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THE ROLE OF CRITICAL METALS IN THE ENERGY TRANSITION, THEIR SUBSTITUTION, REUSE AND DESIGN FOR RECYCLING: ONLINE INFORMATIVE AND EDUCATIONAL RESOURCES[i]

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Abstract:
The article presents informative and educational resources, downloadable for free on the internet. They deal with the mitigation of environmental, social, economic, and supply problems related to the increased demand for the so-called critical metals. These latter are more and more required for the technologies involved in energy transition, such as photovoltaic and wind turbines. But extraction and processing of these materials are often concentrated in a small number of countries, which intensifies the uncertainty of supply. In some cases, these critical metals can be recovered thanks to recycling, or can be substituted, or the whole process can be modified; often the products can be repaired and reused. These actions can mitigate the sharp increase in the demand for critical metals. Modern products are increasingly complex, with a large variety of different metals in close proximity to one another, which makes more difficult separating and recycling materials constituting an end-of-life product. This is particularly true for electric and electronic equipment, which also contains critical metals. Several documents quoted hereafter provide information about how to create products that at end-of-life are easy to dismantle, and the separation of materials for recycling is neither costly nor dangerous. This is the so-called design for recycling. The infinite growth required by our economic model implies production and consumption constantly increasing, which results in large energy and materials usage. This situation, intensified by the planned obsolescence of the products, contributes to the depletion of the limited resources of our planet, and to the social and environmental crisis that we are experiencing. Reuse and repair may extend the useful life of the products that we use, and decrease the consumption of new products and of materials utilised in their production, while reducing waste and creating jobs. Governments and the whole of society can help in this transition favouring the production of durable and repairable goods.

[i] I METALLI CRITICI NELLA TRANSIZIONE ENERGETICA, LA LORO SOSTITUZIONE, IL RIUSO DEI PRODOTTI, IL "DESIGN FOR RECYCLING": RISORSE EDUCATIVE ED INFORMATIVE ONLINE
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Keywords: online informative and educational resources, critical metals, planned obsolescence, energy transition

Riassunto:
L'articolo presenta risorse informative ed educative sulla possibilità di attenuare i problemi economici e di fornitura connessi con l'aumentata richiesta dei cosiddetti metalli critici. Queste risorse sono scaricabili gratuitamente da internet. Questi metalli sono sempre più richiesti per le tecnologie coinvolte nella transizione energetica, usate ad esempio negli impianti fotovoltaici ed eolici. Ma l'estrazione e la lavorazione di questi metalli sono spesso concentrate in pochi paesi e ciò intensifica le incertezze sulla loro fornitura. In alcuni casi, questi metalli critici possono essere riciclati o possono essere sostituiti con altri materiali, oppure, l'intero processo può essere modificato. Altrimenti, i prodotti che usiamo correntemente possono essere riparati e riusati per prolungarne il periodo d'uso. Tutte queste azioni possono attenuare il rapido aumento della richiesta di questi materiali. I prodotti moderni sono sempre più complessi, e vi troviamo una grande varietà di metalli diversi molto vicini tra di loro; ciò rende più difficile separare e riciclare i materiali presenti nei prodotti arrivati alla fine del periodo d'uso. Ciò riguarda in particolare apparecchi elettrici ed elettronici, che pure contengono metalli critici. Molti documenti citati nell'articolo informano su come creare prodotti che, a fine vita, siano facili da smontare e dove la separazione dei materiali sia non costosa e non pericolosa. Questo è il cosiddetto "design for recycling". La crescita continua richiesta dal nostro sistema economico implica produzione e consumi in continuo aumento; ciò comporta l'utilizzazione di grandi quantità di energia e materiali. Questa situazione, intensificata dalla *obsolescenza programmata* dei prodotti, contribuisce all'esaurimento delle limitate risorse del nostro pianeta, nonché alla crisi sociale ed ambientale che stiamo vivendo. Il riuso e la riparazione dei prodotti può prolungarne la durata e diminuire il consumo di nuovi prodotti e dei materiali usati nella loro produzione. Ciò contribuisce a ridurre la produzione di rifiuti e *creare posti di lavoro*. I governi e l'intera società possono facilitare questa transizione preferendo la produzione di beni durevoli e riparabili.

Parole chiave: risorse informative ed educative online, metalli critici, obsolescenza programmata, transizione energetica

1. Aims of the teaching unit

The article presents informative and educational resources on the web that may increase knowledge and awareness regarding the energy transition and the circulation of the materials involved in its realisation. Adequate strategies can mitigate some social and environmental problems while providing jobs for the young generations.

2. Materials and methods

The educational resources presented in this paper consist of text, graphs, tables, videos and images. Such resources, downloadable for free, can be used by the teacher with the method felt as the most appropriate. The content of the article, unless otherwise noted, is derived exclusively from the quoted documents.

3. Introduction

The 2015 Paris Agreement implies the commitment of the countries to *reducing emissions of greenhouse gases* and, in this century, pursuing efforts to limit the increase of global average temperatures to 1.5°C above pre-industrial levels (1). This may also imply the use of modern technologies, such as photovoltaic and wind turbines, and use of electricity in transport and heat applications (2).

Considering the complete lifecycle, for instance, the greenhouse gas emissions of electric vehicles are lower than in conventional cars, and with a *potential for a further reduction, if a low-carbon electricity is used* (3). The deployment of clean technologies, as a part of the energy transition, implies a significant increase in the demand for certain minerals, generally called *critical metals* (3 graph page 6).

Neodymium and dysprosium are used for the permanent magnets of both wind turbines and electric vehicles. Large amounts of silver and copper are used in solar energy technologies. Lithium is an important component in batteries for both electric vehicles and energy storage systems (2 Figure 7.1).

"Critical Metals in Strategic Energy Technologies" is a 2011 EU document. Chapter 4 provides quantitative estimates regarding the metal requirements for energy transition (4); tables 5/6/7/10 deal respectively with photovoltaic, concentrated solar power, wind energy, and biofuels. In this study, biogas and biomethane are not included among biofuels.

Table 7.1 (2) shows the demand in 2021, and the projected 2050 demand for certain critical metals. We may observe, inter alia, the sharp increase regarding lithium and neodymium. Figure 7.2 shows the price increase of five critical metals in 2021; we can observe the lithium increase of nearly 500%, consequent to sharp growth in the demand for electric vehicles.

In 2011 the price of neodymium, used in wind turbine production, went up six-fold (5> 1.2.3 Materials Shortage?).

Table 7.7 (2) shows the supply and demand balance for copper, lithium, neodymium, nickel and dysprosium. *The demand for this latter is projected to be 3.5 times higher than supply by 2030*; in this case, for instance, alternatives will be required.

A document of the International Energy Agency provides the European list of raw materials that, while being strategic to the EU economy, have a high supply risk (6).

3.1 Risks inherent to the supply of critical metals

The mines where these materials are extracted, as well as the processing, are often concentrated in a small number of countries, which may intensify the uncertainty of supply (3 page 13).

Mining assets can be exposed to climate risks; this is particularly true for copper and lithium given their high water requirements. In fact, certain areas are exposed to extreme drought, heat and flooding, which constitute challenges in ensuring a stable supply (3).

A table summarises the effects of mining on people and biodiversity; the text provides information on health and safety risks for both workers and public (3 pages 232-235-211).

A document of the International Energy Agency shows public reports of governance-related risks according to mineral supply chain and region (7 figure 4.19 / 3). Inter alia, we can read: corruption, non-state armed groups, human right abuses, and *child labour*.

"Study on the EU's list of Critical Raw Materials (2020) Final Report" is intended to flag the supply risks of important materials for the EU economy (8). In EU, about 30 million jobs rely on access to raw materials.

"Renewable Energy and Jobs – Annual Review 2021" is a document of the International Labour Organisation; the reader might be interested in figures 1-7-12, table 2 and Chapter 3 (9).

A video deals with the European situation (5> 1.2.1 CRM's in products).

3.2 Environmental impacts linked to the production of critical metals

The extraction of critical metals may imply environmental impacts regarding biodiversity reduction, CO2 emissions, water and soil contamination. For instance, the production of one tonne of Rare Earth Elements (REEs) results in 2,000 tonnes of toxic waste, including 75 cubic metres of wastewater and 1 tonne of radioactive waste (2).

Most of the nickel supply is sourced from Indonesia. Here, mining and refining imply a higher pollution than elsewhere because electricity is produced by coal-powered plants; in this country, decarbonising the production is an important challenge (2).

The production of copper is associated with arsenic pollution, this element is contained as an impurity in the ore and can seriously contaminate air and water; this happens in areas affected by water scarcity in South America (3). Sometimes, the waste from mining activities is linked to environmental disasters. The declining ore quality observed in Chile and the consequent increased arsenic pollution, results in a considerable increase in waste amount, energy cost and greenhouse gas emissions.

Some graphs provide information on use and pollution of water for selected minerals. Mining is an important water user and may cause long-lasting water pollution (3 pages 214-215-216).

A video provides more information on the risks (5> 1.2.2 Mining CRM's).

When a mine is closed down improperly, after utilisation for mining, it can live a negative legacy for society and a lasting environmental impact. Interestingly, in most Australian jurisdictions, the *approval of a project for mining activities also requires that the post-mining land use planning is incorporated in the project design*. This includes measures aimed at minimising disturbance and contamination, thus *enabling subsequent use of the environment for present and future generations* (3 Box 4.2).

3.3 Substituting the critical metals

The so-called stock of material in use is increasing and, over time, it will be available for recycling. But, since a large part of this material is used for durable products, the amount of metals available for recycling is smaller than the annual consumption, especially if we consider that the rate of metal use is growing (10 / 11 figure 1.4).

For instance, since wind turbines arrive at end-of-life in 30 years, clearly, the material employed in their construction will not be available for recycling in the short term (5> 5.5.1 Substitution of materials).

"Substitutionability of Critical Raw Materials" is a document requested by the European Parliament's Committee on Industry, Research and Energy (12). The atlas in Figure 1 shows the top supplier countries of critical raw materials. Table 1 provides a summary on critical raw materials and their applications; for many of these metals, recycling and/or research for replacement materials should be supported. From page 20, we can read a detailed overview of critical raw materials; the document includes a rich reference. For instance, the total world production of indium is 75 tonnes per year; for this element, Europe depends almost completely on imports (12).

Interestingly, Japan, *thanks to a well-developed recycling system* was the *second world producer of indium*, although not having natural reserves of this element (13).

"A Guide to Substitution" is a 2010 document retrieved in the National UK Archives. It contains general principles and examples that may guide the substitution of materials, which should be based on a life cycle study, so as to solve problems without creating new ones. The document discusses the requirements a substitution must satisfy, for instance: functionality, compatibility and availability. Clearly, the knowledge of the properties of the substitute must be deep enough to avoid nasty surprises (14).

"Substitution of critical raw materials in low-carbon technologies: lighting, wind turbines and electric vehicles" is a 2016 document whose content is summarised by the title (15).

Electricity networks use about one third of the copper worldwide (2). In some cases, aluminium can replace this metal, for instance for underground cables of onshore wind power installations.

Substitution is aimed at finding an abundant material that may be substituted for another that is scarce. In some cases, the whole process or the product, or the service has been modified, e.g. when digital photography replaced traditional film based on products provided by the chemical industry (12).

Another example of a whole product that has been changed, and not only a substance, is the replacement of vinyl LPs by more recent products (14).

According to "Small-Size Biogas Technology Applications for Rural Areas in the Context of Developing Countries", *this production of energy is based on low-cost technology that relies on local materials. The biogas digesters are simple to operate and maintain* (16 / 17). The construction of small biogas digesters has been supported in many Asian, African and South American countries.

According to a 2020 document of the International Energy Agency, biogas and biomethane exhibit enormous potential in contributing to the clean energy transition. *The full utilisation of, e.g. animal manure, crop residues, municipal solid waste and wastewater could cover 20% of the global gas demand* (17). A graph on page 6 compares the actual production of biogas and biomethane, and the sustainable potential, which is clearly much bigger. Two documents including text and video deal with anaerobic digesters (18 / 19).

3.4 Critical metals recycling

According to a 2012 document, REEs are very difficult both to recycle and to substitute, although some replacements have been reported. Table 2 (12) deals with typical applications of REEs.

A document (20) provides the point of view of a French private company on recycling REEs.

A video shows an Italian experience on the semi-industrial production of REEs from old TVs, LCDs, electronic appliances and fluorescent lamps (21).

A graph shows the projected surge of lithium-ion spent batteries used for electric vehicles and energy storage, which suggests immense scope for recycling (2 page 16 / 3 page 15).

Figure 7.14 (2) shows the projected cumulative waste from solar photovoltaic projects through 2050; box 7.2 deals with end-of-life management of solar photovoltaic technology.

While recycling practices are well established for other metals, this does not apply for some metals involved in the energy transition, such as REEs, because of limited collection and technical constraints. A graph shows today's recycling rates (3 page 34). We can observe that gold and platinum are recycled at high rates, thanks to their value which encourages collection and recycling.

Half of the used copper is currently wasted; for this and other metals, policies aimed at increasing recycling could help to reduce demand and supply risks (2).

Recycling provides benefits that extend well beyond the availability of certain metals. Recycling has an important role in the reduction of CO2 emissions, thanks to the lower energy consumption in producing from recycled than from primary materials (22 page 4 / 11). For instance, the reduction in CO2 emissions is 58% for ferrous materials and 99% for tin and lead.

Figure 2 of "Metal recycling: The need for a life cycle approach" shows the energy saved thanks to recycling selected metals (23).

Metal recycling, in addition to the environmental and economic benefits, may support ethical sourcing of the materials, for instance ensuring that they do not originate from war areas (24).

Most metals can be recycled many times provided that: the products have been designed according to a right choice of metal combinations, they are properly assembled, product collection is optimised, and a high level of recycling technology is available (11).

While there are 5 grams of gold per tonne of ore, as many as 200-250 grams per tonne are found in computer circuit boards (24). While in most mines that produce platinum-group metals the concentration of these latter is lower than 10 grams per tonne, certain parts of an automotive catalyst may have a content of 2,000 grams per tonne.

Table 3.1 (24) provides information on the quantities of metals contained in mobile phones and computers. The net metal value of a single mobile phone at 2011 prices is about 1 euro, which is significant considering their sheer number. Page 43 deals with the amount of platinum group metals recovered and lost from automotive catalysts.

3.5 Metallurgy and separation of critical metals from other elements

A document and a video (25 / 26) provide some basic information and principles of metallurgy; these documents, although not directly related to metal recycling, may help for a better understanding of the subject.

From page 419 of "Critical Metals Handbook" (24) we find a glossary of technical terms.

A video deals with general principles of metallurgy (5> 2.3.1 An introduction to metallurgical processes / 5> 2.3.2 Metallurgical processes for the recycling of metals). A video is entitled "2.4.1 Trade off: grade and recycling rate" (5).

For instance, gold, silver and copper are lost if they go through a steel recycling process, which suggests the *importance of an accurate separation of materials prior to recycling* (24 / 5> 2.1.2 Introduction to recycling - video). A video shows the separation of materials (5> 2.2.1 Pre-processing).

Two videos provide the point of view of people directly involved in recycling activities (5> 2.6.1 Interview with a recycler / 5> 4.3.2 Interview Recupel/Bebat).

"Hydrometallurgical Recycling of Critical Metals from End-of-Life Devices" Contains 9 papers on this subject, published between 2020 and 2023 (27).

"Metal resources, use and criticality" (11), "Recycling of (critical) metals" (24), and "Gallium" (28) are the titles of three chapters of "Critical Metals Handbook", published in 2014.

According to "Bridging Hydrometallurgy and Biochemistry: A Protein-Based Process for Recovery and Separation of Rare Earth Elements", the achievement of high-purity separation of certain critical REEs, without using organic solvents is possible. The image (29 page 1798) shows that REEs, differently from the others, remain immobilised in the column thanks to a bacterial protein, while the remaining liquid and the other elements are drained off.

Gallium is typically recycled from semiconductor manufacture, and not from post-consumer scrap where it is highly dispersed. Some recycling already occurs from the solar industry but, since the cells that contain gallium are manufactured to be long lasting, *only over time is this activity expected to increase* (28).

Thanks to the fractional crystallisation a 99,99999% purity level can be attained; while gallium crystals grow, impurities cannot contaminate it and remain in the liquid phase (28).

3.6 Challenges encountered in recycling materials

The production of recycled metals starts with the collection of discards, separation and sorting; finally, there are metallurgical processes aimed at producing metal at a purity level high enough to be reused (11).

Modern products are becoming increasingly complex, with a large variety of different metals in close proximity to one another (10 graph in figure 4). This may result in end-of-life scrap with many materials mixed together, which may lead to more and more impure recycled products. Metallurgical technology can deal well with *thermodynamically compatible materials in close proximity,* but this implies that the products need to be designed with recycling in mind (10). When certain metals are mixed, their separation is not always possible, from both economic and thermodynamic points of view (30).

A product design aimed at creating durable products whose disassembly is easy, and with materials appropriately combined, may reduce unrecycled residues. Text and figure 3.2 (24) deal with sustainable use of metals along product life cycles.

Dismantling and pre-processing are based on manual and/or mechanical processes, often combined. Most metals contained in an automotive catalyst, or a lead-acid car battery, or a computer motherboard are *recyclable provided that they have been dismantled before the car is put through the shredder*. Conversely, without prior dismantling, the percentage of silver, gold and palladium that could be recovered would be only between 12% and 26% (24).

In modern cars new challenges are found; in fact, here we find many electronic components scattered throughout the vehicle. Nowadays, their manual dismantling is not feasible at competitive cost, while the current shredder technology does not allow the recovery of the metals that electronic components contain (24).

For a correct recovery of the REEs that constitute magnets, the removal of these latter is essential before any shredding process. In fact, this material is very brittle and the shredding process would transform the magnet into a lot of small pieces that stick to any iron surface, thus becoming not accessible for recovery (24).

Metals are also lost as a consequence of wear and corrosion during their useful life. Certain elements are found in a very dispersed state, and cannot be recovered (11).

While the recycling of a dismantled automotive catalyst is economically viable, this does not apply to a liquid-crystal display screen coated with indium–tin oxide, unless it is subsidised (24). When the technology for recycling is not yet available, waste containing valuable materials can be stockpiled, while waiting for the availability of the necessary technology.

A video deals with the environmental challenges of pyrometallurgy and hydrometallurgy and their mitigation (5> 2.4.2 Environmental issues).

A video provides more information on this subject (5> 4.4.2 Redistribution).

The main issues posed by e-waste are: their huge amount consequent to high demand and rapid obsolescence, their high toxicity, lack of regulation, their complexity and poor design (31).

A website of the Delft University of Technology provides several videos on waste management and critical raw materials (5). The videos present solutions aimed at preventing pollution from critical metals and scarcity of these materials. They consist in making products that we can reuse or recycle. The circular economy focuses on reuse and repair (5> 1.1.1 Introduction: Urgency and challenges with CRM and waste).

Two videos explain the concept of industrial ecology, exemplified by a Danish industrial park, located in Kalundborg (5> 1.4.1 New material philosophies / 32).

In Europe, the Waste from Electrical and Electronic Equipment Directive stimulates the recycling of these products, but its enforcement is often weak. Deposit funding systems may incentivise people to hand back end-of-life devices into a recycling chain (24).

3.7 International movements of e-waste

Metallurgical metal recovery may include smelting, and hydrometallurgical or chemical processes; finally, there is a step aimed at metal refining. Volatile elements, such as mercury and cadmium, go to the off-gas stream; many recovery plants are not adequately equipped to prevent such toxic emissions. The paper also deals with legislative aspects concerning international movements, sometimes illegal, of re-usable products and of waste (24).

Often, cars containing catalysts are exported into countries without infrastructure for recycling the technology metals, which may result in their loss. Such products, sometimes exported illegally, may not enter the recycling chain, or are processed according to inappropriate technologies (24 / 31).

"The global impact of e-waste: Addressing the challenge" deals, inter alia, with international conventions and national legislation in selected countries aimed at the control of illegal movements of e-waste (31).

A video deals with legislative aspects in Europe (5> 2.5.1 Legislation recycling).

3.8 The design for recycling

A high percentage of e-waste is illegally traded or dumped every year. The papers include maps showing the main routes of the illegal shipments; a video deals with e-waste management in Nigeria (33 text and video / 31).

A 2009 video shows *children salvaging metal from discarded computers and televisions, working in unhealthy conditions,* in an African village where e-waste was exported (34).

A video deals with e-waste management in Switzerland. Here is a high collection rate, thanks to a convenient take back system. According to Stengele M., head of Quality, Environment and Safety, *the producers should provide information for a safe removal of lithium-ion batteries because they can self-ignite* (35).

An US video shows a facility where the end-of-life devices undergo activities aimed at their reuse, repurpose and, *as a very last resort, recycling*. According to the video, *recycling electronics is not easy since these products are not designed for it*. Such devices, from the design stage, should be created to be safer and easier to dismantle and to break down; furthermore, they should not contain toxic materials (36).

In conclusion, according to the videos (33 / 35 / 36 / 34), the management of e-waste is costly, unhealthy and dangerous.

"How to Design for Disassembly and Recycling" explains the basic concepts of design aimed at creating products that, at end-of-life, are easy to dismantle and recycle or repair or upgrade (37 video).

"Guide to Design for Disassembly: How to implement it" is a document of a social platform and online collaboration system. According to the document, nowadays *only machines can manufacture and assemble most of our electronic devices*. The document provides tips for creating products that can be easily repaired or upgraded or recycled, e.g.: *use standard components and durable enclosures, avoid glues, and provide repair documentation* (38). A website provides information on Life Cycle Analysis, design for reuse, repairability and dismantling (39> Eco-design tools).

Depollution/pre-treatment may imply recovery of fluids, manual removal of power cables and weights; as a next step, the products are crushed for recovery and recycling of materials. The document proposes an improvement plan aimed at, e.g. facilitating access, identification and removal of components (39> Products> Air-conditioner / 39> Products> Washing machine).

After grinding the products and magnetic sorting of the resulting scrap, thanks to its different density aluminium is separated from other materials using heavy liquids, as shown in the graph. But, in the case of washing machines which have a *concrete ballast,* the treatment with heavy liquids is not effective in separating *aluminium and concrete*, because of their similar density. This implies further costs for separation; a *cast iron ballast* prevents this inconvenience (39> Materials> Aluminium).

In the heat exchanger of the air-conditioner, there is an assembly of materials that are not compatible with each other for recycling: aluminium and copper. *Grinding these parts does not separate the materials; for better recycling the parts should be constituted by a single material* (39> Products> Air-conditioner). Again, according to the document, inter alia, *the spare parts of air conditioners should be available* over a period of time compatible with the life span of the product.

In some cases, fasteners could be chosen that break during grinding thus liberating the different materials, which clearly allows their separation (39> Products> Air-conditioner).

In cell phones, only the battery is removed before grinding. Inter alia, access to the battery and recovery of precious metals could be improved, and the chargers need to be standardised (39> Products> Mobile phone).

The document provides some examples regarding the strategic metals found in printed circuit boards. Here, steel used as a heat sink, thanks to magnetic sorting, is easier to separate than aluminium, and for this reason is more suitable (39> Materials> Strategic metals).

In order to recover precious and semi-precious metals, cards with tiny components should be removed before grinding. In fact, they are not compatible with grinding operations of household appliances since they would end among dust and other impurities that are not recycled.

According to "The importance of design in lithium ion battery recycling – a critical review", nowadays lithium ions batteries are designed without recycling in mind. This 2020 document suggests some improvements that can make disassembly and separation of materials easier (40).

3.9 Reducing the contamination of metals

Ferrous materials are widely recycled; the presence of residual metals that cannot be separated by metallurgical processes, such as copper and tin, worsens the quality of steel. For this reason, products should be so designed as to avoid the tangling of copper with steel, as shown in the image of an engine before and after entering a shredder (39> Materials> Steel). For similar reasons, tin associated with steel, such as in tinplate, should be avoided. Other chemical elements shown in the table, if not separately recovered, are less harmful for the quality of the steel. However, such chemical elements are lost during the metallurgical processes, which is not good. Another consideration is that the *presence of large pieces of steel can damage the shredder*.

A table deals with the influence of metal contamination on the properties of aluminium. The design for recycling avoids the close association of aluminium with these metals, in order to avoid the aforementioned inconvenience, as observed in the bi-material heat exchanger (39> Materials> Aluminium).

Mixing of different aluminium alloys results in a poor quality recycled product. For this reason, a visible marking on the back of the part indicating the quality of the alloy would be useful to avoid improper mixing of materials (39> Materials> Aluminium).

3.10 Extending the life of products to reduce resource consumption

Planned obsolescence was invented in the US to stimulate the economy during the great depression. The basic idea was that the sooner products break, the sooner people buy new ones and, for instance, filament light bulbs and nylon stockings were made thinner to last a much shorter time (41 video / 42 video).

This planned obsolescence reduces the durability of products in several ways: they break easily and cannot be repaired or, over time, their appearance is no longer fashionable or dysfunctionalities may occur (43 video).

The infinite growth required by our economic model implies production and consumption in constant increase. But *this system contributes to the depletion of the limited resources of our planet, and causes the social and environmental crisis* that we are experiencing (43 video).

Some videos examine several end-of-life alternatives aimed at extending the life of a product, which provide social benefits, reduce raw material use and energy consumption (5> 3.1.2 Introduction to remanufacturing, refurbishment and recycling / 5> 5.2.1 Product design in relation to recycling / 5> 5.1.2 Introduction to product design).

Remanufacturing transforms a used product to like-new conditions, providing the same or better performances, and a warranty as a new product (5> 3.2.1 Remanufacturing).

Refurbishment restores the functionality; the product is tested to function properly and guaranteed to be defect-free. In certain apparatuses for health care, the warranty covers for 1 year all the appliances, and the *availability of spare parts for at least 5 years is guaranteed* (5> 3.2.2 Refurbishing).

Reuse is very well known and often results from second-hand product sales without any operation on the items. Whereas, *repurposing* is more complex because this implies a reuse in a different application, and will target a new market; this is a new business model and implies the consideration of legal aspects. A relevant example is the repurposing of batteries no longer suitable for use in electric vehicles; they can still be useful in storing surplus electricity produced by wind turbines and photovoltaic panels (5> 3.2.3 Re-use and repurpose).

According to Dr. Muenzen, researcher, a battery that cannot continue powering a car, can be used 6-7 years more for powering a home (44 Video).

A video deals with marketing of re-products (5> 3.3.1 Market Re-products).

3.11 Examples of sharing economy

In the traditional economy when a person needs a drill for a DIY project, he has to buy it and after the use he may store it for a long period until the next usage, if any. Scaling this situation across an entire population, we can imagine the amount of critical materials that are sitting unused. Conversely, a sharing platform might allow people to rent the drill at a daily rate. The same applies for cars or many other goods that people, thanks to a platform, could find and use easily and economically (5> 6.2.1 Sharing platforms).

An Australian video shows the community laundry where the residents, inter alia, share the washing machines (45).

3.12 Making the most of batteries

Generally, electric vehicle charging is performed in a uni-directional mode where the energy flows from the grid to the car, and cannot flow in the reverse direction. *This uni-directional charging, potentially uncoordinated, may lead to simultaneous concentrated energy demands* (46).

Conversely, in Utrecht many charging stations are bi-directional, they can provide energy to and receive it from vehicle batteries (47). Several car models can already utilise such bi-directional chargers for *vehicle-to-grid* or *vehicle-to-home* technology.

According to Sturmberg B., Research leader of the Australian National University, the energy contained in the battery of an electric vehicle can meet the electricity requirements of an average home over 2-4 days (48).

According to "Utilization of Electric Vehicles for Vehicle-to-Grid Services: Progress and Perspectives", when electric vehicles are parked, the integration of their batteries with the grid may offer economic and environmental benefits (46 / 3). Figure 1 (46) illustrates the bi-directional energy flow in different times of the day, which is a *solution to grid congestion and circumvents the need to upgrade the grid infrastructure*.

The storage capacity of a lot of batteries is an effective tool to manage the volatility of a grid where much energy is from renewable sources (49 Video).

"How does Vehicle to Grid (V2G) work?" is a video that may help to learn (50).

The paper (46) provides indications aimed at avoiding a reduction of the battery life span, which an improper management of recurrent charging and discharging cycles might cause.

Dr. Priestley, an Australian expert helps to *learn about safety concerns regarding lithium-ion batteries*, that now are very little regulated (51). Inter alia, overheating and physical damage of these batteries may lead to problems.

3.13 The extended producer responsibility

According to this policy, *the producer is financially responsible for his own products when they arrive at end-of-life*. This may create incentives for an environmentally-conscious design of products, in terms of reduced use of hazardous materials, enhancement of components and materials reuse, and easy recycling (52 / 53> What is Extended Producer Responsibility? – Video).

"Extended Producer Responsibility - A Guidance Manual for Governments" is an OECD document. According to this paper, an *important function of this policy is the transfer of the cost of waste management from municipalities and general taxpayer to producer and ultimately to consumer* (54). In fact, *when the cost of end-of-life management is incorporated in the price of the product itself,* the true environmental impact of the product emerges, and the consumer may choose accordingly. Box 1 deals with the benefits of the extended producer responsibility.

An environmentally-conscious design of the products is obtained, e.g. thanks to a reduced number of screws and unification of the materials used in the components, *marking of plastics* and use of plastics that at end-of-life can be recycled instead of down-cycled. Tables 3-1 and 3-2, and figure 3-1 (52) provide some examples. *Several car manufacturers provided their designers with the opportunity to learn about dismantling their products, which suggested improvements for their design activity* (52 pages 15 and 21).

Changes aimed at facilitating the end-of-life management should not increase impacts in other phases of the product life cycle. Producers may choose how to exercise these responsibilities, provided that the required occupational health and safety are guaranteed (52).

The first image of a document shows in a simple way the basic concept of the extended producer responsibility (55).

3.14 Reuse, repair, remanufacturing, recycling and jobs

Box II.4-8. (56) is entitled "Remanufacturing at Xerox"; the products of this company are designed with remanufacturing in mind, and most of the product at end-of-life can be rebuilt. This has kept at least half a million of tons of electronic waste out of landfills between 1991 and 2001. Box I.3-1. (56) explains how a company, that transitioned *from selling to leasing* office carpets, is saving as much as 80% of the material. The company created more durable materials, and used carpets could be completely remanufactured into new ones.

Notoriously, leasing implies that the manufacturer or the retailer sells the access to the function of a product, while remaining owner of it, and takes it back at the end of the useful life of the product (24).

Table ES-4 provides selected employment estimates in the recycling sector. Table I.3-1. deals with employment implications of durable, repairable, and upgradable products (56).

Envie is a network aimed at creating job opportunities in repairing electrical and electronic products for young people. According to the article, a metric ton of waste can generate 30 jobs when the materials are sorted and recycled, or 85-130 jobs if the products are reused. Conversely, a metric ton of waste buried or incinerated can generate respectively just 1-3 jobs (57> Repair, Reuse and Job Creation). According to Raillard J-P, Chairman of Fédération Envie, cities and regions can play an important role in enhancing waste reuse and management.

According to a 2019 United Nations report, the world produces as much as 50 million tonnes per year of electrical and electronic waste, while only 20% of it is formally recycled. This global e-waste is expected to reach 120 million tons a year by 2050 (58).

The Green Alliance estimates that a greater UK government ambition to expand the circular economy, could help to create as many as 472,000 new jobs by 2035 (59). This could be possible thanks to increasing remanufacturing by 50%, growth in servitisation, recycling and repair work. This would require, for instance, reducing VAT on repairs and refurbishment, and supporting workers transitioning into the circular economy.

At the same time, strategic funding aimed at the creation of new courses, central to the circular economy, should be provided to universities and colleges. *Increasing visibility and awareness about the circular economy among young people is important* (59).

Repair Café is an international foundation based in Amsterdam, whose aim is to make repair a part of the local community once again. It aims to maintain and spread repair expertise. This website may also help people to find or to start a Repair Café, as well as to find a repair guide (60).

"Europe, Let's Reuse Refurbish Repair" is a coalition of European organisations pushing for system change: the product should be designed for repair and last longer, and the repairer should be supported (61). In the website we find a video that explains the aims of the movement, and a link dealing with success stories of financial incentives to make repair affordable. In some parts of Austria and Germany, citizens are refunded up to 50% of the total cost of repair, which supports local business while reducing environmental degradation. Other European countries have reduced taxation on small repairs; some links provide more information.

Energy transition requires a steady supply of critical materials; according to the International Renewable Energy Agency, *governments are expected to play an active role, not leaving all responsibility to the market alone* (2).

The study on the negative or *positive* consequences of using renewable energy sources are beyond the scope of this article. A few documents on this subject are quoted, however (62 / 63 / 64 Video / 65 / 66).

Conflict of Interest Statement

The author declares no conflicts of interest.

About the Author

The author is a former middle school teacher, and wrote about 70 educational papers starting 36 years ago. Areas of interest: Health Education, Environmental Education and Prevention of Natural Disasters. The author has a University Degree in Biology.

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