and human rights but also accelerate the shift towards a truly sustainable and equitable global energy system.

Introduction

Many metals are processed in wind power and PV plants. The production of metals from ores is very energy-intensive. Photo: yasin hm, Unsplash

After a political thwarting of the energy transition in Germany in recent years, the danger of heavy dependence on fossil resources has been highlighted by Russia's invasion of Ukraine and associated geostrategic conflicts. The absence of gas deliveries from Russia left German politics and industry ill-prepared, and large price increases for private and industrial customers were the result. Although the German government reacted with a rapid expansion of LNG (liquefied natural gas) terminals and a search for new sources of raw materials for oil, natural gas and hard coal, there exists a threat of creating new dependencies and solidifying old ones. At the same time, German Finance Minister Christian Lindner (FDP) has emphasised support for the expansion of renewable energies: "We are backing freedom energies." This expansion of wind and solar plants, now being pushed by German Minister of Economic Affairs and Climate Action Robert Habeck (Green), has large material requirements. A wind turbine, for example, consists of up to 80 tonnes of steel and 8 to 30 tonnes of copper. In photovoltaic plants, 170 tonnes of iron and 4.5 tonnes of copper are used per MW of installed capacity.[3] Until now, German industry has imported some of the raw materials it needs from Russia, such as copper, iron, nickel and aluminium.[4]

The European Union is also striving to advance both decarbonisation and independence from raw materials from non-democratic states. The implementation of the European Green Deal,[5] the introduction of human rights and environmental due diligence legislation[6], and the expansion of the circular economy[7] all point in the right direction. However, in order to reduce the ecological, social and climate consequences of metal consumption in the medium and long term, a raw materials transition is needed. The goal of the raw material transition is to reduce demand for metal. Sector-specific targets are an important lever. The energy sector is challenged

This iron mine is located in the middle of the Carajás National Park in Brazil.
Photo: Marcelo Correa, Flickr.com

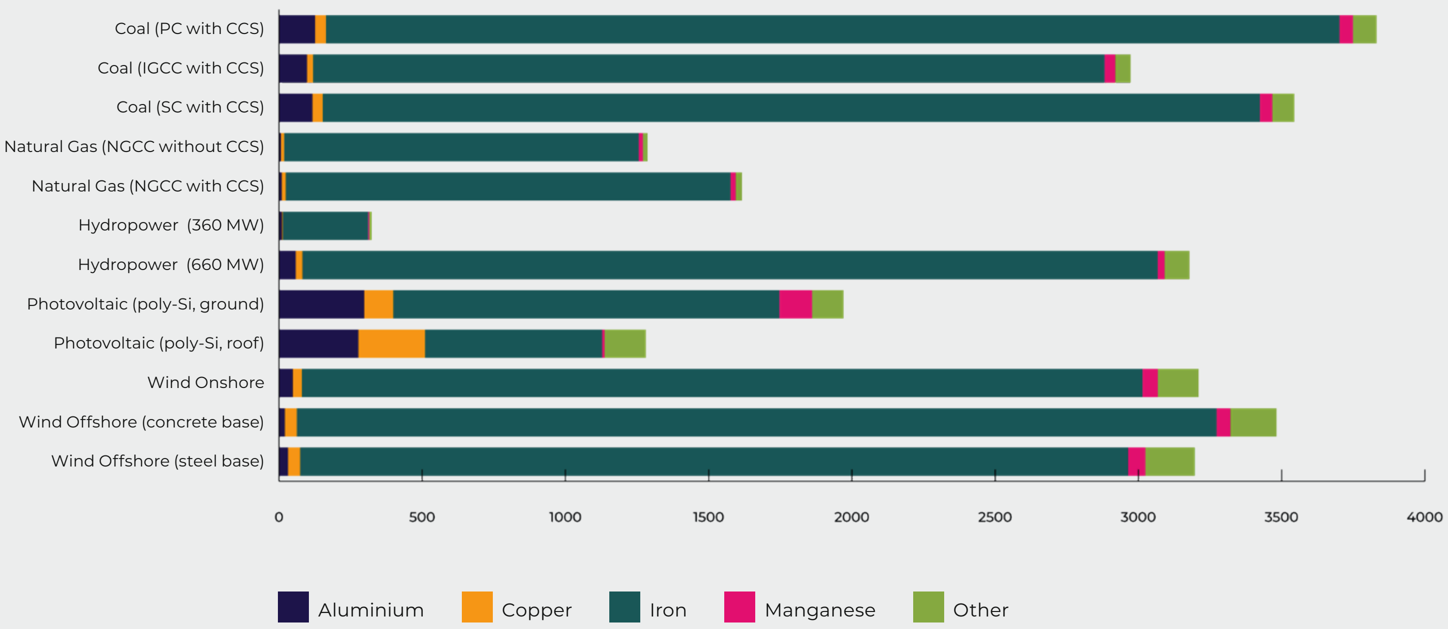
in a different way than the mobility sector, as there is no alternative to the expansion of renewable energies, which must be given priority. In the mobility sector though, we need a rapid shift away from motorised individual transport in addition to a conversion to electric engines. A new car in Germany weighs 1.6 tonnes on average and car production requires many times more raw materials than wind power and PV plants. There is no way around the need to reduce metal consumption in the mobility sector by drastically reducing the number and size of cars.

The Human Cost of Mining

Examples of human rights violations and environmental destruction through mining can be found on all continents. Protests against mining are often motivated by the consequences for the local population and their environment, but even mining in general can be reason for protest. Again and again, protests are criminalised and sometimes violently suppressed.[8]

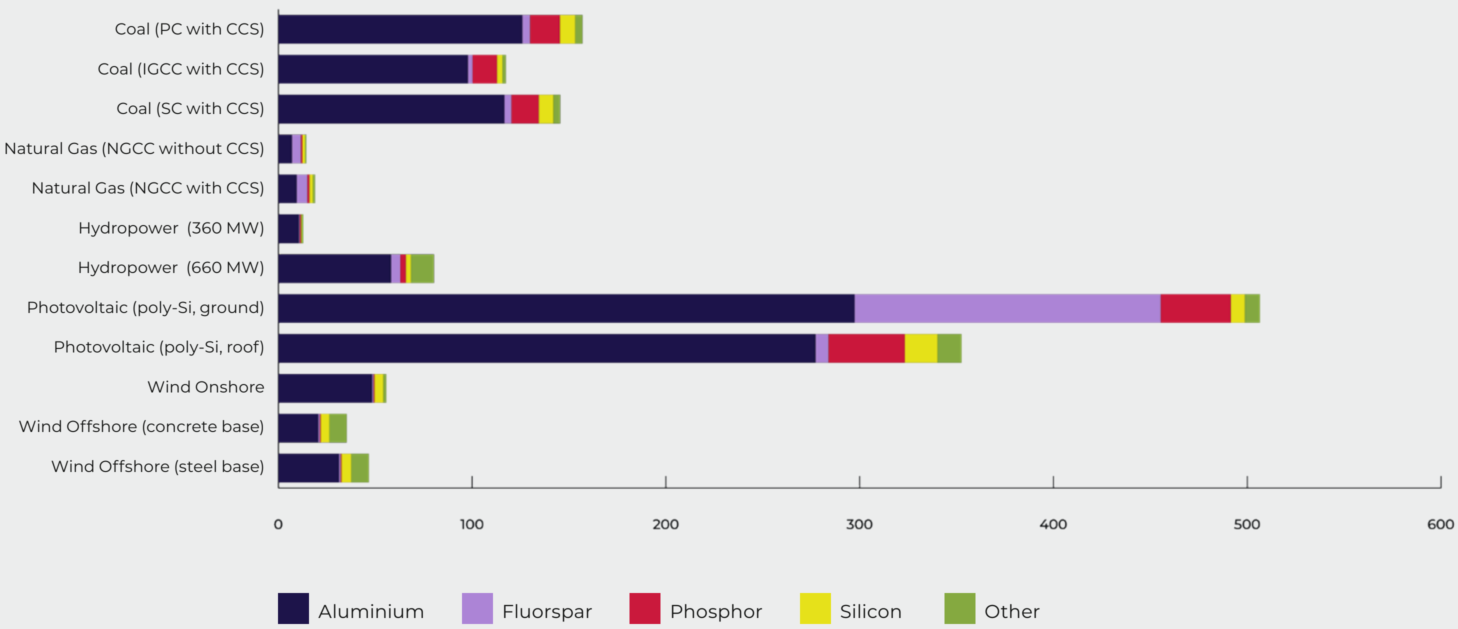
A total of 1,733 environmentalists and land defenders have been murdered in the last ten years, as documented by the British NGO Global Witness. Mining is one of the most dangerous and risky industrial sectors to oppose.[9] In addition, mining poses further ecological risks. Water consumption and the use of chemicals are immense, lower grades of ore in future mines increase the risks. Furthermore, mining is responsible for deforestation in many regions. In addition, up to 15 percent of global CO_2 emissions are caused by ore mining and the processing of primary metals.[10]

Figure 1 – Metal requirements for selected energy technologies in g per MWh



Own depiction,
data by the Luxembourg Institute of Science and Technology (LIST) on behalf of UNECE (2021):
Life Cycle Assessment of Electricity Generation Options. United Nations Economic Commission for Europe

Figure 2 – Demand for critical raw materials for selected energy technologies in g per MWh



Own depiction,
data by the Luxembourg Institute of Science and Technology (LIST) on behalf of UNECE (2021):
Life Cycle Assessment of Electricity Generation Options. United Nations Economic Commission for Europe

Human Cost of Mining

Resettlement in Guinea

Nearly all of Germany's bauxite imports come from Guinea. A mine in the Boké region was expanded with the support of the German government. In 2021, amid the Corona pandemic, 105 families were resettled on barren land in houses which were not weather-proof. The land had not been sufficiently recultivated beforehand. Only six manual water pumps are available to supply the resettled population with water, making agriculture, and thereby earning one's own living, impossible.

Unrest in Peru

The civil society network Observatorio de Conflictos Mineros de América Latina (OCMAL, Observatory of Mining Conflicts in Latin America) reports that mining projects in Peru are the biggest trigger for social conflicts, and that copper mines play a significant role in this.[11]

Deadly Protests in the Philippines

There is also resistance to copper mining in the Philippines, where the largest copper-gold deposit in Southeast Asia is at the centre of a bloody conflict.[12] For more than 30 years, Australian, Swiss and local mining companies have been trying to build a mine in Tampakan, Mindanao. But massive protests by indigenous communities, civil society and the Catholic Church have so far been successful. In return, more than a dozen soldiers and indigenous people have lost their lives in the conflict, including Juvy Capion and her two sons.[13] She was killed by the military in a dawn attack on 18 October 2012. The target of the attack was her husband and the father of their sons, Daguil Capion, one of the leaders of the protests. He faced criminal accusations and turned himself in after the death of his wife and sons, but was released due to a lack of evidence of involvement in attacks on soldiers.[14]

To avoid such bloody conflicts and other mining-related human rights violations, a socio-ecological transformation of the economy and a 'raw materials transition'[15] with clear targets for circular usage and reduction are necessary.[16] Even if, contrary to public debate, the expansion of wind and solar plants are not the biggest drivers of high metal consumption,[17] the renewable energy industry must address raw material procurement, raw material use, as well as waste generation and the circular usage of raw materials. In our recently published study "Metals for the Energy Transition", we examined which metallic raw materials are needed for the German 'Energiewende' and to what extent. Two things became clear: Firstly, the metal intensity of renewable energies does not differ significantly from energy production based on fossil resources (see Figure 1). On the contrary, the metal requirement of solar power plants, for example, is significantly lower than that of coal-fired power plants. In terms of critical raw materials[18] wind power plants, for example, require significantly less than coal-fired power plants (see Figure 2).

The results are based on a life-cycle analysis of different energy production technologies by the Luxembourg Institute of Science and Technology (LIST) for the UNECE study "Carbon Neutrality in the UNECE Region: Integrated Life Cycle Assessment of Electricity Sources". Secondly, the demand relating to the expansion of wind and solar power plants is low compared to electromobility. The batteries for projected Volkswagen electric car sales in 2030 alone would need a total of about eight times as much aluminium and nickel in comparison to the total planned addition of wind turbines in Germany from 2022 to 2030.[19]

Although the metal requirements of wind and solar power plants are lower than those of electromobility, overall, they are still high. There are, however, practicable alternatives to electromobility, for example by expanding local and long-distance public transport, or giving preference to other modes of transport, such as cycling or walking. This is different with renewables. Here we will also have to use metallic raw materials in the future. It is therefore all the more important that wind and solar power plants use their circularity potential to reduce the consumption of primary raw materials.

In this study, we examine:

- the potential and current status of recycled material use in the renewable energy sector in Germany and Europe;
- how recycling and closed-loop circular usage potentials are currently being researched and used; and
- what economic, political and legal leverage exists along the production chains to encourage recycling?

Taking Stock of the Circular Economy – Where Do We Stand?

Unused warehouses and machines, forgotten cables and pipes, small electronic devices in drawers and on shelves – a long list of metals no longer in use. Photo: Peter Herrmann, Unsplash

By circular economy we mean a holistic economic practice that, to the greatest extent possible, does not produce waste. This means that all materials are always reused in closed cycles. Due to their properties, metals offer particularly great potential for such a circular economy and today are already recycled, relatively often. Our understanding of recycling implies that the recovered metals are equally reintroduced into future production processes and not used in downcycling, i.e. becoming an inferior product. This systemic solution framework contrasts with the current so-called linear economic model, in which products move from production to use and then directly to disposal. The idea of linking production and end-of-life ("cradle to cradle" principle) dates back to the 1990s. Since then, the concept of recycling has been developed further and its implementation in industry and society has been tested.[20]

The European Commission defines circular economy more extensively than the German definition: "The aim of a circular economy is to maintain the value of products, materials and resources for as long as possible by returning them to the product cycle at the end of their useful life, while at the same time generating as little waste as possible."[21] In contrast, the German Circular Economy Act, passed in 2012, sees itself more as a "duty to avoid waste" and obliges the "producers or owners of waste [...]" to recycle their waste. The recovery of waste has priority over its disposal".[22] Until now, there has been a lack of understanding that these are valuable raw material sources, rather than waste that has to be avoided and managed. Therefore, the focus in the previous Circular Economy Act was on increasing recycling quotas, which includes downcycling. It is only with the coalition agreement of the SPD, the Greens and the FDP of 2021 that there are signs of a more holistic understanding of circular economy, which could lead to a fundamental change in production processes and consumption habits.[23]

Only a third of electronic equipment is recycled. The vast majority is exported illegally or ends up unregistered in household waste and landfills. Photo: Emmet / pexels.com

In principle, the recirculation of metals is not loss-free. There are losses at various points in a life cycle – collection, sorting, separation, processing, refining, and smelting, pre-production, production, and use. Metals dissipate, meaning these “lost metals” escape future human use because the energy required to recover them is too high or recovery is technically impossible. An example of this is fine particles that dissipate through abrasion and become dispersed in the environment. For example, platinum particles from catalytic converters are distributed in small quantities on roads. These particles cannot be recovered due to the huge energy expense that would be necessary, so the platinum dissipates. The same applies to minute quantities in electronic devices, for example nanoparticles, which end up mixed with other waste in landfills.

Getting close to one hundred percent recycling of materials is, therefore, not possible. As a result, primary raw materials must be continuously introduced into the system in order to maintain it.

Nevertheless, there are many approaches and possibilities to significantly reduce the consumption of primary raw materials. Possible solutions lie in longer service life, reparability or in a product design that is geared towards material recovery. It is important to note that there is not one (!) solution and that in some cases, there are conflicting goals. Gentle production processes as well as efficient collection, separation and recovery of metals help to increase the recycling rate and thus reduce primary consumption. At the same time, extended use and ease of repair, in addition to resource savings, also leads to less material being available for recycling.

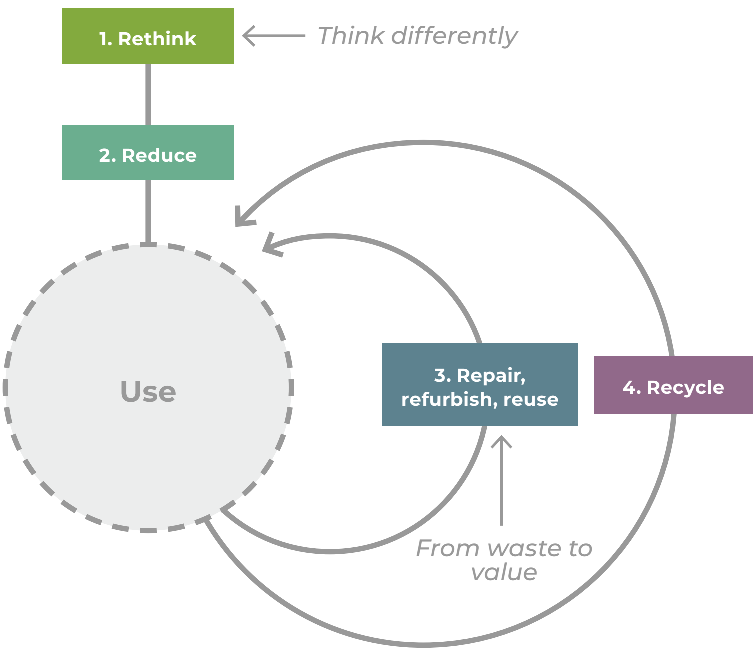
Principles of the Circular Economy

The basic principles of circular economy apply to all products and materials. However, for the purpose of this paper, we are explaining these within the context of the renewable energy sector and the metals used therein (see Figure 3). Figure 4 illustrates reduction potentials for different critical metals within the different steps of circularity.

Rethink: Rethinking in this case could mean finding ways to reduce overall energy and material demand e.g. by moving away from our material intensive (auto)mobility system towards fewer and smaller vehicles and more alternative and public transport.

Reduce: The second principle involves switching existing technologies to new ones that contain fewer critical metals. Substitution of materials can be implemented in wind turbines or system batteries, for example.

Figure 3 – Leveraging circular principles during the life cycle of metals



Source: Metabolic Institute, Copper 8, Polaris Sustainability & Quintel (2021): Exploring solutions to mitigate surging demand for critical metals in the energy transition.

Repair, refurbish and repurpose: The third principle is to extend the life of products and individual parts. This includes, for example, the reuse of solar cells, permanent magnets in wind turbines or batteries for electric vehicles.

Recycle: The fourth and final principle is the recovery of raw materials at the end of a product's life cycle.[24]

For different metals relevant to energy transition, consumption can be reduced by leveraging these principles (see Figure 4). The major metals aluminium, copper and iron are not listed, but have large shares in the production of renewable energy technologies (EET) in terms of quantity, which presents major potential for recycling as well as reduction.

A study published by the European Environment Agency (EEA) presents a model for a circular energy system. In this model, circular optimisation is used throughout the life cycle of EET.[25] This optimisation starts at the production source, i.e., with the materials, where the use of primary raw materials and the extraction of raw materials will be reduced. More circular optimisation is to be used in the design, which should increase sustainability and recyclability and reduce the use of toxic substances to a minimum. This link in the circularity chain is fundamental because it sets the conditions for all subsequent steps.

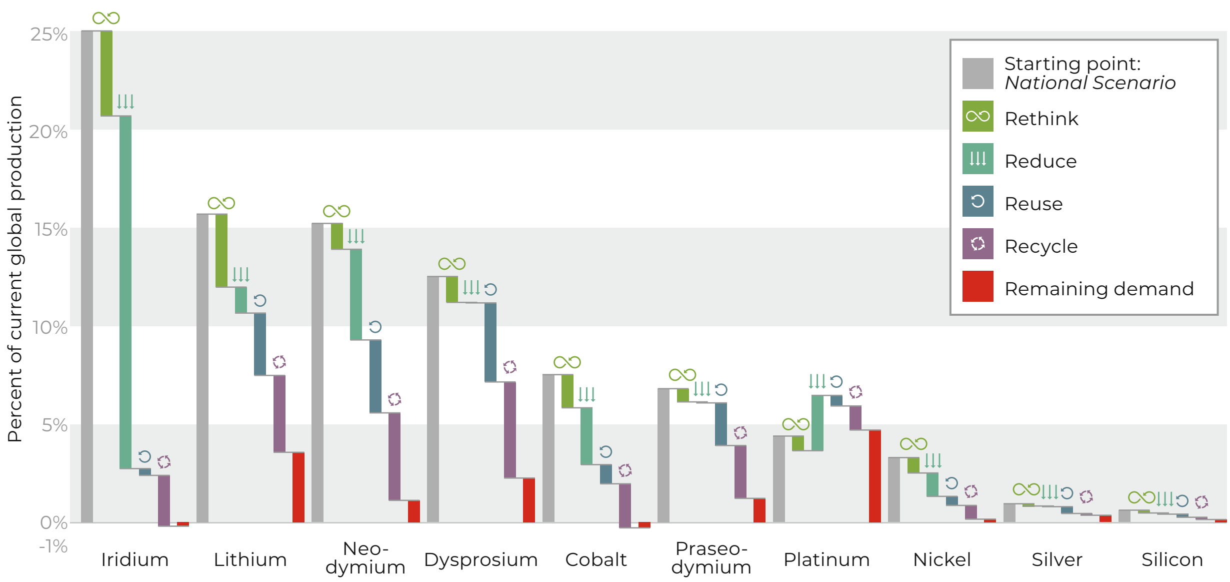
Only then are production and distribution considered. For this, the EEA emphasises an efficient and resource-saving production model as well as innovative business models based on leasing instead of ownership. Later in this publication, we will address criticism of the leasing model.

During usage, services for repair, upgrades and maintenance throughout a life cycle are important to enable the longest possible use. When the end of the first life cycle is reached, effective collection and sorting infrastructure, recycling and material reprocessing, and return-to-production processes must be ensured to close the material loop.[26]

The EU has adopted a number of circular economy laws over the last few years, most recently the Circular Economy Action Plan (CEAP) in 2015. Since 2022, circularity management standards have also been developed for different industrial sectors. This includes textiles, chemicals, electronic devices, batteries and vehicles. Then again, the current recirculation rate of materials in the EU is only 11.8 percent.[27] This is partly because manufacturers have little data on circularity along their supply chain. Mandatory life cycle assessments could help identify circularity potentials and at the same time provide an overview of greenhouse gas emissions that occur over the entire life cycle of a product. Some research projects on life cycle management potentials for renewable energy technologies refer to the Waste from Electrical and Electronic Equipment Directive (WEEE),[28] which now also applies to solar modules. Since its inclusion in WEEE, solar manufacturers have been subject to legal requirements including responsibility for registration to a national register and product recall.

Another concrete example of circular economy principles in the EU are the eco-design guidelines (Design for Recycling or D4R), which explain how products should be designed: Designers must consider a product's waste stream from the conception stage, and plan so that the product or its individual components can be collected, sorted and effectively recycled to the highest standards. Although the focus here is currently still mainly on plastic products, the extent to which this concept could be transferred to metallic products should be examined. It is important that D4R principles are developed per product and material, yet at the same time are adapted to local or regional frameworks. After all, in order to implement the directive successfully, it must be ensured that a material or product can be processed in local waste management at the end of its cycle. On the part of national policy however, this also means that seamless and area-wide processes for efficient collection, separation and recovery of materials must be accessible, guaranteed, and promoted.

Figure 4 – Leveraging circular principles in the recycling of different metals



Source: Metabolic Institute, Copper 8, Polaris Sustainability & Quintel (2021): Exploring solutions to mitigate surging demand for critical metals in the energy transition.

Savings Potential Through Recycling

Sustainable use of raw materials in harmony with climate, environmental and human rights goals requires a raw materials transition. This includes a significant reduction in the consumption of primary raw materials. The reuse of metallic raw materials can make an important contribution to this. The expansion of the industrial use of recycled material and secondary metals saves enormous amounts of primary resources. At the same time, energy consumption associated with extraction, processing and transport, environmental damage and human rights risks along the often opaque mining supply chains are reduced.

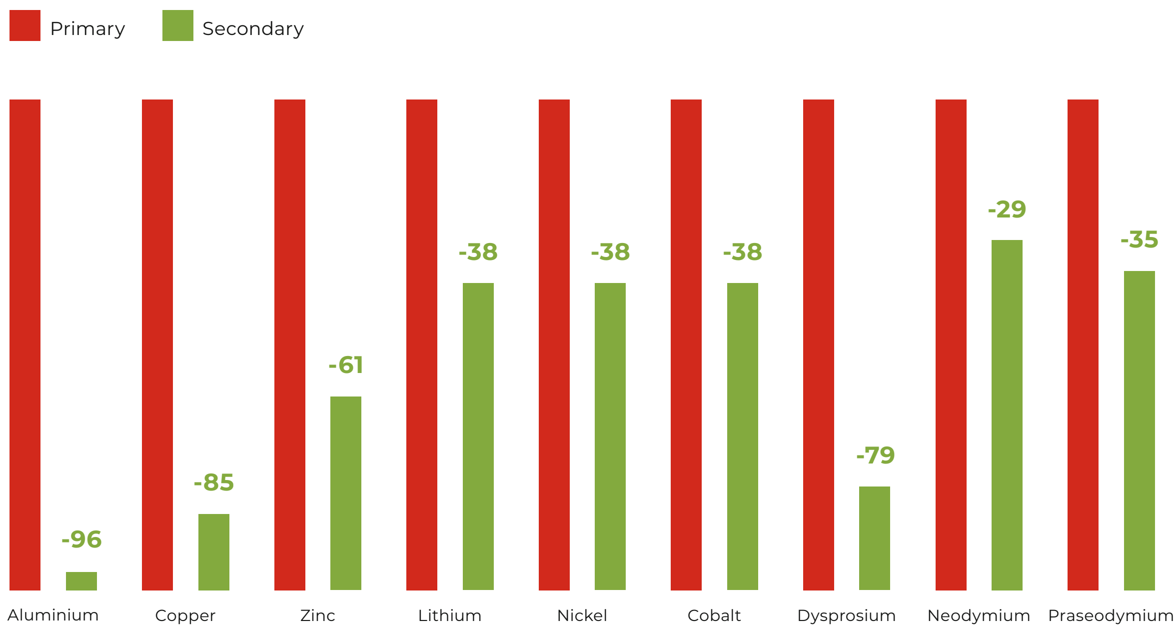
A study by KU Leuven on behalf of the European non-ferrous metals association Eurometaux has clarified the potential for saving CO_2 emissions through the use of recycled material (see Figure 5). The 96 percent saving for aluminium is particularly remarkable, as it illustrates how energy-intensive the processing of bauxite into aluminium is during primary production. Although bauxite and aluminium account for only 1.9 percent of the metals mined in 2019,[29] its processing makes up two[30] to three[31] percent of global CO_2 emissions.

The energy savings and resulting massive reduction of CO_2 emissions through the use of secondary material would both relieve the climate and reduce mining pressure in some regions.

There is also great potential for savings in steel production. Iron ore, the basic material for steel, accounts for 93.6 percent of the mass of metals extracted by mining in 2019.[32] Further processing into steel accounts for eight[33] to eleven[34] percent of global CO_2 emissions. With these volume shares, a transformation to circular economy is desirable, especially in the steel sector. According to a study by Clare Broadbent, using scrap steel instead of mined iron ore would lead to savings of 73 percent for CO_2 emissions, 64 percent for processing energy, and 90 percent in terms of raw material.[35]

Together with copper (up to 85 percent CO_2 savings through recycling),[36] these two metals are needed most for the energy transition in terms of quantity (see Figure 1 on page 8). An increase in recycling rates would have a particularly large effect on people and the climate, due to the quantities involved.

Figure 5 – Comparative CO_2 savings (in %) of metals and their recycled material



Own Depiction.
Source: Gregoir, Liesbet (2022): Metals for Clean Energy. Pathways to solving Europe's raw materials challenge. KU Leuven.

Product-related requirements for recycling and the use of recycled materials – an example from EU Battery Regulation

The European Union is currently revising the European Battery Regulation as part of the European Green Deal. It is expected that by the end of 2022, EU member states, the EU Commission and the EU Parliament will have agreed on new standards in battery production. The standards will serve as a basis for further product-related standards to be developed within the framework of the Green Deal. This could also include specifications for manufacturers of solar and wind power plants. It is therefore worth taking a look at the EU Commission's proposed regulations from December 2020, in which the EU prescribes minimum collection targets for spent portable batteries for its member states. By 31st December 2025, 65 percent of all batteries are to be collected. By 31st December 2030, 70 percent. The recycling rates of raw materials from these batteries are also to be successively increased and by 2030 should have risen to 95 percent for cobalt, nickel, copper and lead. For lithium, it should be 70 percent, although this value is still controversial. EU parliamentarians in particular consider this value to be too low. From 1st January 2030, recycling regulations will also apply. In batteries, at least 4 percent of lithium and nickel, 12 percent of cobalt and 85 percent of lead must come from recycled products. This value is to increase to 10 percent for lithium, 12 percent for nickel, 20 percent for cobalt and 85 percent for lead by 1st January 2035.[69]

In reality, current recycling capacities and technologies in Europe and worldwide are significantly underdeveloped. According to a study by Material Economics for example, a large portion of Europe's steel demand could be covered by secondary production:

> *"Our analysis shows that if downgrading of steel is avoided, secondary steel production could meet as much as 85 percent of the EU's steel needs by 2050. (...) Realising this opportunity will require significant changes to minimise losses in volume and quality from one use cycle to the next. The contamination of steel with copper could pose particular challenges. EU secondary steel production would also have to be restructured, while continued primary production would be more focussed on exports. However, the industry already faces major challenges: global overcapacity, flagging profitability, high CO_2 emissions, and the threat of tariffs. A circular steel economy offers a promising path forward by boosting productivity and making the EU a pioneer and leader in the technologies of the future."* [37]

This could lead to massive savings in CO_2 emissions in steel production. The study also verified great potential for emissions reduction for aluminium through increased circularity management.[38]

A large part of the steel demand could be supplied from recycled material which would relieve people, the environment and the climate. Photo: yasin hm, Unsplash

Recycling scrap reduces CO_2 emissions and mining.
Photo: PowerShift e.V.

Resource Efficiency and Sufficiency – Using Materials Modestly and Reducing Overall Demand

Necessary precision work, the construction of PV systems.
Photo: Newpowa, Unsplash

Over the past decades, research and development in the field of renewable energies has benefited from numerous investments and targeted subsidies. Emerging technologies have made great strides in the areas of efficiency, resource and land conservation.

Currently, most commercially available PV panels have an efficiency of about 20 to 22 percent in converting sunlight into electricity. Prototype solar cells in a laboratory have achieved an efficiency of 39 percent in non-concentrated sunlight, and 47 percent in concentrated sunlight. There is still considerable room for improvement when it comes to commercial solar cells.[39]

In addition, the production of photovoltaic modules within Europe can greatly reduce CO_2 emissions from EET, not least due to lower emissions from transport. According to calculations by the Fraunhofer Institute, reducing imports from countries such as China, where production is heavily dependent on fossil fuels, could save up to 40 percent of CO_2 emissions from solar module production.[40]

Further developments in wind turbines also now allow fewer turbines to generate the same amount of electricity. In a recent article by Hans-Josef Fell and Thure Traber, "Germany does not need more wind turbines", the two renewable energy experts explain that in order to add 64 GW of wind capacity by 2030, significantly fewer wind turbines would have to be commissioned than before, thanks to the use of new and modernised turbines. According to their calculation, "with an average connected load of 5MW per turbine, a total of 11,140 new and refurbished wind turbines would be needed. In total, therefore, if the whole of Germany were to be supplied with 100 percent renewable energy in all energy sectors – electricity, heat, transport, industry - about 24,000 wind turbines would have to be installed by 2030, much less than the 30,000 turbines installed today." The two researchers determine that this means that the federal government's target of expanding the country's land area by two percent for the expansion of renewables for the currently needed 24,000 wind turbines would be sufficient. This, they write, could overtake the 2030 targets of 80 percent green electricity and even achieve 100 percent renewable energy supply.[41]

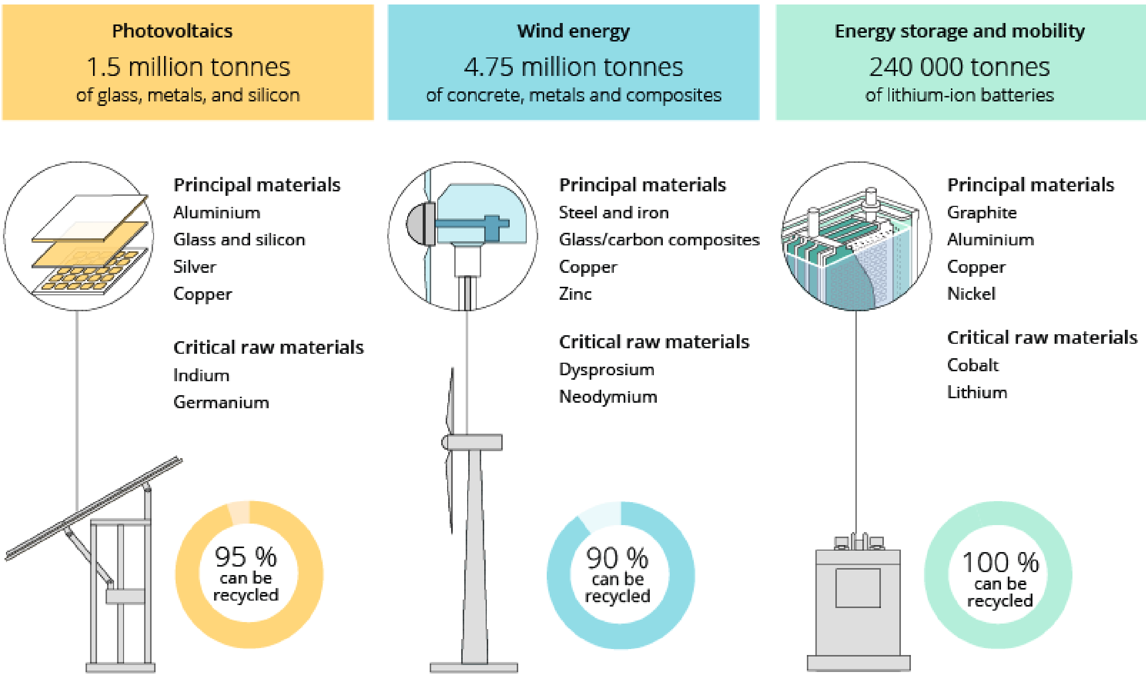
EET Sectors Under the Microscope – Where Potential Can Be Harnessed

Hopefully not a future scenario for PV and wind power plants: becoming mountains of scrap. Better to repair, replace, reuse and recycle. Photo: Eveline de Bruin, Pixabay

In Europe and especially Germany, many older solar and wind power plants will reach the end of their life cycle in the next few years. They could then be recycled and reused for the construction of new plants. The European Environment Agency expects a sharp increase in waste streams in this area by 2030. For example, the solar power industry is expected to produce up to 1.5 million tonnes of waste annually, composed of glass, metals and silicon. In the case of wind energy, the figure is almost five million tonnes of cement, metals and composite materials per year. These secondary raw materials must not be lost. All the more so because (metallic) raw materials used in EET have high recycling potentials. According to the European Environment Agency, the economically feasible recycling rates are 95 percent for solar plants, 90 percent for wind turbines and even 100 percent for batteries (Figure 6).[42] Of course, it lies in the control of politics whether and above what amount circular usage is economically profitable. Legal regulations, DIN standards for design, the WEEE and the European Waste Shipment Regulation, circular economy legislation, reporting obligations and, where applicable, subsidies have a strong influence on economic efficiency. Many environmental and social follow-up costs are not priced into mining, which is why the price of primary materials does not reflect the real cost.

Considering how easy it would be to combine human rights, the environment and climate with economic efficiency, recycling should be the first choice for metallic raw materials in the EET sector. What stands in the way of recovering these valuable raw materials? Why is there so little support so far for the recycling of strategically important products and their equally strategically important raw materials? The EEA estimates that this is largely because neither the technologies nor the markets in the EET sector are designed for reuse beyond their first life. Recycling fails due to the use of non-recyclable composites, for example in wind turbine rotor blades, the use of hazardous materials, and low concentrations of valuable elements within individual building components. In addition, logistical problems arise due to the remote locations, size and safety requirements related to the local energy infrastructure.[43] This makes, for example, the repair and replacement of smaller components expensive and unprofitable.

Figure 6 – Annual recycling potential of materials in the renewable energy sector until 2030



Source: European Environmental Agency (2021): Emerging waste streams. Opportunities and challenges of the clean-energy transition from a circular economy perspective.

For solar power systems, the challenges of the recycling processes are linked to their construction and material composition on the one hand, and to maintenance when installed at high altitudes on the other. Industry representatives emphasise that recycling has not yet reached a high level of economic efficiency and is therefore economically "uninteresting".[44]

In the case of wind turbines, according to the EEA, it is likely that the rising prices for rare earths will make the recycling of permanent magnet generators in wind turbines worthwhile in the future. Magnet production and the extraction of rare earths contained in them largely take place in China.

Since recycling is most likely to take place in already existing production facilities, reprocessing within the EU is unlikely for the time being. However, due to their size and durability, it is relatively straightforward to reuse the large permanent magnets from wind turbines.

The rotor blades pose a further challenge. Until now, it has not been possible to separate and recycle the glass and carbon fibre composites at the end of their life cycle. Some wind turbine manufacturers are, therefore, planning to use them as fuel in cement production, while others are researching product designs that can be recycled. One conflicting goal is to keep the weight as low as possible in order to save transport costs and emissions, but at the same time to use materials in the design that are as pure as possible, and which can be easily recycled afterwards. The establishment of a regional repair and recycling infrastructure with short transport routes for wind turbine components could solve this problem.

Every screw must fit, but circularity must also be designed into the product.
Photo: Los Muertos Crew, Pexels

Solar

In the solar sector, economic advantages have been documented through the use of recycling. Recycling raw materials from PV modules such as silicon, indium, gallium, glass, aluminium, copper, silver or germanium offers opportunities to use scarce raw materials for longer. According to the European Commission's Scientific Service (JRC), more than 95 percent of the material can already be recycled today, saving costs and time. New modules made from primary silicon require three times the production time of modules with the same output made from recycled materials, which makes the latter more cost-effective. However, the recycling market for solar modules is not yet fully developed. One reason for this so far has been the long product lifespan - 25 years or more - thanks to which the solar industry, which is considered a young technology, has generated little waste. According to JRC, only one percent of recyclable panels reached the end of their life cycle in 2017, which is why recycling was not yet economically viable.[45]

This is confirmed by a group of researchers who examined resource efficiency of PV modules and their corresponding recycling processes on the basis of life cycle analysis. The group around Fulvio Ardente writes that many solar cells have a longer lifespan than predicted. Due to insufficient recycling volumes and poorer quality of recycled materials, the profitability of the recycling sector is currently limited. Legal obligations, changes in consumer behaviour and, above all, optimised management of waste streams from solar installations are essential to prevent negative impacts on climate and environment and to minimise material losses of precious and rare raw materials: "Improper collection and/or disposal of PV waste leads to the loss of valuable resources and a proliferation of potentially hazardous substances contained in the modules."[46] Companies also complain about Germany's lack of transparency with regard to the disposal of solar power systems. The founder of a French PV recycling company explained that it was difficult for them to understand what happens to the modules at the end of their life cycle. After comparing installation and disposal figures, they suspect that a large part is illegally exported abroad and not recycled.[47]

According to the EEA, the solar power sector is expected to generate up to 1,500,000 tonnes of waste annually, and wind power almost 5,000,000 tonnes of waste (see Figure 6 on page 19).[48] By comparison, in 2016 the figure was only 100,000 tonnes of waste.[49] By 2050, the number of recyclable and reusable solar modules is expected to increase significantly, reaching between 60 and 75 million tonnes. In view of the associated negative environmental impacts and the potential loss of valuable resources, the industry is expected to future-proof itself according to these new market conditions: *"Recycling such volumes requires companies to be prepared by setting a standard for the industry."* [50]

Ardente's research group also compares the European FRELP (Full Recovery End of Life Photovoltaic) recycling process with standard processes in different member states and examines two optimisation approaches to minimise the climatic, environmental and social impacts caused by transport and incineration, as well as other steps. It becomes clear that FRELP is more complex and multiphase than conventional recycling processes and therefore involves higher energy, time and transport costs. However, the associated environmental impacts of FRELP recycling are marginal compared to the production and usage phases of solar modules. Enabling efficient recycling through political, regulatory and economic measures remains essential, because as the researchers write: "Despite the low recycling efficiency, the basic process is characterised by high environmental benefits, especially with regard to climate change."[51]

Researchers from FRELP told PowerShift that a lack of disassembled solar panels was sometimes their biggest obstacle. While in their pilot project "FRELP BY SUN" they are currently testing a new pilot plant that processes 30 PV panels per hour to recover top-class quality aluminium (16 percent), silicon (four percent) and white glass (65 percent),[52] the use of this technology in the market is not yet guaranteed.

FRELP is used by recyclers around the world, sometimes modified or with additional process steps by certain plant manufacturers, such as the VCT Group in Canada. The research group around Ardente has proposed improvements that enable synergies with each other. For one, the decentralised treatment of PV waste, i.e., the pretreatment of disposed solar modules, which makes it possible to sort out materials and manage them on site. This avoids transport and thus reduces the negative climate, environmental and social impacts by up to 32 percent. Pyrolysis treatment is applicable in smaller facilities and can significantly increase the efficiency of recycling processes, as treating smaller quantities also results in lower material losses. In addition, the negative effects on the environment and climate from pyrolysis are lower than with conventional and FRELP recycling processes. However, the pyrolysis treatment requires the use of fluorine-free backing films. According to the researchers, the development of supportive framework conditions should take into account that material- and product-specific goals are defined, laws are thought out concurrently with product design, and information on solar module composition is transparent and openly available.[53]

Aiming high: The German government has significant expansion targets, but the industry's efforts have been limited when it comes to questions of its own sustainability. Photo: Hans Linde, Pixabay

Wind

In order to obtain an overview of the application of circular economy concepts in the wind power industry, we analysed the annual reports (2020/21) of the leading wind power companies in Germany (Vestas, Enercon, Nordex, Siemens Gamesa, GE Renewable Energy). The various reports show that the companies' circular economy approaches are closely linked to science-based targets (SBTs), environmental management in accordance with ISO 14001, life cycle assessments in accordance with ISO 14040, and due diligence along the supply chains.

Within the framework of environmental management, key numerical data was identified and collected at all companies, and new collection mechanisms were planned for areas where data was previously lacking. All manufacturers except the American company GE Renewable Energy already use life cycle analyses to identify, exploit and permanently control recycling potentials, among other things. In some cases, manufacturers impose data collection and reporting obligations on their suppliers as well as the formulation of science-based targets, or plan to do so in the future in order to identify raw material consumption and recycling potentials, and to close knowledge gaps. Both data collection and reporting obligations on waste and recycling indicators along the supply chain are necessary to enable holistic, circular management, and to build synergies and material cycles across supply chains. However, companies provide only very limited information on their supply chains and not all set quantified targets.[54]

This shows the power of the large, international corporations over their supply chain. Vestas in particular, and to a lesser extent Siemens Gamesa, demonstrate this with quantified specifications and reporting obligations for supplier companies. The metal producers have a special position of power and responsibility here, as they control a comprehensive part of the value chain from mining and smelting to further processing and refinement.[55]

Where to put the old rotor blades? So far, the industry has given this question too little thought.
Photo: Photoholiday, Pixabay

Metals play a minor role in the reports of wind power companies. This is possibly because, unlike with rotor blades, companies assume that sufficient recycling capacity for metals are already in sight. In addition, recycling already makes economic sense today in view of the price development of metallic raw materials. Nevertheless, based on the reports, a future enhancement of the recycling potential of metals can be identified, in the smaller electrical components contained in the nacelle. With an improved capacity for repair, separation and sorting processes and a product design based on closed-loop circularity, it will also be possible to recycle small components through which several metals are processed efficiently and with lower losses. Rare earth elements are largely excluded from the reports. If mentioned at all, there are only unquantified declarations of intent to reduce consumption. So far, there is no recycling infrastructure for rare earths, although research projects have already investigated some promising recycling potential and methods.[56]

From Nordex's report, it has become clear there is an important difference between the recycling of one's own construction components at the end of the life cycle, and the recycled amounts in purchased components for new turbines.

According to Nordex, the problem lies in the hitherto incomplete data on primary and secondary material amounts along the supply chain. Nordex plans to close these gaps with its own life cycle analyses. Legal regulations and reporting obligations along the supply chain would improve the data situation across all sectors. So far, companies only provide information, if at all, on what proportion of their waste is recycled. No company discloses the proportion of secondary material that is used in the plants, because reliable data is still lacking.

Rotor blades play a more central role than metallic raw materials for all wind power companies. This is due to the impending end-of-life for first-generation wind turbines under the Renewable Energy Sources Act (EEG) of 2000. With the upcoming dismantling or repowering at the end of the 20-year EEG subsidy period, all companies will over the course of the next few years face a disposal problem regarding the lightweight but very large rotor blades, made of composite materials that are difficult to separate. Energy recovery in concrete production is also only possible for glass fibre models, as the carbon fibre versions of some rotor blades could clog the air filters of incineration plants, or trigger short-circuits due to their electrical conductivity.

High circular economy targets would also reduce dependency on raw materials. Photo: Hans Linde, Pixabay

Here, the sense and purpose of recyclable product design becomes particularly clear: there is a need to move away from increasingly complex materials that are difficult to separate from one another towards materials that are more pure and easier to recycle. Demonstration and research projects already exist in this regard.[57]

The industry association Wind Europe has set up a dismantling and decommissioning task force for rotor blade recycling, in which several wind turbine manufacturers participate.[58] Vestas has recycled the first 285 rotor blades in a pilot project in the USA and, like Siemens Gamesa, is part of the research projects CETEC (Circular Economy for Thermosets Epoxy Composites)[59] and DecomBlades[60], which are researching recycling methods and circular product design.

Both Vestas and Nordex are planning to expand their regional repair capacities in order to reduce transport costs and emissions, and to keep smaller construction components in use for longer instead of replacing them with new ones. Nordex addresses the disassembly and separation of components as a challenge in the report. The company refers to rotor blades and small electronic components within the turbine. In contrast to the already well-functioning recycling of unmixed industrial scrap or large construction components, there is still potential for expansion here.

What is striking in the reports is that many of the measures taken are voluntary. Participation in certification procedures is not mandatory and companies can set their own environmental and energy management targets. Nordex's stakeholder survey described in the report shows there is great interest in the industry for measurably increasing climate and environmental compatibility, as well as responsible supply chains and transparency. Nevertheless, the voluntary nature of the measures and targets leads to a disparity in the efforts undertaken, even within the wind power industry. While Vestas, for example, has presented a comprehensive circular economy strategy that includes the entire supply chain with quantifiable targets, General Electric's reporting hardly goes beyond statements of intent and employee training on waste prevention. Here, binding trans- or international regulations are urgently needed in order to achieve the often-cited level-playing-field, i.e., fair competition within a socially and ecologically acceptable framework.

In the areas of repowering and industry-wide dismantling standards (Enercon, Siemens Gamesa, Nordex), the wind power industry is in some cases even ahead of the legislative process and has already developed its own sustainability certifications. As praiseworthy as such initiatives may seem at first glance, the fact that companies and business associations are self-certifying instead of having this done by democratically controlled state agencies is critical. Clear legal regulations and administrative bodies that can enforce them are needed in a timely manner.[61]

Innovative Business Models – Circling Towards a Raw Materials Transition

Not only politicians and researchers, but also more and more companies are recognising the relevance of the use of recycled materials and circular management of metals and are testing their economic implementation in innovative business models. We have examined various approaches and talked to industry experts about potentials and challenges.

Much of the responsibility for implementing a circular economy in the renewable energy sector lies with solar and wind turbine manufacturers. Some manufacturers are paying attention to circular product design, increasingly considering raw material composition, separability and sortability for subsequent recycling.

- **Renting instead of buying as a business model:** In Germany, there are already some providers[62] who rent out solar plants instead of selling them. In this case the responsibility for and long-term management of the systems remain with the distributor. This means that providers are more strongly encouraged to develop solar systems that are as durable, repairable and recyclable as possible, and to maintain them for as long as possible through regular maintenance. Suppliers could thus reduce their costs and increase their security of supply through their own secondary material. However, there is a risk that leasing providers will charge excessive maintenance and repair costs due to their service monopoly. Legal regulations are needed here, for example to create competition between local maintenance and repair service providers and to prevent a repair licensing model in favour of individual companies.

- **A second life at RINOVASOL, Germany:** RINOVASOL refurbishes and recycles discarded PV modules. However, according to the company's management, more collection points are needed to enable circularity, because until now the industry has lacked recyclable modules. Moreover, used solar panels are often scrapped and sent for material recycling instead of being repaired. Refurbished industrial modules could be used by private individuals with lower productivity requirements far beyond their official lifespan. Besides this, the company is researching organic PV modules. In the future, individual components could be produced with local carbon-binding materials such as hemp. Rinovasol currently operates 40 sites in various countries.

- **Recycling at VCT Group, Canada:** "We are closely following the development of recycling options and look forward to a future where the solar industry achieves a truly circular economy," writes VCT Group on its website. However, so far the options for panel recycling have been severely limited. For large-scale installations the company says there are only accidental losses of one or two panels per project, mostly during the construction phase. As these are new projects, they say any expected mass retirement of panels is still decades away. Modules are mainly taken out of service because of damage caused by adverse weather conditions. Until the industry expands its capacity in Canada, the VCT is using two approaches: Broken modules are stored for the time being to keep them out of landfills or made available to hobbyists in the region.[63]

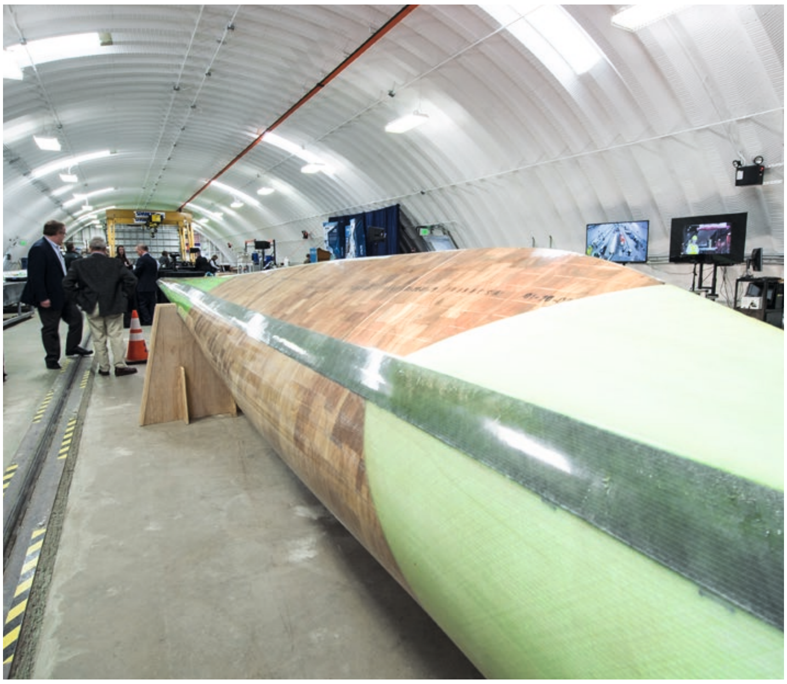
- **Mobile recycling at FLAXRES:** The high costs and emissions related to transporting discarded modules are a problem. The company is trying to remedy the situation with mobile recycling plants. Here, glass and aluminium frames, which account for the largest share by weight, are separated on-site and recycled in local plants. The hard-to-separate materials, such as silicon, which only make up a small part of the total weight, are then transported to special

recycling plants where they are separated by short, high-intensity light pulses. This form of recovery is only economically viable on a larger scale and therefore, unlike glass and aluminium recycling, cannot be implemented on a decentralised basis.[64]

- **Moving up the recycling chain with ROSI Solar, France:** Since 10 to 13 percent of the global annual production of silver goes into solar plants but is not recycled, the engineering start-up from Grenoble has decided to develop new recycling and upcycling processes for discarded solar panels. Besides silver, the founder explained to us that materials such as silicon and copper are also lost when panels are shredded. At ROSI Solar, materials are to be separated by thermal and gentle chemical processes in order to recover the silicon and silver in a pure and cost-efficient way.

- **PV Cycle Europe:** Independent companies have been founded in Germany, France and Italy with the aim of establishing and expanding the region's recycling network. For example, PV Cycle Germany enables manufacturers and importers of e-products and batteries to deal with waste easily by offering WEEE-compliant collection points, relieving them of administrative and operational tasks. At the same time, PV Cycle advises ministries and authorities on improving legal requirements and supports market platforms for second-hand modules.

- **Wooden rotor blades from Voodin Blade and Stora Enso:** As an alternative to the barely-recyclable rotor blades made of carbon fibre and glass fibre composites, the Finnish company Stora Enso has developed wind turbine blades made of veneered wood with the German start-up Voodin Blade. A prototype with 20-metre-long blades is currently under construction and is said to be both more recyclable and lighter than the competitors' products made of composite material.[65]



Wind turbine blades made of wood could make wind turbines more sustainable. Photo: Dennis Schroeder, NREL

Demands: Raw Materials Transition – Now!

Raw Materials Transition Now

The expansion of wind power and solar plants will increase massively in the next few years. This will result in a change in material flow. Fossil-based raw materials, such as coal, crude oil or natural gas will be needed in much smaller quantities, while there will be a shift in demand for metals and other raw materials. Some raw materials will be needed in larger quantities than today's fossil-based infrastructure. The changes in demand are associated with two major challenges. On the one hand, a sustainable supply of metals must be guaranteed. Secondly, the amount of electronic waste will also increase massively in the medium term. The longest possible use and reuse of metallic raw materials in PV and wind power plants is therefore an ecological and social necessity, but also a great opportunity to tackle both challenges simultaneously. This requires however that care is taken today to ensure that the design, functionality, production, use and circularity of PV and wind power plants are set up for the future.

Human Rights and Environmental Due Diligence Obligations

In PV and wind power plants, metallic raw materials are used which, in certain circumstances violate human rights and environmental standards during mining. In order to minimise these risks, in recent years various rules and laws have been passed at European and German level. Both the German Supply Chain Act of 2021 and the EU Conflict Minerals Regulation of 2016 already apply to some industry participants. The EU Battery Regulation and the European Due Diligence Rules - both expected to be adopted in 2023 and 2024 respectively - complement these rules. The Conflict Minerals and Battery Regulations define very specific requirements that apply to the use of certain raw materials by companies.[66] The Battery Regulation also sets recycling and recycled material use quotas and is the first product-specific legislation under the European Green Deal. It is intended to serve as a blueprint for other products. Companies involved in the production of PV and wind power plants would do well to initiate appropriate measures today.

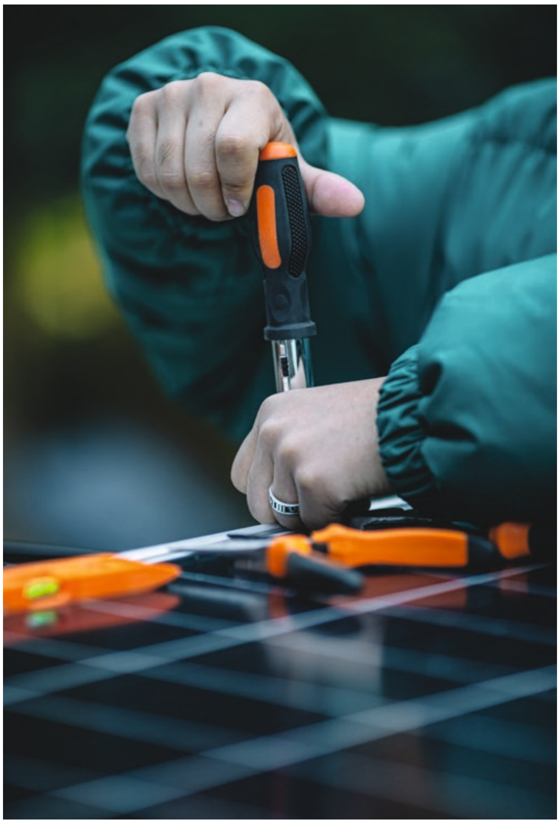
As the German government emphasised in its response to a minor question from the CDU/CSU: "Importers who comply with their due diligence obligations in accordance with the law show increased resilience due to better knowledge of the risks in the supply chain, especially given the current crisis-related reduced security of supply" [67]

The risks considerably increase for mined raw materials when compared to secondary raw materials. This means that the more secondary raw materials are used in a product, the easier it becomes to mitigate risks.

Expanding the Circular Economy

So far, as the EEA writes, moves toward circularity have failed due to the use of non-recyclable composite materials, the use of hazardous substances and low concentrations of valuable elements within individual building components. In addition, logistical problems exist due to remote locations, size and safety requirements.

Political determination and timely adaptation of relevant legislation to expand the circular economy are necessary to advance both supply security, and climate, environmental and human rights protection. While better collection and sorting would certainly help in



Repairability increases sustainability and secures jobs.
Photo: Newpowa, Unsplash

the case of PV plants, decentralised recycling options may be needed for wind power plants. Consideration should be given to creating recycling facilities at locations where wind turbines are used. This would also have the effect of stimulating employment and creating more value in the regions. Furthermore, promotion of environmentally friendly recycling methods would be helpful.

In the Battery Regulation, there are both fixed recycling quotas and recycled material use quotas at a European level. The German government and the European Commission should examine the extent to which comparable quotas can be applied to the recycling of PV and wind power plants. The quotas of the Battery Regulation also apply to companies that import batteries into the European market, i.e., have them produced abroad. This type of regulation could certainly also have effects on the European market.

At the same time, eco-design requirements must be expanded and strengthened. On the one hand, products recycled at the end of their life cycle must contain as few different substances as possible, dispense with complex and difficult-to-separate mixtures and alloys, and be easy to break down into their individual parts. On the other hand, substitution research and the use of more ecological materials must be promoted in order to replace hazardous and poorly recyclable materials.

So far, one of the biggest obstacles to better circular management of PV and wind turbines is the lack of collection infrastructure. Without sufficient material input, no functioning recycling and remanufacturing infrastructure can emerge. To prevent illegal exports and improper disposal, products must be registered when they are placed on the market and their whereabouts monitored after the end of their life cycle.

More public collection points are needed, as well as sufficient information for private and commercial operators of solar and wind power plants on proper disposal. Collection and recycling must be as decentralized as possible in order to reduce transport costs and emissions and – where ecologically sensible due to scaling effects – be supplemented by centralized structures. In addition to public collection points, manufacturers must be held responsible for taking back their products at the end of their life cycle and either reprocessing or recycling them. With the expected price increases of critical raw materials, manufacturers would even benefit from creating a constant source of valuable secondary materials through take-back. In France for example, the state-approved collection agency (Soren) has already collected 18,000 tonnes of end-of-life scrap from solar modules between 2015 and 2021 and redistributed it to recycling companies through a tendering process.[68]

While recycling will play an important part, the real core of circular economy lies in measures before it even comes to that. Though the use of recycled materials is usually less material and energy consuming than primary materials, it is not neutral. That's why a stronger focus needs to be put on prolonging the life cycle, e.g. by refurbishing and reusing functioning solar panels that may be replaced by newer more efficient models. Wind turbines should become more modular to make them easier to repair and to upgrade later on. Producers need to be accountable for dealing with their products at the end of its life to create incentive to design them as long-lasting and repairable as possible. Product passes are needed to ensure the tracing and management of material streams as well as making products more transparent to consumers.

In order to be able to implement all these requirements in the limited time available, politics, research, civil society and industry must work together.

We need a clear political and legal framework that set a visible course, provides orientation, informs about the state-of-the-art and which is as coherent and uniform as possible across the EU. Inter-industry guidelines for the structuring of efficient collection, separation and value-added processes must be implemented.

It must also be clear, however, that we cannot recycle our way out of the current crisis in order to meet the challenges of climate change and the upcoming shortage of raw materials. In addition to improved circularity, we must reduce our material footprint and thus the absolute consumption of raw materials.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p.8 **Figure 1**
Metal requirements for selected energy technologies in g per MWh, Own depiction, data by the Luxembourg Institute of Science and Technology (LIST) on behalf of UNECE (2021): Life Cycle Assessment of Electricity Generation Options. United Nations Economic Commission for Europe

Figure 2
Demand for critical raw materials for selected energy technologies in g per MWh, Own depiction, data by the Luxembourg Institute of Science and Technology (LIST) on behalf of UNECE (2021): Life Cycle Assessment of Electricity Generation Options. United Nations Economic Commission for Europe

p.12 **Figure 3**
Leveraging circular principles during the life cycle of metals, Source: Metabolic Institute, Copper 8, Polaris Sustainability & Quintel (2021): Exploring solutions to mitigate surging demand for critical metals in the energy transition. Online: *circulareconomy.europa.eu/platform/sites/default/files/metaboliccopper8_report_towardsacircularenergytranstion_en_v04_su-lr.pdf*

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p.14 **Figure 5**
Comparative CO_2 savings (in %) of metals and their recycled material, Own Depiction. Source: Gregoir, Liesbet (2022): Metals for Clean Energy. Pathways to solving Europe's raw materials challenge. KU Leuven.

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